A Case Study of a GIS Model for Steep Slope Risk Management

Mitchell Jones

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Supervised by: Prof Rien Visser

NZ School of Forestry, Christchurch, New Zealand

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"Every situation, no matter how complex it initially looks, is exceedingly simple."

Eliyahu M. Goldratt, The Goal

Abstract

Brief background

Slash mobilisation in New Zealand forestry has been recently brought into the public eye. There is pressure to manage the risk of steep slopes better. Several tools have been developed to quantify the risk these areas pose. This report provides an overview and testing of one of those tools.

Overview of the tool

The "Catchment Risk Matrix" is a model within ArcGIS Pro that uses elevation data to assess the risk posed by each catchment in an area using catchment size, slope, and the Erosion Susceptibility Classification (ESC). This model is then used to drive operational restrictions within high-risk catchments.

What was done and found?

A case study for three Gisborne sites was conducted to test the Catchment Risk Matrix.

The tool was run using a variety of Flow Accumulation Thresholds (FAT) at two of the sites and using different Digital Elevation Model (DEM) resolutions at all three of the sites. It was found that changing the DEM resolution had the biggest impact on the Slope Code parameter and changing the FAT had the biggest impact on the Hazard Code.

The tool was easy to use and presents a useful example for how companies can manage risk with the use of Geographic Information Systems (GIS).

An example is also presented where the model was expanded to include other parameters based on Rayonier Matariki Forest's Slash Mobilisation Risk Assessment system.

Conclusions

Users should be advised of the influence different Digital Elevation Model resolution and Flow Accumulation Thresholds have on the quality of the output from the model. The results of this study should be kept in mind when choosing the FAT and DEM resolution.

There are opportunities for this model to be expanded further but, as it stands, the model provides a good base to build upon. The model was easy to use and worked in a predictable way across the three sites.

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1. Introduction

During harvest operations in New Zealand residues are often built up on landings and in the cutover. When these residues are subject to intense weather events they can move into waterways and have negative impacts. The problem of slash leaving forest sites and causing damage downstream has been understood for some time (Baillie & Cummins, 1999). It has also been well accepted that the clearance of forests has an increased effect on regional land sliding (Montgomery et al., 2000).

Over the past five years there have been a number of storms that resulted in forestry residues migrating downstream. These events had a significant impact on the receiving environment and have highlighted the need for better management in steep, erosion-prone land.

As climate change continues to worsen, this type of storm is going to become more common (MoE, 2023). The forestry industry in New Zealand therefore must adapt and manage steep slopes better to prevent future events having the same result. Failure to do so could result in legal action, further restrictions to the industry, and the erosion of any remaining social license (Miller, 2023).

The National Environmental Standard for Plantation Forestry (NES-PF) recognises the need for harvest plans to identify slash “high-risk areas”. It is necessary to have a way of determining where these high-risk areas are. Within the industry, companies use a variety of techniques to estimate the risk associated with slash mobilisation. However, there is no standardised approach.

A “Catchment Risk Matrix” developed by a company operating in the Gisborne region will be the focus of this study. The Catchment Risk Matrix determines the operating restrictions within catchments depending on their calculated risk.

This report will assess and improve the existing Catchment Risk Matrix for harvest residue mobilization, to help the users of this matrix better understand how sensitive user-inputted parameters are and how they influence the associated risk posed in different catchments.

2. Literature Review

Slash Mobilisation

Since 2018, the issue of slash mobilisation has become more apparent in the mainstream media. On Queen’s Birthday 2018 a large storm resulted in 200mm of rainfall in Tolaga Bay (Kenney, 2018). This event resulted in a huge amount of woody debris migrating downstream and taking out whatever was in its path. Significant damage was done to farmland and houses downstream of forest activities. Public outrage resulted in legal action being taken against the forestry companies.

Severe Tropical Cyclone Gabrielle hit the Gisborne and Hawkes Bay regions on the 13th of February 2023. This storm caused a number of large debris flow events that had a significant community impact. The ministerial inquiry into the damage caused by woody debris stated that forestry has lost its social license to operate in the Gisborne region (MFE, 2023).

On the 23rd of September 2023, the highest rainfall in 23 years occurred in the popular tourism city of Queenstown. A slip on a forestry access road in a recently felled corridor near the Skyline Gondola resulted in a landslide that took woody debris downslope and caused damage to the Queenstown

Cemetery. The Queenstown Mayor declared a state of emergency and stated it was due to the damage caused by this debris (ODT, 2023).

Under Schedule 3 of the NES-PF a harvest plan must identify high risk slash zones within the harvest plan in order to comply with permitted activity restrictions (NES-PF, 2017). An excerpt of this requirement in the NES-PF is shown in figure 1.

5 Harvest plan

The plan must include—

(a) the harvesting method, whether ground-based or hauler, or any other method, and the hauler system type:

(b) the planned timing, duration, intensity, and any proposed staging of the harvest:

(c) the management practices that will be used to avoid, remedy, or mitigate risks due to forest harvesting on features identified under clause 3(3) and mapped, including the slash management and procedures for—

- (i) avoiding instability of slash at landing sites:
- (ii) keeping slash away from high-risk areas (no-slash zones):
- (iii) slash management in the vicinity of waterways, including identifying any areas where it would be unsafe or impractical to retrieve slash from water bodies:
- (iv) measures to ensure that slash is not mobilised in heavy rain events (5% AEP or greater) and contingency measures for such movement, including requirements for slash removal from streams and use of slash traps:

(d) any operational restrictions to—

- (i) minimise damage to indigenous vegetation:
- (ii) avoid damage to downstream and adjacent infrastructure and properties.

Figure 1: Schedule 3, Clause 5 of the NES-PF

It is necessary, therefore, to have a method of identifying high risk areas. The NES-PF gives no guidance on what a high-risk area is, and there is no unified approach in New Zealand for determining high risk areas (Basher et al., 2015). Regulators would benefit from further study into analysing risk of slash mobilisation as it would allow them to implement an evidence-based approach for policy (Amishev et al., 2014; Bloomberg & Palmer, 2021; Phillips et al., 2017a).

Risk

In terms of natural hazards, risk is commonly defined as the product of susceptibility, probability, and consequences as shown in the equation below.

$$Risk = susceptibility \times likelihood \times consequences$$

Susceptibility is the tendency of an area to undergo the effects of a hazardous process. For slash mobilisation this is influenced by parameters such as geological factors, slope, Melton's Ratio, watershed area, rainfall, and past event frequency (Phillips et al., 2017b).

The likelihood is probability of occurrence for a given time frame and area.

Consequences are any negative effects caused by the hazardous process. These effects could be on site or off site of the hazard. For incidents involving slash mobilization, consequences identified by the media include damage to property (Muphy, 2023), loss of life (Hayes, 2023), environmental damage, loss of productivity, legal action being taken (Chadwick & Garbett, 2020; Stevens, 2023), monetary damages (Kitchin, 2022).

Quantifying each of these individual aspects has been recognised as a problem. Good quality storm data is needed to analyse susceptibility, hazard, and risk. However, there is currently no standard approach for collecting such data in New Zealand (Phillips et al., 2017b).

A risk matrix is a common tool used for classifying risk based on the likelihood and consequences of the hazard. Likelihood and consequences are estimated and then plotted against each other, as shown in the figure 2.

Risk matrix					
Likelihood	Consequences				
	Insignificant	Minor	Moderate	Major	Very serious
Almost certain	Medium	High	High	Very high	Very high
Probable	Medium	Medium	High	High	Very high
Likely	Low	Medium	High	High	High
Rare	Low	Low	Medium	Medium	High
Very rare	Low	Low	Medium	Medium	High

Figure 2: Example Risk Matrix (Marsick 2012)

The forestry industry within New Zealand is no stranger to risk matrices such as the one shown in Figure 2. It is a common approach for Health and Safety (Safetree, 2017). In the past, Nelson Forests Ltd has used a risk matrix for particularly difficult areas (Phillips et al., 2017b). Factors looked at by Nelson Forests included geology, slope, frequency of landslides, rainfall data catchment size, and proximity to streams. The consequences of a possible failure were also used in the analysis. These factors were then used to assess the probability that a landslide would occur. Consequences such as people, property, cost, reputation damage and ecological damage were assessed. These factors could then be combined to give an overall risk that ranged from negligible to high.

It is worth noting there is a national standard on assessing and managing risk. This is under the AS/NZS 4360:2004 and is intended to be applicable to any risk (Standards Australia & Zealand, 2004).The standard lays out a seven-step plan which can be summarised as follows:

1. Communicate and consult with stakeholders.
2. Establish the context.
3. Identify risks.
4. Analyse risks.
5. Evaluate and treat risks.
6. Monitor and review the management plan.
7. Record the risk management process.

Quantifying the risk of slash mobilisation will allow for better management of the risk, provide regulators with a better understanding, and help forest owners better recognise their risk profile (Amishev et al., 2014).

Debris Flows

Debris flows are a geological hazard where a mass of water and solid debris travels down a slope under the influence of gravity (Fannin & Bowman, 2008). As part of this, they can entrain nearly anything in their path (Iverson et al., 2011). Debris flows behave in a similar manner to flash floods, except for the fact they have more debris and less water (Oregon Board of Forestry, 2001).

These are natural events that occur worldwide and can happen in any type of forest (SCION, 2017). There have been suggestions that even with quantitative risk analysis, best management practices, and good operational restrictions, debris flows cannot be avoided on steep slopes with intense rainfall (Raymond, 2015). Despite this, there is good evidence that the clearance of forests has an increased effect on regional land sliding (Montgomery et al., 2000).There have been a number of studies determining where debris flows are likely to occur and the parameters that affect the flow behaviour. Currently in New Zealand there is little information on standards for minimising debris flow risk (Visser et al., 2018).

Models

There are a number of basic formulas that give an estimate of erosion and debris flow. These formulas have been utilised in several models overseas and in New Zealand and have been proven to be effective internationally. One of the limitations of these models is that they do not consider land cover, soil types, or rainfall. Because of these shortcomings, the boundaries of the formulas must be altered for unique locations to account for this (Wilford et al., 2004). A summary for the Hawkes Bay Regional Council accepted these kinds of formulas as being locally variable but useful as a screening tool (McSaveney, 2007). A major benefit of using these formulas is that little data is needed for them. They can usually be calculated from just a Digital Elevation Model (DEM) collected by Light Detecting and Ranging (LiDAR). Such data is widely available within New Zealand and is becoming more easily accessible (de Gouw et al., 2020).

The Universal Soil Loss Equation (USLE) is a formula that is used to predict soil loss from water erosion (Alewell et al., 2019). USLE multiplies factors of rainfall-runoff erosivity, soil erodibility, slope length, slope steepness, landcover, and prevention measures to give a value of annual soil loss. One of the drawbacks of the formula is that the coefficients used are empirical with values that are difficult to obtain.

There are a number of measures that can be used to model flow behaviour. Melton's Ruggedness Ratio is defined as the watershed relief (difference in elevation between the highest and lowest points of the catchment, in meters) divided by the square root of the area of the catchment (in m^2). Melton's Ratio is used to predict flow behaviour during a flood event. An increasing Melton's ratio corresponds to a change from flood behaviour to debris flood behaviour, and then to debris flow behaviour. The Relief Ratio is the watershed relief divided by the length of the watershed. It is essentially a measure of the steepness of the watercourse. Table 1 shows a range of Melton's Ratio, Relief Ratio and watershed length values and the expected flow behaviour. The proportion of area with slope within certain bounds is also used as a discriminating factor.

Table 1: Class boundaries of catchment characteristics for the various hydrogeomorphic processes of floods, debris floods and debris flows (from Wilford et al., 2004).

Variables	Class boundaries		
	Floods	**Debris floods**	**Debris flows**
Melton ruggedness ratio M and length L	M < 0.3	M > 0.3 but < 0.6 M > 0.6 and L > 2.7 km	M > 0.6 and L < 2.7 km
Melton ruggedness ratio M and Relief ratio r	M < 0.3	M > 0.3 but < 0.77 M > 0.77 and r < 0.42	M > 0.6 and r > 0.42
$P_{30°-40°}$ and Length L	L > 9 km of if L < 9 km, then $P_{30°-40°}$ <0.045	$P_{30°-40°}$ = 0.045 to 0.18 and L = 2.7 to 9 km	$P_{30°-40°}$ > 0.18 and L < 2.7 km
Relief ratio r and Length L	r < 0.15	r 0.15 to 0.35 or r > 0.35 and L > 2.7 km	r >0.35 and L < 2.7 km
Melton M and $P_{30°-40°}$	M < 0.3	M = 0.3 to 0.64 or M > 0.64 and $P_{30°-40°}$ < 0.315	M > 0.64 and $P_{30°-40°}$ > 0.315
Relief ratio r and $P_{30°-40°}$	r < 0.15	r = 0.15 to 0.35 or if R > 0.35 then $P_{30°-40°}$ < 0.34	r > 0.35 and $P_{30°-40°}$ > 0.34

Table 1: Melton's Ratio Values (McSaveney, 2007)

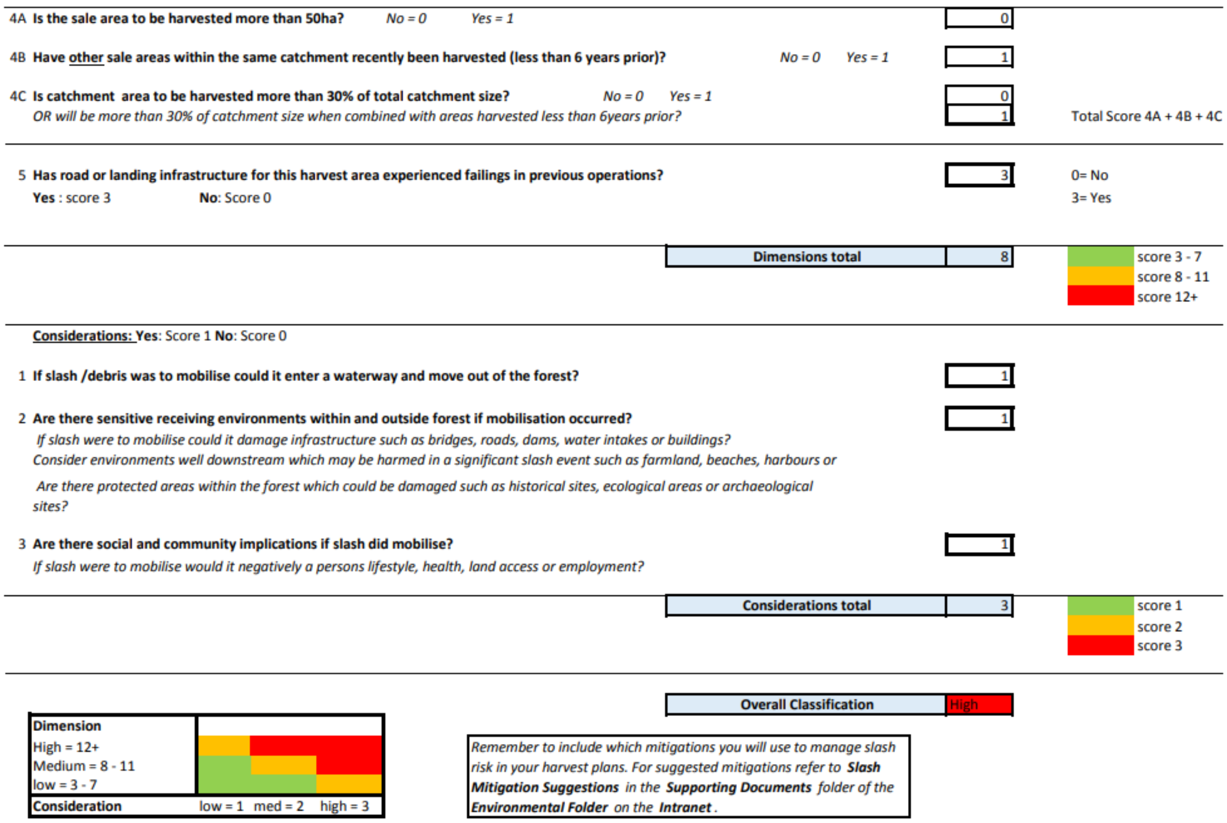
The boundaries shown in Table 1 emphasises the difficulty in determining where debris flows are likely to occur. The number of different combinations of parameters and associated thresholds indicates the associated complexity.

However, despite the limitations of these formulas, they are useful to provide a starting point for identifying which catchments need further investigation and have been used to good effect when adequate boundaries are used. A model developed in British Columbia incorporated Melton's Ratio and watershed length limits to estimate whether a debris flow would occur. The model was compared with field evaluations and it was found to be 92% accurate in determining debris flow catchments (Wilford et al., 2004). The application of Melton's Ratio in New Zealand has been used in several GIS-based approaches. In one study in the Coromandel and Kaimai Ranges a Melton's Ratio value of 0.5 was used as a discriminator to determine whether the catchment was likely to produce debris flows. Known debris catchments were evaluated and the Melton's Ratio was calculated and compared to the value of 0.5. The Melton's Ratio was greater than 0.5 in all of catchment areas within the Coromandel/Kaimai region analysed (Welsh & Davies, 2011).

Bloomberg and Palmer (2021) used a GIS model to determine Melton's Ratio, watershed length, and runout distance. The Melton's ratio and watershed length was used to determine whether catchments had the potential to initiate debris flows. This was then compared with a GNS Science report, and the model was determined to have a decent correlation with the verified results. There were some discrepancies between the results of the GNS Science report and the thresholds for Melton's ratio and watershed length suggested by previous studies overseas. This may be an indication that New Zealand requires different thresholds than those established elsewhere due to the different conditions.

Slash Mobilisation Risk Assessment (Rayonier)

The Rayonier slash mobilisation risk assessment is a table that is filled out and a corresponding risk score is given (RMF, 2019).The table features parameters that are given a weighted score. These weighted scores are then summed to give an overall risk score. Parameters within the table are divided into the groups of dimensions and considerations. Considerations are whether the debris could move out of the forest, sensitive receiving environments, and social/community implications. The dimensions are factors that contribute to the susceptibility. Dimensions include average slope, rainfall amounts, Hazard Code, harvest area size, history of erosion, area harvested relative to catchment area, and previous road/landing failures. The figure below shows part of the tool.



4A **Is the sale area to be harvested more than 50ha?** *No = 0* *Yes = 1* 0

4B **Have other sale areas within the same catchment recently been harvested (less than 6 years prior)?** *No = 0* *Yes = 1* 1

4C **Is catchment area to be harvested more than 30% of total catchment size?** *No = 0* *Yes = 1* 0
OR will be more than 30% of catchment size when combined with areas harvested less than 6years prior? 1 Total Score 4A + 4B + 4C

5 **Has road or landing infrastructure for this harvest area experienced failings in previous operations?** 3 0= No
Yes : score 3 **No**: Score 0 3= Yes

Dimensions total 8 score 3 - 7 / score 8 - 11 / score 12+

Considerations: Yes: Score 1 **No**: Score 0

1 **If slash /debris was to mobilise could it enter a waterway and move out of the forest?** 1

2 **Are there sensitive receiving environments within and outside forest if mobilisation occurred?** 1
If slash were to mobilise could it damage infrastructure such as bridges, roads, dams, water intakes or buildings?
Consider environments well downstream which may be harmed in a significant slash event such as farmland, beaches, harbours or
Are there protected areas within the forest which could be damaged such as historical sites, ecological areas or archaeological sites?

3 **Are there social and community implications if slash did mobilise?** 1
If slash were to mobilise would it negatively a persons lifestyle, health, land access or employment?

Considerations total 3 score 1 / score 2 / score 3

Overall Classification High

Dimension
High = 12+
Medium = 8 - 11
low = 3 - 7
Consideration low = 1 med = 2 high = 3

Remember to include which mitigations you will use to manage slash risk in your harvest plans. For suggested mitigations refer to ***Slash Mitigation Suggestions*** *in the* ***Supporting Documents*** *folder of the* ***Environmental Folder*** *on the* ***Intranet***.

Figure 3: Slash Mobilisation Risk Assessment

SINMAP

SINMAP is a free software tool that performed an accurate assessment of erosion susceptibility for two Hawkes Bay catchments (Harrison et al., 2012). Parameters used in SINMAP for calibration include root cohesion, soil cohesion, slope angle, soil density, soil depth, depth of water table, friction angle of the soil. A variety of DEM resolutions were tested, and it was found that the higher resolution resulted in better results. Slip data was compared against the SINMAP stability prediction, and a solid correlation was found.

Using the default parameter value results in poorer accuracy, and harvest planners may not have access to accurate parameter values. The forest management company PF Olsen has trialed the SINMAP method to assess areas of high risk, however the results of these trials have not been published (Amishev et al., 2014).

Some of the main limitations of SINMAP are the lack of data for the large number of parameters, the local variability of these parameters, and the lack of DEM data (Basher et al., 2015; Phillips et al., 2017b). The increase in availability of LiDAR within New Zealand since 2015 has reduced the area not covered by DEM's, although within the remaining area not covered there are areas of significant risk. Another limitation is that SINMAP is also only able to predict shallow landslides, so it is only relevant for areas where this is the dominant form of erosion.

Gisborne District Council

In 2016 the Gisborne District Council produced a spreadsheet matrix that could be used to identify the potential risk for forest sites (Phillips et al., 2017b). The spreadsheet was developed in conjunction with industry workshops. Forestry professionals were interested in the project and wanted to see it developed further. There were concerns that it may become a necessary component of the consenting process. There was also the concern that the matrix may be subjective. The report acknowledges this but outlines the evidence, literature and experience that reduces the subjectivity. The matrix was only a draft and the results of the 6-month trial have not been published.

GIS Based Models

There has been research done to determine the viability of a GIS-based approach to landslide susceptibility. Bloomberg et al. (2011) decided against a process-based GIS approach for the development of the Erosion Susceptibility Classification. Instead, they opted to use empirical data from the Land Use Classification. The justification behind this was the highly variable nature in quality of spatial data and the lack of reliability for detecting small areas of susceptible land.

The need for high quality data in remote areas has been well understood as a limitation of using GIS for modelling risk for some time (Oregon Board of Forestry, 2001). This becomes increasingly difficult for widespread national spatial datasets (Hadji et al., 2013). There have also been indications that many landslide hazard GIS models are based on inaccurate data or are not properly modelled (Carrara & Pike, 2008). Bloomberg and Palmer (2021) stated that as high-quality LiDAR data is becoming more readily available the application of GIS models is becoming more accessible for forestry applications.

Literature has indicated that risk mapping should be investigated further so they can be used by harvest planners to reduce the risk of debris flows and landslides.

DEM Resolution and LiDAR Accuracy

DEMs are often represented using a raster, a format that stores data as a grid of pixels. Spatial resolution of a DEM is defined as the distance across the ground represented by each pixel. The higher the raster resolution, the smaller the size of the cells. The resolution of input raster's has been recognised as a significant limiting factor for the accuracy of spatial analysis (ArcGIS, 2014).

Often, for large computational processes within GIS, a lower resolution DEM is used to reduce computation time. Doing so results in loss of small-scale features which has an influence on reliability when using them for topographic study (Vase & Teng, 2007).

LiDAR is a method for determining distances by measuring the time lasers take to reflect. This is commonly used to determine elevation. Studies have compared survey elevation points and LiDAR data and confirmed that it provides a good representation of ground elevations (Vase & Teng, 2007b). However, LiDAR can also have errors associated with low, dense vegetation and saturated soil conditions (Lidberg et al., 2017).

3. Opportunity and Objectives

It is clear that many companies are developing their own systems for quantifying risk. This study will cover one such system. The intent of this is to inform the company with more details about the issues that affects the utility of their system. This will also provide a guideline for other companies to follow.

The aim of this study is to evaluate and improve a Catchment Risk Matrix model for slash mobilisation. The Catchment Risk Model has been developed by a Forest Engineer that I have worked with previously.

Specifically, the evaluation will include a sensitivity analysis on the Flow Accumulation Threshold and DEM resolution will be carried out. This will provide users with a better understanding of how these parameters are influencing the outputs of the model. A consequence parameter will also be added to the model to provide a better overview of the risk.

4. Methodology

Catchment delineation process from DEM:

A common way of determining catchments is using the Spatial Analysis toolkit within ArcGIS Pro. The LiDAR DEM is brought into GIS then a Fill tool is used to fill any sinks or gaps in the data. A Flow Direction tool is then used to calculate which direction water would flow from each pixel, using elevations. A Flow Accumulation is then applied to create a raster of accumulated flow into each cell. A condition is then applied to determine only the pixels that have more accumulation than the defined threshold. This is then used as the stream network and the Watershed tool is used to delineate the catchments within the DEM. The flow chart in figure 4 visualises this process.

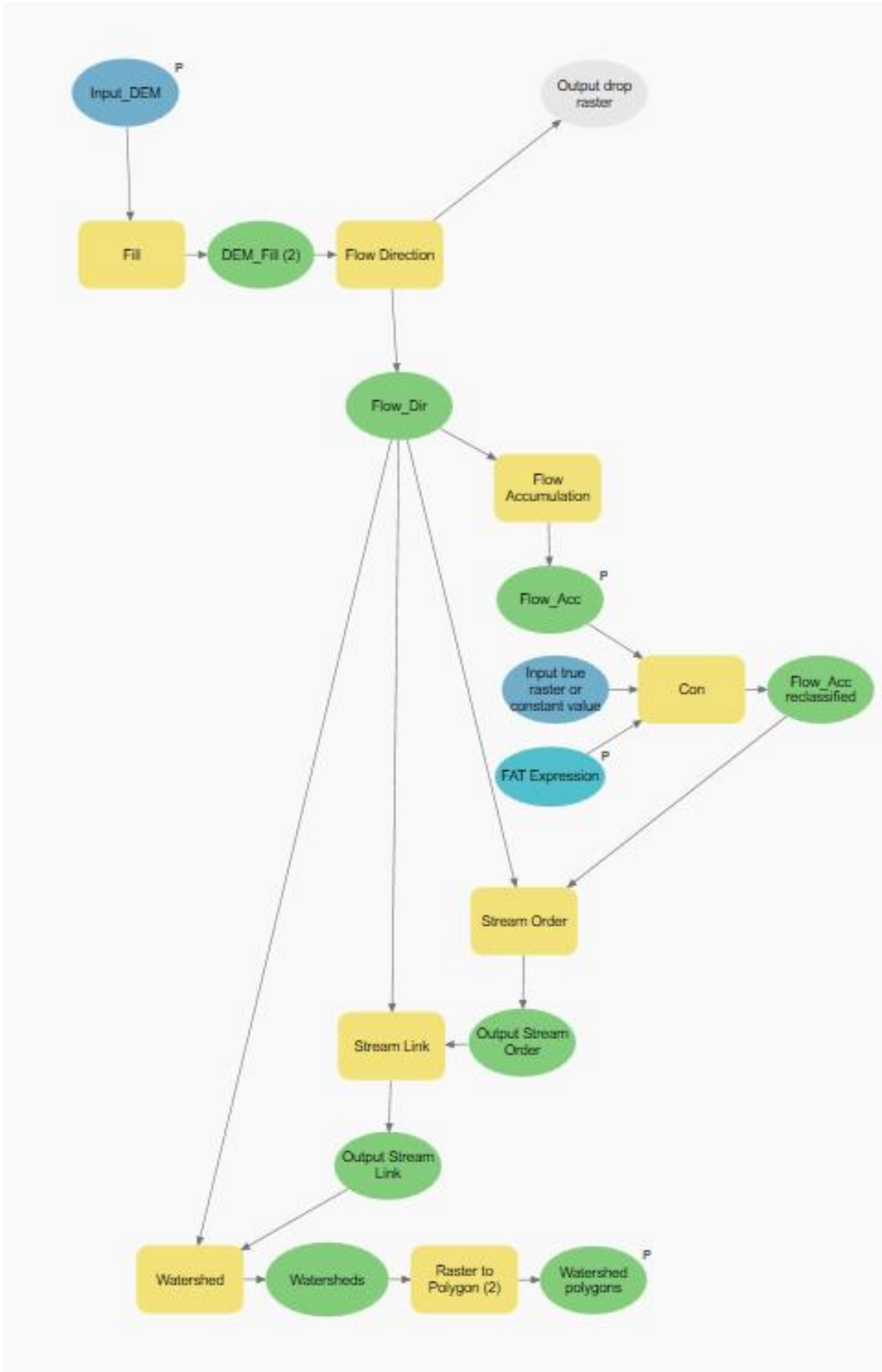


Figure 4: Flow chart of delineating catchment from DEM

This process for delineating catchments includes a user defined Flow Accumulation Threshold (FAT). The FAT defines what cell value for flow accumulations is high enough to be designated as a stream. This threshold essentially determines what density of streams to map and therefore at the scale for mapping the catchments. For reference, Figure 5 compares catchment maps with FAT values of 750,000 and 2.5 million. The catchments identified are outlined in red.

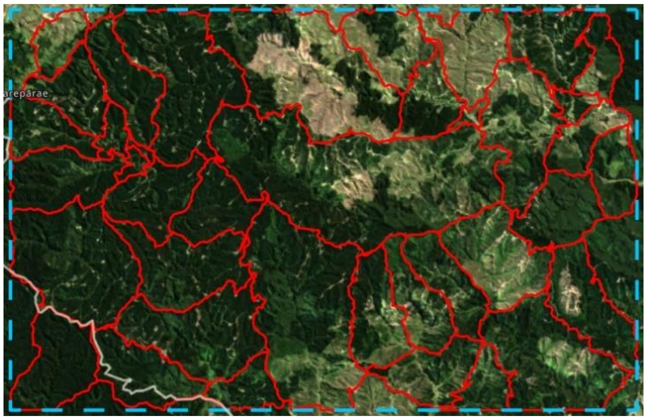


Figure 5a: Catchments with a FAT value of 750,000

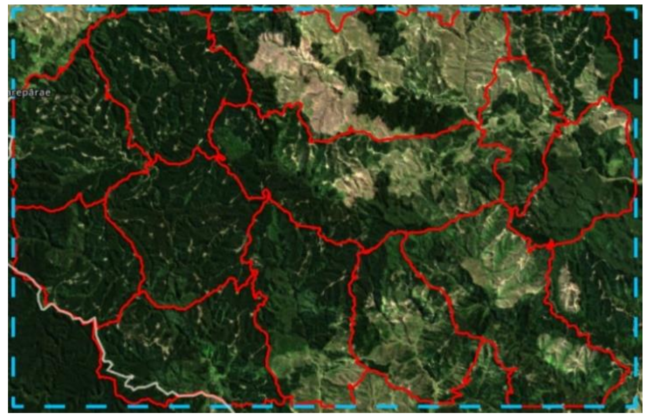


Figure 5b: Catchments with a FAT value of 2.5 million

It can be easily seen that the catchments in Figure 5a are larger than the catchments in Figure 5a. The exception to this is the large catchments that remain large when the FAT is increased. Note there are some areas around the margin that are not mapped as being in a catchment. This is due to there being no streams meeting the FAT within those areas.

Choosing a threshold value that determines where a stream channel begins is influenced by contributing area, slope, climate, and soil characteristics (ESRI, 2023). There is great variance on the method used for choosing an appropriate FAT. Often choosing an FAT is done iteratively by testing different values and finding what best matches observed stream heads.

Choosing a small catchment threshold will go into more detail with streams and hence produce more catchments. When the catchments are very small, 'scaling laws' can be violated which does not give an accurate representation of the behaviour of the catchment as a whole. The scaling laws referred to are the constant drop and power law scaling of slope with area. The constant drop law states that the average fall along streams is independent of stream order. The power law scaling of slope with area law states the average stream slope is linked to the catchment area by a power law.

A method for determining an appropriate flow accumulation threshold has been developed (Tarboton et al., 1991). This work was completed in 1991 and as such 60m DEMs were being used. Nowadays it is not uncommon in New Zealand to have DEMs down to 1m. Despite this, the general approach has remained the same. Essentially, the catchments should be as high resolution as possible without violating the aforementioned scaling laws.

Catchment Risk Matrix:

The Catchment Risk Matrix is a semi-automated model within ArcGIS Pro that was created using the ModelBuilder function in ArcGIS Pro.

LiDAR data is used to create a map of catchments within a given area and then the risk associated with each of these catchments is assessed. The process used for this is as described under "Catchment delination process from DEM". The figure below shows the user interface of the tool.

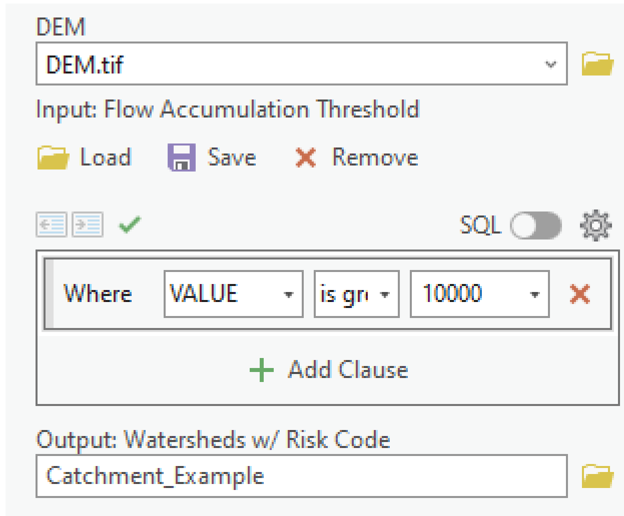


Figure 6: Catchment Risk Matrix user interface

As seen in Figure 6, the user is required to input a DEM, a Flow Accumulation Threshold, and a destination for where the output file is to be save.

The model is split into three sub-models that are linked together by the overarching model (see figure 7). Sub-model 1 has inputs of a DEM and a Flow Accumulation Threshold. The output of sub-model 1 is a polygon shapefile of the catchments, the process used is as shown in Figure 7. Sub-model 2 has inputs of a DEM and the catchment polygons found previously. Sub-model 2 finds the area with slope greater than 35 degrees for each catchment. Sub-model 3 takes the output of sub-model 2 and calculates the risk parameters and gives each catchment a risk code.

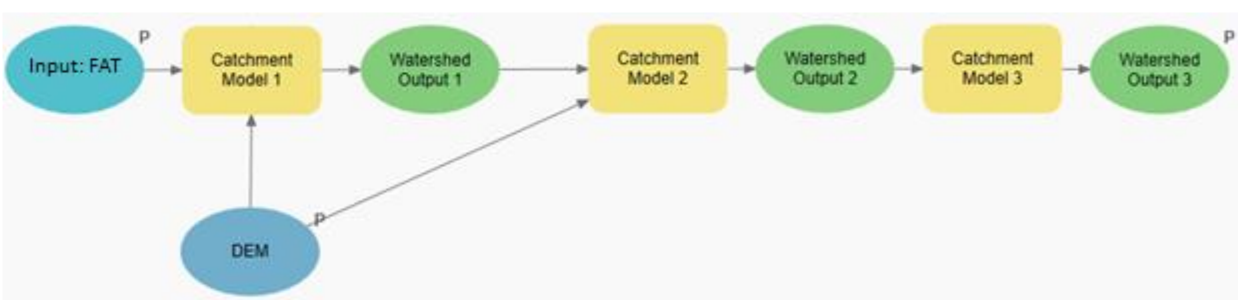


Figure 7: Sub-models of the Catchment Risk Matrix

The risk is calculated based on the area of the catchment, the percentage of the catchment with a slope greater than 35 degrees, and the main Hazard Code within the catchment. Each of these parameters are ranked from one to three and then an overall risk code is calculated by summing the results of each parameter. To get the area the calculate geometry tool within ArcGIS Pro is used. This is then converted to hectares for better user understanding.

The percent area with slope greater than 35 degrees is found using the process outlined below. This process is highly dependent on the DEM resolution.

1. Run the slope tool to generate a slope raster.
2. Reclassify this to contain only slope greater than 35 degrees (using the reclassify tool).
3. Convert the raster to a polygon.
4. Cut any of the slope polygons that fall on the boundary of a catchment (intersect tool)
5. Dissolve all the slope polygons that fall within the same catchment (dissolve tool).
6. Calculate the area of these dissolved polygons for each catchment (calculate geometry)
7. Divide the area of the dissolved polygons by the area of the catchment and multiply by 100(calculate field tool)

This process for finding the slope code is demonstrated in figure 8 where the red regions show the area where slope is greater than 35 degrees.

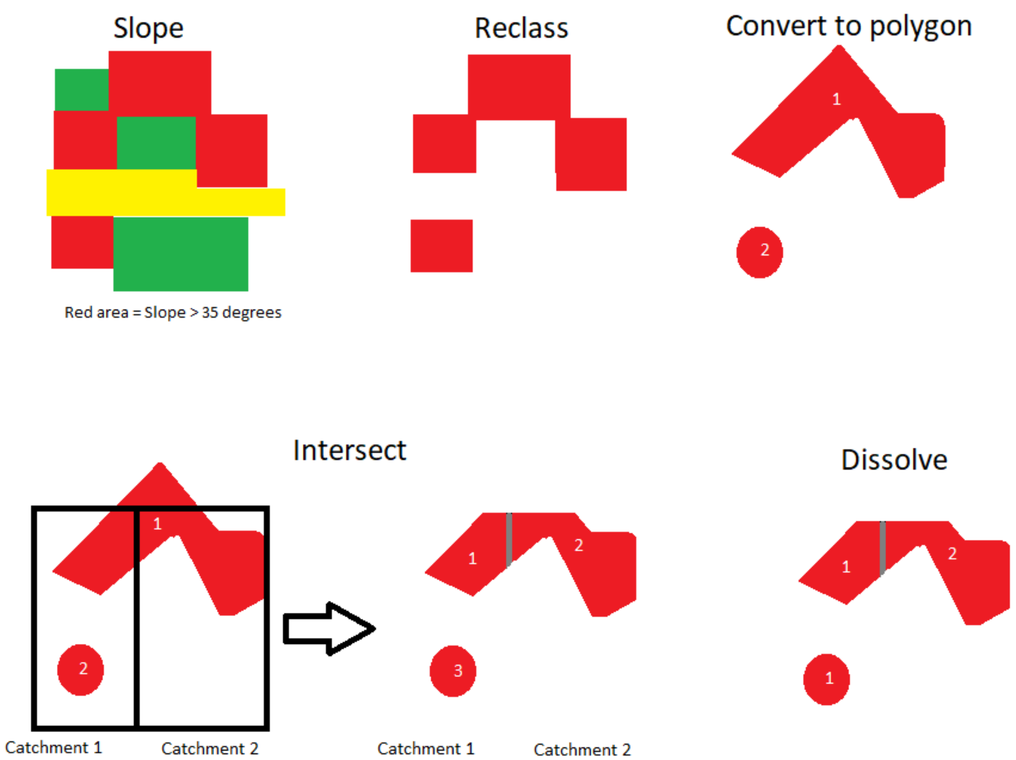


Figure 8: Pictorial depiction of the process for assigning area with slope greater than 35 degrees.

To find the Hazard Code for the catchment the spatial join tool is used. The target feature is the catchment, the join feature being the ESC layer, join operation is set to ‘one to many’, and the match option is ‘have their center in’. This assigns the catchment to whichever ESC class is at their centroid.

The boundaries for each parameter are shown in the table below.

	1	2	3	4

ESC	Low	Medium	High	Very High
Slope	<40%	<80%	≥80%	-
Area	<20ha	<50ha	≥50ha	-

Table 2: Boundaries for Catchment Risk Matrix parameters

For example, a 32ha catchment that has 26ha with slope greater than 35 degrees and is located in a green ESC area would be assigned a code of 2 for area, 3 for slope, and 1 for ESC. Note that the actual bounds used by the company differ from those used in this study.

Method for analysis

At Site A and Site B, a sensitivity analysis of the Flow Accumulation Threshold was conducted to see how the risk varies with changes in the threshold. The model was run at seven different FAT values for DEM resolutions of 1m, 2m, 5m, 15m, and 25m. This resulted in 35 outputs which were used to analyse how the FAT affects the risk codes. After the model was run, the summary statistics tool was used to find the total area in each code for each FAT. This total area for each code was then used to calculate the percentage of area made up by each code. Sites A and B were chosen as they are the biggest and smallest sites so it was expected that they would show the greatest variance.

A sensitivity analysis was also carried out on the resolution of the DEM to see what impact it has on the assessment of risk. The availability of quality DEM data will affect the output of the model. As mentioned in the literature review low-quality elevation data is a key limitation of GIS-based analysis. For sites A, B and C, the model was run at DEM resolutions of 1m, 2m, 5m, 15m, and 25m. The 1m LiDAR DEM data was retrieved from LINZ Data Service. The dataset was recorded by Aerial Surveys (LINZ, 2020). The lower resolution DEMs were made by using the Resample tool within ArcGIS Pro. The polygon output for each run of the model was then split into three rasters representing the ESC, slope, and area codes. These rasters were used to analyse how the resolution of the DEM affects the risk classification for each class (ESC, slope, and area).

For example, the polygon output from the 1m DEM converted into an ESC raster layer. The polygon output from the 2m DEM was then converted to a raster in the same way. The ESC layer from the 1m DEM was then subtracted from the ESC layer created with the 2m DEM layer. This shows where areas of the ESC layer have changed codes. This is shown in figure 9.

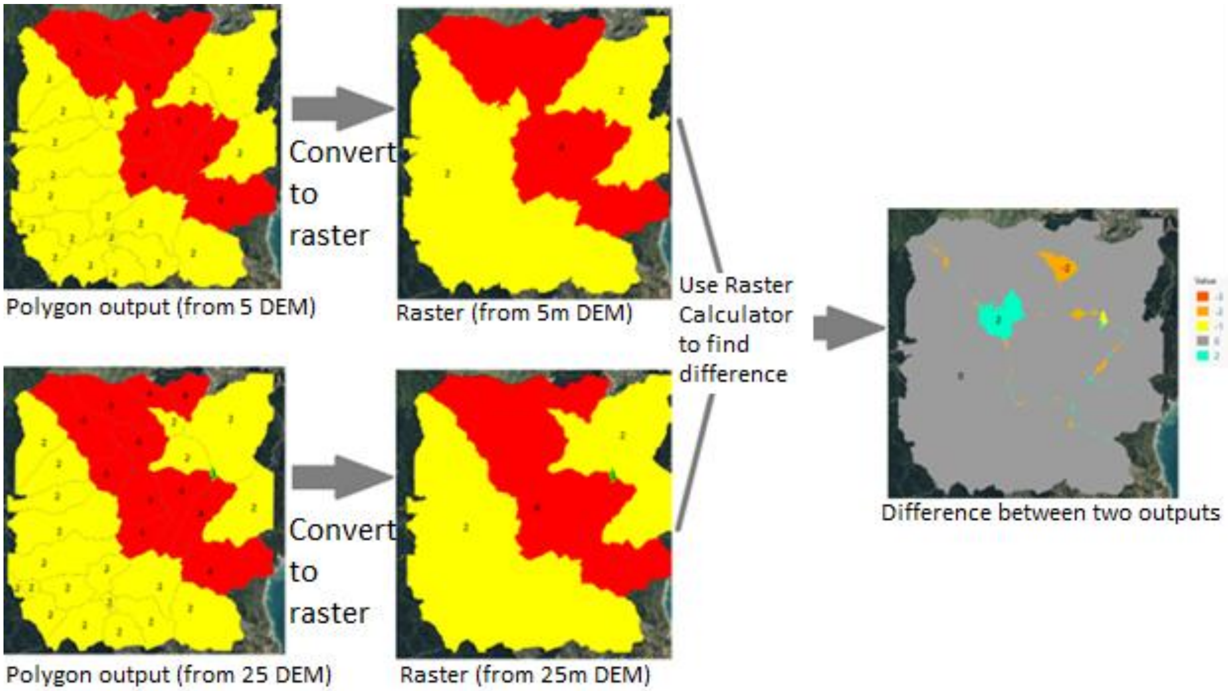


Figure 9: Finding difference between outputs using Raster Calculator.

The example in Figure 9 shows that when the DEM resolution was changed from 1m to 25m most of the area stayed in the same Hazard Code, with a few minor differences. These differences are highlighted in the far-right image. This process was completed for the 3 different sites, 4 different DEM resolutions, and 3 different risk parameters (area, slope, and ESC).

By completing the sensitivity analysis data on the time taken to complete each step of the model was also able to be recorded. This data is recorded automatically within ArcGIS Pro and can be used to investigate how the time taken is influenced by the Flow Accumulation Threshold and the DEM resolution. Users of the model may preferentially choose to run the model with a lower resolution DEM or a different FAT if it runs quicker. The model usually takes around half an hour to run on a HP EliteOne 800 computer with an i5-7500 CPU and 16GB of RAM.

One obvious way of improving the model is to incorporate a tool that allows users to assess possible down-stream consequences. Currently the downstream risk is not quantified, and the model is only a measure of susceptibility. The variable will be calculated from a series of yes or no questions inputted by the user. Adding this variable gives a better picture of catchment risks.

An analysis of how slope maps change with a decreasing DEM resolution was also carried out. This provided an insight into why the slope codes are changing with the DEM resolution. A slope map was generated using the ArcGIS Pro Slope tool for 1m, 2m, 5m, 15m, and 25m. The Raster Calculator tool was then used to subtract the 1m DEM slope map from the other slope maps. This gives a map of the difference between the 1m DEM slope and the lower resolution DEM slope. Summaries of this were calculated using the Summary Statistics tool.

Site Descriptions

Two of the sites were located in the Gisborne District and one in the Wairoa District. This area was chosen because it has been subject to a large degree of scrutiny in the past due to slash mobilisation events, the inherent slope instability due to topography and soil types, and because the matrix is intended to be used within this region. Table 3 shows the ESC breakdown, and total size of the three sites.

	Site A	Site B	Site C
Area in Low ESC (ha)	91	602	401
Area in Moderate ESC (ha)	1679	272	3862
Area in High ESC (ha)	0	602	0
Area in Very High ESC (ha)	5961	1174	1028
Total Area (ha)	7731	2325	5290

Table 3: ESC summary of the three sites

The site boundaries and Erosion Susceptibility Classifications are shown in Figures 10, 11 and 12.

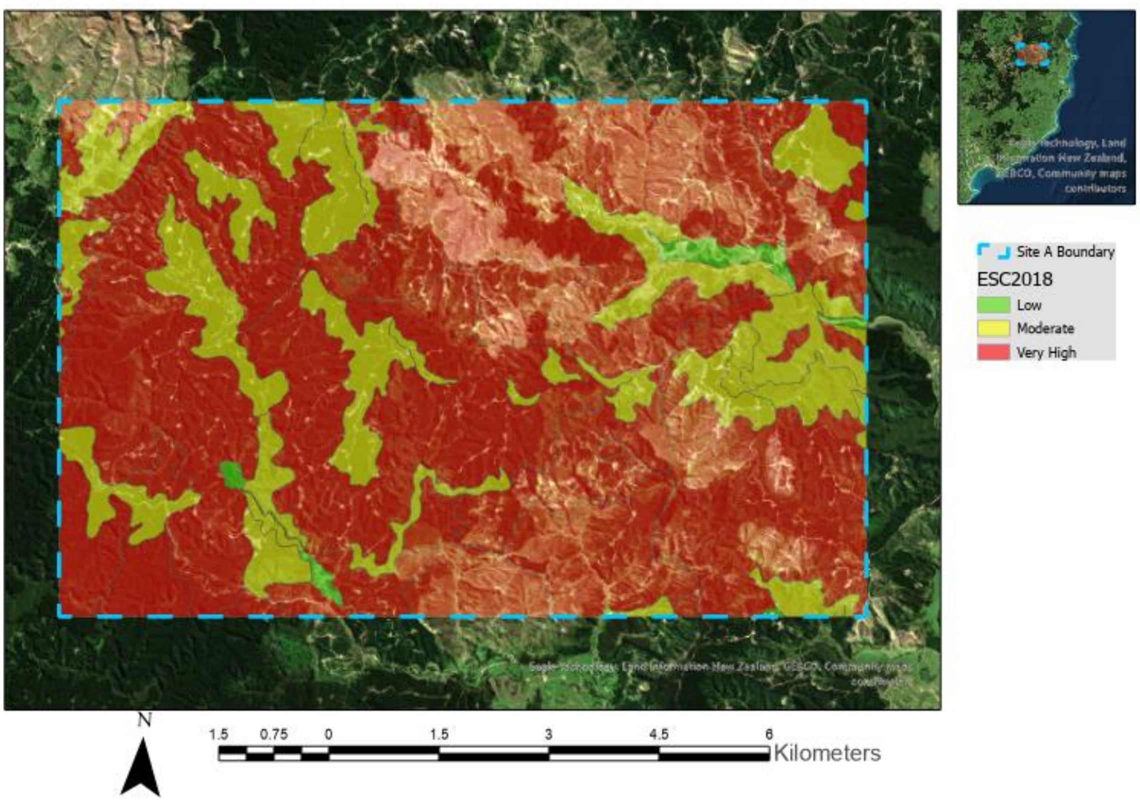


Figure 10: Location of Site A with ESC superimposed.

As shown in Figure 10, Site A is located to the North-East of Gisborne city in an area between Mangatuna and Tauwhareparae. Of notable importance, this site is upstream of Tolaga Bay, to the south-east. The ~7700ha in Site A is made up of mainly plantation forestry with some native forest spread throughout. The coordinates for the upper right corner are 2,057,920E, 5,753,036N. Figure 10 also shows the distribution of ESC across the site. The area is predominately red, with some thin fingers of yellow (Moderate) and green (Low) spread throughout.

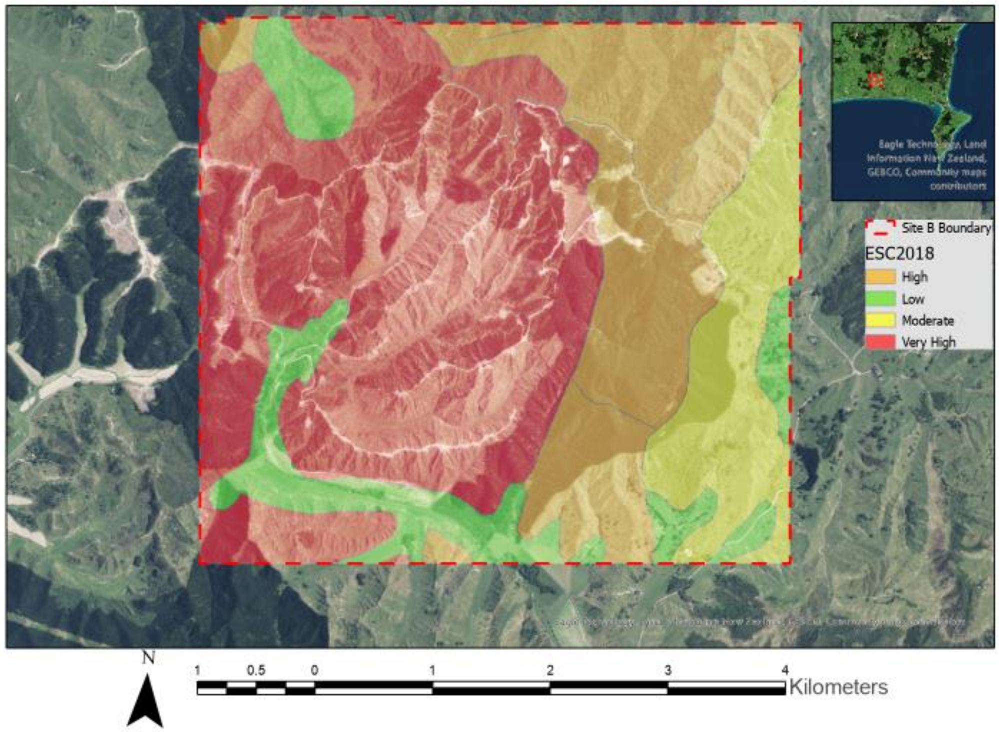


Figure 11: Location of Site B with ESC superimposed.

Figure 11 shows that Site B is located east of Wairoa township. The site is ~2300ha, with plantation forestry around the middle, native forest to the north and pasture to the east and south. The location is around 3.5km north of Whakaki Lagoon. The coordinates for the upper right corner for this site are 1,997,045E, 5,676,719N. Figure 11 shows the area is mostly in red (Very High) ESC on the west side of the site. The orange (High) and yellow (Moderate) classes are located to the eastern side and the green is throughout the area but mainly in the south.

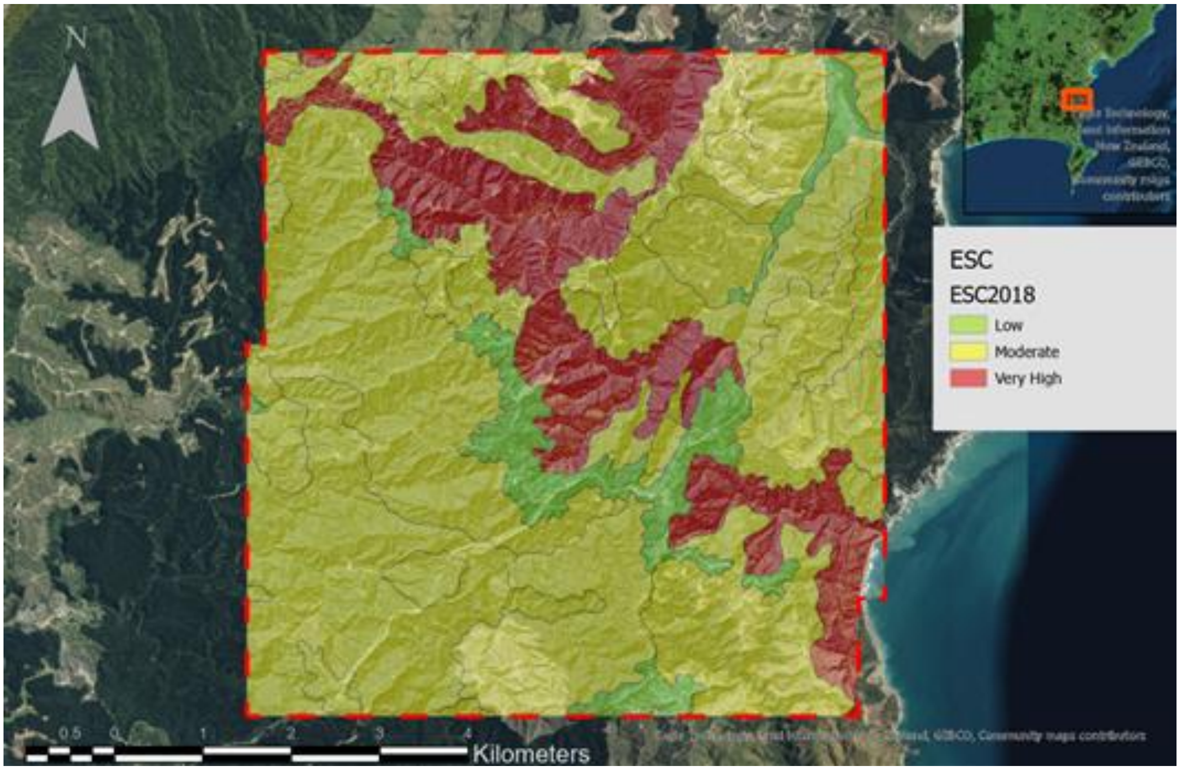


Figure 12: Location of Site C with ESC superimposed.

As seen in Figure 12, Site C is on the Southern boundary of the Gisborne region and is bisected by Wharerata Road (State Highway 2). It is approximately 5000ha, with majority being plantation forestry, followed by native forest. The coordinates for the upper right corner are 2,025,581E, 5,690,105N. The site is mostly in yellow (Moderate) ESC, with some red (Very High) and green (Low) spread through the middle.

5. Results

The results section will feature two main forms of bar charts. One of these shows the proportion in each risk category at each FAT in a stacked bar chart. The other bar chart in this section will show the difference between the outputs of the 1m DEM and the lower resolution DEMs. The process to find the difference is shown in Figure 9.

Risk Sensitivity to FAT

The influence of FAT on risk will be broken down into the Hazard Code, Slope Code, and Area Code so that the results are easier to understand.

Hazard Code

First, we look at how the proportion of area with each Hazard Code changes as the FAT is altered. To exemplify the potential for change to Hazard Codes when the FAT is altered, the outputs from two different FATs at Site A is shown. The following figure shows the model's Hazard Codes and the stream network for Site A when a FAT of 500k was used.

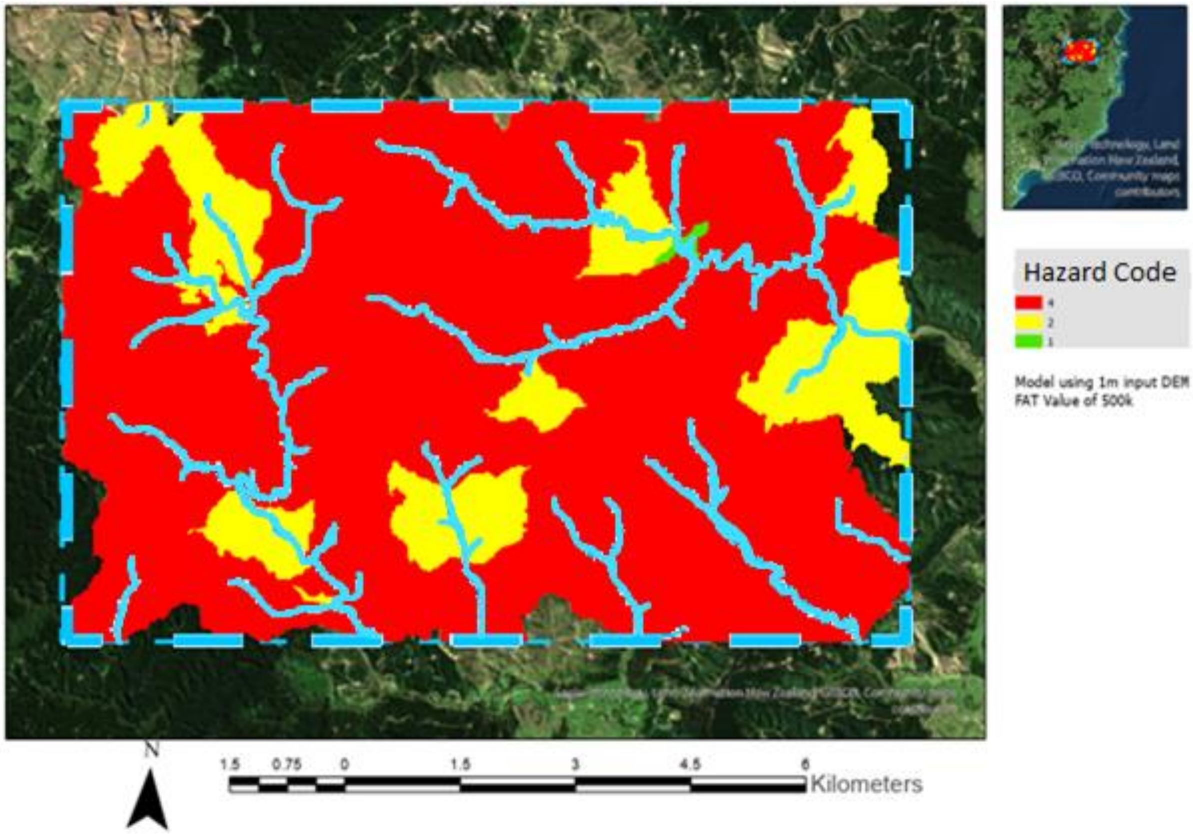


Figure 13: Site A Hazard Codes from model when FAT of 500k was used.

Figure 13 shows that most of the area is assigned to Hazard Code 4 by the model when using an FAT of 500k. This figure is quite similar to Figure 10 in terms of area assigned to each Hazard Code. For comparison, the result of the FAT being increased to 2.5 million is shown in the figure below.

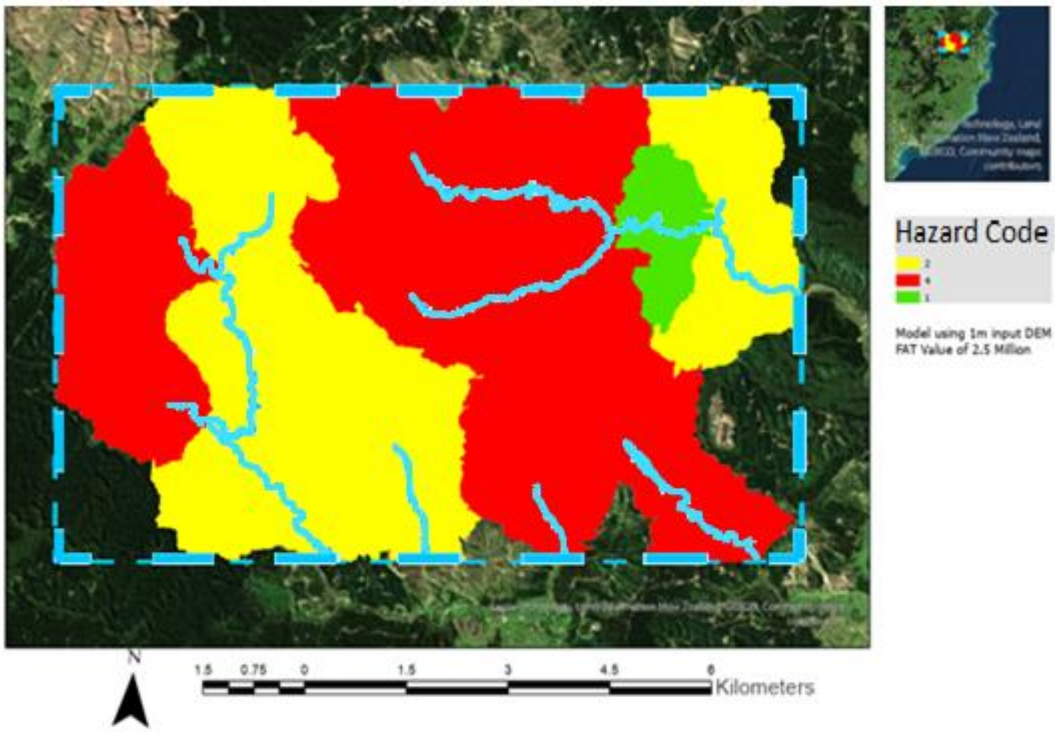


Figure 14: Site A Hazard Codes from model when FAT of 2.5 million.

Figure 14 shows that when the FAT value was increased to 2.5 million, the small pockets of area in Hazard Codes 1 and 2 grow much larger.

Next, we compare the proportions of Sites A and B in each risk category for a range of FAT values. Figure 15 shows the results at Site A.

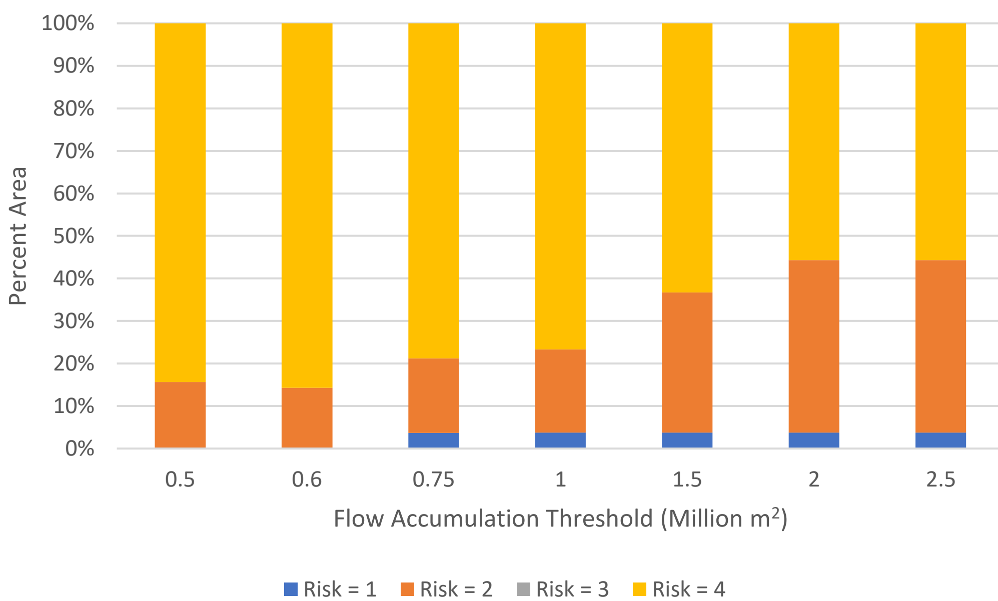


Figure 15: How Site A Hazard Codes are influenced by FAT

In Figure 15 as the FAT value gets larger the amount of area in ESC risk category of 4 reduces while the area in ESC risk categories 2 and 1 increase. When comparing these percentages with the area in each ESC class shown in Figure 10, the FAT that results in the closest alignment is 500k.

This contrasts with the result we get when performing a similar analysis for Site B (see figure 16).

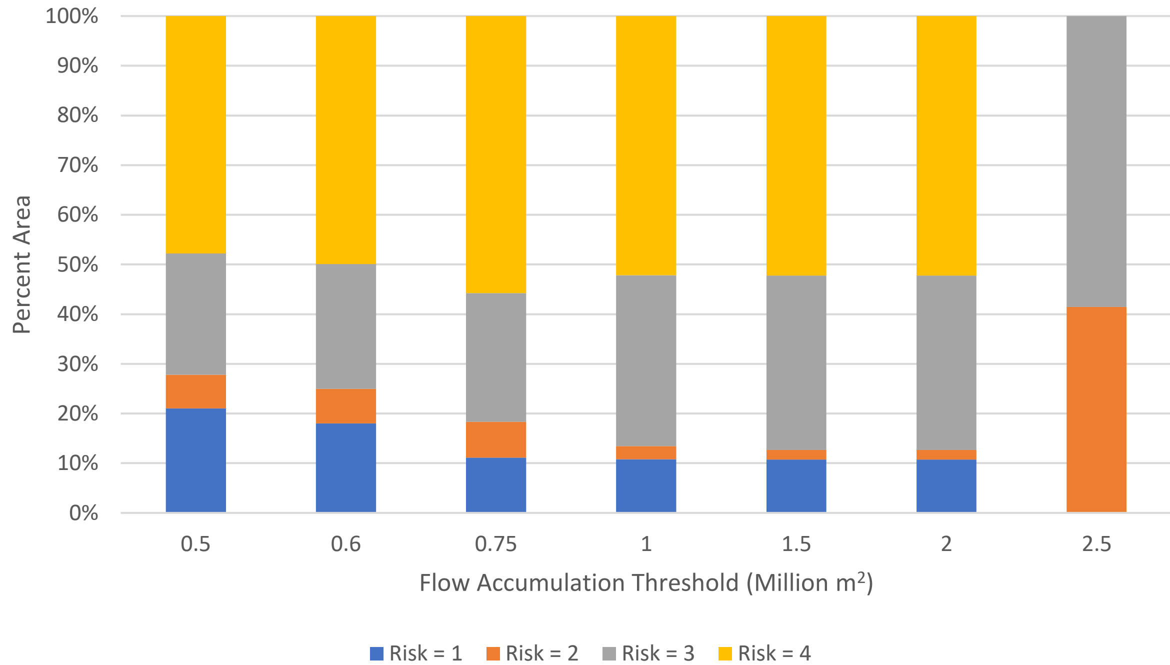


Figure 16: How Site B Hazard Codes are influenced by FAT

Figure 16 show that there was not a substantial difference in Hazard Codes at Site B until a FAT of 2.5 million was used. At an FAT of 2.5 million there was only two catchments. This results in the abnormal results seen at this FAT. Below 2.5 million less than 10% of area is in a Hazard Code of 2. At an FAT of 2.5 million, this increases to 41%.

Slope Code

Now the proportions of Site A and B in each Slope Code will be compared for a range of FAT values.

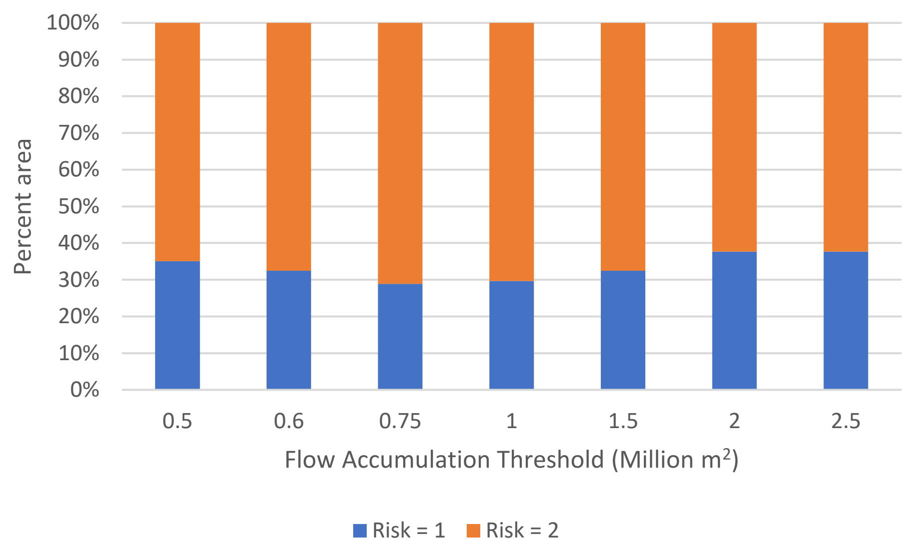


Figure 17: How Site A Slope Codes are influenced by FAT

Figure 17 shows that there is little influence on the slope code by changing the FAT. Across all runs with varying FATs there were no catchments with a Slope Code of 3.

Figure 18 shows the Slope Code at Site B with varying FAT values.

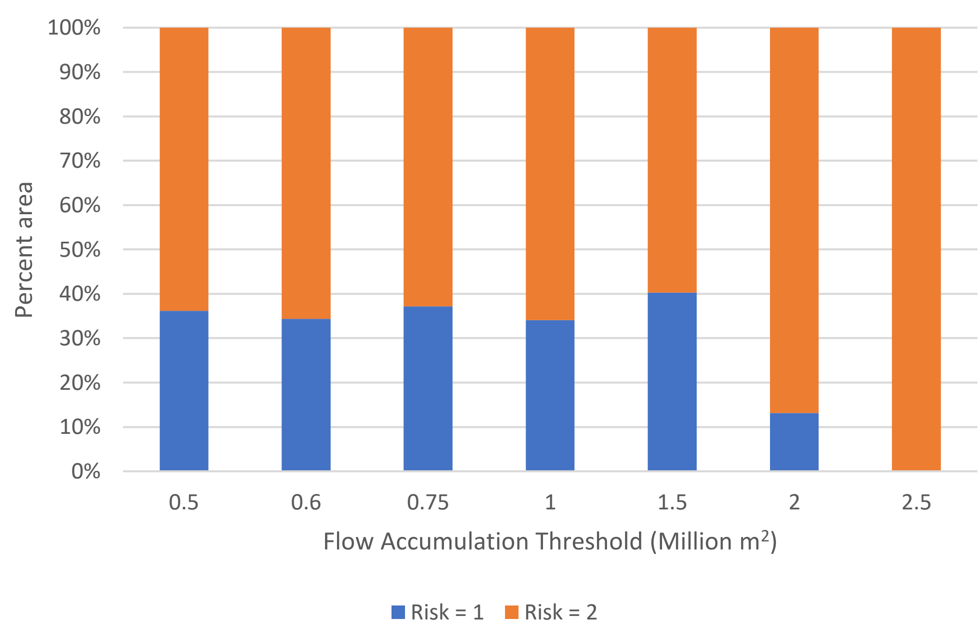


Figure 18: How Site B Slope Codes are influenced by FAT

In Figure 18 the Risk Code stay reasonably steady up to a FAT 1.5 million, after which more area is assigned a Slope Code of 2.

Area Code

We now compare the proportions of Sites A and B in each Area Code for a range of FAT values (see figures 19 and 20). Note that the remainder of the area above 10% for each FAT value at each site is equal to three and the plots are truncated at this point to increase readability.

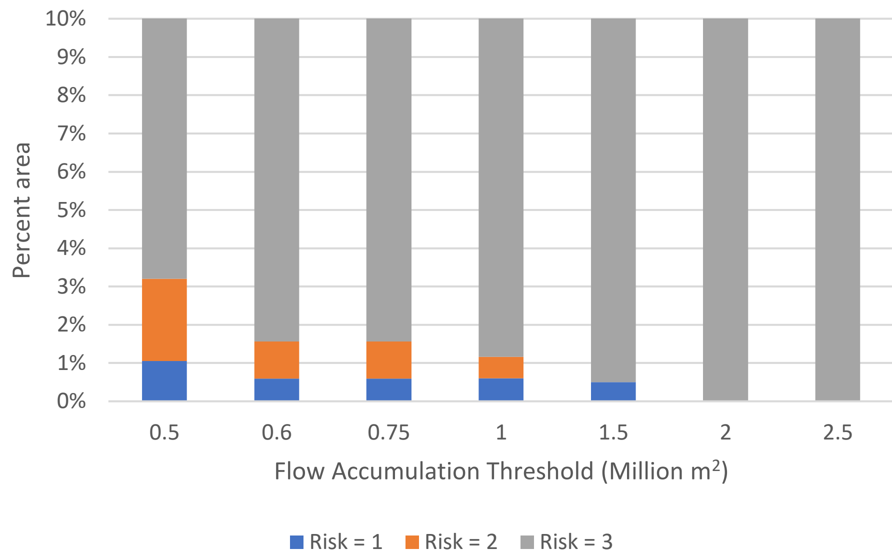


Figure 19: How area risk codes are influenced by FAT at Site A

Figure 19 indicates that most of the forest at Site A is made up of catchments with a risk category of 3 for the Area Code. The lowest percentage in class 3 for area code is 97%, when the FAT was set to 500,000. As the FAT is increased, more area is put into this class. When the FAT was set to 2 million 100% of the site was class 3 for Area Code.

The corresponding plot for Site B is shown below to allow comparisons. As seen in Figure 20, 94% of Site B was assigned an Area Code of 3 when a FAT of 500k was used. When the FAT was set to 2.5 million 100% of the site was given an Area Code of 3. Changing the FAT from 1.5 million to 2 million had no effect on the Area Code. Site B had a lower proportion of area with an area risk code of 3 than Site A, regardless of the FAT.

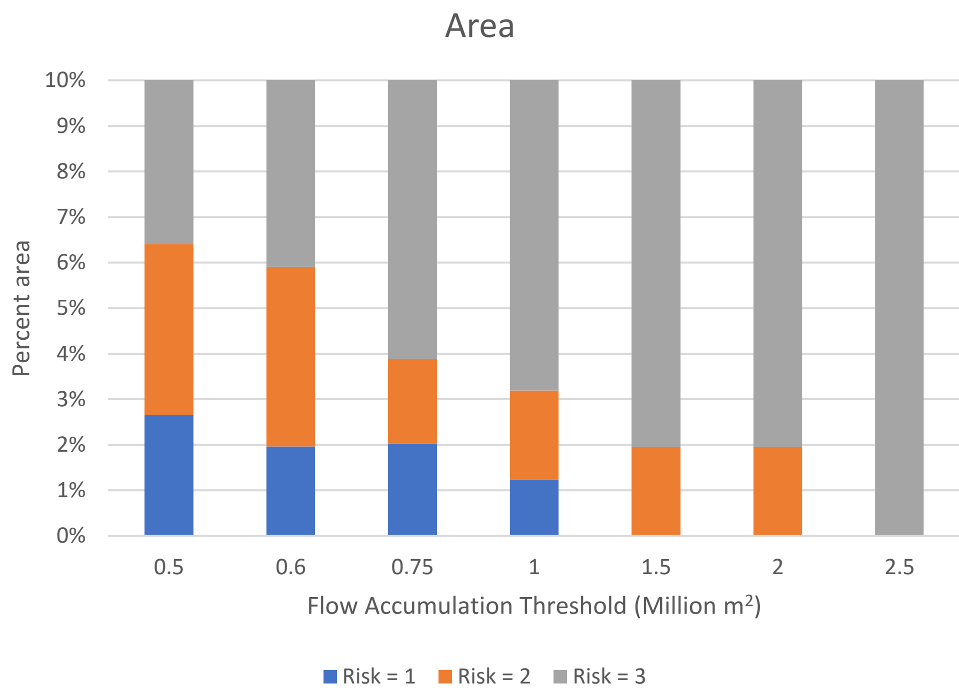


Figure 20: How area risk codes are influenced by FAT at Site B

DEM Resolution Sensitivity

The input DEM resolution was altered to see what impact it had on the output of the risk codes. The results were split into the three parameters (ESC, Slope and Area) to allow for better understand of the data.

Hazard Code

At Site A, as the DEM resolution decreased, the Hazard Code stayed quite similar, with the most substantial difference being some area going down a code. The largest change was in the 25m DEM where 232ha moved down a class. The following figure shows how the Hazard Code changed with DEM resolution at Site B.

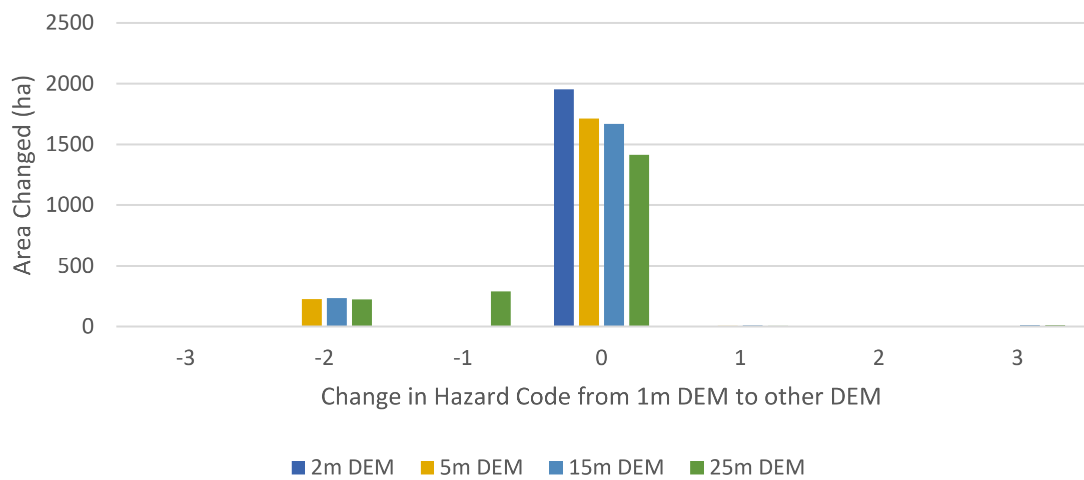


Figure 21: How changing from 1m DEM changes the Hazard Code (Site B)

Figure 21 shows that as the DEM resolution was decreased the amount of area staying the same Hazard Code decreased also. The Hazard Code tended to decrease rather than increase.

At Site C the Hazard Codes stayed relatively similar when the DEM resolution was decreased. Some areas increased in Hazard Code and some decreased. There was no clear trend upwards or downwards for the Hazard Code.

All three sites had some areas that moved Hazard Code when the DEM resolution was altered. In sites A and B any change tended to be a decrease in Hazard Code. The most substantial change in any of the sites was at Site B. At Site B around 11% of the area had a decrease of 2 for the Hazard Code when the DEM resolution was 5m or lower.

Slope Code

To illustrate the sensitivity of Slope Code to DEM, we compare how much of each site changes Slope Code as DEM resolution is changed. Figure 22shows the Slope Codes across Site A from a DEM of 1m.

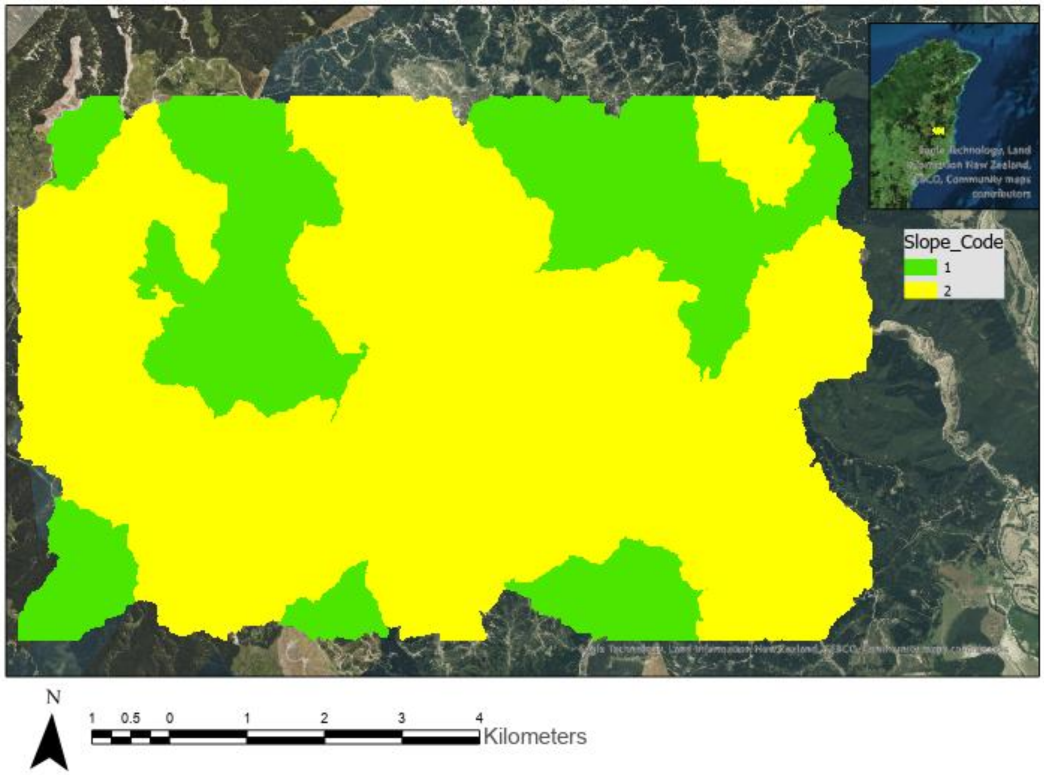


Figure 22: Slope Code for Site A from 1m DEM

As seen in Figure 22, most of the site (72%) is classified as a Slope Code of 2 when a 1m DEM was used. The rest of the area has a Slope Code value of 1.

Figure 23 shows the Slope Codes across Site A from a 25m DEM.

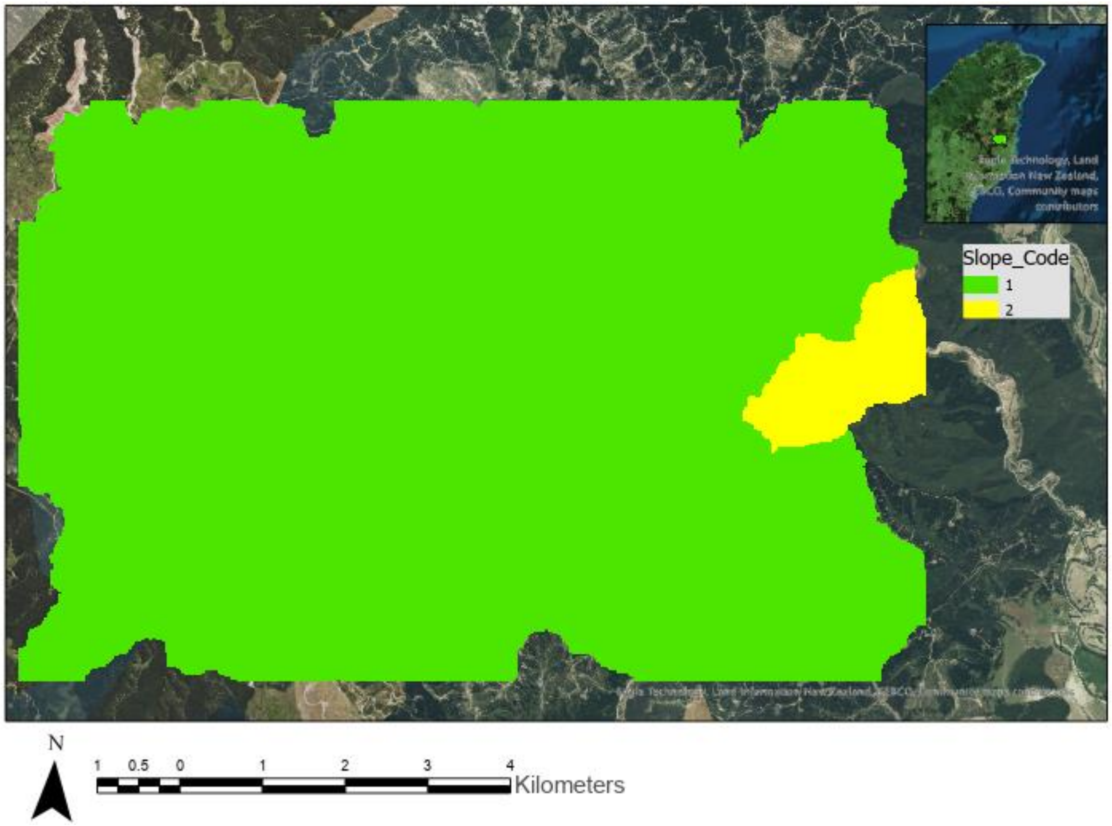


Figure 23: Slope Code for Site A from 25m DEM

Figure 23 shows that when a 25m DEM is nearly all of the area (96%) is given a Slope Code of 1, with the remainder (one catchment) being assigned a Slope Code of 2. It is evident from this that the DEM resolution can have a significant effect on the Slope Code. The following analysis shows this further.

Figure 24 show the area that changed slope code class for the runs with different DEM resolutions at Site A.

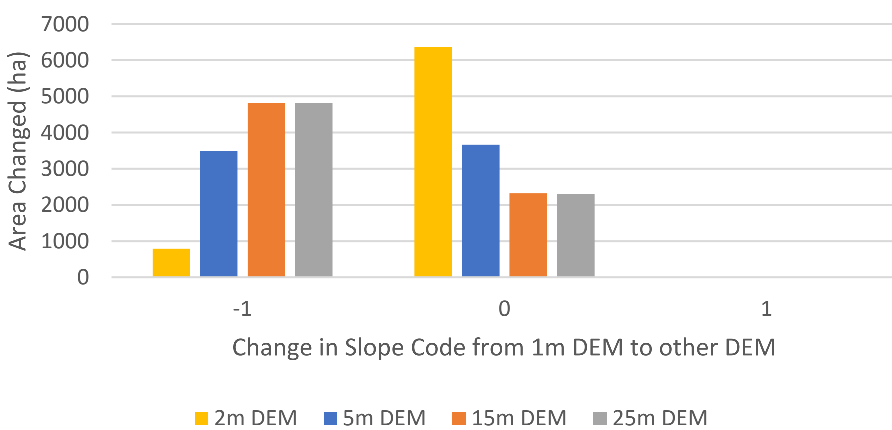


Figure 24: How changing from 1m DEM changes the Slope Code (Site A)

From Figure 24, when the DEM resolution was decreased the slope code class either stayed the same or reduced. As the DEM resolution got larger area that moved down a class tended to increase. The most change was observed in the 15m DEM run, where 4,829ha moved down a class. Between the 15m and 25m DEMs there was little difference.

Figure 25 shows what this relationship is like at Site B.

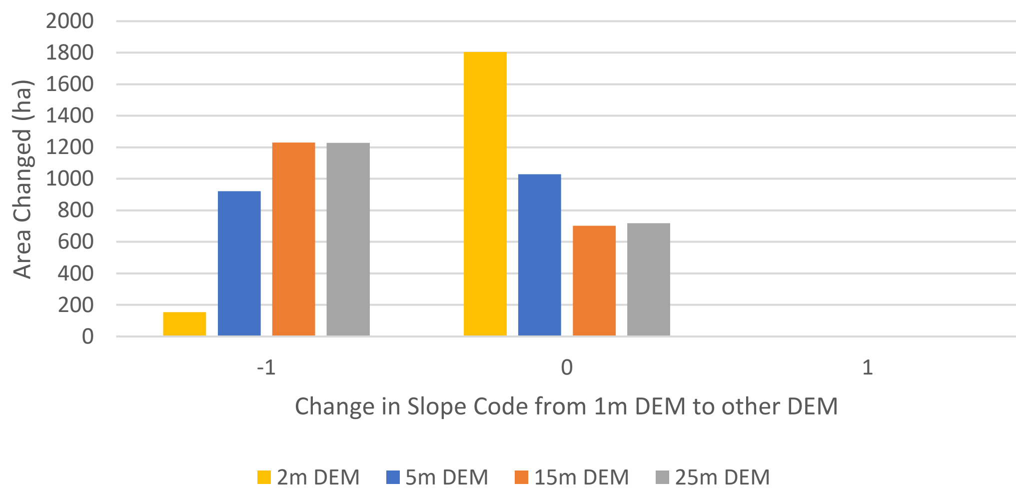


Figure 25: How changing from 1m DEM changes the Slope Code (Site B)

Figure 25 shows as the DEM resolution decreases the slope code tends to decrease. No areas had an increase in slope code when DEM resolution was decreased. This was true for all the DEM resolutions tested (up to 25m). As in Site A there was not much of a difference between the 15m DEM and the 25m DEM.

Figure 26 shows how the DEM resolution changing affects the slope code at Site C.

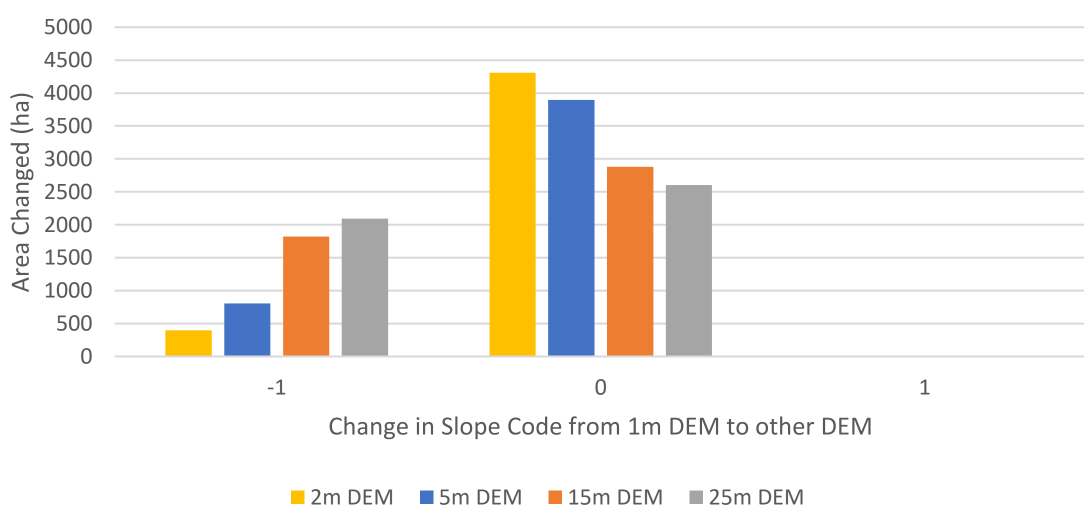


Figure 26: How changing from 1m DEM changes the Slope Code (Site C)

In Figure 26 a similar relationship to the previous two sites can be seen. That relationship is when the DEM resolution is decreased, more area is put into a lower class, though the proportion of changes is smaller than for Sites A and B.

Area Code

The following analysis shows how changing the DEM resolution changes the Area Code. Note that area that did not change an Area Code is not shown in the following figures for ease of understanding. Instead, these values are shown in table 4.

	Site A	**Site B**	**Site C**
DEM Resolution			
2m	98%	99%	100%
5m	98%	96%	98%
15m	99%	96%	98%
25m	99%	96%	98%

Table 4: Area (ha) that had unchanged Area Codes when DEM was changed from 1m.

The Area Code mostly stayed the same for Site A when the input DEM resolution was changed. The largest change was 71.6ha moving up a code when the 2m DEM was used.

At Site B changing the DEM resolution did not have a great impact on the area code. Due to the smaller size of Site B, these changes are much more significant than those in Sites A or C. When changing the DEM resolution from 1m to 2m, very little decreases and a small amount increases. For the other DEM resolutions, a small amount increases and more decreases, but changes are still only at around 4% of total area.

Site C had slightly different results than the other two sites. Site C had a clear cluster of around 70ha moving up by one Area Code when the DEM resolution is lower than 2m.

Across the three sites there was little change in the Area Code. The greatest change by percentage was seen in site B where a total of 4.04% of area changed codes. Across the three sites there was no clear trend towards moving up or down in Area Code.

Slope

This section shows how the topography of the area changed with DEM resolution. This aims to further explain the variations seen in the Slope Code when the DEM resolution was changed. Figure 27 shows how the overall percent area greater than 35 degrees changes when the DEM resolution changes for the three sites.

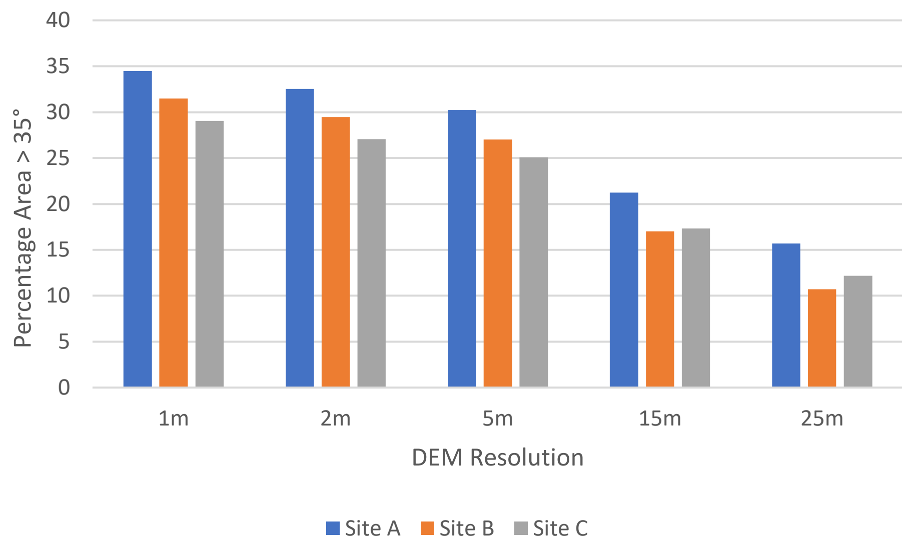


Figure 27: Percent Area > 35 degrees sensitivity to DEM resolution

Figure 27 shows that as the DEM resolution is decreased (increasing number), the percentage area greater than 35 degrees decreases across all three sites. Site A can also be seen to be the steepest site for the given criteria (proportion of area greater than 35 degrees), followed by Site B, and then Site C.

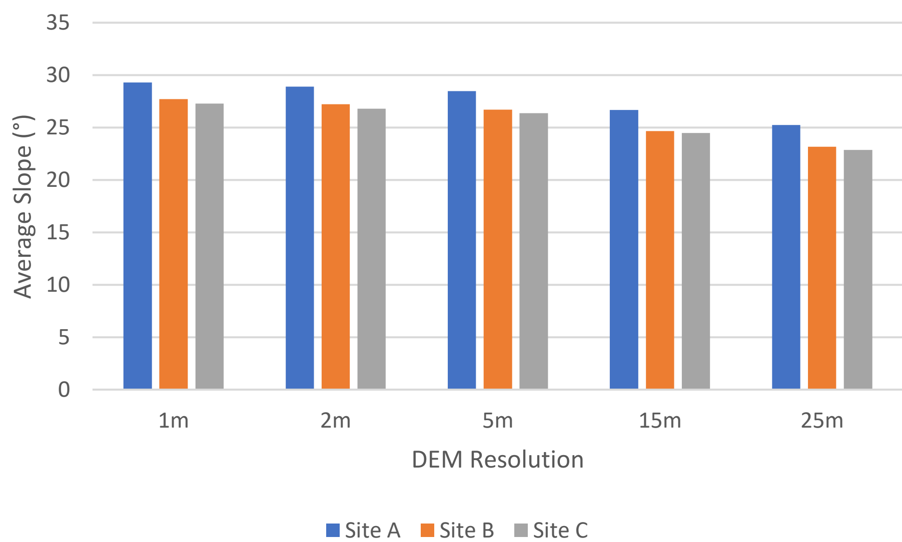


Figure 28: Average slope variation with DEM resolution

Figure 28 shows that as the DEM resolution decreases, the average slope decreases for all three sites. The same trend for steepest sites can be seen. Site A is also the steepest based on the average slope, regardless of DEM resolution.

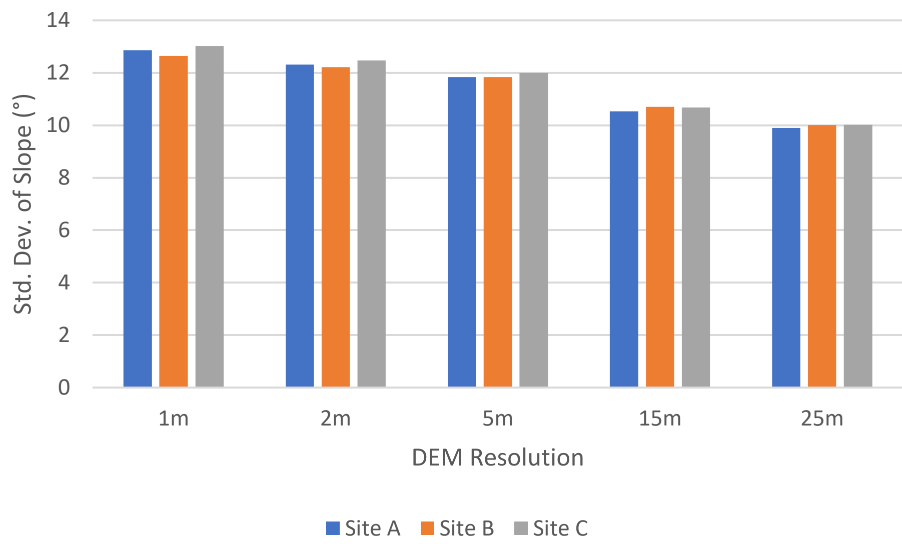


Figure 29: Standard Deviation of slope with DEM resolution

Figure 29 shows that when the DEM resolution decreases, the standard deviation of the slope decreases across all three sites. Across the three sites the standard deviation is reasonably similar, given the same DEM resolution is used.

Time

The graph below shows the time taken to run the model for the three sites at a fixed FAT and varying DEM resolution.

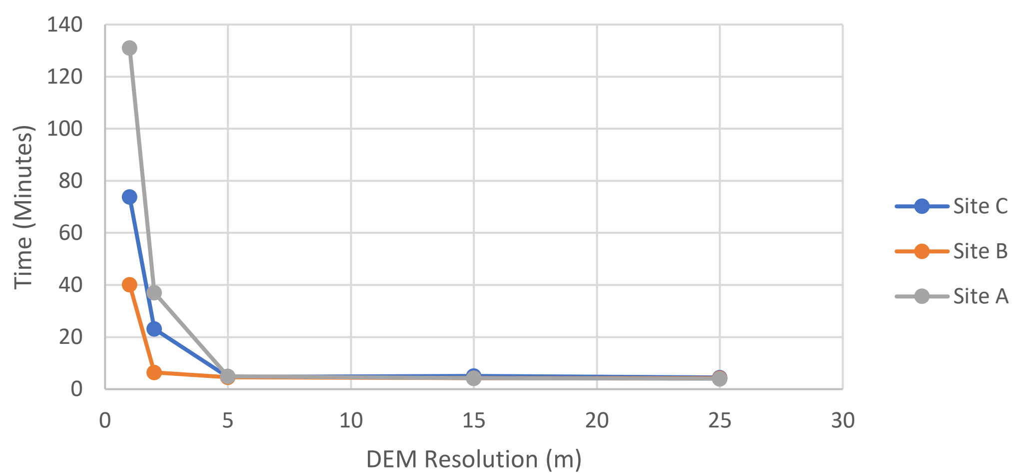


Figure 30: Time taken to run model at different sites and DEM resolutions.

As seen in Figure 30, the time taken to run the model was the same across sites and DEM cell size above 5m. This time remained at around 5 minutes.

When the DEM cell size was below 5m the time taken for the model to run increased dramatically. It appears to follow a power law relationship, but more rigorous study would need to take place to confirm this. Also, the sites with larger areas take longer to run.

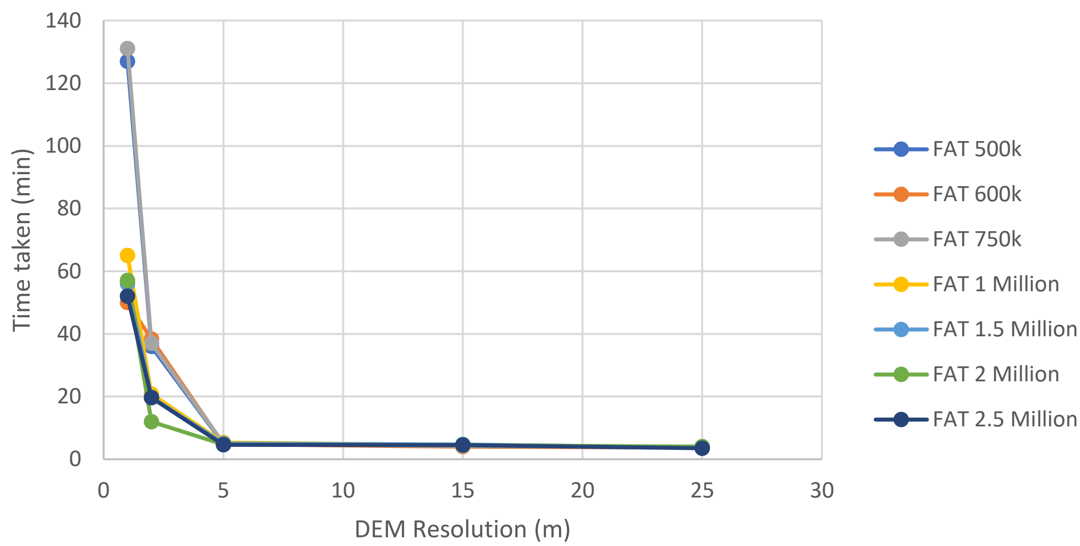


Figure 31: Time taken for model to run for differing Flow Accumulation Threshold (FAT) values at Site A.

As seen in Figure 31 the time taken for the model to run was not influenced by the FAT value unless the DEM had a resolution of 5m or less. Below a DEM resolution of 5m it seems that as the Flow Accumulation Threshold increases, the time taken for the model to run does too.

Further Improvement to the Model

As an example of how this model could be developed further it was incorporated into a modified version of the RMF Slash Mobilisation Risk Assessment. The first 'dimension' regarding harvest slope and ESC is split into the three parts that are the outputs of the Catchment Risk Matrix. The following figure shows the original 1st dimension.

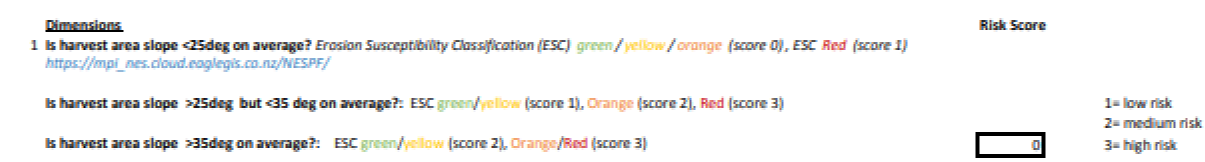


Figure 32: RMF Slash Mobilisation Risk Assesment 1st Dimension

This can be compared with the modified version shown in figure 33.

Catchment Risk Matrix	Risk Score	
1A What is the Area Code output from the Catchment Risk Matrix?		1= low risk 2= medium risk 3= high risk
1B What is the ESC Code from the Catchment Risk Matrix?		1= low risk 2= medium risk 3= high risk 4= very high risk
1C What is the Slope Code from the Catchment Risk Matrix?		1= low risk 2= medium risk 3= high risk
	Total score = 1/3(1A+1B+1C)	

2. Is area susceptible to high intensity AND/OR extended rainfalls?

Figure 33: Altered RMF Slash Mobilisation Risk Assessment and Catchment Risk Matrix 1st Dimension

Figure 33 shows how the outputs of the Catchment Risk Matrix are used as dimensions for the RMF Slash Mobilisation Risk Assessment. In order to use these tools together, the Catchment Risk Matrix can be run for the whole forest, then each catchment with harvesting operations should be assessed further using the RMF Slash Mobilisation Risk Assessment. This incorporates factors such as rainfall, downstream risk, etc. The overall classification can then be appended to the watershed shapefile which can be used as the basis for symbology for a visual overlook of the high-risk catchments.

6. Discussion

Flow Accumulation Threshold (FAT)

When the FAT value was changed the main code influenced was the Hazard Code at both Site A and Site B. For Site A the Area Code varied slightly, and the Slope Code showed no large differences. At Site B all the parameters varied more than Site A when the FAT was altered to 2.5 million. This could be because of the smaller area.

The catchments are assigned a Hazard Code by whichever ESC class the centroid is in. Catchments may be designated as a low Hazard Code because of their centroid but the rest of the catchment is in a higher ESC class. As the FAT is increased, the catchments that have their centroid in a lower class get bigger, distorting the results. Areas tending to move down in Hazard Code could be explained by most of the area being in red, with some smaller sections of lower ESC.

The Hazard Code being assigned to catchments by their center may not be appropriate, especially when larger FAT values are being used. Instead, the catchment could be assigned to whichever class is the majority of the catchment. Another option would be to align with the highest risk ESC class within the catchment. This would mean any restrictions under the NES-PF would be the same for each catchment.

I expected that the Slope Code would have changed with the FAT as well, but this was not the case. The Slope Code is based on percentage of steep areas within catchments, and it was expected that as catchments were mapped at a larger scale this proportion would decrease due to an averaging effect. This was not the case at Site A. Perhaps because of the large study area, an FAT would have to be larger than 2.5 million or smaller than 500 thousand to influence the Slope Code. This effect was visible at Site B when the FAT was increased to 2.5 million.

Time

Computer specifications, settings, and background processes will all have an influence on the time for the model to run.

When the DEM resolution is 5m or lower the time taken for the model to run remained at around 5 minutes regardless of the area of the site, the FAT, or the DEM resolution. The relationship between the time taken to run the model and the DEM resolution can be approximated by a power law for DEM resolutions between 1m and 5m. This could make it tempting for a user to run the model at a lower resolution. This would result in a lower quality output.

Digital Elevation Model (DEM)

Across the three sites there were common trends visible when the DEM resolution was altered. It was observed that the Slope Code was most susceptible to variance from the DEM resolution changing. With a decreasing DEM resolution, more area tended to move down a Slope Code classification. This is because as the DEM resolution is decreased, the terrain becomes more averaged out. The Area Code and Hazard Code were not impacted heavily by a change in the DEM resolution.

The lower resolution DEM resulting in poorer slope outputs matches what was found in New South Wales (Vase & Teng, 2007). Lower DEM resolution resulting in poorer quality analysis also correlates with what was found when SINMAP was analysed (Harrison et al., 2012).

Limitations and areas for improvement

The accuracy of the model itself has not been assessed. A study comparing the output of the model with known landslides is an area that could be explored further. This study could alter thresholds until the output of the model is most closely applied with observed landslide occurrence.

The boundaries of the parameters may need to be altered. No area being within a Slope Code of 3 could be evidence that the lower boundary is too high given that these sites are considered to be steep forest country. Also, across the three sites the Area Code was 3 for over 90% of each site, suggesting the boundary for this is quite low. These alterations would be simple to complete within the model but need guidance so that they best represent the boundaries of risk.

Only three sites were looked at and they were all located in a similar area. The results found may not be applicable when the model is being used in a different region due to topographic variations or differences in ESC. Results seen may be anomalies due to the sites chosen but the study presents an overview of things to be aware of when using the model. However, if this model is found to not be appropriate in other areas, perhaps the parameter boundaries could be altered (McSaveney, 2007).

It has been assumed that the 1m DEM gives the most accurate representation. This may not be true, as some amount of smoothing the data would average out anomalies, errors with the LiDAR, and very small, steep mounds. The data used has a spatial accuracy of ±2 m with 90% confidence (LINZ, 2020). Studies have indicated that it is reasonable to assume that 1m DEMs are reliable for this kind of spatial analysis (Vase & Teng, 2007b).

Combining the model with the Slash Mobilisation Risk Assessment brought in more parameters and included the consequences of an event occurring. The parameters brought in are not very spatially variable and can usually be easily identified. This is a benefit when compared with SINMAP.

The model could place buffers along waterways. It is possible to calculate watercourse width for given storms using LiDAR. This would help operators to better understand where the 5% Annual Exceedance Probability (AEP) floodplain as required by the NES-PF. Obviously streams up in headwaters need less of a buffer than large rivers that have several channels merging into them.

Models like this hold little value if the input data is inadequate or the outputs are not understood or being used in a meaningful way.

7. Conclusion

The purpose of this study was to evaluate and improve a Catchment Risk Matrix model for slash mobilisation. Three sites had sensitivity analysis undertaken for the DEM resolution and two of the sites also had a sensitivity analysis for the Flow Accumulation Threshold.

When the Flow Accumulation Threshold is altered the parameter that was subject to the most change was the Hazard Code. This is because as the catchments get larger, they still assign all of the area to whatever is in the centroid of the catchment. One way to improve the performance of the model in this regard would be to alter the way the Hazard Code is assigned to catchments. A better approach may be to calculate what Hazard Code most of the catchment is in or assign the catchment the highest ESC in the catchment.

Users of the model should have some understanding of how the model works, so that they can assess when errors are occurring and are able to use their best judgement regarding the quality of the outputs. The necessity for quality input data has been outlined in this report. Land managers should use the best quality elevation data available, which will result in analysis taking longer to process but produce much more accurate results.

Overall, currently the model is a good base for future improvements that build upon it. Analysis of steep slope stability remains an important issue in the context of New Zealand forestry. This type of model is useful only if it uses accurate input data and the results are used in a meaningful way.

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