OVERVIEW OF THE SPATIAL DISTRIBUTION OF AVALANCHE ACTIVITY IN RELATION TO METEOROLOGICAL AND TOPOGRAPHIC VARIABLES IN AN EXTREME MARITIME ENVIRONMENT

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ABSTRACT: The spatial distribution of avalanche occurrences on the Milford Road, Fiordland, New Zealand have been qualitatively examined and related to meteorological and topographic parameters. Using an 18 year data set of over 2800 avalanche occurrences from the Transit New Zealand Milford Road Avalanche Programme we have explored the spatial relationship between avalanche occurrences, topography, and storm direction. The climate is strongly maritime with annual precipitation exceeding 8m (water equivalent), while winter storms often deposit in excess of 2m of snow in the start zones. Pleistocene glaciation of resistant bedrock has resulted in a landscape characterised by U-shaped valleys with very steep sides and extensive snowfields perched almost 1000m above the valley floor. Avalanche activity has been represented on a high resolution aerial photograph in ESRI's ArcGIS and linked with a 5m DEM, the preceding 72 hours meteorological data, and field observations. This Geographic Information System (GIS) allows for hypothesis testing and visualisation of avalanche occurrences under various temporal, spatial and meteorological parameters. This analysis is aimed at maintaining the institutional memory of the programme and quantifying what local forecasters suspect about the influence of topography and dominant meteorological conditions in relation to the spatial distribution of avalanching on the Milford Road.

KEYWORDS: avalanche; avalanche forecasting; maritime climate; visualisation; hypothesis testing.

1. INTRODUCTION

This paper describes the analysis of meteorological and topographic parameters to examine and visualise the spatial distribution of avalanche occurrences on the Milford Road, Fiordland, New Zealand. The Milford Road (State Highway 94) between Te Anau and Milford Sound, is the only public highway with a significant avalanche problem in New Zealand. It has long been known that the Milford Road has as severe an avalanche problem as any other mountain highway in the world (Conway et al., 2000; LaChapelle, 1979). The Milford Road is in the South West of the South Island, in the Fiordland region (Figure 1) and is characterised by a landscape formed during Pleistocene glaciation of resistant bedrock, that has resulted in U-shaped valleys with very steep sides and extensive occasionally permanent snowfields perched above (Owens and Fitzharris, 1985).

Significant avalanching occurs in Fiordland because of the over-steepened terrain combined with very heavy precipitation that exceeds 8000 mm per year (Owens and Fitzharris, 1985). Winter storms often deposit in excess of 2m of snow in the start zones. A typical storm in Fiordland will start with a strengthening North Westerly flow, ahead of a Southerly front, with a change to cooler clear weather following the front. This progression is controlled by synoptic scale weather patterns, and often has a duration of between 3 and 5 days. North Westerly and Southerly storms also occur independently of each other, followed by clearing weather following the front.

LaChapelle (1979) recommended that the avalanche terrain be mapped and the level of hazard assessed. This was undertaken by Fitzharris and Owens (1980), and they also recommended improvements in data gathering, traffic control and avalanche forecasting and control. Following the death of a roading overseer in 1983, authorities initiated a formal programme of weather and snowpack monitoring and avalanche hazard control in 1984 (Weir, 1998). An experienced avalanche forecaster was employed, high level automatic weather stations (AWS) were

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established, stricter control of traffic was maintained and helicopter bombing for artificial release of avalanches was introduced. Standardised procedures for avalanche occurrence, snow and weather data gathering were adopted and these data have now been loaded into a Microsoft Access relational database. A testament to the success of the Transit New Zealand Milford Road Avalanche Programme is that since the avalanche programme officially started in 1983, there has been no loss of life. Over the years the avalanche programme has been under constant assessment, improvement, international peer review (Föhn, 1999), and research (Fitzharris and Owens, 1984; Weir, 1998; Carran et al., 2000; Conway et al., 2000, 2002).

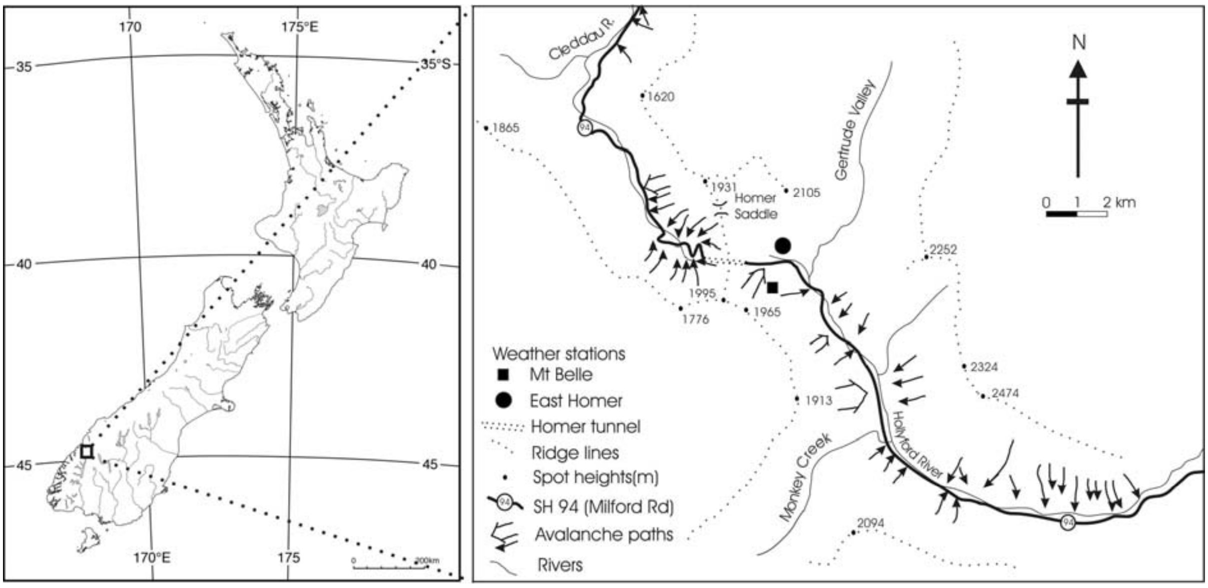

Figure 1: Location map, showing New Zealand, the Milford Road, and Mt. Belle and East Homer Weather stations

2. PREVIOUS WORK

2.1 *Milford Road avalanches*

Fitzharris and Owens (1984), Owens and Fitzharris (1985; 1989) and Dingwall et al. (1989), have all commented on the steep nature of the avalanche paths in Fiordland. Fitzharris and Owens (1984) have highlighted that while starting zones of Fiordland are similar to elsewhere, the tracks are significantly steeper. This has even resulted in the formation of avalanche tarns at the base of some of the steeper avalanche paths (Fitzharris and Owens, 1984). These factors contribute to make the Fiordland area a unique and challenging location to conduct research on avalanches. Work by Petrie (1984) examined the spatial distribution of avalanching, he considered 16 large events and related this to synoptic weather records. Three main processes for large avalanches were distinguished, rain on snow, snow overloading and thaw events. Rain on snow was found to be associated with a North Westerly airstream on the western limb of an anticyclone, located to the east of the South Island. Snow overloading events were associated with a series of southerly fronts, often followed by a depression moving southwards, and thaw events were associated with a slow moving intense anticyclone crossing the South Island. Petrie also found slopes with North East aspects had the greatest amount of lee slope loading, as they are subject to loading from a wider range of common wind directions. McLauchlan (1995) assessed impact pressures and velocities, finding velocities up to 83 ms^{-1}, and high densities up to 775 kgm^{-3} in avalanche deposits. Weir (1998) conducted an analysis and reassessments of the avalanche hazard, inserting new traffic volumes into existing hazard equations. A peer review of the avalanche safety procedures was undertaken in 1998, in which several recommendations were made (Föhn, 1999). Conway et al., (2000) has developed a model that calculates the effect of increased stress by the addition of new snow and the strength of subsurface layers to predict the timing of avalanching, while Carran et al. (2000) also conducted research to aid in predicting stability, involving the use of a lysimeter to improve the tracking of liquid moisture through the snowpack. The Transit New Zealand Milford Road Avalanche Programme is continually collecting an ever increasing amount of information on avalanche occurrences and an increasing array of meteorological parameters, but currently lacks the means to visualise their text based database. One option is to create a Geographic Information System (GIS) for this purpose.

2.2 *GIS and avalanche research*

The use of a GIS with a Digital Elevation Model (DEM) has the potential to contribute to several components of avalanche forecasting and control. They can assist in modelling avalanche formation processes, such as snow accumulation and snowdrift, provide a spatially based inventory of avalanche events, and associated control practice, allow visualisation, and allow automated processes for avalanche terrain mapping.

Bolognesi *et al.* (1996) presented the idea of using a GIS to describe starting zones to assist in hazard mapping and provide input for avalanche hazard forecasting. However it is only in recent studies that attempts have been made to automate the process of identifying avalanche paths and thereby the avalanche hazard (Gruber and Haefner, 1995; Maggionni *et al*., 2002; Tracy, 2001). Maggionni et al., (2002) used specific terrain parameters to predict avalanche occurrence frequency from an extensive database from around Davos, Switzerland. Using a GIS as a tool for visualisation is becoming more and more accepted as a common method to display avalanche hazard as shown through the work of Gruber (2001), Leuthold et al. (1996), McCollister et al. (2002; 2003), Stoffel et al. (1998) and Purves et al., (2003). Purves et al., (2003) further extend this idea by allowing a forecaster to query the available data, using a nearest neighbour approach, and use this for hypothesis testing. McCollister et al., (2003) also incorporates a nearest neighbour approach with a GIS to visualise predicted avalanche probabilities. A probabilistic method allows McCollister to examine the spatial relationship of avalanche occurrences under various meteorological parameters, and express the result as a probability of occurrence. Patterns are found at the slide path scale, but no patterns are found when grouped by aspect, suggesting local topography is more important when relating wind direction to avalanche activity.

3. AIMS

In recognising the fundamentals of avalanche forecasting (LaChapelle, 1980; McClung, 2002b; McClung and Schaerer, 1993), there is a need to improve methods of data storage and analysis for the purpose of maintaining institutional memory. A GIS would facilitate visualisation of the avalanche database, and provide a method to represent, store, and analyse the spatial data, thereby maintaining and contributing to the institutional memory regarding avalanche occurrences on the Milford Road. Maintaining this institutional memory is an integral part in succession planning, and provides the necessary background for avalanche hazard management and forecasting (LaChapelle, 1980; McClung, 2002a, 2002b; McClung and Schaerer, 1993).

Therefore, the aims of this paper are two fold: to describe the GIS that links information on the spatial extent of avalanche occurrences, photos, meteorological data, 5m DEM and high resolution aerial photograph and to show how the use of this GIS system for hypothesis testing and visualisation, through querying a range of temporal, spatial and meteorological parameters will lead to a better qualitative understanding of the effect of topography and meteorological parameters on the spatial distribution of avalanche occurrences on the Milford Road.

4. INFORMATION AND APPROACHES

The broad approach taken was to create a GIS system that links the spatial information on avalanche occurrences with the meteorological data and display this on our detailed aerial photograph and DEM. The avalanche and meteorological information comes from the Transit New Zealand Milford Road Avalanche Programme. This database, now spanning over 18 years has over 2800 individual avalanche occurrences. The associated meteorological observations for the same time period are also available. Currently the Transit New Zealand Milford Road Avalanche Programme has six AWS which telemeter meteorological data back to the forecasting office in the town of Te Anau, 70 km south of the main avalanche area. The longest records available are for Mt Belle (1600m) and East Homer (900m) AWS (Figure 1 and Table 1).

Mt. Belle AWS at starting zones, 1600m	**East Homer AWS at road level, 900m**
Air Temperature (°C)	Air Temperature (°C)
Snow Depth (m)	Snow Depth (m)
Previous Hours Precipitation (mm)	Previous Hours Precipitation (mm)
Wind Speed (km/h)	Air Pressure (hPa)
Wind Direction (V)	
Relative Humidity (%)	

Table 1: Hourly observations of meteorological variables from Mt Belle and East Homer AWS.

4.1 *Avalanche Data*

The Transit New Zealand Milford Road Avalanche Programme stores information on avalanche occurrences in a variety of forms. Since 1985 a consistent and accurate avalanche database has been maintained. This database containing all standard avalanche observation information is complemented with photographs showing spatial extent of avalanching, where the extent has been manually drawn on a base photograph of the avalanche path in question. Unfortunately, neither the database nor the photographs individually provide a complete data set on spatial extent of avalanching. Out of the 2805 avalanche events, approximately 1500 have images, and 1400 have information about avalanche width. However, all avalanches on record have information on size and path name. Therefore, using the information available in the database on width and extent of cover over the road, in combination with the photographs, representative outlines for avalanche occurrences were created. This was done, not only due to data constraints, but also in the interest of maintaining spatial consistency. Representative avalanche outlines were calibrated and drawn within ESRI's ArcGIS 8.3 for a given size on a given path from available photos and database information. In total there are 75 avalanche paths, where zones in a path are considered as a separate path. These representative outlines were then used to describe the spatial extent of all avalanches of a given size on that particular path. This resulted in a maximum of 11 different outlines for each of the 75 avalanche paths, describing all full and half sizes from size class 0 to 5. This method obviously works with the assumption that there is a positive relationship between avalanche class size and spatial extent, as shown by Keylock et al. (1999). However, we do observe in this data set that this is often true, and readily acknowledge that an individual avalanche of a particular size may well exceed the representative outline of that size. What this method lacks in precision it gains in being able to qualify the data, while also facilitating the examination of spatial patterns from a dataset that previously was only being stored in a database form showing no spatial information.

Each of the representative avalanche outlines was then duplicated as required, and coded with the unique identifier from the avalanche database. On the basis of this code, the outline of every avalanche can now be connected to the avalanche database, avalanche occurrence photo, where available, and associated meteorological data.

4.2 *Meteorological Data*

To examine the effect of meteorological parameters on the spatial distribution of avalanche occurrences, we connected the outlines of avalanche extent to the appropriate meteorological data. Meteorological data was selected from Mt Belle and East Homer AWS which both record standard meteorological parameters (Table 1). Mt Belle AWS has been operational since 1985 with hourly observations starting from 1989. East Homer AWS has hourly meteorological observations from 1993 onwards. Each avalanche occurrence was sorted into an avalanche day, and a mean time of occurrences was calculated for all avalanches on that day. Using this mean time of avalanche occurrence the proceeding 72 hours meteorological parameters were extracted from Mt Belle and East Homer AWS. For this analysis we only present results from the 72 hour vector averaged wind direction and speed from Mt Belle AWS, other parameters can be queried but these have not been used in this analysis. This was done as a first approach, to clearly differentiate between the documented two major storm directions, North West and South. Using only the 72 hour vector averaged wind direction and speed does mean that only storms of 72 hours duration or longer are examined, and shorter storms will be excluded. Using only the available hourly data, this resulted in a data set of 2237 avalanches occurrences on 299 individual avalanche days.

4.3 *Topographic Data*

Representative outlines of avalanche occurrences are drawn within ArcGIS on a high resolution aerial photograph and a 5m DEM. An aspect grid was created from the 5m DEM and this was used to determine average aspect of the avalanche occurrences. The DEM was produced from using automatic and interactive photogrammetric terrain modelling processes. The aerial photography used to produce the DEM was acquired on 15 Dec 1988. This photography has a nominal scale of 1:50,000 and was taken with a 152mm focal length lens metric aerial camera with a negative size of 23cm by 23cm. The film was then scanned using a ZI Imaging Photoscan 2001, with a spot size of 14 µm. The photogrammetric processing was undertaken using BAE Socet Set photogrammetric software. A DEM with a grid spacing of 3m was generated using the automatic terrain extract module of the software, using hierarchical image matching algorithms to locate conjugate points in stereo overlaps between photos. Interactive terrain editing tools were then used by an experienced photogrammetrist at Aerial Mapping New Zealand Ltd. to edit the DEM where the automatic terrain extraction had not been successful. Particular attention was paid to the ridge lines and outcrops to ensure that they were well represented by the terrain model. In open ground the DEM is estimated to have a relative accuracy of ±3 metres, with an absolute accuracy of ±5 metres.

4.4 *Outline of the GIS system*

Using the above three data components we can join them in the GIS to create a relational spatial database. Queries are facilitated under a standard select by attributes command, using Boolean language allowing searches of the entire database and associated linked tables. On return of the search criterion the linked tables can also be viewed and further queried. Examples of search criterion include; Path name, location, aspect, trigger, size, time range, multiple meteorological parameters, and many others. This GIS would allow a forecaster to specify any range of parameters, and visualise the resulting spatial distribution. This GIS can be used in two main ways. Firstly one could query a particular time period, to see which paths avalanched during the last storm, and then see the associated meteorological parameters. The alternative way this system could be used is for hypothesis testing of scenarios. An approaching storm is forecast to have a given wind speed and direction with a certain amount of precipitation. The forecaster could query the meteorological data for similar conditions, and view all of the resultant avalanche occurrences. These avalanche occurrences can then be further queried, for example, to only consider avalanche paths that have already been controlled, or only occurrence with a similar snow depth. The end result of any query is displayed on the high resolution aerial photograph in plan view. A density function was added to colour code the avalanche occurrences on particulars paths, by the number of occurrences on that path. Depending on the number of overlapping polygons in any query they are coded into discrete classes and coloured from light yellow through to red to represent the greatest number of occurrences. While this GIS does not provide a probability of avalanche occurrence on a path, it allows a forecaster to obtain a qualitative understanding of where avalanches have occurred under similar conditions in the past.

4.5 *Approach to the analysis of the spatial distribution of all avalanche occurrences*

Using the GIS this analysis was undertaken to look at the effect of topography on the spatial avalanche distribution. Aspect was chosen as a topographic variable as slope and elevation of the starting zones are less variable. All avalanche occurrences were divided into 8 aspect classes; North, North East, East, South East, South, South West, West and North West. The number of avalanche occurrences in each aspect class was then summed, and every avalanche occurrence in that aspect class was assigned this number. The purpose of this was to colour code all avalanche occurrences, by the total number of occurrences in their aspect class. The reason for this is twofold; this displays which aspects have the most avalanches, and which avalanche paths are on these aspects. This allows us to examine the spatial extent of all avalanche occurrences by aspect.

4.6 *Approach to the analysis of the effect of meteorological parameters on the avalanche distribution*

Using the GIS this analysis was undertaken to look at the effect of meteorological parameters on the spatial avalanche distribution. Here we wanted to consider the effect of the meteorological parameters on avalanche paths, not aspect. We wanted to get a better understanding of which paths avalanched more frequently under specific meteorological conditions. Two dominant storm types were selected to for this purpose; Southerly and North Westerly storms. These were selected as they both show characteristic meteorological trends. The southerly storm is usually colder, has lighter winds and less precipitation than the North Westerly storm. A Southerly storm will often bring snow down to road level, and deposit light dry snow in the start zones. A North Westerly storm will regularly bring rain to the start zones, especially in spring, or heavy wet snow. To allow sufficient data for the analysis all days with a 72 hour vector averaged wind direction between and including 134° to 225° were considered as a Southerly storm, irrespective of wind speed. This resulted in 19 avalanche days being selected, with 99 avalanches occurrences. As the majority of the data set contained days with North West wind, a tighter constraint was placed on the selection of North Westerly storm days. With the intention of observing the effect of lee slope loading, a moderate to strong wind speed threshold was selected. The selected days for a North Westerly storm were days with a 72 hour vector averaged wind direction between and including 270° to 360°, with 72 hour vector averaged wind speeds between and including 20 to 25 ms^{-1}. This resulted in 53 avalanche days being selected, with 408 avalanches occurrences. For the two scenarios, the number of avalanche occurrences in each path was summed, and every avalanche occurrence in that path was assigned this number. The purpose of this was to colour code all avalanche occurrences, by the total number of occurrences in that path. This allows us to examine the spatial extent of all avalanche occurrences by path in relation to the two storms.

5. RESULTS & DISCUSSION

This section will discuss the qualitative results of the two sets of analysis undertaken using the GIS.

5.1 *Spatial distribution of all avalanche occurrences by aspect*

When we examine the spatial distribution of avalanche occurrences by aspect we observe that there are more frequent avalanches on North East, followed by South and East aspects. When we look at the avalanche paths in these aspects we note that there are more paths in the North East and Southern aspects. Therefore it is not surprising that this should also be reflected in more avalanche occurrences. We also see that these are the paths that are frequently bombed for artificial release. The South and East aspects are also lee to the prevailing North West wind.

Avalanche occurrences are least frequent on the South West aspect. When we consider the avalanche paths in this aspect we see that most of them do not affect the road directly or are obscured from view from the road, possibly leading to a lower rate of recording, especially of smaller events.

5.2 *Effect of storm direction on the spatial avalanche distribution*

The spatial distribution of avalanche occurrences classified by avalanche path for both Southerly and North Westerly conditions showed some clear patterns. For the Southerly storm we observe slightly lower values of avalanche occurrences on avalanche paths with a Southerly aspect, and higher values on avalanche paths with North West, North and North East aspects. This clearly shows the effect of lee and cross slope loading, and windward scour of these aspects, under southerly wind directions. A discrepancy to this pattern exists with high values of avalanche occurrences on two paths with a South East aspect.

For the North West storm we observe a slightly less clear pattern (Figure 2). High values of avalanche occurrences are observed on paths with South West, North East and East and South East aspects. The effect of lee and cross slope loading is once again noticeable, but the effect of windward scour is less clear, with high avalanche occurrences also present on avalanche paths with North West aspects. We believe this is due to the warmer nature of the North Westerly storm. North West winds will often be warm and lead to rain to high elevations, making a consolidated snowpack which is difficult to entrain by wind. Southerly storms are often colder and deposit drier snow to low elevations, allowing wind redistribution to occur more easily.

This GIS analysis, while not providing a probability of avalanche occurrence as McCollister et al., (2002, 2003) does, allows a forecaster to obtain an improved qualitative understanding of where avalanches have occurred under similar conditions in the past. It also succeeds in working as a tool to allow easy querying of the database, and thereby permit hypothesis testing and visualisation.

A logical next step to the analysis of the spatial distribution of avalanche occurrences is to quantify the change in distribution, for a given query, relative to all avalanche occurrences. This would allow us to observe how a storm changes the relative distribution of avalanching, and provide further insight to spatial patterns associated with meteorological and topographic parameters.

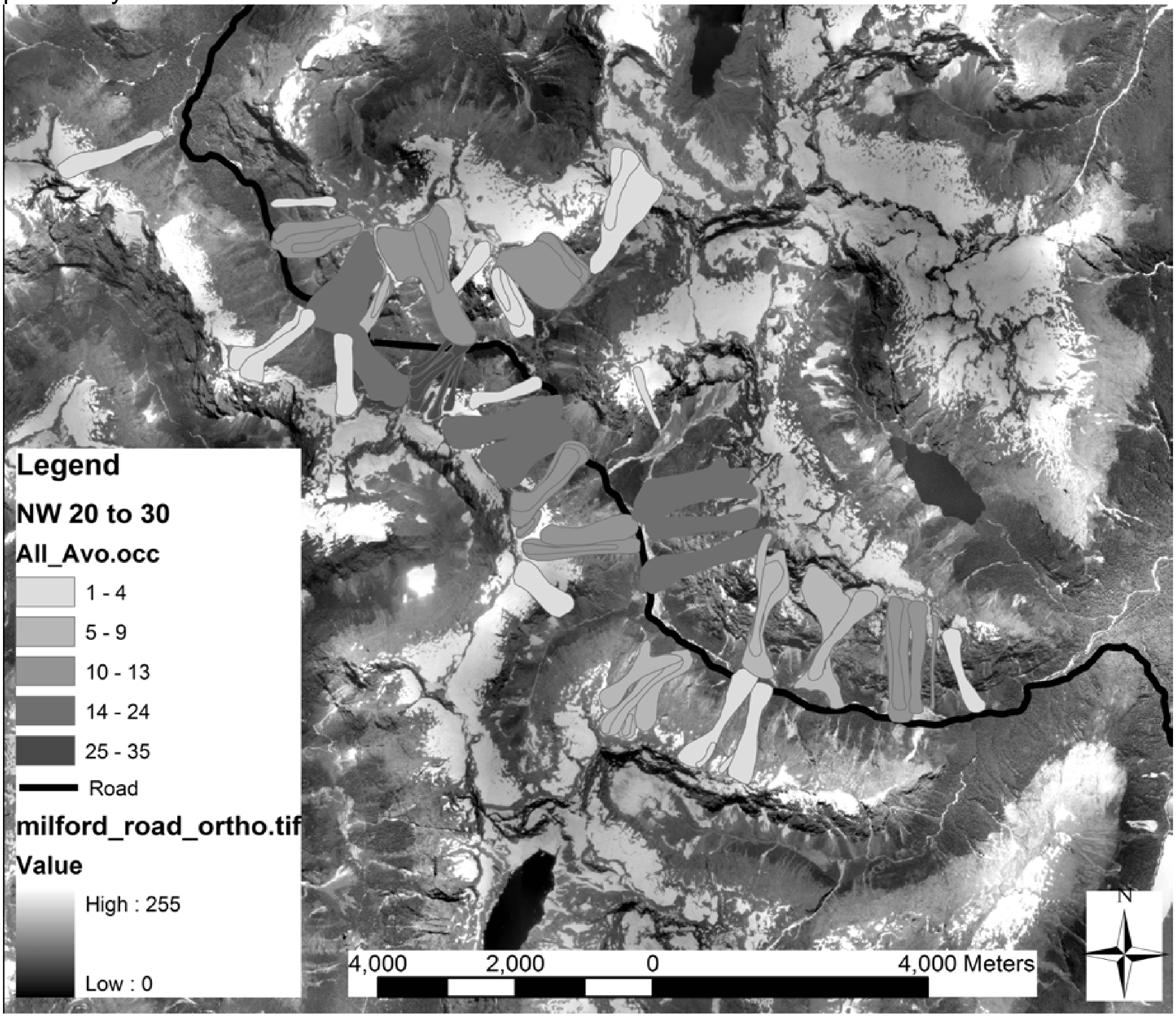

Figure 2: The GIS analysis showing the effect of a North West storm on the spatial avalanche distribution on the Milford Road.

6. CONCLUSION

In this paper we have provided an outline of the GIS, explaining the various data components available for query and analysis. We have also shown how this GIS system can be used for hypothesis testing and visualisation thereby maintaining the institutional memory of the programme. Using two examples of the spatial distribution of avalanche occurrences, grouped by aspect, and the change in spatial distribution from two storm directions we have shown how this GIS can assist in improving a forecaster's qualitative understanding of the spatial distribution of avalanche occurrence under specific, spatial and meteorological conditions. While not providing a numerical or probabilistic result to the question of whether there will be avalanches or not, it allows the forecaster to easily review and query the existing database.

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