Risk Analysis of Yellow Creek Fan in the Fox Glacier Valley

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Table of Contents

Pages:

Executive Summary

Research Question

- What effects do significant rainfall events have on debris flow hazards in the Fox Valley and how can these be mitigated?

Research Context

- Fox Glacier is located on the West Coast of the South Island and is a hugely popular tourist attraction. The Fox Glacier Valley is prone to rock fall and debris flow due to its steep slopes and high rainfall. The walking track up to Fox Glacier has been constantly moved over the years due to the risk of rocks falling down and seriously injuring tourists. This research was carried out on the Yellow Creek debris fan due to it being one of the most active in the Valley. The walking track used to be on yellow creek fan but due to the danger of rock fall and debris flow it has currently been moved to the riverbed. The main objective has been to help The Department of Conservation (DOC) and the Glacier Guides to improve the safety and quality of the public walking track up to Fox Glacier. To do so we need to determine and analyze the areas of risk. From here we can then provide information to our Community Partner Wayne Costello so that he and his team from DOC can make a more accurate judgment on track position and closure.

Summary of Method

- The first step was to figure out what could be done to answer our research question and what data was necessary to collect in field.

- To collect data in the field we used drmble R8 GNSS and measurements were taken of large boulders using measuring tapes on and around the Yellow Creek Fan.

- We used the data from this to create the fan profile. Using this profile and data we created hazard area maps and debris flow models.

- The rainfall and track closure data which was collected by DOC and Glacier Guides was statistically analyzed to predict likelihood of future track closure.

Key Findings

- The whole area of the fan is prone to rock fall and debris flow, although the primary and secondary channels are the more likely locations for a debris flow to occur.
- Well-established vegetation areas show areas of less rock fall and debris flow activity.
- A statistical analysis of the rainfall data and track closure data indicate that rainfall directly influences track closure.
- Statistically, rainfall amount had the greatest correlation with track closure.
- Statistical models coupled with knowledge of daily rainfall amounts can be used to help predict the likelihood of track closure.

Limitations of the Research

- The main limitations of the research were time constraints, distance to field site, weather, limited experience with the field equipment, and limited knowledge of analysis methods.

Suggestions for Future Research

Some suggestions for future research could include researching into other hazardous areas in the valley.

- Looking at rock fall and debris flow in the Gun Barrel slope and comparing it to Yellow Creek fan.

- Sediment samples could be taken next time to help predict the energy needed to initiate a debris flow.

- The effect of climate change on precipitation in the area and track closure frequency.

- Fan evolution over time could be used to aid and predict future fan evolution, as well as better tract placement and hazard mitigation.
- Effect of underground waterways on initiation of debris flow and sediment transport

Introduction

The research question this report focuses on is: What effects do significant rainfall events have on debris flow hazards in the Fox Valley and how can these be mitigated? This project aims to analyse the risk of rock fall and debris flow to the public, then advise The Department of Conservation (DOC) and local glacier guides on the probable hazardous areas around the Yellow Creek fan. DOC can then make better judgement calls on when and where to close the track and provide a safer, more permanent track layout to the public. To achieve these objectives, we had to go to Fox Glacier and use high precision GPS to gather fan profile data along with finding hazardous areas on Yellow creek fan. This data was then put into GIS soft wear and used to model what happens to the fan in debris flow events and create maps showing previous and current hazard areas. Other data used was rainfall and track closure data, provided by DOC. This data was statistically analysed and compared to find what conditions the track had been closed in and how often it was closed due to debris flow risks.

This research matters because it not only concerns the safety of the public but it also has an effect on the local economy in Fox Township as most locals rely on tourism as a source of income. If the track were closed due to the risk of rock fall or debris flow, there would not be any reason for tourists to stop there. This has devastating flow on effects for the local economy and community.

Source: Justin Harrison

Theory/Concepts/Literature Review

Because no previous research had been carried out on debris flow in the Fox Valley, we studied several broader reports and articles to get a better understanding about rock fall, debris flow and glacial valleys. These reports also help with identifying particular conceptual or methodological points that have contributed to the design of this current research.

It was necessary to gain a better knowledge into the likely depositions created by a debris flow. For this, the paper Depositional Processes in Large-Scale Debris-Flow Experiments by J.J. Major provided a base knowledge of likely depths and extent of a debris flow with specific parameters in a controlled environment. While this information is very simplified in terms of channel profile, and in reality there would be much more impact from variations in the topography, it does provide imagery of example debris flow deposition and extent which provided an idea as to possible debris flow impact. This provided a general idea as to what the model outputs would show and likely depositional profiles for possible debris flows in Fox Glacier Valley.

Glacial-topographic interactions in the Teton Range, Wyoming, David Foster, Simon H. Brocklehurst and Rob L. Gawthorpe, 2010
The article seeks to combine topographic analysis with modeled distributions of precipitation, insolation and flexural isostasy to present a conceptual model of topographic evolution in the Teton range, Wyoming (Foster, Brocklehurst, & Gawthorpe, 2010). The article finds that the topography of the Teton Range suggests that long term glacial erosion has been capable of keeping pace with rapid rock uplift in the area (Foster, Brockleurst, & Gawthorpe, 2008), the Southern Alps of New Zealand, home of the Fox Valley and Glacier, display a similar response to rapid uplift as (Brocklehurst & Whipple, 2007) have previously shown. This helps us understand the interaction between climate and topography and what effect the Fox Glacier may have had on the valley as it has retreated leaving over steepened hillslopes susceptible to failure. The article speculates that some form of dynamic topographic steady state may have developed once the failure threshold of hillslopes dominates high peaks, summit elevations remain relatively constant (Foster,

Brocklehurst, & Gawthorpe, 2010). Any over steepening of these hillslopes will therefore result in slope failure leading to landslides creating alluvial fans and debris flows such as the Gun Barrel fan and the Yellow Creek fan. The Teton Range highlights that a clear interpretation of how topography, climate and erosion interact in glacial mountain ranges is a vital precursor to gaining clearer insights and developing more realistic numerical models of glacial landscape evolution (Foster, Brocklehurst, & Gawthorpe, 2010) which in turn helps us undergo our research project

Methods

The methods used to conduct this research involved both fieldwork and analysis of the data gathered in the field along with data sourced from the Department of Conservation (DOC). Fieldwork was conducted on Yellow Creek Fan in Fox Glacier Valley. Due to time constraints we only had one weekend in the field to gather all the data needed to help us achieve our objectives. Data was gathered using Trimble R8 GNSS units, three rovers and one base station were used to gather fan profile data along with positions of hazardous areas such as large boulders, areas of boulder clusters and previously active debris flow channels. Rainfall and track closure data was also statistically analyzed. DOC gathered this data from 2013 up until 2015. The data was used to help predict likelihood of track closure in high precipitation events.

Hazard Maps

To get the following images of Yellow Creek debris fan from the LINZ Data Service taken in 2011, and in order for us to indicate or point out the areas that are hazardous to tourists, ArcMap was used. ArcMap (or ArcGIS) is a geospatial processing program that is used to view, edit, create and analyze geospatial data. This also includes images or pictures of any kind. ArcMap also allows the user to explore data within a data set, symbolize features accordingly and create maps. Another reason for using ArcMap is to be able to shade areas of risks and to be able to explain the morphology of the fan in detail.

Firstly the Yellow Creek fan image was loaded into ArcMap as a raster layer. An 'unknown' geographic coordinate system was used as the image did not have any spatial reference, and therefore could not be projected without the 'unknown' coordinate system. New feature classes were created in order to produce areas that needed to be shown as hazards these were then overlain onto the original image. The final maps identify areas that are vulnerable to debris flow and rock fall at the time the data was collected. Hazard areas will change over time as the main channel avulses across the face of the debris fan.

Debris Flow Modeling

In order to project and predict the potential extent of a debris flow, some form of modelling needed to be done. Initial research and reading of Debris Flows: Mechanics, Prediction and Countermeasures (Takahashi 2007), presented the option of using a set of equations which model the likely-hood of initiation and development of debris flow, as well as modelling the flow and extent. This set of equations required very specific input parameters and information which we did not have available, and which would also be very difficult to collect while in the field. For this reason a more simplified version of modelling which displayed potential extent and depth of the debris flow was chosen, this model was the Kanako debris flow model, which was primarily developed by Kana Nakatani at the Kyoto University in Japan. The model was developed with the intention of modelling the effects of Sabo dams on debris flow deposition. It uses a series of partial derivative equations to model different parts of a debris flow. The model user interface is displayed in figure 1.

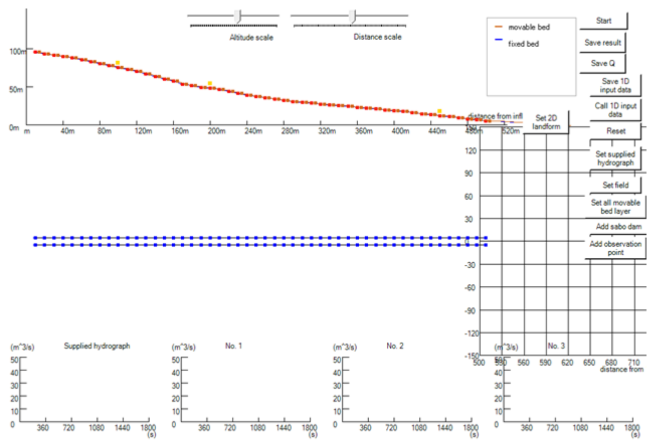

Figure 1-Kanako Debris Flow Model user interface

The information required as an input for this model is a set of hydrograph data, which is a combination of the potential water in the system and the sediments in the system as a percentage of fine and course sediment. The other main part of the information is the profile of the channel which is being modelled as a potential debris flow location. In this case both the main channel and the secondary channel profiles were input into the model, while the default hydrograph data was used. The fan profiles were built using from the data captured with the Trimble R8 Geographic Navigation System Satellite units which were put into a shapefile. This data was processed using Quantum GIS to build a fan profile based on distance and elevation. For this the measure tool and identify tool were used to determine distances between points and elevation of each of these points. The image in figure 2 shows the fan profile raw data and the fan profile overlayed on an aerial photograph of the fan for the purpose of context.

With these sets of data the model can be run for the main and secondary channel in order to produce potential extents and depths of debris flow. While it would have been good to create a more extensive debris flow model, time limitations and limitations of knowledge and mathematical ability made this an unrealistic option.

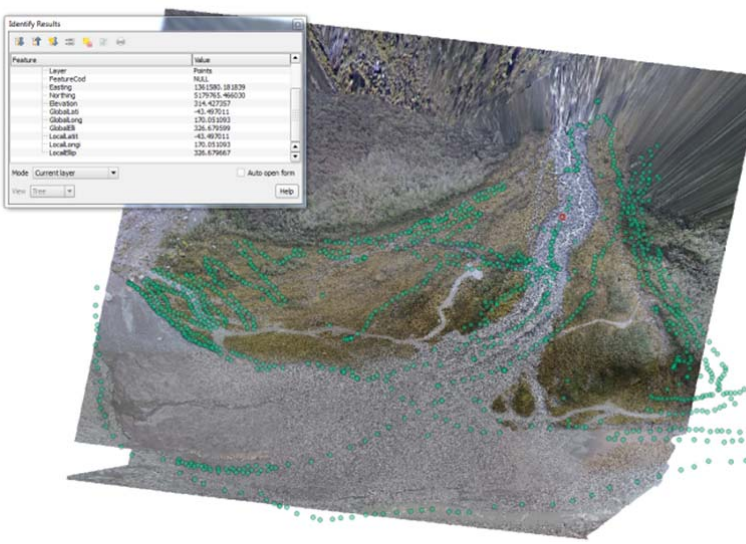

Figure 2-Fan profile shape file overlaid on
An aerial photo

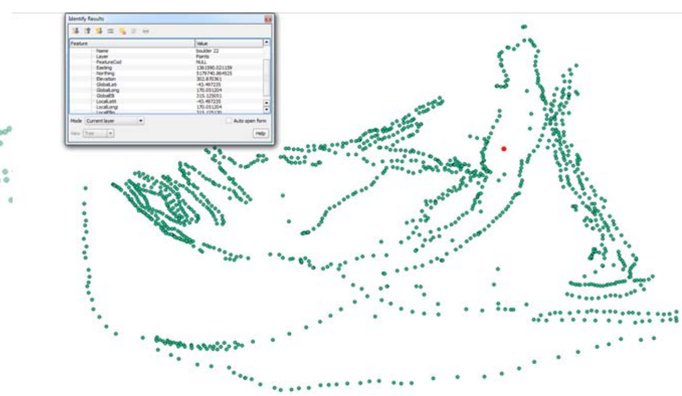

Figure 3-Fan profile shape file

Statistical Analysis

As rainfall is considered a primary risk factor to debris flow, data is constantly collected by the Department of Conservation (DOC) for daily precipitation amounts at the beginning of the Fox Glacier walking track. A rain gauge, located at the public parking area, measures rainfall in millimeters. Daily track closure status data, as determined by DOC, has been collected from 2013-2015. During this timeframe, DOC had multiple closure points along the glacier access track depending on possible hazards. These closure points were defined as: terminal viewpoint (200m), photography viewpoint (500m), Yellow Creek debris fan (600m), and car park (1200m). Because the focus was on the Yellow Creek debris fan, only track closures from the fan back to the car park have been considered. Closures at the terminal viewpoint or the photography viewpoint were not considered. This data was then used to determine the percentage of days that the trackwas closed at Yellow Creek debris fan.

The rainfall data and closure data were then collated into a single table by date for analysis. Statistical analysis was conducted using JMP software. Distributions of rainfall data were calculated by year, season, and month. Distribution of track closure status was determined in terms of overall likelihood as well as likelihood by month and season. Nominal logistical regression was conducted on closure status at Yellow Creek against daily rainfall, 3 day cumulative rainfall, and 5 day cumulative rainfall. Additionally, the influence of month, season, and year were examined.

The coefficients for each of the parameters investigated in the nominal logistical regression analysis were used to generate predictive models for likelihood of track closure at different amounts of rainfall.

$$\text{Likelihood of closure at Yellow Creek} = \frac{1}{(1+\exp(-(\text{ intercept} + \text{variable*rainfall amount})))}$$

The intercept estimate represents the likelihood of closure at zero rainfall. The variable estimate determines the change in likelihood of closure at differing amounts of rainfall.

Results

Hazard Maps

To access the Fox Glacier on the West Coast, a track has been constructed on the side of the valley and has been moved over the years due to rock fall in order the keep the public safe. The image below is the Yellow Creek debris fan on the West Coast and it is one of the most active areas in the Fox Valley and is particularly vulnerable to debris flow and rock fall. This area is also where the current research was carried out. The whole area shown on the image is very active and prone to debris flow and rock fall, which is why it can be a real threat to human life. When looking at the image, one can see the old walking track (brown line that runs through the fan, as well as the Fox River (blue thick line), the Yellow Creek River (thin blue line) that runs through the fan, and small old river channels (black lines) on the fan as well. The areas that are shaded in red indicate the areas that are mostly affected by erosion from the Yellow Creek River and from the Fox River.

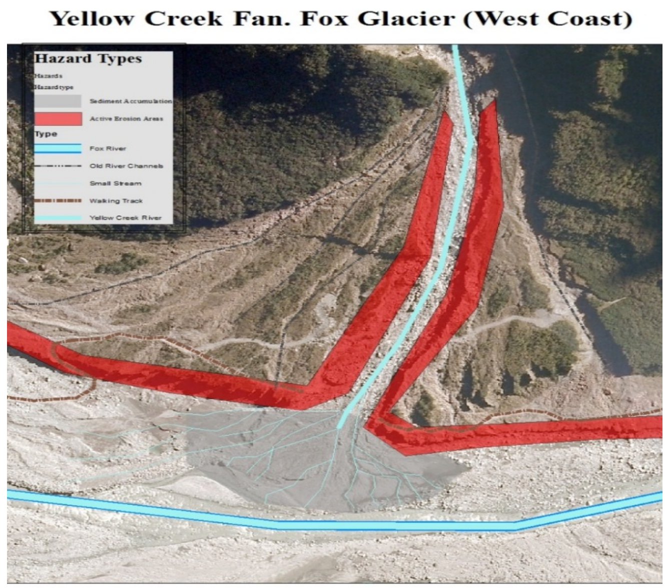

Figure 4- Yellow Creek Fan Erosion

During our feildwork on the Yellow Creek debris fan two months ago, we noticed that most of the areas were covered with shrubs, mosses and red algae (areas shaded in green). From talking to local glacier guides we found the mosses and shrubs take up to 5 years or more to be well established and red algae take approximately 3 years. This indicates that these green areas have not been recently active.

Yellow Creek Fan. Fox Glacier (West Coast)

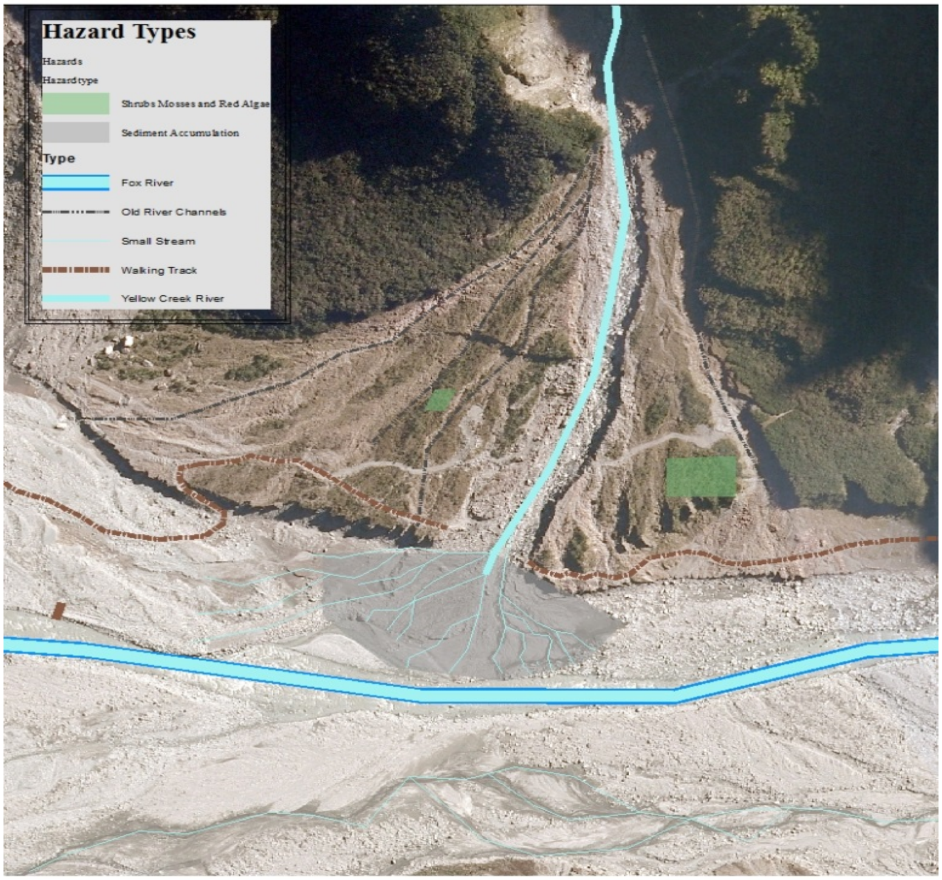

Figure 5- Shrubs, Mosses and Red algae

From the fan profiles produced we found the left side of the fan (the area shaded in orange) is much higher than the area to the right of the main channel. This tells us that the left hand side of the fan, which is one of the main routes DOC uses when they change the track layout, has the potential to be highly active with both debris flow and rock fall.

We also found that the Yellow Creek channel changes direction once it reaches the Fox River bed. This is due to a levee that has been built on this area in order to prevent the Yellow Creek River from flowing onto the current track location. Further human influence is seen in the Yellow Creek channel where DOC has removed debris so they do not block the channel.

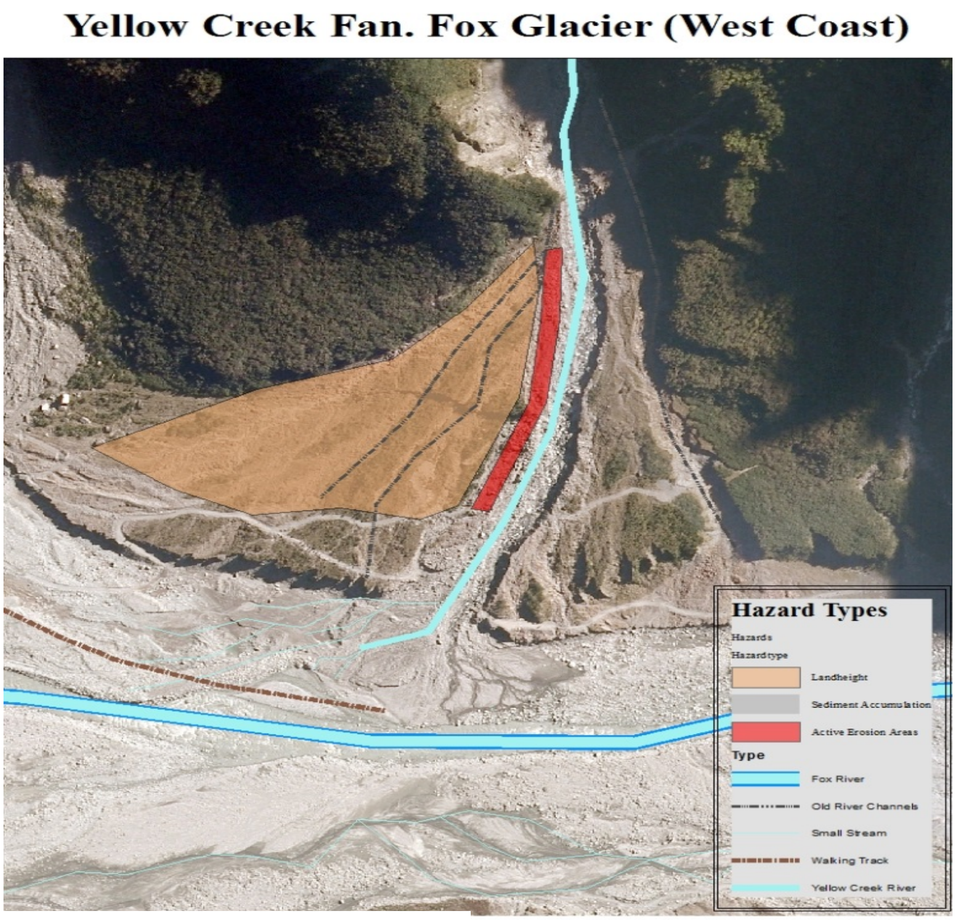

Figure 6- Hazard Areas

Debris Flow Modeling

The outputs from the model are the debris flow extents using both the 2d and 1d models. The 1d model was used for the purpose of modelling the effects of a Sabo dam on debris flow extent and depth. While a Sabo dam wasn't present in either of the channel and is not a viable option for the study site, it does model the impacts that any sort of blockage or other protection method could have on the depositional profile and extent of a debris flow in each of the channels.

Firstly the output of the 1d model which was run using the default hydrograph data and a Sabo dam added to the channel profile approximately half way up the modelled channel. This model output for the main channel displayed a depositional depth of over 10 metres behind the Sabo dam, meaning the dam was overtopped and there was some deposition in front of the Sabo dam. This deposition was however very shallow, showing that a large percentage of the debris flow material was actually trapped by the Sabo dam. This output was very similar when the model was run on the secondary channel profile. The main difference being that there was a deeper deposition at the bottom of the secondary channel model output. The amount of sediment which overtopped the Sabo dam in the secondary channel was very similar to that of the main channel, the difference in deposition is most likely due to the difference in steepness of the channel.

The 2d model was run without the addition of Sabo dams in order to determine the likely outflow extent and depth of a debris flow event. This model gave outputs, which are displayed on the following page, to show extent. As can be seen from these model outputs the extent of possible debris flow extends at least 240 metres from the end of the channel, This is enough to extend well past the position of the current track, at its deepest the deposition of the projected debris flow was approximately 20 cm, extending over an area 240 metres long and 60 metres wide. The width and depth of deposition of the projected debris flow in the secondary channel is very similar to that of the main channel, these outputs are based on level ground from the end of the channel and so do not project exactly what would happen in a specific event, rather give an estimate of potential depositions. The fact that there is a steep bank approximately 10 metres from the end of the secondary channel would significantly alter the debris flow process. This model, despite a number of inaccuracies, does provide a projection as to possibilities to aid in mitigation and planning.

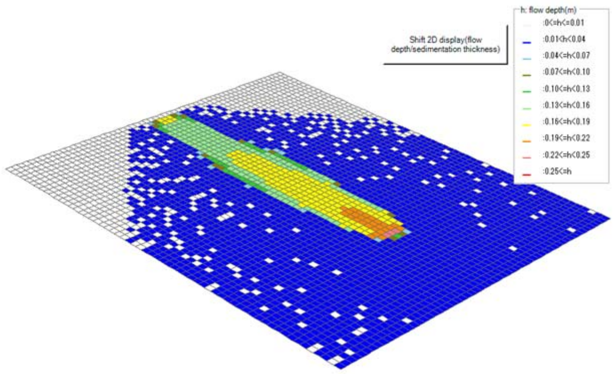

Figure 7 - Extent and depth of debris flow from main channel

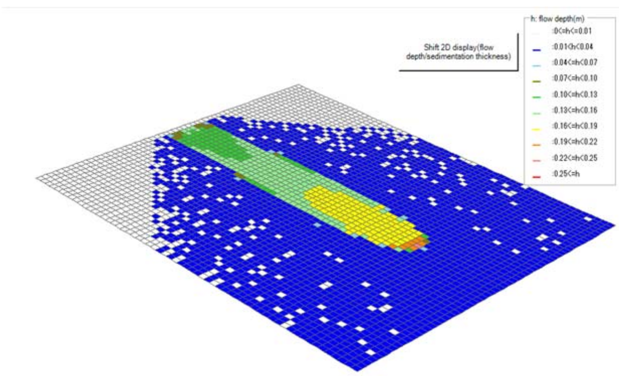

Figure 8 - Extent of a debris flow from the secondary channel

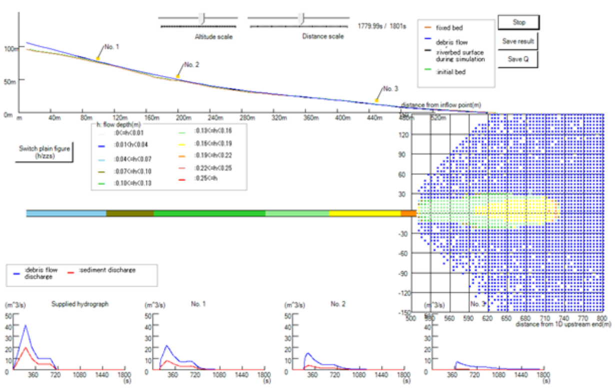

Figure 9 - 2d model showing area of debris deposition from main channel.

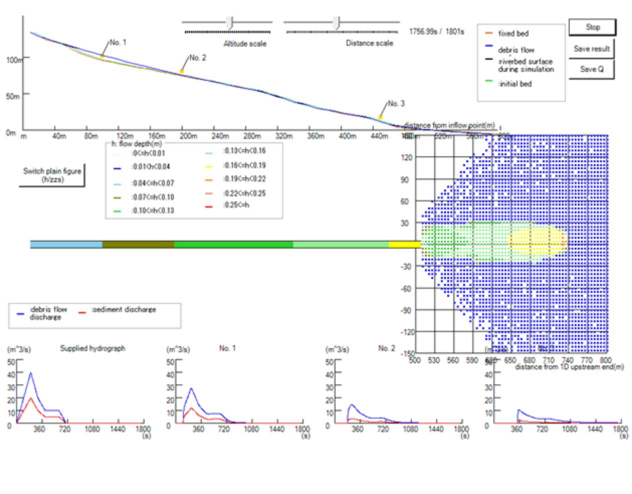

Figure 10 - 2d model showing area of debris deposition from main channel.

Statistical Analysis

Department of Conservation data from 2009 to present day generated annual rainfall amounts from between 4500 and 6089 mm per annum (Figure 6).

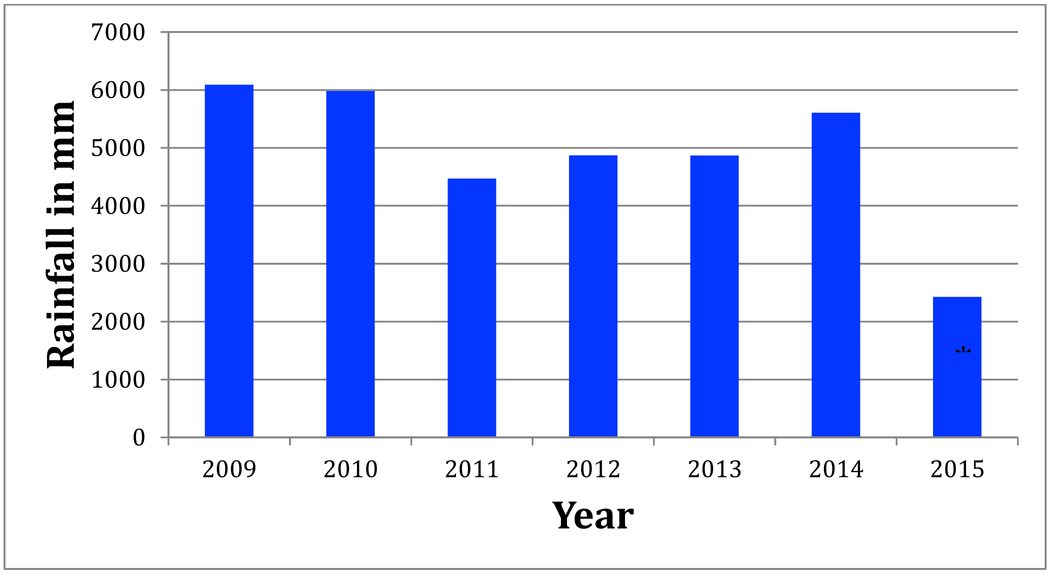

Figure 11 – Graph shows the amount of rainfall the Fox Glacier valley received from 2009-July 2015.

The distribution of rainfall by month (Figure 7) and season (Figure 8) demonstrate that spring and winter have higher daily rainfall. The individual months show that the increased likelihood of closure for spring and winter was consistent across all associated months.

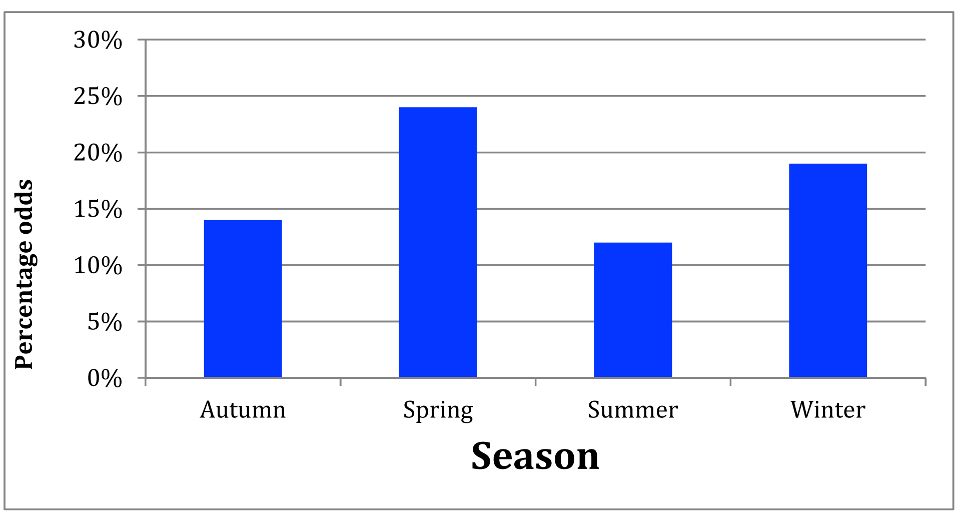

Figure 12- Graph shows the percentage of days closed at Yellow Creek fan per season

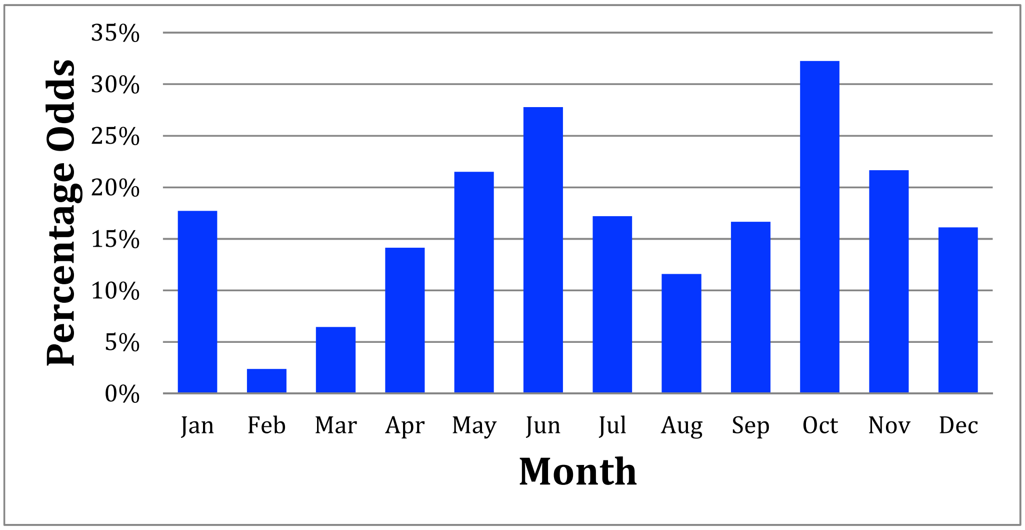

Figure 13-Graph shows the percentage of days closed at Yellow creek fan per month

The overall likelihood of closure at Yellow Creek was found to be 17% over the last 3 years. When broken down by month and season, the likelihood of closure was highest during the spring and winter months.

Using the coefficients generated from the logistical regression (Figure 9), the following predictive models were created to determine the predicted likelihood of track closure:

- Likelihood of closure for daily rainfall amount
  1/(1+exp(-(2.82810 + -0.06120*rainfall amount)))
  $p<0.0001$

- Likelihood of closure for 3 day cumulative rainfall amount
  1/(1+exp(-(2.99715+ -0.02406*rainfall amount)))
  $p<0.0001$

- Likelihood of closure for 5 day cumulative rainfall amount
  1/(1+exp(-(2.92604 + -0.01454*rainfall amount)))
  $p<0.0001$

Parameter Estimates Single Day Total				
Term	**Estimate**	**Std Error**	**ChiSqure**	**Prob>ChiSq**
Intercept	2.82809799	0.1520992	345.73	<.0001
Rainfall(daily)	-0.0612041	0.0049001	156.01	<.0001
Parameter Estimates 3 Day Cumulative Total				
Term	**Estimate**	**Std Error**	**ChiSqure**	**Prob>ChiSq**
Intercept	2.9715113	0.1677944	313.62	<.0001
Rainfall(daily)	-0.0240574	0.0020692	135.17	<.0001
Parameter Estimates 5 Day Cumulative Total				
Term	**Estimate**	**Std Error**	**ChiSqure**	**Prob>ChiSq**
Intercept	2.92604189	0.16845559	301.71	<.0001
Rainfall(5 day)	-0.0145383	0.0013271	120	<.0001

Figure 14 – Table shows the coefficients used to generate the models

Discussion

The data collected from DOC for rainfall at the car park leading to Fox Glacier clearly demonstrates this area of the West Coast of New Zealand encounters heavy rainfall. A statistical analysis of the rainfall data and track closure data indicate that the amount of rainfall in any given day ($p<0.0001$) or the cumulative amount over a 3 day period ($p<0.0001$) or a 5 day period ($p<0.0001$) significantly affects the likelihood of track closure at Yellow Creek.

The predictive model equations generated using nominal logistical regressions are represented graphically in Figure 10. These graphs demonstrate the response curves for the predicted likelihood of closure at various rainfall amounts for each 1 day, 3 day and 5 day rainfall amounts. The p value <0.0001 indicate the equations truly represent the historical data from 2013-2015, and can be used to effectively provide prediction of the likelihood of closure of the track leading to Fox Glacier at Yellow Creek fan.

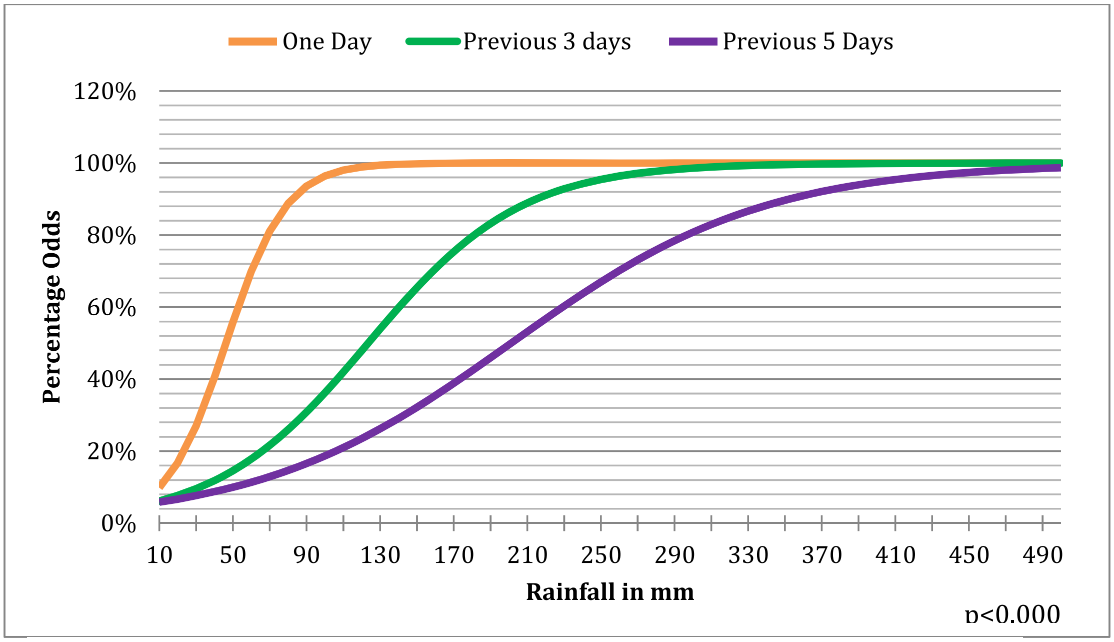

Figure 15 - Graph show the predicted likelihood (in percentage odds) of closure at various rainfall amounts.

This model, coupled with the knowledge of daily rainfall amounts, can be utilized in the future to help predict the need for track closure during times of high debris-flow risk caused by rainfall, ultimately improving the safety of visitors.

The model provided a good indication of the possible extents of a debris flow, although could not give an accurate output of a debris flow event in the fox valley due to the lack of some of the required data, particularly sediment source data. The outputs which were generated using the model showed debris flow extents in excess of 240 metres, with a depositional depth of 20-30 centimetres, which is more than enough to cause significant track damage and threat to life to tourists walking the track. The scale of the debris flow modelled using default settings is much likely smaller than that of a potential debris flow from the yellow creek fan, the sediment output over time shown here shows a maximum discharge of 40 cubic metres of sediment and water per second, a realistic debris flow event would likely have a higher discharge

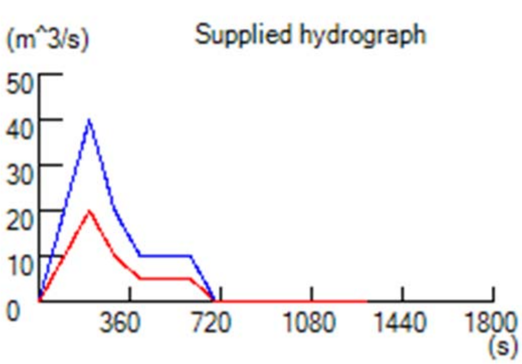

Figure 16 – default hydrograph

based on the quantities of rainfall recorded and size of catchment area of the yellow creek. If the research were to be repeated the use of sediment data and potential water in the system would give a more accurate model of a potential debris flow.

With the purpose of the study bring to determine conditions required for track closure and the possible extents of a debris flow event in the area, the data and methods could only be used to produce theoretical results, and with the time and previous knowledge constraints the depth of this analysis could not be done as thoroughly as would be possible with more time. The modelling of possible debris flows is very limited due to the complexity of this form of analysis and the lack of previous knowledge of group members in this field. For this purpose the Kanako modelling software was used, this software does not have any input for modelling the topography of the land after the channel ends, this area is modelled as flat which on the Yellow Fan is not accurate to the true topography. The logistical regression model created from the historic rainfall data is a more accurate prediction method due to the availability of all the required variables for an accurate model. The accuracy of the statistical modelling can be much more certain than that of the physical model in this situation due to the number of variables, and the availability of the data. The mapping of hazardous areas and fan topography, while useful for understanding the current and previous states of the fan system will only be accurate for a short period of time due to how dynamic the fan is. For this to be useful the maps will require constant updating as the fan changes. While the methods applied did create a accurate track closure prediction model the work on modelling the extent of possible debris flows would require more focus in future research, more accurate prediction methods are available but will however require more data and field work on the fan in order to gather this data.

Conclusion

This report has attempted to answer the research question by using a combination of statistical analysis, physical modelling and mapping. Using GIS methods, maps were created displaying erosion, vegetation and topography for the purpose of understanding debris fan morphology and potential hazard areas. Through use of debris flow modelling, potential debris flow extents and depositions were modelled that highlighted possible threats to the track. Statistical analysis of rainfall and track closure data demonstrated that the probability of future track closures could be predicted with almost 100 percent certainty. We applied these methods to help DOC and glacier guides improve the safety of tourists as they walk the track to the glacier terminus, we have researched and analyzed areas of risk, and provided information and data that can be utilized in the future, in order to help ensure visitor safety.

Acknowledgments

Throughout this research we were fortunate enough to have the help and support from a number of important people. We would like to acknowledge the following people that have put time and effort into helping us with this research process. Thank you to;

Wayne Costello and DOC: For providing the rainfall and track closure data along with other pieces of information that was needed.

Christopher Gomez: For advising and explaining to us what we could do with the data and the models. Also for simplifying complex parts of the research down so that we knew how to answer our question.

Heather Purdie: For the advice and help we have received. Also for the constructive feedback she have given us especially with our presentation.

Eric Pawson : For his guidance on all aspects of the GEOG309 *Research Methods in Geography* course.

References

- Brocklehurst, S. H., & Whipple, K. .. (2007). Glacial erosion and relief production in the eastern Sierra Nevada, California .

- Foster, D., Brocklehurst, S. H., & Gawthorpe, R. L. (2010). Glacial-Topographic Interactions in the Teton Range, Wyoming. Journal of geophysical reasearch, vol 115.

- Nakatani, K.; Iwanami, E.; Horiuchi, S.; Satofuka, Y.; Mizuyama, T. (2012). *Development of 'Hyper Kanako', A Debris Flow Simulation Based on Laser Profiler Data*. 12th Congress Interpraevent 2012, conference proceedings.

- Takahashi, T. (2007). *Debris Flow: Mechanics, Prediction and Countermeasures*. Taylor & Francis