INFLUENCE OF HYDROMETEOROLOGICAL CONTROLS ON DEBRIS FLOWS NEAR CHILLIWACK, BRITISH COLUMBIA

by

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ABSTRACT

This study aims to identify hydrometeorological variables near Chilliwack, BC which have initiated past debris flows in order to gain insight about conditions that could inform emergency planning and adaptation in future. A database of storms between 1980 and 2007 and their hydrometeorological characteristics including storm total rainfall and duration, intense rainfall total and duration, and 1 to 4 week cumulative antecedent rainfall were compiled. Stepwise logistic regression was used to determine a model which isolated intense rainfall total and occurrence of storms during the rain-on-snow season as the most significant variable distinguishing between debris flow and non-debris flow storms. However, the low predictive power of this analysis suggests that other characteristics, such as land-use, sediment supply, and snow melt may play a large role in debris flow initiation in this region.

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1: INTRODUCTION

1.1 Study Objectives

On the morning of January 7, 2009, a state of local emergency was declared in Chilliwack, British Columbia, when an estimated 3,000 m^3 to 4,000 m^3 of mud and several large trees were deposited by a debris flow into Ryder Creek. The debris dam caused flooding, erosion, and sediment deposition in the surrounding rural area, subsequently forcing several residents to evacuate their homes (Golder & Associates, 2009)(Figure 1). The risk of continuing hazardous and unstable conditions caused one homeowner to abandon his residence and relocate (Henderson, 2009).

Figure 1 One of the homes affected by the debris flow on Chilliwack River Road, January 2009 (Gerraghty, 2009).

Chilliwack, British Columbia, lies approximate 100 km east of Vancouver within the Fraser Valley, with a population of approximately 82,000 residents. Agriculture is an essential part of Chilliwack's history and economy, but the rural residences situated on the productive soils of the Fraser Valley come with a price. The combination of coastal weather systems, steep slopes, and orographic precipitation leaves communities in Southern British Columbia susceptible to human and economic losses caused by precipitation driven debris flows. Since the beginning of the 20th century, almost 100 fatalities have been associated with landslides, debris flows, and mudslides in British Columbia (Public Safety Canada, 2009).

Debris flows are fast moving saturated sediment flows that are triggered as a result of high volumes of precipitation from extended or intense rainfall. Damages from debris flows can range from small-scale inconveniences to large-scale devastation of property and infrastructure. Not only do debris flows present direct hazards to lives and infrastructure, but sediment deposits also alter the morphology of streams and valley floors, alter riparian habitat, and increase water turbidity which can impair drinking water quality (Benda & Dunne,1997).

Throughout the next century, climate change is expected to influence precipitation patterns and the frequency and intensity of rainfall which in turn might affect the occurrence of future debris flows (Dehn, Buma, & Gasparetto, 2005). A potential increase in storm events caused by climate change could trigger more precipitation-driven natural hazards in vulnerable areas and negatively impact community infrastructure, development sites, and public safety (Jakob & Weatherly, 2003).

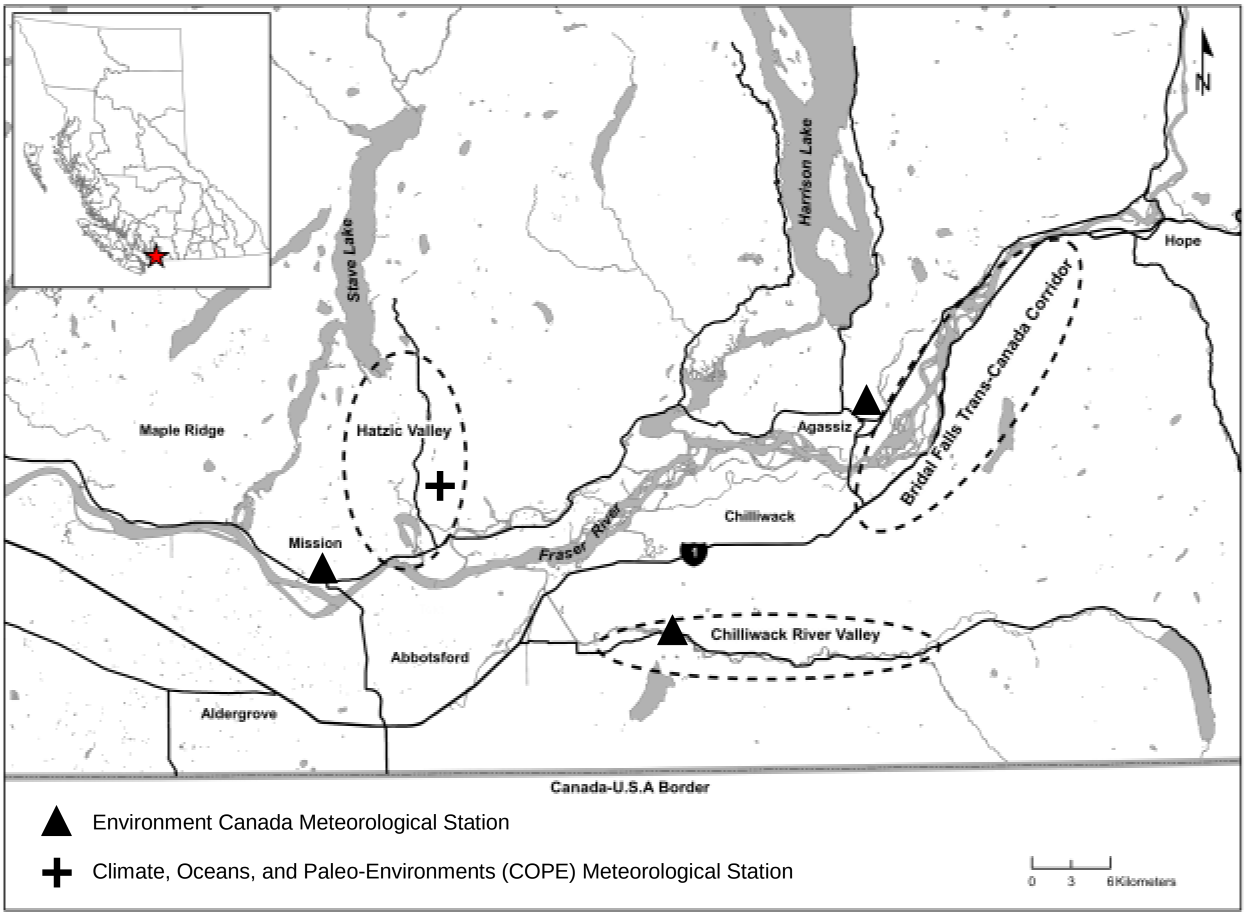
Understanding which meteorological conditions and other potential triggers are associated with debris flow occurrence could assist with both adaptive and mitigating actions that could be taken against the effects of these hazards within the Fraser Valley. Hypothesized probabilities of debris flows would be of interest to planners and managers of the Fraser Valley Regional District, Ministry of Transportation, and Emergency Management BC, who could use the research results to develop emergency management plans for communities that are susceptible to such events. The goal of this study is identify hydrometeorological variables that are correlated with past debris flows in Chilliwack, BC, in order to gain insight about conditions that could inform emergency planning and adaptation in future. To do this, a database of 18 debris flow associated storms occurring between the years of 1980 to 2007 was compiled. Debris flows were characterized based on their hydrometeorological conditions, and then compared with similar storms in the region that did not produce debris flows between 1980 and 2007. The goal was to isolate which (if any) variables play a key role in differentiating between storms that produced debris flows and storms that did not. Finally, climate modelling studies were examined to identify projected, future changes in these hydrometeorological conditions, in order to determine whether they are predicted to increase or decrease.

2: Background

2.1 Study area

Chilliwack's urban centre and surrounding agricultural land are flanked by the Pacific Ranges of the Coast Mountains to the north and the Skagit Ranges of the Cascade Mountains to the south (Figure 2). Hatzic Valley is a north-south running valley flanked by mountains to the east and west which is primarily used for agricultural land and rural residences. The majority of debris flows occur on the eastern slope of the valley, and but also less frequently on the western slope. Debris flows in Hatzic Valley have been reported on Kentworthy Creek., Cascade Creek, Pattison Creek, Field Creek, Carratt Creek, Eng Creek, Dale Creek, McNab Creek, Saporano Creek. The Bridal Falls corridor runs southwest to northeast along the Trans-Canada highway between Bridal Falls and Hope. Elevations in the study area range between ~ 10 m to 1360 m (Hatzic Valley), 1530 m (Bridal Falls), and 1700 m above sea level (Chilliwack River Valley). The dominant biogeoclimatic zone of the Chilliwack area is Coastal Western Hemlock, which is characterized by long, mild, wet winters that contribute to continually wet soil conditions through the dominant debris flow months of October to March.

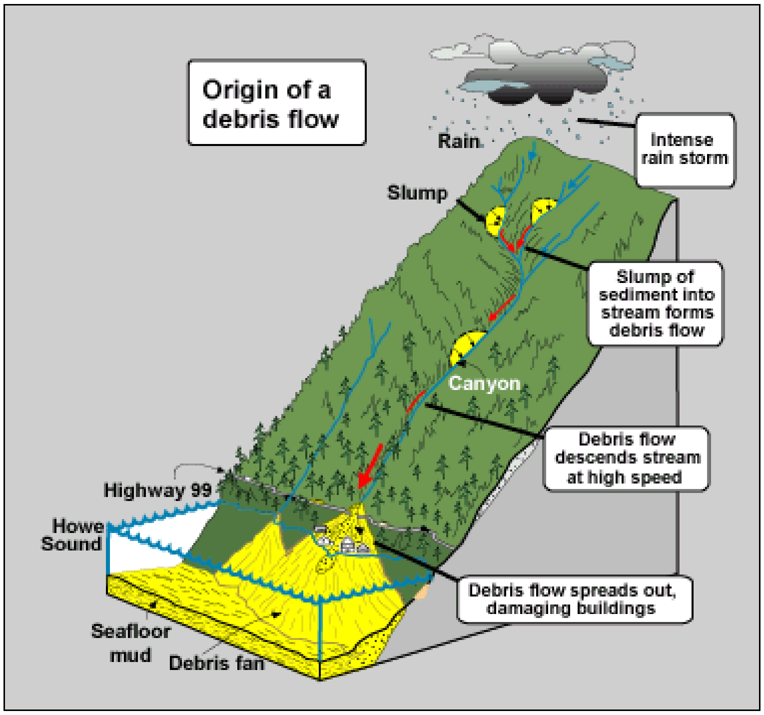
Figure 2 Map of the study area and debris flow affected areas. Meteorological stations used in the study from 1980-2007 are located at Mission West Abbey (49° 09’ 09” N, 122° 16’ 15” W, 221 m a.s.l), Agassiz CDA (49° 14’ 33” N, 121° 45’ 35” W, 15 m a.s.l), and Chilliwack River Hatchery (49° 05’ 00” N, 121° 42’ 00” W, 213 m a.s.l). An additional meteorological station was implemented in Hatzic Valley from 2010 – 2011 (49° 13’ 20” N, 122° 12’ 57” W, 292 m a.s.l) by the Climate, Oceans, and Paleo-Environments Lab from Simon Fraser University.



2.2 Debris flow characteristics

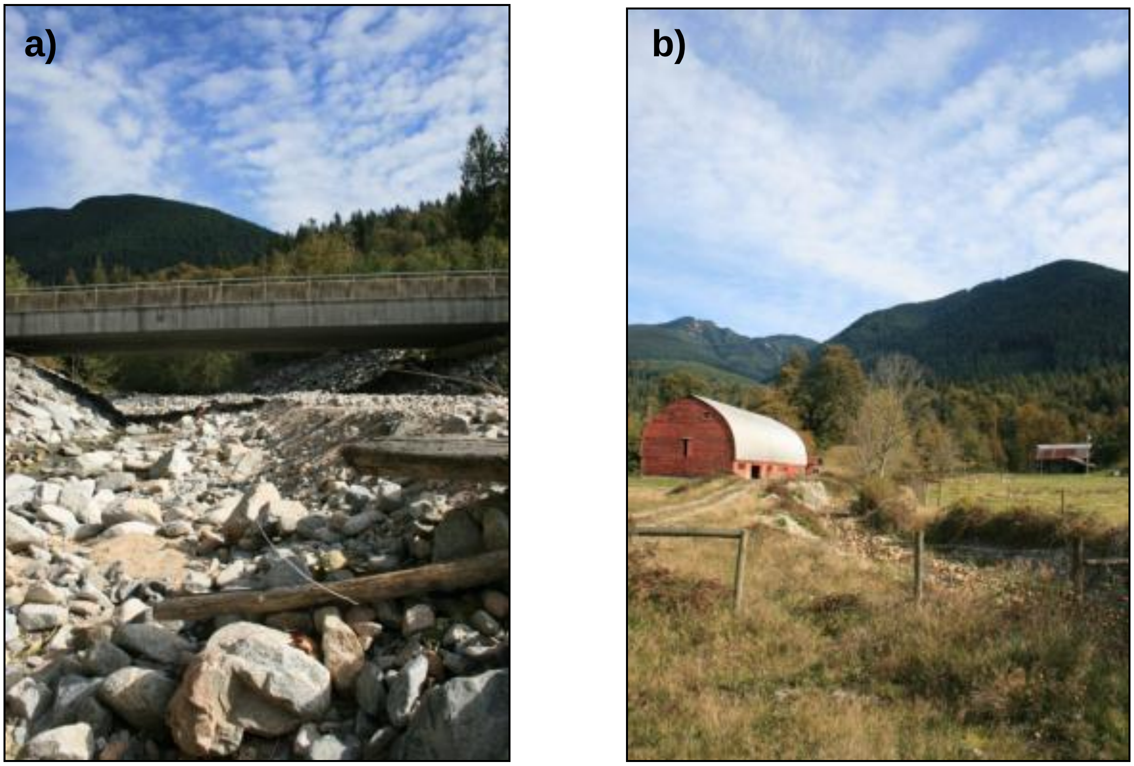
Channelized debris flows, also known as “debris torrents”, are common during the autumn and winter season in the Pacific Northwest of Canada and the United States (Nistor & Church, 2005). Debris flows are fast moving saturated sediment flows often triggered as a result of high volumes of precipitation, snowmelt, or other excess water. Debris flows can reach peak velocities of up to 10m/s (Lorenzini & Mazza, 2004). During a debris flow, large amounts of material are mobilized within a basin and travel down a creek channel or gully. As the debris flow moves down slope, it often increases in volume until it reaches the apex of the fan and begins to deposit material (Brayshaw & Hassan, 2009). Debris flows can be classified as a moving fluid in which a high percentage of solid material, such as trees, woody debris, clasts, soil, and other materials are transported (Lorenzini & Mazza, 2004). Sediments in debris flows are poorly sorted within a semi-fluid matrix, with sediment concentrations that are greater than 50% by volume. All mountainous regions within the Chilliwack study area are comprised of alpine complexes of colluvium, rock, and till that are common ingredients in debris flows. Lower elevations are blanketed in a till veneer of stratified silt, sand, clay, and areas of glaciofluvial deposits (BC Geological Survey, 2010). Figure 4a illustrates the variety of sediment, cobble, and debris which is transported in Hatzic Valley, BC, and Figure 4b shows the close proximity of debris flow creeks to buildings and infrastructure.

Figure 3 Causes of debris flows include precipitation causing soil saturation or leading to slumps of debris and sediment into creek channels



(Turner et al, 1996)

Figure 4 Two creeks in Hatzic Valley, BC display deposition from debris flows and bed-load. Dewdney Mountain is seen in the background. a) Large cobble, small boulders, and debris in Pattison Creek, b) Dale Creek in close proximity to buildings roads.



2.3 Factors contributing to debris flow initiation

There are two types of debris flow initiation that may occur in the Chilliwack area. The first results from a blockage of material within the creek channel, creating a debris dam. Water pressure builds up behind this dam and eventually bursts through, carrying water and saturated debris down-slope. Debris flows associated with debris dams are more difficult to predict unless creek channels known to produce debris flows are routinely monitored for build-up of debris. The second type of debris flow initiation occurs when precipitation saturates the sidewalls of creek channels and causes soil to slump into the channel, and then the soil is mobilized down-slope. This latter type is likely to occur more directly in response to changes in meteorological conditions.

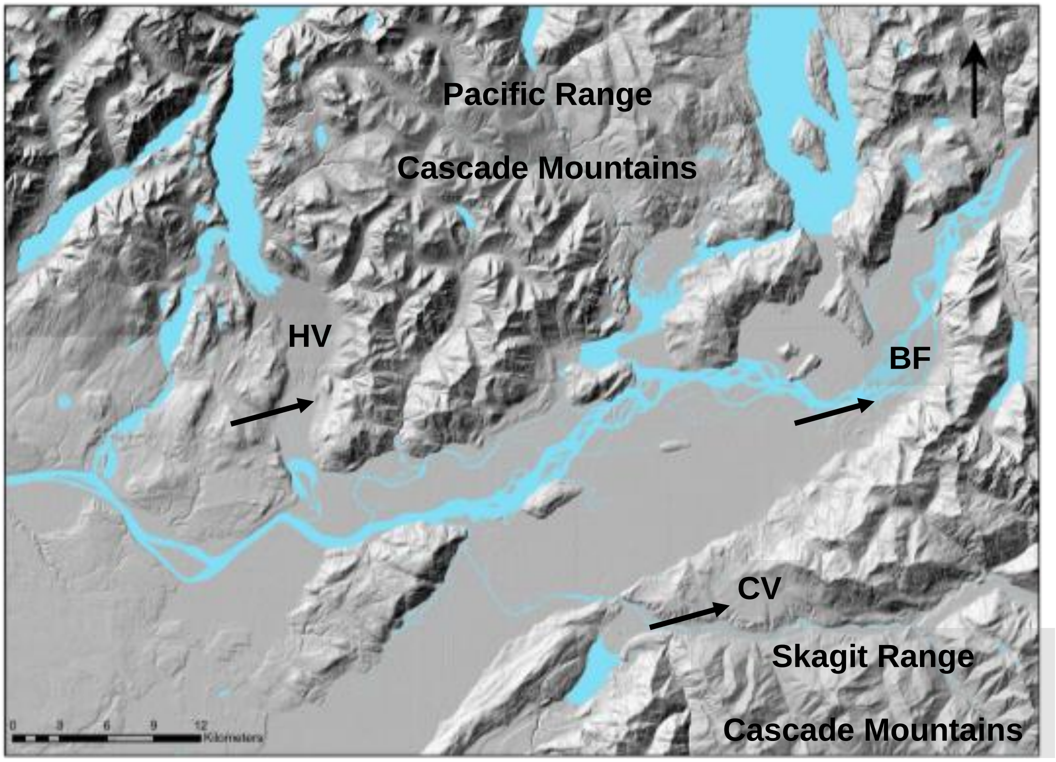
There are several factors that contribute to both types of debris flow initiation, including geomorphological characteristics such as slope and aspect; climate-related parameters such as climate antecedent and climate triggering events; and anthropological factors such as land-use.

2.3.1 Geomorphological characteristics

Geomorphological characteristics play a strong role in determining regions where debris flows are likely to occur. Slope is also an important factor in debris flow initiation within channelized debris flows, which are common in stream channels of mountain drainage basins like those found in the Chilliwack region of BC. Debris flow channel profiles can be divided broadly into three zones: initiation, transportation and erosion, and deposition (Brayshaw & Hassan, 2009; Lorenzini & Mazza, 2004). From a compilation of several debris flow studies in British Columbia, Van Dine (1996) found that the “initiation” zone generally has a slope angle greater than 25° (47% slope grade). The “transportation and erosion” zone required a slope greater than 15° (27% slope grade), while “deposition-creating” levees require less than 15° (27% slope grade). A debris fan typically begins at a gradient less than 10° (18% slope grade) (Van Dine, 1996). Within the Chilliwack River Valley, Wolter et al (2010) found that landslides are initiated on slopes of 25° to 50°, with an average of 37°. Brayshaw & Hassan (2009) found that stream channels associated with debris flows in the Noorish Creek and Chilliwack River Watersheds had a mean channel gradient of 29 ± 6° (57 ± 13% slope grade). Of the slopes examined, approximately 70% of creek slumps that initiated debris flows entered channels with gradients greater than 26.6°. Brayshaw & Hassan’s (2009) study is roughly consistent with other landslide research finding average slope angles of 22° to 28° (Coe et al, 2004, Ohlmacher, 2000). For this study area, slopes were calculated for 10 creeks from each region and ranged between 7° and 34.7° with a mean of approximately 24°. The majority of the creeks sampled coincide with acceptable slope angles of debris flow initiation, and therefore slope is likely not a limiting factor to debris flow initiation in the Chilliwack area.

Aspect may also influence debris flow occurrence due to the dominant direction of weather systems that collide slopes in the Fraser Valley. Precipitation systems on the south coast of BC tend to move from west to east, causing a windward (wetter) and leeward (drier) moisture effect on slopes. Chilliwack Valley slopes face mostly west or south. Hatzic Valley and Bridal Falls have slopes which face west and northwest therefore are also strongly affected by the weather systems from the west (Figure 5).

Figure 5 Digital Elevation Model of the Study Area. Hatzic Valley (HV) and Bridal Falls (BF) have a similar west and northwest aspect, respectively. Chilliwack Valley (CV) aspects are predominantly north and south. Arrows represent the direction of predominant movement of weather systems.



(Source data: Natural Resources Canada; Geogratis)

2.3.2 Climate-related factors

Climate-related factors, such as large amounts of precipitation, can cause slumping of soil and debris from channel banks into the stream which is moved rapidly down-slope. In essence, failure of a slope occurs when water enters the slope at a rate greater than it can drain (Caine, 1980; Crozier, 2010). Large volumes of water facilitate soil mobility due to soil particle dispersion in water. Once soils become saturated they are less viscous, which decreases internal friction and soil cohesion (Takahashi, 2007). Crozier (2010) identifies critical slope water content for debris flow initiation arising from two sources:

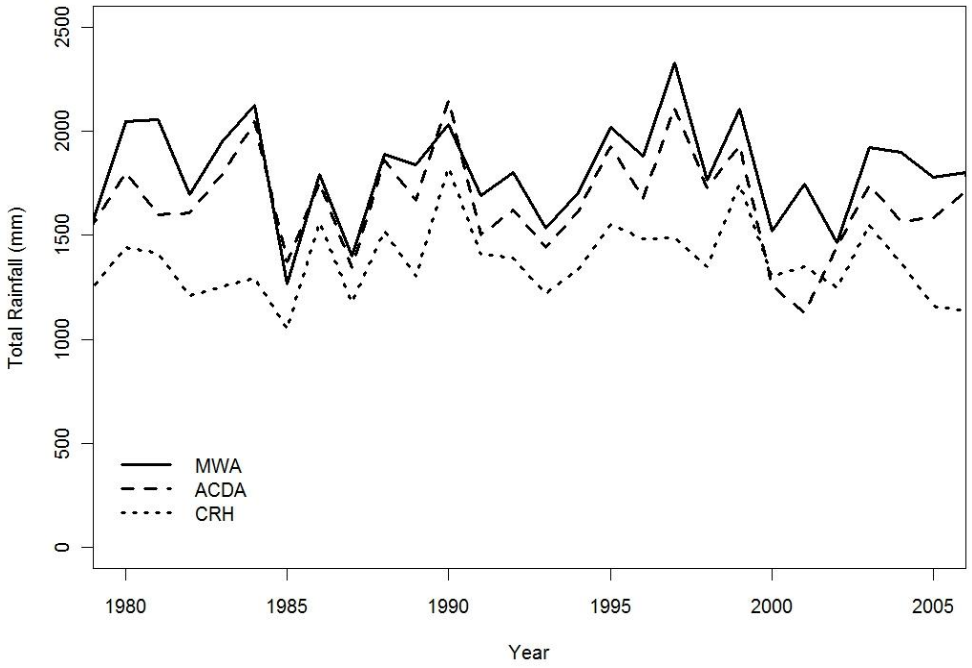
climate antecedent and climate triggering events. Climate antecedent events are the build-up of soil moisture over time, resulting from poor drainage and long periods of rain. These can result in a saturation of soils which eventually slump into stream channels on their own, or as a result of a short-term rainfall-triggering event.

Climate triggering events, such as periods of short-term intense storm rainfall, exacerbate potential slumps by triggering soil motion in areas that are already near a saturation threshold. Rapid snowmelt and rain-on-snow are other climate-triggering events that have been linked with debris flow initiation. A sudden change in temperature can quickly change snow into an available water source for soil saturation. Alternatively, rain-on-snow, or precipitation falling as rain on top of already-fallen snow, adds the moisture of snow already on the ground to the rain from the current storm.

The climatological characteristics of the Lower Fraser Valley in BC make it particularly susceptible to debris flows because it is strongly influenced by both climate antecedent and climate triggering precipitation events. The Pacific Northwest has a mild and wet climate. Chilliwack has an average temperature of 10.5°C, and temperature rarely drops below 0°C. Thus, most precipitation tends to fall as rain at lower elevations. The City of Chilliwack has an average total yearly rainfall of 1680 mm, which falls year-round but is most pronounced between October and April (Environment Canada, 2011). An extended rainy season in winter contributes to large amounts of antecedent precipitation and preconditions the sloped areas around the Lower Fraser Valley to be susceptible to debris flow activity.

The precipitation of the Pacific Northwest (PNW) is greatly influenced by topography, and most notably by the mountain ranges that lie therein (Mass, 2009). As warm air masses (relative to the cooler continent) reach the coast from the Pacific, they are funnelled along the Fraser Valley and forced upwards as they hit the Cascade Mountains. As the warm air rises and cools, it causes rainout over the Chilliwack region. Wind direction during a storm can channel these weather systems into specific valleys and create isolated extreme precipitation events that make the slopes of these valleys highly susceptible to debris flows. This heterogeneity in the topography can create very different daily and yearly total precipitation readings from among weather stations within the Chilliwack region (Figure 6), depending on the orientation the wind, the aspect of the slope, or topography.

Figure 6 Variability in the topography of the Fraser Valley also creates variability in the mean monthly rainfall among stations at Mission West Abbey (MWA), Agassiz CDA (ACDA), and Chilliwack River Hatchery (CRH).



Finally, the mild winter climate makes the region susceptible to frequent rain-on-snow and rapid snow events. Precipitation increases at higher elevations due to orographic uplift, with most precipitation falling as snow during the winter months. There are no meteorological stations near peak elevations in the Chilliwack area, but records from Grouse Mountain on the north shore of Vancouver show that precipitation falls predominantly as snow at 1200 m from November through to April. Since the peak elevations of mountains in each of the three study areas in Chilliwack range between 1360 m to 1700 m, snow is also quite likely present on those slopes for a similar length of time. During rain events on warm winter days, the combination of above freezing temperatures and rain cause the snow to melt. Guthrie et al (2010) state that during these events, ambient air temperature facilitates snow-melt when rain falls on ripening snow which has a coarse crystalline structure, and has a temperature which is approaching 0°C. The melted snow adds extra moisture to the already moist underlying soils and can cause a debris flow with less rainfall than would be needed to initiate a debris flow on drier soils.

These conditions all suggest that climate antecedent and climate triggering events are probably contributors to debris flows in the Lower Fraser Valley, an assumption supported by previous work. Jakob & Weatherly (2003) examined hydroclimatic thresholds for debris flows in the North Shore Mountains near Vancouver and found that the three dominant variables are total rainfall, amount of antecedent soil moisture, and creek discharge during the initiating storm. At this time, no similar studies have been conducted for the Chilliwack region. The presence of localized weather systems within the Fraser Valley means that the same data and results cannot necessarily be extrapolated from North Vancouver to Chilliwack. Additional differences in topography, soil, geology, and vegetation cover suggest that an individual evaluation of debris flow triggering variables is needed to obtain an accurate understanding of local debris flow triggers near Chilliwack (Benda & Dunne, 1997; Jakob et al, 2006).

2.3.3 Land-use and Climate Change

Chilliwack is a growing, and the city is expected to reach over 100 000 residents by 2021 (Chilliwack Economic Partners, 2010). A steady increase of population also means an increase of housing developments, with possible expansion towards the slopes surrounding the city centre. As developments move towards the mountains, they move closer to the dangers that come with living at the base of a mountain including debris flows and other slope failures. Not only does the mere proximity of development to slopes create cause for concern, but also the associated changes to the landscape.

Historically, the landscape of Chilliwack has been continuously altered. Rivers have been diverted and dammed, dykes and canals have been constructed, and forest cover has been drastically altered. The first sawmill in the Chilliwack area went into operation in the 1870s and logging has since been an active part of Chilliwack's economy (Chilliwack Museum, 2011). Today, the Chilliwack Forest District covers approximately 1.4 million hectares of land in the Lower Mainland of British Columbia (BC Ministry of Forests, Lands and Natural Resources Operations, 2011) with modern day forestry activities abundant throughout Hatzic Valley, Chilliwack Valley, and to the southeast of Bridal Falls.

Logging for forestry or clearing for agriculture and development contribute to conditions favourable to debris flows and landslides. Vegetation and root systems provide support to slopes by anchoring soil and sediment. Removing trees and root systems destabilizes soil which run-off or slump into creeks, thus providing more sediment and debris for creek channels to expel. Human activities which remove vegetation, alter slope stability, surface permeability and natural drainage which can all lead to debris flow and landslide conditions (Crozier, 2010).

3: Methods

In order to determine hydrometeorological conditions under which debris flows occur, I differentiate between the characteristics of non-debris flow (NDF) and debris flow initiating (DF) storm events. First, a dataset of debris flow records was compiled which indicates the general location and date of each debris flow between 1980 and 2007. Second, I assembled a dataset including every rain storm event measured from three spatially representative weather stations near Chilliwack during the same time period. The hydrometeorological conditions considered potentially important to debris flow initiation were determined and characterized for each storm. Third, I used a stepwise logistic regression to find the best model to describe the relationship between debris flow initiation and hydrometeorological variables based on Akaike's Information Criterion (AIC). Finally, I displayed the predicted curves from the logistic model which best fit the data.

3.1 Debris Flow Record

Debris flows that occurred between 1980 and 2007 in the Fraser Valley were compiled from records by Septer (2007) and Gerraghty (2008). The study period was restricted to debris flows after 1980 because debris flow events before that time are sparsely recorded. Twenty-seven separate debris flows were identified among the three study areas: Hatzic Valley (12 debris flows), Bridal Falls corridor (11 debris flows), and Chilliwack River Road (4 debris flows). Several of the debris flow creeks in the study area are unnamed, but I assigned their study site location based on the region that they were specified by Septer (2007) and Gerraghty (2009). The Bridal Falls site also includes debris flows reported in nearby Harrison Hot Springs and Flood.

This dataset is limited to debris flows that were officially reported in the Chilliwack region, and therefore likely only those that were large enough to be noticed and cause damage. More debris flows are likely to have occurred elsewhere in the study area but have gone unreported. While some of these unreported debris flows might be identifiable through air photo analysis and field inspection, assigning a specific date and time to them would not be possible, and therefore they cannot be associated with a particular meteorological storm event. The debris flows and associated storms cited here are considered a sample of events, which is acceptable as this study is mainly concerned with debris flows of sufficient magnitude to be considered hazardous to residents and infrastructure.

Another important consideration is that the debris flows used in this study do not differentiate between natural areas and areas that have been subject to anthropogenic disturbance. In particular, the debris flows included in this database may have occurred in both logged and non-logged areas. Air photo records were too sparse and intermittent for the study area to complete a comprehensive study of logging both spatially and temporally.

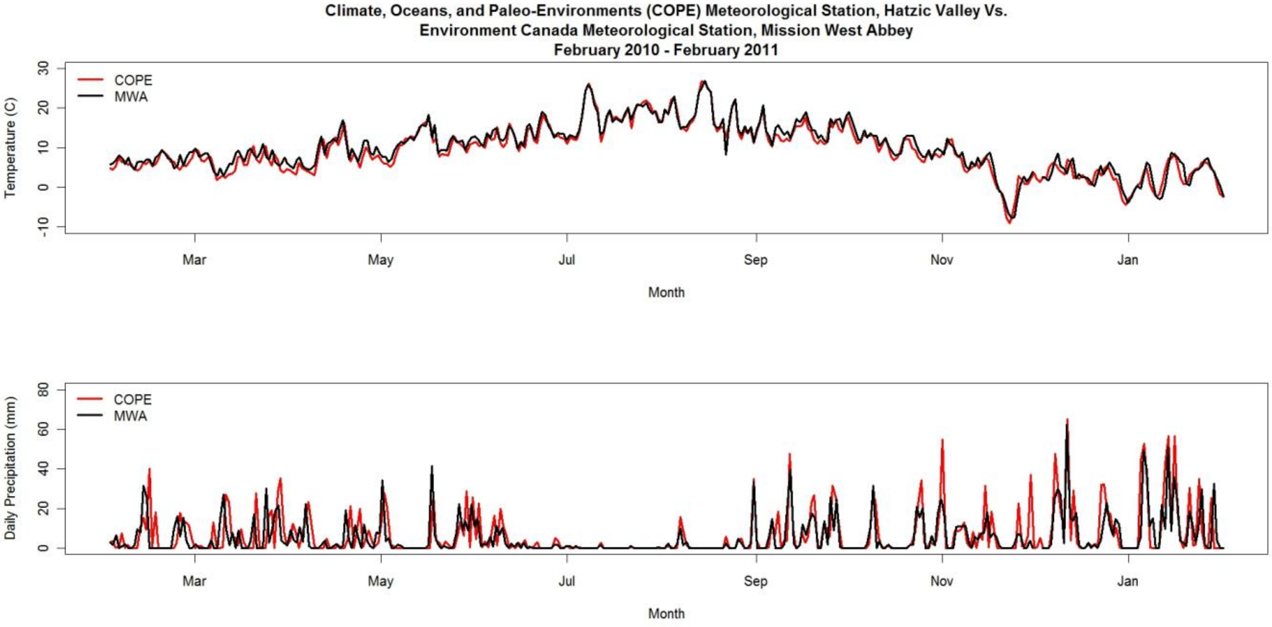
3.2 Hydrometeorological Data

Precipitation is one of the main drivers of debris flow initiation (Caine, 1980; Crozier, 2010; Takahashi, 2007; Van Dine & Bovis, 2002), so data on hydrometeorological conditions during meteorological storm events were acquired to differentiate between non-debris-flow (NDF) and debris flow initiating (DF) conditions. Meteorological station data were acquired from Environment Canada for three weather stations in the Fraser Valley of British Columbia. These stations were chosen based on completeness of their records between 1980 and 2007, and for their ability to approximate the meteorological conditions in the regions where debris flows have occurred. The effects of wind direction and topography in the Chilliwack area can create high spatial variability in rainfall patterns; so more than one station was needed to represent the study area. As a result, stations at Mission West Abbey (221 m a.s.l), Agassiz CDA (15 m a.s.l), and Chilliwack River Hatchery (213 m a.s.l) were chosen to represent conditions in Hatzic Valley, the Bridal Falls Highway 1 corridor, and Chilliwack River Road, respectively (Figure 2). Meteorological stations were chosen for each debris flow region based on the assumption that their close proximity allows them to adequately reflect the magnitude and duration of storms that occurred near debris flow events. Each meteorological station is located within 5 to 10 kilometres of the debris flow areas.

In order to represent the most reliable and accurate conditions at each debris flow site, the ideal location of all three meteorological stations would be as close as possible to the known debris channels. Since this was not possible, an additional *in situ* meteorological station was erected in Hatzic Valley (292 m a.s.l) at a similar elevation to compare data to Mission West Abbey (221 m a.s.l). The assumption was that an *in situ* station would potentially report different, and more representative meteorological conditions than that of the Environment Canada Mission West Abbey station located up to 10 km away. A year-long hydrometeorological dataset from the Climate, Oceans, and Pale-Environments (COPE) Lab at Simon Fraser University was used to compare precipitation data to Mission West Abbey between 2010 and 2011. An assessment of a year’s worth of data shows no major discrepancies between the COPE and Environment

Canada data for temperature, although the COPE station shows slightly (~5-20 mm) higher precipitation values during most precipitation events (Figure 7). Although only conducted for a short time period, the graph suggests that Mission West Abbey may be capturing the same daily pattern of rainfall but is underestimating the amount of precipitation in Hatzic Valley particularly in the wetter months. In fact, the COPE station recorded approximately 390 mm more rain than at Mission West Abbey for the year-long study period of February, 2010, to February, 2011. Placing a meteorological station *in* situ would be an improvement to the accuracy of rainfall data collected in Hatzic Valley. In the meantime, Mission West Abbey is the closest station to Hatzic Valley and captures the precipitation pattern but underestimates rainfall in Hatzic Valley, which should be kept in mind when considering rainfall measurements.

Figure 7 Comparison of total precipitation and temperature between Hatzic Valley as recorded by the Climate, Oceans, and Paleo-Environment (COPE) and Environment Canada Mission West Abbey meteorological stations. The in situ COPE station is situated at an elevation of 292 m and the MWA station is at 221 m. Stations are approximately 10 km apart.



The Environment Canada meteorological stations are also likely at much lower elevations than the approximate initiation zones of debris flows, which are about 1100 m (Mission West Abbey), 1400 m (Chilliwack Valley), and 1500 m (Bridal Falls) above the meteorological station locations. Rainfall values are generally greater at higher elevations due to orographic effects. Therefore, the three meteorological stations located in the valleys are likely to underestimate precipitation values higher on the slopes where debris flows are triggered. In addition, precipitation falling at higher elevations may be falling as rain or snow depending on the ambient temperature.

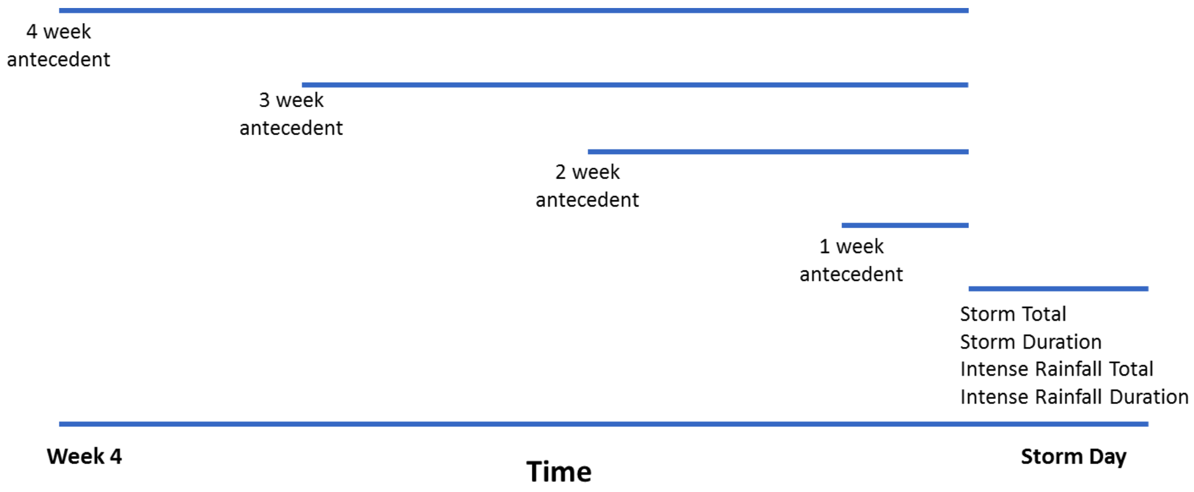
Hydrometeorological characteristics deemed potentially important for debris flow initiation were quantified for every storm from all three stations for 1980-2007 (Table 1). Daily precipitation values were used to include information about total precipitation (mm) and duration (days) of storms, and intense rainfall with these storms, and the cumulative precipitation that occurred one to four weeks prior to each storm (Figure 8). Other landslide and debris flow studies have included hourly precipitation data to produce hourly precipitation rates. A complete and consistent record of hourly precipitation data for the three study stations was not available, so daily rainfall data was used to measure short-term intense daily precipitation.

I identify a storm event using Environment Canada's definition of heavy rainfall in the Lower Mainland of British Columbia as 50 mm/24 hours or 75 mm/48 hours (British Columbia Ministry of the Environment (b), 2010). All events which meet the storm event criteria were identified at all three meteorological stations. The storm date was identified as the first day of the storm event that met these criteria. Once all storms events were identified, the total rainfall that fell during that storm S_{tot} was calculated by summing the daily rainfall for each consecutive day preceding or succeeding the storm date that exceeds 15 mm/24 hours. I assume that daily rainfall values less than 15 mm/24 hours represent typical light rainfall not associated with storm events in this region. The storm duration D_s was then considered the number of days in a storm which exceeds the 15 mm/24 hour threshold.

Total rainfall was also calculated for days of intense rainfall IR_{tot} during each storm. Intense rainfall was calculated as the sum of rainfall on consecutive storm days with greater than 25 mm in 24 hours. Intense rainfall duration D_{ir} accounts for the total number of consecutive days in a storm where rainfall exceeds 25 mm/24 hours. By including intense rainfall IR_{tot} , and intense rainfall duration D_{ir}, I was able to capture rainfall totals and durations of the most intense periods of the storm, which is considered to be a trigger of debris flow initiation (Caine, 1980; Crozier, 2010).

The cumulative antecedent rainfall A_l is totalled for 1, 2, 3, and 4 weeks (7, 14, 21, and 28 days) before the storm start date. The storm start date is considered to be the first day of the $S_{tot,}$ and the antecedent rainfall counts back from the day before the storm start date. Antecedent rainfall was chosen based on studies by Jakob & Weatherly (2003), White & Schwab (2005), and Chleborad (2000), which showed that a 7 to 28 day period is necessary for soil conditions to reach saturation levels sufficient to instigate landslides in the Pacific Northwest. One-week antecedent rainfall is the cumulative 1 week total of rainfall that falls prior to the beginning of the storm. The two-week antecedent includes the one-week antecedent total in addition to the rain that fell in the second week before the storm begins. The accumulation of rainfall continues until four-week antecedent which includes the total rainfall of all 4 weeks before the storm begins.

Figure 8 Timeline of antecedent rainfall and storm totals for all storms between 1980-2007.



The occurrence of storms during the rain-on-snow *ROS* season can contribute additional critical water content that can contribute to debris flow initiation. The presence or absence of a storm during the *ROS* season was noted in the data record as a 1 or 0, respectively. Previous landslide investigators have delineated *ROS* events as occurring primarily between January and March in the North Coast Mountains (Jakob & Weatherly, 2003). Although January to March is considered the predominant *ROS* season, snowpack can develop earlier or remain later than this window of time, which would extend the possibility of *ROS* events further throughout the year. However, in the absence of a more detailed documentation of rain-on-snow events from the meteorologic station data and debris flow records, I have used the January-to-March designation as a first approximation.

Once all storms between 1980 and 2007 were identified, I matched each debris flow to its corresponding hydrometeorological storm characteristics. All debris flows corresponded with the storms identified in from the meteorological station data, and typically occurred within 24 to 96 hours of a storm start date. No storm lasted longer than 96 hours. Storms that were associated with debris flows were assigned a DF designation which could then be compared with the non-debris flow NDF classified storm, which was basis for a binomial distribution of data.

Up to this point, statistics on storms and intense rainfall have been calculated consistently for both DF and NDF storms. However, in reality, the precipitation most important for triggering a debris flow falls prior to the event. This precipitation amount represents the threshold over which a debris flow will occur. The comparison between the DF threshold of rainfall variables and the NDF rainfall variables allow us to distinguish between storm characteristics that trigger debris flows. Thus, I have also calculated the debris flow storm threshold total SDF_{tot} and the debris flow intense rainfall total $IRDF_{tot}$ for DF storms. These values account for the storm total rainfall and intense rainfall total that falls before debris flow initiation and can be compared to the NDF storm S_{tot} and intense rainfall IR_{tot} totals.

An SDF_{tot} for each debris flow-initiating storm was defined as the amount of rain that falls from storm start date, up to and including the day of the debris flow. This definition may overestimate the total precipitation for each DF storm, but the rainfall total for the day of the debris flow was included for two reasons. First, the exact time of day for each debris flow is not known. If the debris flow was to occur in the evening, then the rainfall on the day of the debris flow would have contributed to the initiation. Second, the rain may not have fallen consistently throughout the day, or the rain may have fallen intensely during a shorter period of time. If a debris flow occurred in the morning and the majority of the rain fell prior to initiation, then excluding the day of the storm would not account for potentially critical amounts of rain. Debris flow intense rainfall total $IRDF_{tot}$ was also included in order to calculate the total amount of rainfall on consecutive days exceeding 25 mm/24 hours during a storm and before debris flow initiation. Debris flow intense rainfall duration D_{irdf} was subsequently defined as the number of days of intense rainfall before debris flow initiation. This gives a representative amount of intense rainfall that may be associated with debris flow initiation~~.~~

In summary, a total of 203 storms comprising 186 non-debris flow and 18 debris flow initiating storms were identified and examined for differences in storm characteristics (APPENDIX A). Details of the 18 debris storms are summarized in Table 2. The meteorological stations record 79 storms at Mission West Abbey (MWA), 80 at Agassiz CDA (ACDA), and 44 at Chilliwack River Hatchery (CRH). The highest frequency of storms occurred from October through to April which coincides with the highest monthly rainfall totals for meteorological station.

Table 1 Definitions of hydrometeorological variables

Variable	Term	Definition	Unit
Storm Event	A rainfall event which includes >= 50 mm/24 hours, or >= 75 mm/48 hours		
Storm Date	The first day of the storm that meet the criteria of a storm event >50 mm/24 hours or >75 mm/48 hours		
Storm Start Date	The first day of the storm that meet the criteria of a storm event >15 mm/24 hours		
Storm Total	S_{tot}	The total precipitation that falls during a storm, calculated by summing the daily storm precipitation which exceeds 15mm/24 hours threshold	mm
Storm Duration	D_s	The number of days in a storm which exceed the 15mm/24 hour threshold	days
Intense Rainfall Total	IR_{tot}	The total amount of rain on consecutive days exceeding 25 mm/24 hours during a storm	mm
Intense Rainfall Duration	D_{ir}	Total number of consecutive days where rainfall exceeds 25 mm/day.	days
Storm Debris Flow Total	SDF_{tot}	The total amount of rain that falls from the beginning of a storm up to and including the day of a debris flow	mm
Storm Debris Flow Duration	D_{sdf}	The number of days in a storm which exceed the 15mm/24 hour threshold up to and including the day of a debris flow	days
Intense Debris Flow Rainfall Total	$IRDF_{tot}$	The total amount of rain on consecutive days exceeding 25 mm/24 hours during a storm and before debris flow initiation	mm
Intense Rainfall Debris Flow Duration	D_{irdf}	Total number of consecutive days where rainfall exceeds 25 mm/day before debris flow initiation	days
Antecedent Rainfall	A_i	The cumulative amount of rain that falls during the preceding 1, 2, 3, and 4 weeks before a storm begins	mm
Rain-on-snow	ROS	The presence or absence of a storm during the rain-on-snow season (January to March)	1,0
Pineapple Express	PE	The presence or absence of a Pineapple Express storm which makes landfall between 45° and 55° N during a storm	1,0

Table 2 Summary of hydrometeorological variables (mm), including presence or absence of rain-on-snow season (*ROS*), and presence or absence of Pineapple Express (*PE*) from sampled debris flow and associated storms. Environment Canada Meteorological Stations (MET) represent Hatzic Valley at Mission West Abbey (1), Bridal Falls at Agassiz CDA (2), and Chilliwack Valley at Chilliwack River Hatchery (3).

ID#	Start Date	Storm Date	Debris Flow Date	DF	S_{tot}	D_s	SDF_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	A_1	A_2	A_3	A_4	*ROS*	*PE*	MET
1	25/12/1980	25/12/1980	26/12/1980	1	101.6	1	101.6	1	101.6	1	101.6	1	75.6	129	175	218.8	0	1	1
2	10/07/1983	11/07/1983	12/07/1983	1	180	5	133	2	118	2	118	2	14.9	36	55.3	106	0	0	2
3	01/01/1984	03/01/1984	04/01/1984	1	179.6	4	149.4	3	118.8	2	118.8	2	34.2	34.2	58.2	78.2	1	1	1
4	08/11/1989	09/11/1989	10/11/1989	1	154.4	3	132.8	2	132.8	2	132.8	2	120.4	150.6	211.2	264.7	0	0	2
5	08/11/1989	09/11/1989	12/11/1989	1	174.9	3	174.9	3	153.9	2	153.9	2	88.8	109.8	155.6	204.2	0	0	3
6	08/11/1990	09/11/1990	11/11/1990	1	197	3	197	3	197	3	197	3	49.4	101.8	127.4	170	0	1	1
7	29/01/1997	29/01/1997	29/01/1997*	1	60.4	1	60.4	1	60.4	1	60.4	1	16.4	157.9	168.4	237.5	1	1	3
8	17/03/1997	18/03/1997	19/03/1997	1	124.5	3	124.53	3	124.5	3	124.5	3	2.9	48.3	74.1	106.6	1	0	3
9	17/03/1997	19/03/1997	20/03/1997	1	140.8	3	140.8	3	117	2	117	2	22.7	72	114	161.8	0	0	2
10	06/01/2002	07/01/2002	07/01/2002	1	141.5	3	111.7	2	141.5	3	111.7	2	10.8	11.5	34.1	154.9	1	0	2
11	15/10/2003	17/10/2003	17/10/2003	1	316.6	6	217.4	3	217.4	3	217.4	3	48.2	72.6	72.6	87.4	0	1	1
12	29/01/2004	29/01/2004	29/01/2004	1	66.6	1	66.6	1	66.6	1	66.6	1	82.4	99	186.8	184.4	1	1	1
13	17/01/2005	18/01/2005	19/01/2005	1	160.2	3	160.2	3	160.2	3	160.2	3	5.6	5.6	8.8	30	1	1	2
14	16/10/2005	16/10/2005	17/10/2005	1	78.2	2	78.2	2	78.2	2	78.2	2	42	95.7	186.5	189.5	0	0	1
15	02/11/2006	06/11/2006	06/11/2006	1	228.4	5	228.4	5	210.8	4	210.8	4	33.2	56.8	85.2	86.8	0	1	2
16	10/03/2007	11/03/2007	12/03/2007	1	112.4	2	112.4	2	89.2	1	89.2	1	35	47.4	117.6	155	1	1	2
17	06/01/2009	07/01/2009	07/01/2009**	1	154	2	154	2	154	2	154	2	42.7	77.2	77.2	85.1	1	1	2
18	06/01/2009	07/01/2009	07/01/2009**	1	100.9	2	100.9	2	100.9	2	100.9	2	21.9	78.3	103.1	123.7	1	1	3

*Chilliwack River Hatchery has missing values for the January 29, 1997 debris flow storm, and so the record from the next closest station at Chilliwack was used to fill the missing values

** The 2009 storms was added to the debris flow record after the 1980-2007 data had been collected. It was added in to increase the sample size of DF storms.

3.3 Data Analysis

In order to produce a model which best classifies each individual storm (DF or NDF), I first tested all hydrometeorological variables for correlation with other variables. Then, non-correlated variables were compared using stepwise logistic regression to find the model which best fit the data. The predicted curves from the best fitting logistic model were then plotted to illustrate the probability of debris flow occurrence based on the most significant rainfall variable values.

All explanatory variables were tested for pair-wise correlation in order to measure the degree of association between variables, and to determine whether the relationship was statistically significant. P-values > 0.05 represent no significant relationship between variables. The variables without significant P-values can thus be included together in a model. Likewise, correlation coefficients with values between -0.3 to 0.3 are considered to represent little to no association between variables. These uncorrelated variables can also be included together in a model.

After all variables were assessed for correlation, I conducted a stepwise logistic regression searching over all possible uncorrelated hydrometeorological variables which might describe the response of a debris flow. Logistic regression is a form of a generalized linear model (GLM) which is a statistical technique used to model the relationship between a response variable (debris flow) and a set of explanatory (hydrometeorological) variables (Atkinson et al., 1998).

Logistic regression and discriminant function analysis are two methods which have been used in other landslide and debris flow studies to describe the relationship between a binomial response variable (the presence or absence of a debris flow) and a set of explanatory variables (Van Den Eeckhaut et al., 2006; Dong et al, 2011; White &Schwab, 2005; Jakob & Weatherly, 2003; Atkinson et al., 1998). Discriminant function analysis aims to classify observations into one of several classes, and assumes normal distribution of the data. Logistic regression aims to predict the probability of an observation into only one of two categories, and does not assume normally distributed data (Press & Wilson, 1978). Discriminant analysis and logistic regression allow explanatory variables to be continuous (amount of rain in millimeters), but only logistic regression allows for discrete variables (ROS-season versus non-ROS-season). Since the goal was to establish a dichotomous classification of presence or absence of a debris flow, and the hydrometeorological data was not normally distributed, I chose to use logistic regression.

The logistic response function can be written as (Van Den Eeckhaut et al, 2006):

$$p = \frac{1}{1+e^{-(\beta_0+\beta_1 x_1+\beta_2 x_2+\ldots\beta \; x_n)}}$$

where p is the probability of occurrence of a debris flow, β_0 is the intercept, and β_1 is the coefficient for the explanatory variable x_1 that was chosen through step-wise logistic regression.

The logistic step-wise model selection process in the software program R (R Development Core Team, 2010) examined all non-correlated variables individually, their additive effects, and their interaction effects. Step-wise analysis constructs each model step-by-step and includes an additional variable with each iteration in order to evaluate which variable best discriminates between DF and NDF groups. Each subsequent variable is then added step-wise, including only the best discrimator at each step, until no further significant variables can be added. The step-wise logistic regression ranked models based on their Akaike's Information Criterion (AIC) value which is a measure of a model's relative goodness of fit, and can be written as:

$$AIC = -2(\text{log-likelihood}) + 2K$$

where K is the number of parameters included in the model (number of variables and the intercept). AIC is widely used in statistical model selection because of its ability to measure the balance between goodness of fit and model complexity (Anderson et al, 2001). AIC rewards competing models for higher log-likelihood values which finds the parameter values that give the highest probability of observing the data. However, AIC penalizes models that require more parameters. This method recognizes that additional model parameters may increase the goodness of fit, but it discourages over-fitting the model. Therefore, AIC chooses the model with the minimum number of parameters which best describes the data (Allison, 2001). AIC values are arbitrary on their own, but serve as a means to rank models against one another. Lower AIC values are considered to be more desirable models, and thus the logistic model with the lowest AIC value was chosen.

4: RESULTS

4.1 Comparison of non-debris flow and debris flow initiating storms

Examination of the timing of storms indicates that the majority of storm events occur between October and February, with the maximum number of storm events occurring in November. Not surprisingly, the highest frequency of storms coincides with the highest frequencies of debris flow occurrence, suggesting that the wetter months of the year are most susceptible to debris flows (Figure 9).

A comparison between DF and NDF storms suggests that they possess similar characteristics overall. The mean values for both storm and intense rainfall totals do not differ greatly between DF and NDF storms (Figure 10). The mean cumulative weekly antecedent rainfall values are also similar for DF and NDF storms (Figure 11). While the range of values appear greater for NDF than DF storms, this wider range is likely attributable to the difference in sample sizes between NDF (n = 186) and DF (n =18) storms.

Figure 9 **Monthly frequency of large storms, combined across meteorological stations (*n* = 204) and the number of debris flow storms from the study period which occurred during each month. Debris flows predominantly occur during the months of most frequent storm activity.**

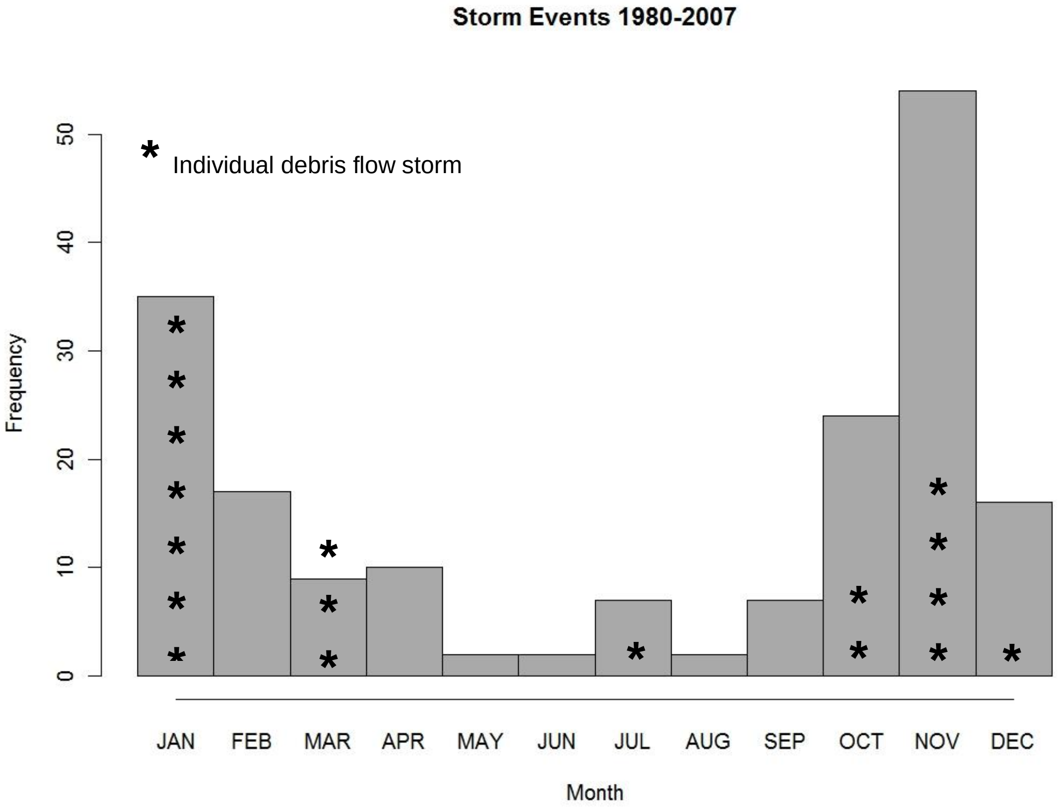
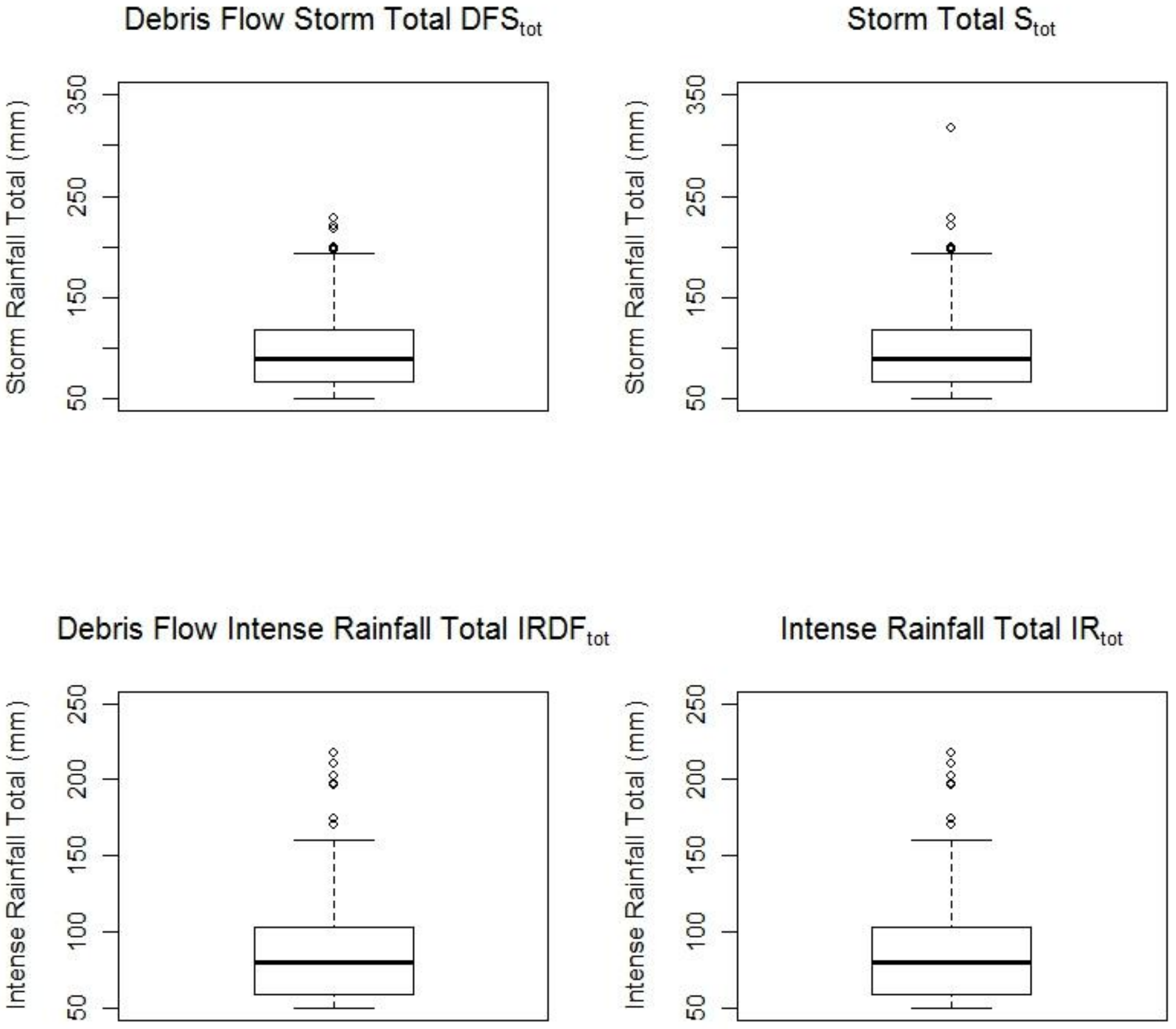


Figure 10 Range of storm total SDF_{tot} and S_{tot} and intense rainfall $IRDF_{tot}$ and IR_{tot} for debris flow (n = 18) and non-debris flow (n = 186) initiating storms combined across the three meteorological stations. Note the difference in rainfall scales.



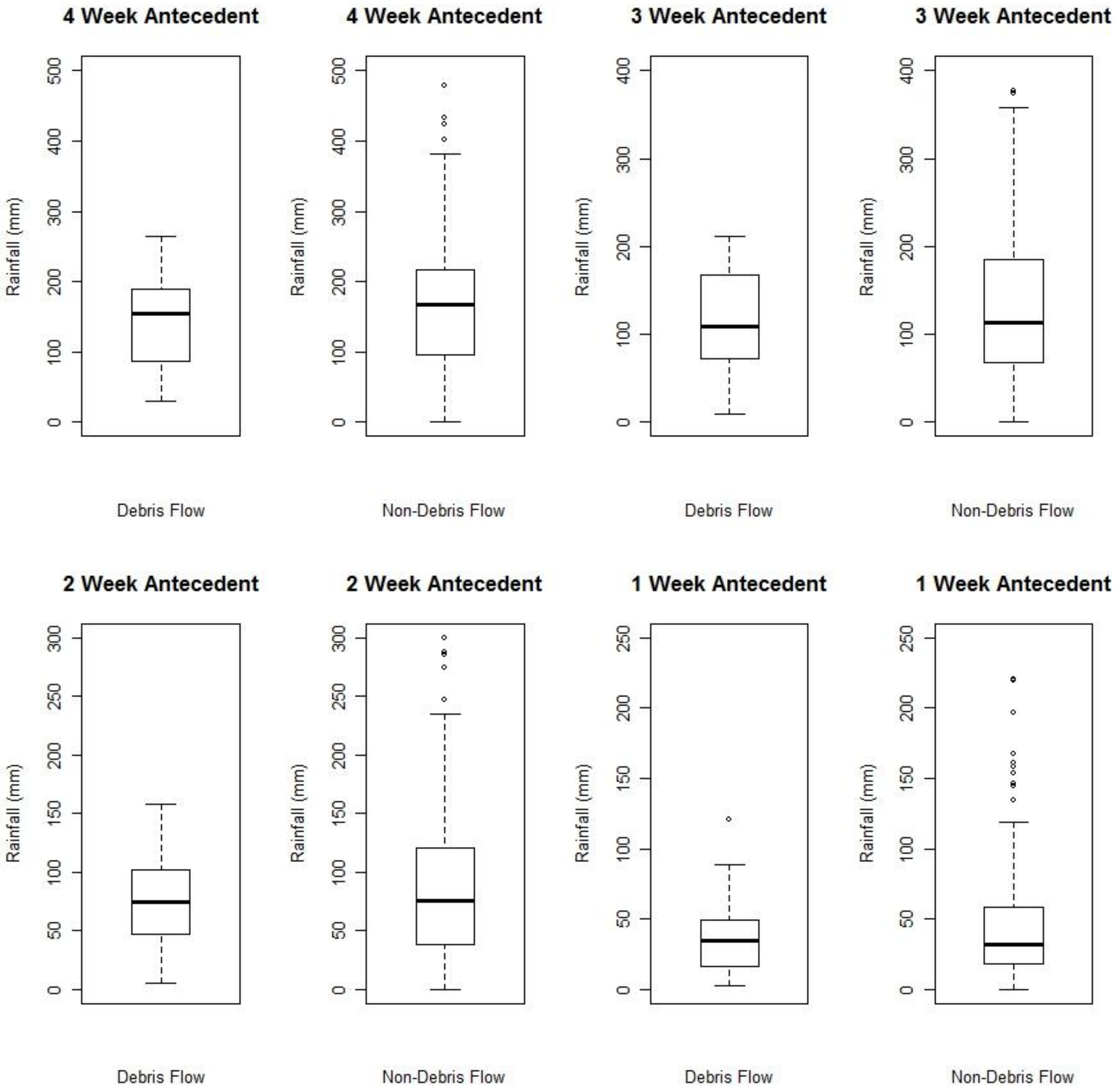
Debris Flow Storm Total DFS_{tot}

Storm Total S_{tot}

Debris Flow Intense Rainfall Total $IRDF_{tot}$

Intense Rainfall Total IR_{tot}

Figure 11 Range of cumulative weekly antecedent A_i rainfall for debris flow (n = 18) and non-debris flow (n = 186) initiating storms combined across the three meteorological stations. Note the difference in rainfall scales.



4 Week Antecedent

4 Week Antecedent

3 Week Antecedent

3 Week Antecedent

2 Week Antecedent

2 Week Antecedent

1 Week Antecedent

1 Week Antecedent

4.2 Logistic regression analysis

Construction of a correlation matrix demonstrated that the precipitation total and duration variables for storms (S_{tot} and D_s) and intense rainfall (e.g., IR_{tot} and D_{ir}) were correlated and should not be included in the same model. The correlation between precipitation totals and duration makes logical sense when one considers that a storm with a longer duration would allow for a greater accumulation of total storm rainfall (Figure 12). S_{tot} and IR_{tot} were also correlated, as well as D_s and D_{ir} because IR_{tot} and D_{ir} are nested within the values of S_{tot} and D_s. Also, antecedent rainfall A_i for two or more durations are correlated because each consecutive week includes the cumulative rainfall of the preceding week, and therefore multiple A_i should not be included in the same model. Variables combinations which were included in the logistic regression analysis included each individual variable alone, and the additive or interactive effect of *ROS*; one of S_{tot}, D_s, SDF_{tot}, SDF_d, IR_{tot}, D_{ir}, $IRDF_{tot}$, $IRDF_d$,; and one of the A_i (Table 3).

The step-wise model selection returned AIC values of all constructed models (Table 4) but only the models with the lowest AIC values, representing the models which best fit the data, were chosen to describe the difference between the DF and NDF storms. The top 10 models all include IR_{tot}, and within a small range of AIC values. 7 of the top 10 are similar in that they include IR_{tot}, *ROS* and in many case include some form of antecedent rainfall, however only the top model is being considered as the model that best fit the data.

Figure 12 Intensity-Duration of S_{tot} and IR_{tot} . Red circles indicate a debris flow initiating storm.

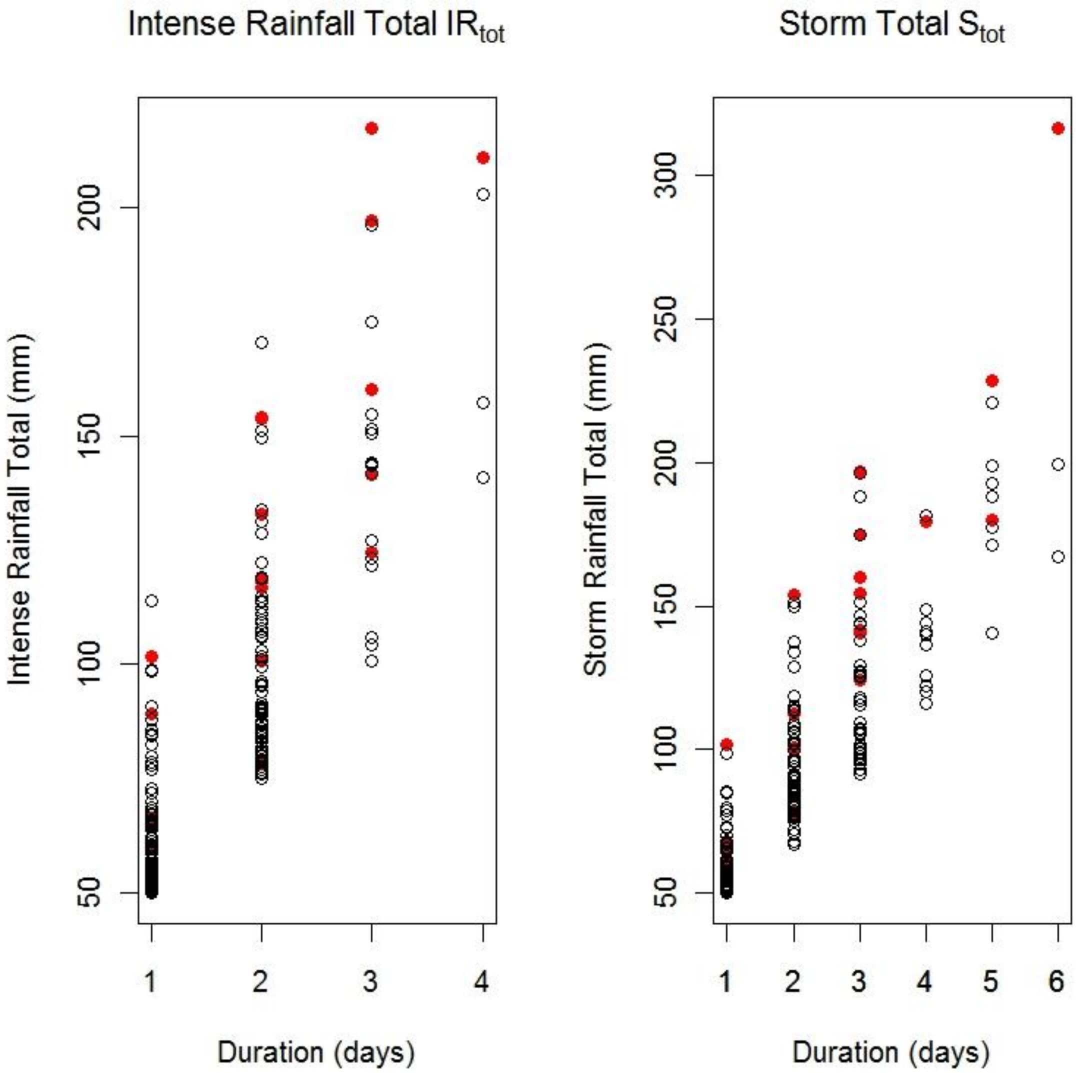


Table 3 Correlation matrix of all hydrometeorological variables. The upper diagonal part of the table contains the correlation coefficient estimates, while the lower diagonal part contains corresponding p-values. Bolded values are not correlated. P-values > 0.05 represent no significant relationship between variables and were considered together in a model. Correlation coefficients with a value between -0.3 to 0.3 are considered to have little to no association between variables and were considered together in a model.

	S_{tot}	Ds	SDF_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	A_4	A_3	A_2	A_1	ROS
S_{tot}	*****	0.860	0.982	0.791	0.898	0.731	0.898	0.730	**-0.119**	**-0.134**	**-0.110**	**-0.094**	**0.015**
D_s	<0.001	*****	0.856	0.963	0.633	0.701	0.633	0.702	**-0.073**	**-0.072**	**-0.088**	**-0.122**	**0.002**
SDF_{tot}	<0.001	<0.001	*****	0.836	0.898	0.748	0.900	0.751	**-0.112**	**-0.124**	**-0.105**	**-0.099**	**0.020**
D_{sdf}	<0.001	<0.001	<0.001	*****	0.588	0.695	0.592	0.701	**-0.057**	**-0.050**	**-0.074**	**-0.124**	**0.010**
IR_{tot}	<0.001	<0.001	<0.001	<0.001	*****	0.836	0.998	0.832	**-0.102**	**-0.114**	**-0.085**	**-0.079**	**0.060**
D_{ir}	<0.001	<0.001	<0.001	<0.001	<0.001	*****	0.832	0.996	**-0.048**	**-0.029**	**-0.046**	**-0.114**	**0.108**
$IRDF_{tot}$	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	*****	0.834	**-0.102**	**-0.110**	**-0.081**	**-0.076**	**0.04**
D_{irdf}	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	*****	**-0.048**	**-0.021**	**-0.039**	**-0.109**	**0.099**
A_4	**0.090**	**0.301**	**0.111**	**0.419**	**0.149**	**0.492**	**0.149**	**0.496**	*****	0.908	0.823	0.592	**-0.041**
A_3	**0.057**	**0.308**	**0.077**	**0.481**	**0.104**	**0.686**	**0.118**	**0.765**	<0.001	*****	0.897	0.647	**-0.007**
A_2	**0.119**	**0.214**	**0.135**	**0.293**	**0.228**	**0.510**	**0.253**	**0.578**	<0.001	<0.001	*****	0.726	**-0.088**
A_1	**0.184**	**0.082**	**0.161**	**0.077**	**0.260**	**0.107**	**0.279**	**0.121**	<0.001	<0.001	<0.001	*****	**-0.071**
ROS	**0.832**	**0.981**	**0.782**	**0.886**	**0.394**	**0.125**	**0.442**	**0.159**	**0.559**	**0.924**	**0.210**	**0.317**	*****

The best fit model indicated that difference in IR_{tot} for NDF storms and $IRDF_{tot}$ for DF storms, as well as the occurrence of a storm during the *ROS* season were the explanatory variables that best characterized the probability that a debris flow would (or would not) occur.

Table 4 Top ten models from step-wise logistic regression and AIC values

Rank	Model	AIC
1	$DF \sim IR_{tot} + ROS$	103.46
2	$DF \sim IR_{tot} + ROS + IR_{tot}*ROS$	103.88
3	$DF \sim IR_{tot}$	104.58
4	$DF \sim IR_{tot} + ROS + Ant_1$	105.25
5	$DF \sim IR_{tot} + ROS + Ant_3$	105.31
6	$DF \sim IR_{tot} + ROS + Ant_4$	105.44
7	$DF \sim IR_{tot} + ROS + Ant_2$	105.45
8	$DF \sim IR_{tot} + Ant_3$	106.36
9	$DF \sim IR_{tot} + Ant_2$	106.46
10	$DF \sim IR_{tot} + Ant_4$	106.49

The *p*-values for the model are significant for IR_{tot} at $\alpha = 0.5$, indicating that it is very unlikely that the observed results would be seen by chance alone (Table 5). The *p*-value for *ROS* is not significant, but the *ROS* variable still contributes to the best-fitting model.

Table 5 Output of model Debris Flow ~ Intense Rainfall Total + Rain-on-Snow

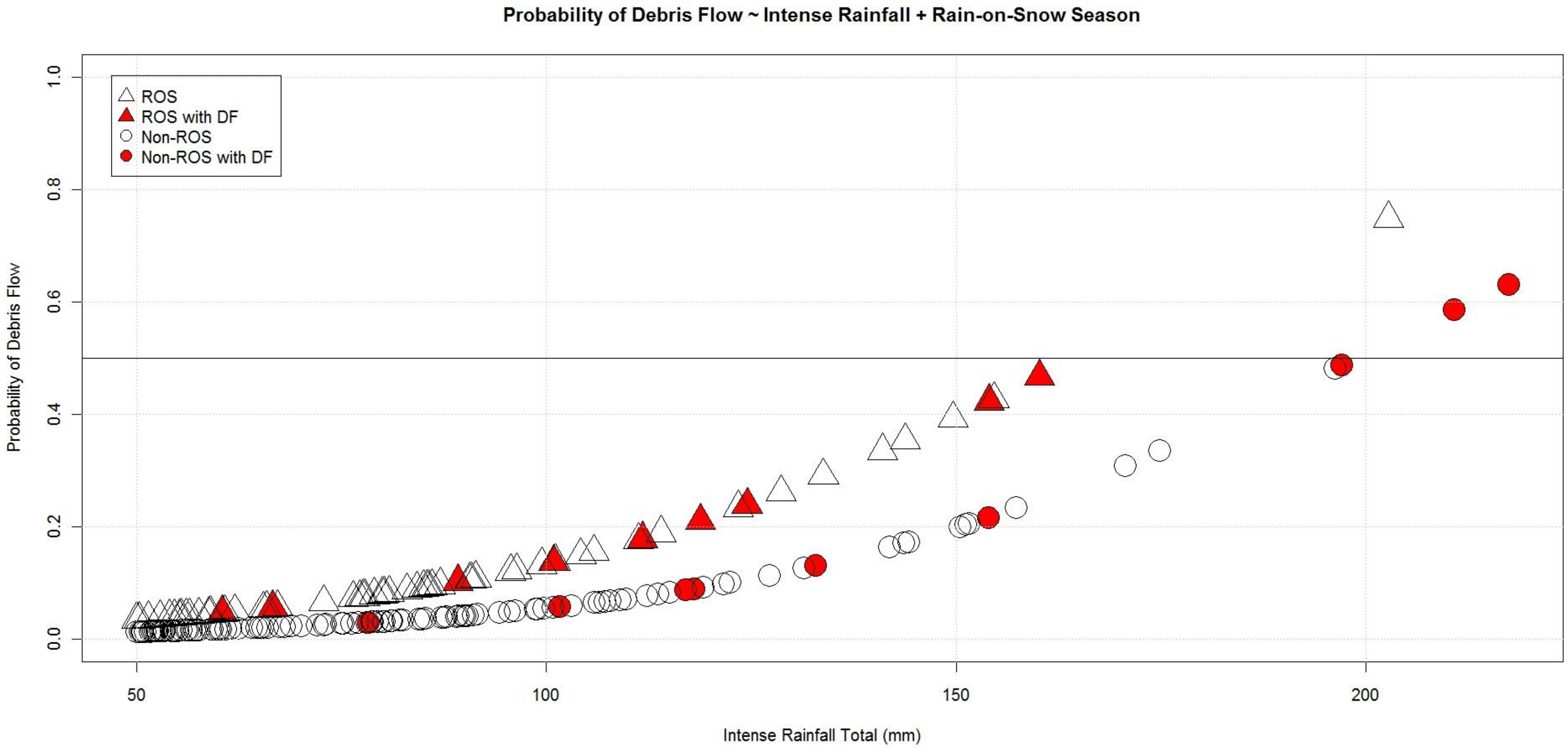
Variable	Coefficient Estimate	Standard Error	*z* value	2.5% Confidence Interval	97.5% Confidence Interval	*p* value
Intercept	-5.694	0.893	-6.377	-7.642	-4.100	0.00008
Intense Rainfall Total	0.028	0.006	4.400	0.016	0.042	0.007
Rain-on-Snow	0.969	0.550	1.763	-0.107	2.082	0.078

All storms are plotted along a logistic curve to show the probabilities of a storm total triggering a debris flow (Figure 13). The two curves in Figure 13 represent storms that occurred during the *ROS* season and those which did not. In addition, debris flows are demarcated on each of the curves. Half (9 of 18) of the debris flow storms occurred during the *ROS* season, and half did not.

All 9 *ROS* debris flow initiating storms occurred at intense rainfall values below approximately 160 mm of intense total rainfall, and all at probabilities < 0.5. Only 2 of the 9 non-*ROS* debris flow initiating storms had probabilities greater than 0.5, with total intense rainfall greater than approximately 200 mm of intense rainfall per storm.

The logistic curve shows that there is no clearly defined grouping that distinguishes between the debris flow and the non-debris flow causing storms, suggesting that there may be other underlying conditions that contribute to debris flow initiation aside from IR_{tot} and *ROS* alone. However, the difference in DF occurrence on the two curves does suggest that it may take less IR_{tot} to initiate a debris flow if the intense rain happens during the *ROS* season.

Figure 13 Logistic curve describing the probability of the occurrence of a debris flow (DF) based on intense rainfall total and storm occurrence during the rain-on-snow (*ROS*) season between January and March. The solid line represents probability = 0.5.



5: DISCUSSION

My analysis of all possible combinations of explanatory variables suggested that intense rainfall IR_{tot} and *ROS* are the most significant predictors of debris flow occurrence. However, even as the best predictors, IR_{tot} and *ROS* serve as a relatively poor means of distinguishing between DF and NDF storms. Sixteen of the 18 storms that produced debris flows were estimated to have had less than 0.5 probability of debris flow occurrence based on the hydrometeorological variables used.

Including *ROS* season as a hydrometeorological variable has its caveats since classifying *ROS* events that occurred in the past is somewhat speculative because it is dependent on existing debris flow documentation, or some other estimation of whether the documented debris flow occurred in the elevation zone most susceptible to ROS events. The winter rain-on-snow zone in Coastal British Columbia occurs roughly between 300 m (a.s.l) and 800 m (a.s.l) (Guthrie, 2010). Precipitation occurring below 300 m falls predominantly as rain throughout the year, and above 800 m precipitation is considered to be dominated by snow during the winter months. Assessing if debris flows started below, within, or above the 300 m to 800 m ideal rain-on-snow zone is not possible because the elevation at which they occurred is not known exactly. Ideally, records from meteorological stations at higher elevations would be used in this analysis, however there are stations at an appropriate elevation and proximity to the study sites to provide an accurate reflection of snow depth conditions. The three meteorological stations selected at lower elevations do record the amount of snow on the ground, however this is not an accurate representation of the amount of snow available for melting at elevations where

ROS typically occur (300 m to 800 m). Snow fall, snow depth, and melt rate during each storm was therefore not considered within the model.

Figure 13 shows that half the DF storms with low probability occur during the typical *ROS* season, suggesting that perhaps less rain in needed to trigger a debris flow if additional soil moisture is available from melting snow. However, establishing whether a debris flow is actually the result of a ROS event is difficult without knowing the actual presence or absence of snow around each debris flow initiation site, snow depth, and the potential snow water equivalent. In reality, a storm that occurs between January and March would only be considered a ROS event if enough snow were present to contribute to a *ROS* driven slope failure. Furthermore, *ROS* events have been documented at other times of year in the Chilliwack region, suggesting that the selection of a narrow time window of January to March may under represent the occurrence of ROS events in this dataset.

Given the success of using hydrometeorological variables as valuable predictors for debris flow warnings in other regions of BC, there is likely room for improvement of understanding the nature of debris flow initiation in Chilliwack. In the following sections I outline other hydrometeorological, geomorphological and land-use factors that may be confounding this analysis, and compare my results with other regional studies. I then provide some recommendations that can be made from this analysis in terms of improving emergency planning for debris flows within the region. Finally, I place these results in the context of how climate change might influence the conditions that are likely to cause debris flows in the future.

5.1 Other hydrometeorological factors

The outcome of this study suggests that debris flow initiation is controlled by a more complex set of factors than intense rainfall and rain-on-snow season alone. Other possible factors that were not considered directly in model selection but might contribute to debris flow initiation include duration of intense rainfall, climate triggering events such as Pineapple Express systems, and unusually warm temperature anomalies that could initiate rapid snow-melt events.

In order to assess the coincidence of multi-day intense rain with intense rainfall totals and *ROS* season, multi-day intense rain is plotted along the “debris flow only” logistic curve (Figure 14a). The graphic representation of multi-day intense rain shows that as the daily duration of intense rain increases, so does the intense rainfall total, and subsequently the probability of debris flow initiation. Four of the DF associated storms were one-day events, 9 were two-day events, 3 were three-day events, and 1 was a four-day event. The increase in intense rainfall total over time is intuitive as multi-day storms have the potential for higher total cumulative rainfall to saturate and erode soils than single day events.

Some winter storms events delivering high volumes of intense rainfall are associated with infrequent meteorological phenomena known as “Pineapple Express” storms, which may enhance the occurrence of debris flows. Pineapple Express storms are defined by Dettinger (2004) as atmospheric paths that transport approximately 500 kg/m/s of water vapour from the tropical Pacific and move continuously towards the west coast of North America, making landfall between 32.5ºN to 52.5ºN latitude. On average, Pineapple Express storms occur four days per year between October and April. The presence or absence of a Pineapple Express *PE* event during a storm is another descriptive characteristic of large storms recorded in Southern British Columbia. A record of Pineapple Express storms that landed along the West Coast between 45° and 55° N latitude (Dettinger, 2008) was compared with the dataset of all storms and assigned a binary value for presence or absence of *PE* .The presence of a Pineapple Express during each DF storm is plotted on the logistic curve and is present with both high and low probabilities of debris flow initiation (Figure 14b). This comparison suggests that Pineapple Express presence is not a definitive variable in the causation of a debris flow.

More information regarding rapid melting of snow due to temperature anomalies and *ROS* events would help to further understand the meteorological effects on debris flows in mountainous areas where conditions vary by elevation. Average monthly temperatures for the minimum, mean, and maximum between 1980 and 2006 were calculated for the three meteorological stations. The minimum, mean, and maximum temperature for each debris flow day are plotted over the temperatures averages to determine any obvious deviations (Figure 15). Temperature anomalies, particularly a warming during the winter season, could indicate that a rapid snowmelt may have contributed critical water content to the soils. Further investigation of temperature anomalies and rates of melting could significantly improve the understanding of snow-water equivalent available for soil saturation produced by temperature and rain driven melting.

Figure 14 Probability of debris flow based on *IR_{tot}* and *ROS.* **Occurrence of single and multi-day intense rainfall (a), with presence of Pineapple Express (b) are plotted along the logistic curve. NDF storms are removed. Triangles represent *ROS* debris flow storms, and circles represent non-*ROS* storms. Horizontal line indicates 0.5 probability.**

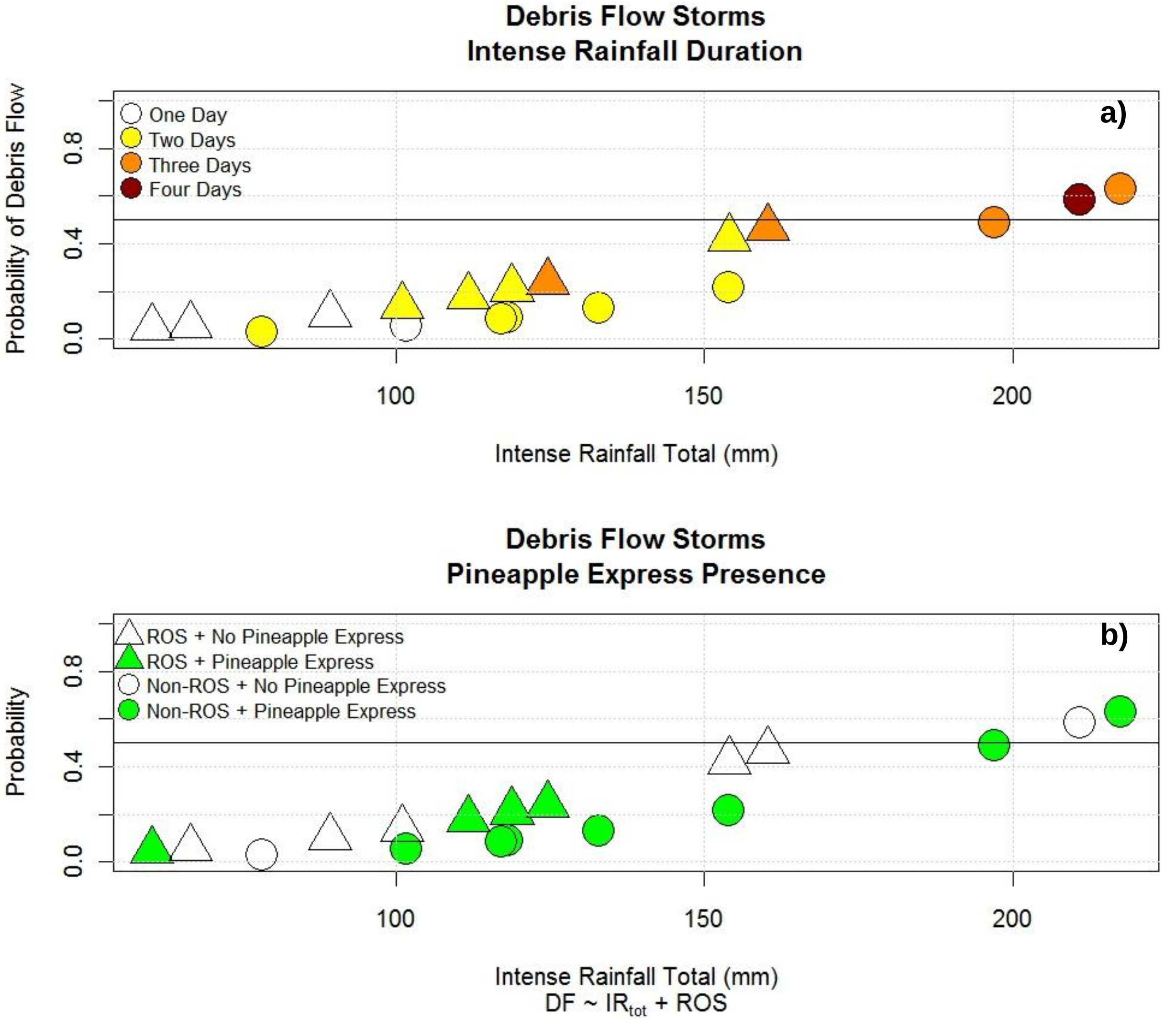
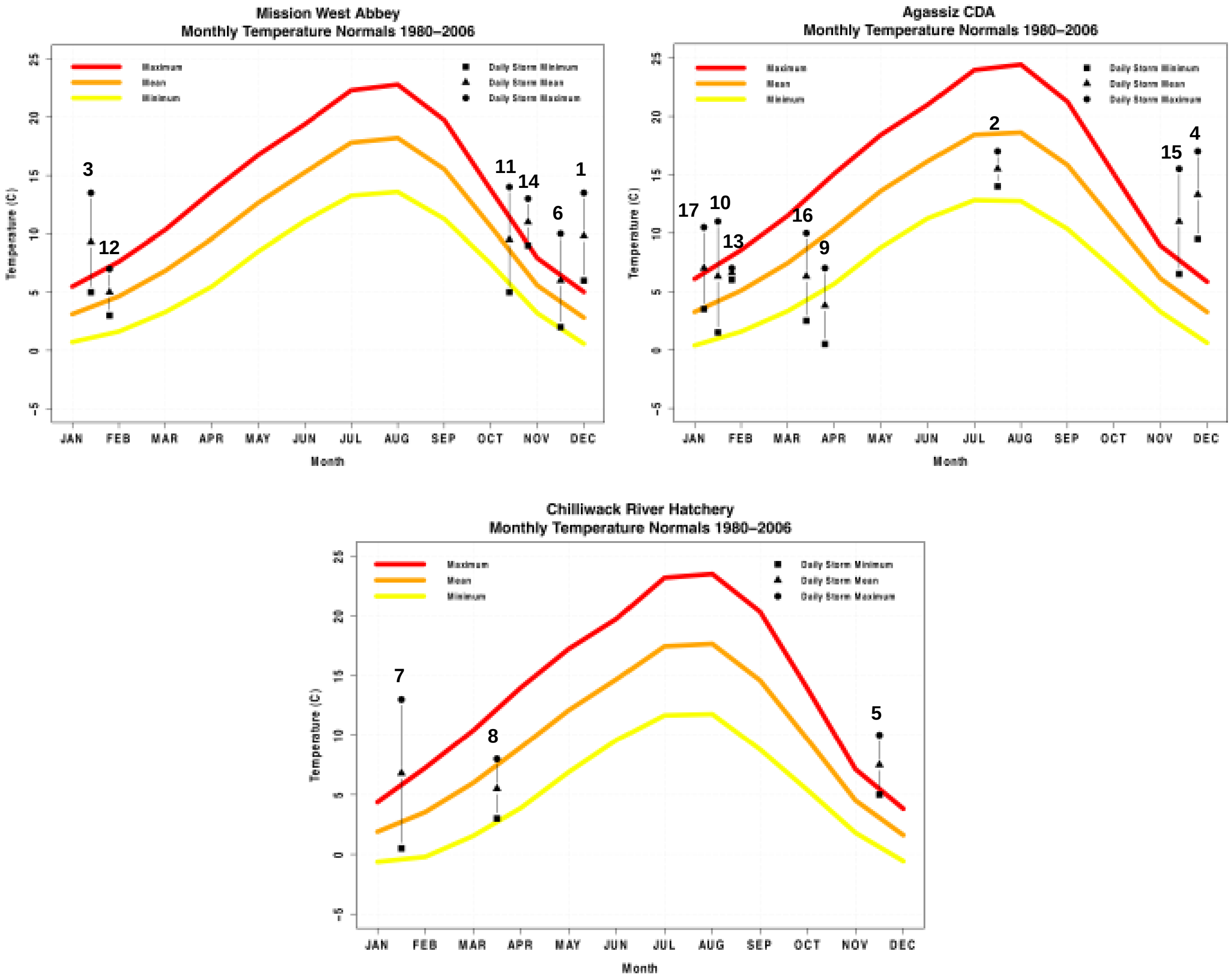


Figure 15 Temperature anomalies for each debris flow storm day plotted over average monthly temperatures between 1980-2006 for Mission West Abbey, Agassiz CDA, and Chilliwack River Hatchery. Storm ID is indicated beside each debris flow associated storm (refer to Table 2)



5.2 Other geomorphological and land-use factors

The most apparent anthropogenic causation of debris flows in the Chilliwack area is deforestation for logging, agriculture, and expansion of developing areas. The Chilliwack area has been logged historically and continues logging through present day. Regardless of the reason for forest alteration, the result is the same: logging for forestry and agriculture destabilize slopes by eliminating soil binding roots systems and freeing sediment for mobilization. In addition, logging roads undercut and weaken slopes at their base, overload slopes at their top, and alter surface drainage (Guthrie, 2002). A study by Guthrie (2002) showed that logging activity greatly increased the number of landslides on Vancouver Island, British Columbia. As the number of landslides increased with logging activities, so did the frequency of those landslides reaching creek channels which can ultimately transform into channelized debris flows. Wolter et al (2010) also found that landslide rates on logged slopes, especially clear-cuts, increased 9 to 31 times greater than those on natural slopes in the Chilliwack Valley. Thus, the extensive logging in the Chilliwack region may have acted to ‘decouple’ the control of hydrometeorological variables on debris flows by allowing more debris flows to be triggered at lower levels of intense precipitation.

One of the limitations of the hydrometeorological model presented here is that it does not account for sediment available for transport in the creek channels. After a debris flow, creeks are scoured free of the necessary volume of sediment until the creek has had enough time to recharge with debris which explains the seldom recurrence of a debris flow on the same creek channel within a short period of time. Creek basins are often classified as either supply-limited or transport-limited (Jakob, Bovis, & Oden, 2005). Supply-limited basins, as found in coastal BC, rely on recharge of creek sediments that are controlled by rock weathering and disintegration. In contrast, transport-limited basins typically have a large volume of readily mobilized materials and produce more debris flows when a climate threshold is exceeded (Jakob, Bovis, & Oden, 2005; Glade, 2005; Bovis & Jakob, 1999). Due to the high volumes of precipitation in the Chilliwack area, debris flows in this area might be limited by the supply of debris rather than by transporting mechanisms (i.e. hydrometeorological controls).

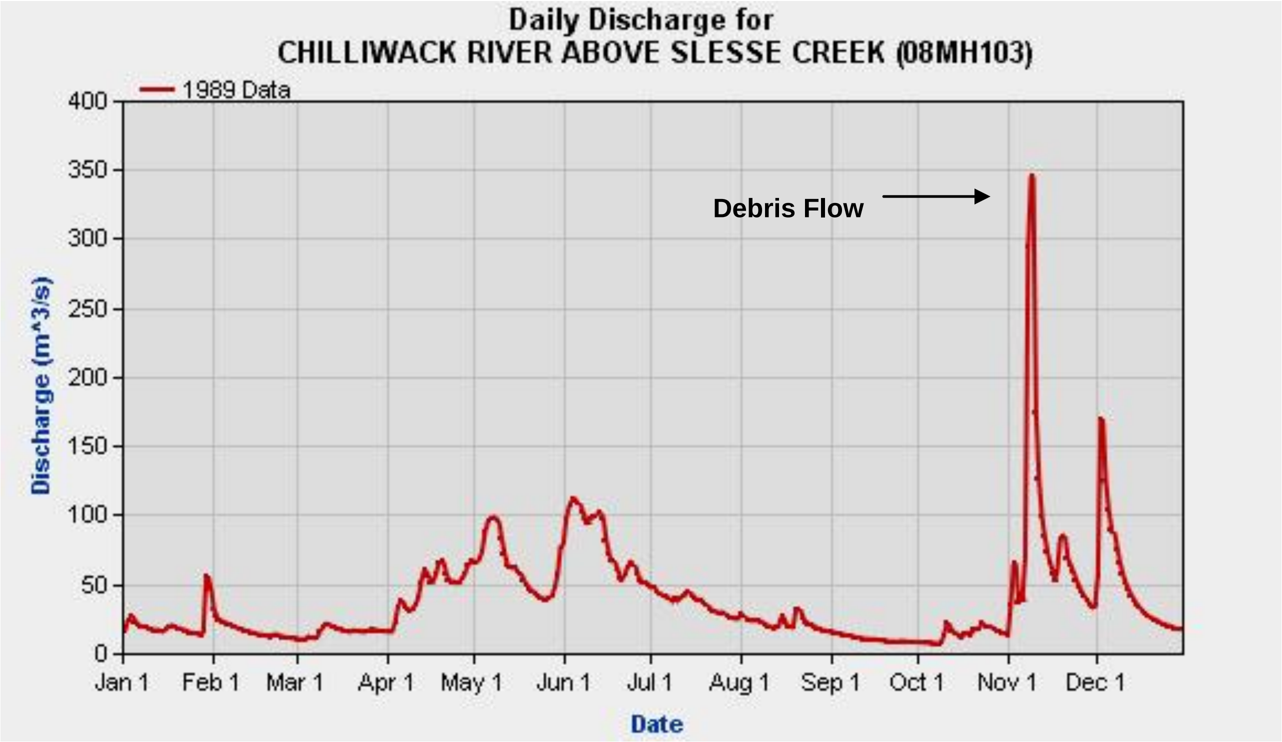
5.3 Comparison with regional studies

This research found that only IR_{tot} and *ROS* play a dominant control on debris flows initiation. The top ten models for consideration were all ranked closely according to AIC. Seven of ten models included some form of antecedent precipitation contributing to debris flow initiation, however none were included in the top three models suggesting that other variables are more important. This result is contrary to a model presented by Jakob & Weatherly (2003) for the North Shore Mountains of Vancouver. Their study used a step-wise discriminant analysis which isolated 4-week antecedent rainfall, storm rates, and stream-flow rates and the key variables that discriminated between debris flow and non-debris flow storms. Several differences in experimental design and available data may be responsible for the differences between Jakob & Weatherly (2003) and this study.

First, Jakob & Weatherly (2003) use a discriminant analysis to identify variables that best separate the storms that lead to landslides from those that did not, however this study uses logistic regression. The difference in the data distribution, and the interest in knowing the probability of a storm being classified as NDF or DF influenced the use of logistic regression of the study in Chilliwack.

The difference in statistical method is likely less of an influence on the results as the difference in data collection and availability. Jakob & Weatherly (2003) utilized one study site at Mackay Creek and used nearby weather stations that provided data for antecedent rainfall and hourly rainfall rate. This study aggregated daily hydrometeorological data from three stations to assess storm characteristics more broadly across the Chilliwack Region. Due to an incomplete and consistent hourly dataset for all three meteorological stations, daily data was used to determine single or multi-day intense rainfall total and duration instead of hourly data to calculate hourly rainfall rates throughout the storm. In addition, their study included hydrometric data from a flow-meter at Mackay Creek which allowed them the advantage of identifying stream-flow greater than 1 m/s as an indicator for a potential debris flow. This study did not have access to complete hydrometric datasets which were representative for each of the three Chilliwack study sites. Hydrographic data for Hatzic Valley and the Highway 1 area was not available for the entire length of the study period from a single station, as well as containing gaps in the record which did not capture the timing of several debris flows. However, hydrometric data from Chilliwack River Valley near Slesse Creek was available for three of the 18 debris flows and the record did show that there were peak stream-flows during heavy rainfall events. A hydrograph of stream-flow shows a drastic spike in stream-flow associated with a large debris flow storm on November 11, 1989 (Figure 16). The spikes in stream-flow that were seen during storms at Chilliwack River that coincided with debris flows which suggests that stream-flow may in fact be an indicator of saturated soil conditions (Jakob & Weatherly, 2003). However, a more thorough record of streamflow data would be needed to confirm this hypothesis.

Figure 16 Stream-flow data from Chilliwack River Valley showing a spike in stream-flow during a debris flow storm on November 11, 1989.



(Environment Canada; Water Survey of Canada, 2010)

Lastly, the North Shore Mountain study was isolated to an area where there were no logging activities, and human influence was not a factor. As described previously, the study for the Chilliwack area was not able to control for many of those factors. Chilliwack has historically been an area of mixed forestry and agriculture, and while those activities continue there is also much growth in urban to rural expansion. Air photo records are temporarily inconsistent in the region and make it impossible to accurately date the occurrence of a debris flow and associate it with a particular storm date. Therefore, identifying the role of hydrometeorology in causing debris flows has been an exercise in utilizing the sparse information to inform managers about one of many variables which cause debris flows in the area.

5.4 Recommendations

Although the model provided in this research did not adequately predict differences in storm characteristics between NDF and DF storms, the analysis is only one step in trying to identify and understand hydrometeorological contributions to debris flow initiation. Additional steps can be taken to improve future collection and assimilation of data, and also to help mitigate and adapt to debris flows that are unpredictable. The first proactive step is to continue monitoring and collecting data in debris flow prone areas to increase the amount of data that can be used to analyse large storms. Second, the use of adaptive infrastructure may help communities cope with the debris flow hazards which are unavoidable. Finally, improving community awareness and education about debris flow can help the public recognize the hazards specific to their area.

5.4.1 Improved monitoring and data collection

The outcome of the model described here provides information regarding rainfall effects on debris flow initiation, but substantial room for improvement is possible if other variables are explored. The District of North Vancouver has recently implemented a regional debris flow warning system to advise residents of the potential risk of a debris flow based on current weather conditions and stream-flow data. However, a lack of adequate information about hydrometeorological controls in the Chilliwack area eliminates the feasibility of a similar system.

In order to improve potential recognition and monitoring of debris flows associated hydrometeorological conditions, I provide four main areas of recommendation. First, consistent and detailed documentation of debris flows in the Chilliwack area would provide more background information to each individual debris flow event. Second, consideration of snow-pillow data could provide measures of snow-water-equivalent runoff in order to explore the effects of *ROS* events. Third, the accuracy of hydrometeorological conditions could be improved by positioning meteorological stations closer to known debris flow areas and at elevations which capture the *ROS* zone. Finally, improvement of the placement of stream-flow gauges in close proximity to watersheds that are debris flow prone may more accurately reflect the stream-flows within each area.

First, a systematically collected recorded database of debris flows would be imperative for creating a large sample of events which would allow for a more robust analysis. The Fraser Valley Regional District or Ministry of Transportation and Infrastructure typically are involved in response efforts and might be choices of organizations to support such a database. A larger sample size would allow for the isolation of effects of logged and un-logged areas, or for the removal of storms during the rain-on-snow season. One of the limitations of the current record that was compiled for this study is that additional debris flows were likely to have occurred during the study period but went unreported. Thus some storms may be incorrectly classified as NDF storms. Capturing all debris flows that happen in an area would be impossible unless routine inspection were carried out. Such routine inspections are likely not feasible due to time and financial restrictions. However, much information can still be gained from systematic reporting of debris flows which are recorded. Useful information would include accurate details of location coordinates, dates, time of day, and any other hydrometeorological or non-hydrometeorological details such as recent land-use change, snow melt, or rain-on-snow conditions. Ideally, all of this information would be kept in a central database in the Fraser Valley Regional District of with the BC Ministry of Environment for consistency of record keeping and accessibility to the public and researchers.

A second recommendation would be to investigate the quantitative contribution of melt water to debris flow initiation during actual rain-on-snow events. The British Columbia Provincial River Forecast Centre collects and interprets snow, meteorological and stream-flow data to provide warning of stream and lake runoff conditions around the province (BC Ministry of Forests, Lands and Natural Resource Operations, 2011 b). The network conducts manual snow surveys as well as employing satellite transmitted snow data from snow pillows. Snow pillows consist of a 3-meter diameter bladder filled with an antifreeze solution and positioned flat on the ground. As snow accumulates on the bladder, antifreeze is displaced up a stand-pipe and the weight of the snow is measured in snow water equivalent. In addition to the snow-pillows, temperature and precipitation gauges are also usually installed at the site and provide a record of real-time hourly data. There are currently snow surveys in Chilliwack River Valley and at Waleach Lake near the Bridal Falls Highway 1 corridor. Both of these stations were established in 1991 and have a substantial enough record to compare with debris flows that have happened since that time. Analysis of these data would represent a logical next step for this study, to determine if additional, strategically placed snow pillows would assist in debris flow determination.

A recent mudslide in the Bridal Falls Trans-Canada highway corridor outside of Chilliwack on June 28, 2011 exemplifies why further research is needed for an accurate and comprehensive prediction model which includes the effect of snow. Less than 10 mm of rain fell in the four days before the slide, thus nullifying the assumption that intense rainfall is the only driver of debris flows near Chilliwack. One idea put forth is that melting snow pack and wet soil caused the 6000 m^3 of debris and mud to close the highway for 24 hours, halt train service, and trap one motorist inside her vehicle (Dugan & Hager, 2011). Since this event occurred outside of the typical October to March debris flow season, investigating snow-water-equivalent from rapid melting in conjunction with any present logging activities would help to isolate the contributing conditions of this atypical debris flow event.

A third improvement to current monitoring would be to improve the network of meteorological stations to track conditions directly in the areas suspected to initiate debris flows, and to verify that stations accurately reflect the regions we have analysed. The two British Columbia Provincial River Forecast Centre meteorological stations in proximity to Highway 1 and Chilliwack River Valley are representative of elevations over 1000 m, and could be used to compare and complement data with the Environment Canada stations at Agassiz CDA and Chilliwack River Hatchery at lower elevations. Not only are stations at upper elevations with additional meteorological information an advantage, but the fact that the system already exists and transmits data remotely is of particular convenience. The stations may be above the recommended rain-on-snow zone of 300 m to 800 m for British Columbia, but a small-scale meteorological station at mid-elevation may be one way to assess precipitation conditions in an area of public risk, particularly along the Highway 1 corridor. The installation of a third meteorological station at mid-slope could create an elevational transect to determine potential debris flow conditions at different points on the slope.

Finally, peaks in stream-flow data from the Chilliwack Valley during large storms suggest that stream-flow data may be a potential indicator of debris flow conditions. Since stream-flow was one of the variables used in differentiating landslide storms from non-landslide storms in North Vancouver (Jakob & Weatherly, 2003), stream-flow may be a good indicator in the Chilliwack area as well. Complete records from hydrometric stations near Hatzic Valley and Highway 1 are lacking for the time period of this study. However, the incorporation of stream-flow data at these places into future analysis may improve the ability of the logistic model to assess the probability of debris flow occurrence. Ideally, data would be collected on representative creeks which experienced known debris flows.

5.4.2 Adaptive infrastructure

Risk management is a human-centred concept and can only be applied in those instances where humans and the things that they value could be adversely impacted (Lee & Jones, 2004). Rapid onset with unpredictable speeds and volume make debris flows extremely difficult to stop once they have started. However, debris flows do not pose a risk to humans when humans and their valuables are not in the debris flow's path. There are two basic choices to avoid debris flow damages: (a) conduct known debris flow causing activities with the upmost precaution; or (b) conduct activities away from potential debris flow areas. The easier choice is the latter. Knowledge of past debris flow and landslide incidents should be used to employ the precautionary principle and mitigate future risks wherever possible. In the case of working with already existing infrastructures, or necessary forestry activities, adaptive measures must be utilized.

Areas such as Lion's Bay, BC have installed debris flow flumes to channelize sediment and debris and move it to a safe location where water could be strained from other materials. Although pricey at $4.4 million in 1986, the structure has successfully reduced the risk to human infrastructure and lives by protecting the surrounding community and transportation corridor along the Sea-to-Sky Highway (Van Dine, 1996). Of the three sites in the Chilliwack study area, the greatest safety concern is the Bridal Falls Highway 1 corridor due to the high volumes of traffic that travel the highway every day. The highway is constructed along the eastern edge of the Fraser River which is situated directly at the base of several active debris flow channels. Although some debris catchments help to protect the highway currently, they have not always been adequate to prevent a large magnitude debris flow from overtaking the highway, as was seen during the June 28, 2011 incident. Further investigation of anthropogenic disturbance and hydrometeorological debris flows triggers would provide authorities with information to aid in the decisions of whether to include or improve debris flow mitigating infrastructures.

Finally, as mentioned previously, the Chilliwack region has experienced extensive logging for development, forestry, and agricultural purposes, and these logging activities have been shown to exacerbate risks of debris flows in populated areas. One example of a forestry company's ingenuity took the form of a curved berm basin at the base of a tributary on Cypre Creek on Vancouver Island. This closed basin has no outlet and so contains and prevents a debris flow from negatively affecting fish habitat further down the creek. It cost approximately $5000 to construct and was able to withstand a 5000 m^3 debris flow the winter following its construction (Van Dine et al, 1997). In the absence of full knowledge of a full predictive model, deflection berms may be a low cost and simple preventative measure in areas of expected small magnitude flows throughout the study area.

5.4.3 Emergency response and preparedness

Chilliwack currently has no debris flow-specific warning system that is similar to that of North Vancouver's. In the absence of a formal warning system, Chilliwack relies predominantly on mitigative and reactive measures to debris flow and landslides. Many of these actions are run independently and co-operatively through local, provincial, and occasional federal agencies as the magnitude of the emergency dictates.

The BC Ministry of Transportation and Infrastructure (MOTI), is typically responsible for maintaining adaptive infrastructure such as debris basins and catchments as seen along Highway 1 between Chilliwack and Hope. Agencies such as the BC River Forecast is responsible for monitoring potentially dangerous stream-flows and peaks flows in watersheds across the province. This agency also provides public access through the Canadian Water Service to real-time hydrometric data which can indicate potentially dangerous creek conditions including floods, debris flows, and mudslides. After a debris flow or landslide, MOTI is often involved with the removal of debris from creek channels, and clearing highways and corridors in order to reopen traffic as soon as possible following a slide. MOE is also sometimes involved in removal of debris from creeks in order to ensure that riparian habitats are not destroyed.

In the event of an emergency, local and regional districts are usually the first to respond and will activate an emergency plan and set up an emergency operations centre. If the emergency is beyond the scope of local authorities, Emergency Management BC (EMBC) will respond and provide provincial support. EMBC is a division of the BC Ministry of Public Safety and Solicitor General which provides training and support to local governments before, during, and after emergencies (EMBC, 2011). If the emergency then escalates beyond the provincial resource capacity, federal support from Public Safety Canada (PSC) is evoked. PSC works with provincial and local authorities, and can provide infrastructural, financial, and expert support (EMBC, 2011). According to the Emergency Management Act federal agencies can only respond to the emergency if the province requests assistance or if there is an emergency response agreement with the province that permits assistance (Geological Survey of Canada, 2011).

Given the current absence of supporting science and financial practicality of a debris flow warning system, the Chilliwack region must rely on their own awareness of the issue at hand. Authorities such as the Fraser Valley Regional District and the Province of BC provide minimal amounts of regionally specific information regarding debris flows and landslides in the area. The public is usually referred to information from the Geological Survey of Canada, and Natural Resource Canada which is broadly applicable to BC and Canada. Although good general information and recommendations are available, site specific information on debris flow hazards, warning signs, and preparedness in the Fraser Valley is lacking. EMBC states that one of their fundamental operating principles abides that it is “up to the individual to know what to do in an emergency to protect themselves and their family” unless they are unable to cope, in which case governments will become involved (EMBC, 2011). Under this mandate, detailed and appropriate information should be provided to the public so that they can be better prepared to embrace that responsibility. A simple step would be to create a publicly accessible fact sheet or briefing, and inventory of debris flows and landslides in the Fraser Valley. A comprehensive and accessible inventory of all reported debris flow and landslide occurrences should be made available to the public to provide more detailed account of landslides in the region, and to be available as a database for future research. A fact sheet can also easily be made available via the websites of municipal and regional governments such as the City of Chilliwack and the Fraser Valley Regional District which includes most of the rural areas susceptible to debris flows and landslides. The fact sheet or report should contain the following information:

- *Location* - Areas that debris flows have occurred in the past and their frequency of occurrence in the area can inform the public of their proximity to hazardous areas.
- *Seasonality* – Since landslides and debris flows usually coincide with the wetter months in BC, seasonality of the hazard can encourage the public to

look for warning signs, adjust their activities in those areas, and promote greater caution with construction.

- *Causes* – Since each area is unique climatically, topographically, and in terms of anthropogenic activities, common causes of specific debris flows in the Fraser Valley should be included. These may include logging, human disturbance of slopes, debris dams, seismic activity, meteorological conditions, etc.
- *Warning signs* – Often times there are warning signs of debris flows that include increased stream-flows, or lack of regular stream-flow which may indicate a debris dam, slumping of hills or creek slopes, etc. Providing this information would allow the public to notice signs of danger, and to report potential hazards.
- *Contacts* – Having a community watching for warning signs may provide an opportunity for pre-emptive measures to be taken. Providing contact information to authorities that can respond to warning signs may be able to mitigate a disaster. In addition, inclusion of the authorities to contact in the event of a debris flow or landslide for a quick response and clean-up.

By providing an easily accessible fact sheet to residents of the Chilliwack area, it may be possible to improve the public knowledge of hazards, and decrease the number of damages.

5.5 Implications for future debris flow occurrences in BC due to climate change

Although the model presented in this study suggests that intense rainfall and rain-on-snow season are the predominant factors in debris flow initiation, triggering mechanisms can change over time due to land-use change, climate change, glacier cover, snowfall, and thawing alpine soils which can alter melt-water events that result in debris flows (Santi et al, 2011). The uncertainties in estimating debris flow triggers – and how they might change in future - make it difficult for planners to prepare infrastructure for adaptation to changes in national, regional, and local climate.

Studies examining projected changes in precipitation for southwestern BC using climate model simulations suggest that short-term and intense precipitation events are predicted to experience small positive and negative changes throughout the 21st Century (Table 6; APPENDIX C). One study providing a quantitative estimation of short-term changes in precipitation as relevant to debris flow initiation examined averaged over 9 models and greenhouse gas concentration scenarios and found that there was an approximate 6 % predicted increase in short-term precipitation intensity by 2100 (Jakob & Lambert, 2009). Although one must exercise some caution when relation coarse-resolution model results to the region like Chilliwack with strong topographic gradients, these model results do suggest that the meteorological conditions may shift towards conditions that are more favourable for debris flow initiation.

Climate model results also seem to suggest that annual precipitation could increase by 0-21% by 2080 (Murdock et al., 2007; Elsner et al., 2010; Jakob and Lambert, 2010; Mote et al., 2010; PCIC, 2010), although not all climate model results agree that total annual precipitation will increase by 2100 (Table 6; Elsner et al., 2010). However, all studies agree that winter precipitation is likely to increase over this time period, and this trend is already being observed in the lower Mainland (Elsner et al, 2010; Murdock et al, 2007; Mote et al, 2010, PCIC, 2010). Increased winter precipitation is of concern because it could increase frequency of saturated soil conditions that contribute to debris flow initiation.

Although antecedent rainfall did not play a dominant role in the first model selected in this study, it did appear as a potential contributing variable in one of the top seven models (Table 4) that were less than 2 AIC points from the minimum AIC value. Thus, some form of antecedent rainfall might still be a relevant hydrometeorological variable in the Chilliwack area. Furthermore, antecedent moisture plays a role in the long-term saturation and moisture retention in forest soils (Pierson, 1980; Johnson and Sitar, 1990). In other areas of British Columbia and Washington, events are often triggered by heavy rainfall on wet hill-slope materials resulting from antecedent moisture (Jakob & Weatherly, 2003). Increase in annual or winter precipitation could increase the occurrence of debris flows by affecting antecedent rainfall conditions.

Climate oscillations such as the Pacific Decadal Oscillation (PDO) and the El Nino-Southern Oscillatio (ENSO) also influence precipitation patterns that could affect the occurrence of debris flows. Jakob, McKendry, & Lee (2003) found a significant increase in short-term rainfall exceedence before 1977 (PDO warm phase) compared to after 1977 (PDO cool phase). This correlation suggests that the PDO warm phase may be associated with high intensity precipitation events (Murdock et al., 2007; Zhang et al., 2010). Increases in winter daily maximum precipitation have also been attributed to ENSO and PDO warm phases which occurred between the 1970s to late 1990s (Zhang et al 2010; Jakob, McKendry & Lee 2003). At present we are in a PDO and ENSO cool phase, and as such we may encounter fewer intense precipitation events until the next shift in PDO and ENSO.

In summary, small increases in short-term precipitation throughout the 21st century could increase the number debris flows in the Chilliwack area (Table 6). Shifts in seasonal precipitation from summer to winter months and an increase in total annual precipitation could also increase the number of debris flows experienced in this region. Long-term climate variability cycles such as PDO and ENSO have been suggested to be correlated with heavy rainfall events, and thus debris flow occurrence associated with those events may fluctuate with PDO and ENSO cycles (Jakob, McKendry, & Lee, 2003).

Table 6 Summary of climate change impacts on precipitation in the PNW. + and - at which expected change is projected to be reached is included in parentheses.

	Expected Change	Authors
Short-term (Intense)	+ 6% (2100) + increase in 1990s compared to pre-1977 + small change +/- annual maximums in Sept, Oct, Nov (2100)	Jakob & Lambert (2009) Jakob, McKendry,& Lee (2003) Salathé et al (2010) Mailhout et al (2010)
Long-term (Annual)	+ 10% (2071-2100) + 1% to +2% annually (2100) + 1% to +5% (2050s) + 2% to +11% (2050s) - 9% to +12% (2020s) - 11% to +12% (2040s) 0% to +21% (2080s)	Jakob & Lambert (2009) Mote et al (2010) Murdock et al (2007) PCIC (2010) Elsner et al (2010)
Seasonal Shift	+ Winter / - Summer + Winter / - Summer + Winter 4% to 14%/ -Summer -14% to – 33% + Autumn +/- Winter -2% to 16% / Summer -8% to 6% +/- disagreement between models	Elsner et al (2010) Mote et al (2010) Murdock et al (2007) Salathé et al (2008) PCIC (2010) Salathé et al (2010)
PDO/ENSO	+ associated with high intensity precipitation + increase intensity with positive PDO + PDO winter daily maximums +/- stochasticity can complicate predictions	Jakob, McKendry,& Lee (2003) Murdock et al (2007) Zhang et al (2010) Jakob & Lambert (2009)

6: Conclusion

This study identifies 203 storms, including 18 storms that initiated debris flows between 1980 and 2007 near Chilliwack, BC. The goal of the study is to determine the probability of a debris flow based on hydrometeorological storm and antecedent moisture characteristics alone. Stepwise logistic regression suggests that intense rainfall total IR_{tot} (total intense rainfall > 25 mm/24 hours) and the occurrence of storms during the rain-on-snow season *ROS* (January to March) are the most significant hydrometeorological variable contributing to debris flow initiating near Chilliwack, BC. The logistic model had limited success in that it predicted that 2 out of 18 debris flows had a greater than 0.5 probability of occurrence based on IR_{tot} and *ROS* alone. The findings of this analysis differ from other studies conducted in regions such as North Vancouver, BC because weekly antecedent rainfall was not a significant variable in debris flow initiation in Chilliwack. The limited success of this model is probably due to other contributing factors not considered in the model, such as amount of snow-melt, stream-flow, land-use change, and consideration of creek channel sediment recharge rates. A survey of recent literature of climate model simulations for the region suggest that climate change is expected to produce minor ($\leq$6%) increases in future rainfall intensity by the end of the 21st century (Jakob & Lambert, 2009). However, these studies provide more support for an 0 to 20% increase in total precipitation by 2100 (Elsner et al, 2010; Jakob & Lambert, 2009; Mote et al, 2010) and a shift from summer to winter precipitation.

Significant improvements could be made to increase the reliability of debris flow prediction, including continued monitoring and data collection, modification and inclusion of adaptive infrastructure, and increased public awareness of emergency preparedness and debris flow education. The results presented here are a stepping-stone towards better understanding debris flow initiation and prediction in Chilliwack. The indefinite results of the model may illustrate that all possible hydrometeorological variables and anthropogenic factors have not been explored. While much research focus has been on hydrometeorological variables, it may be that anthropogenic changes in land-use complicate the predictability of debris flows by shifting the causation away from natural processes.

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APPENDIX A

Summary of rainfall (mm) for 18 debris flow associated storms

	S_{tot}	D_s	SDF_{tot}	$Dsdf$	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	A_1	A_2	A_3	A_4
Minimum	60.4	1.0	60.4	1.0	60.4	1.0	60.4	1.0	2.9	5.6	8.8	30.0
1st Quartile	104.3	2.0	104.1	2.0	101.1	2.0	101.1	2.0	17.7	47.6	72.9	92.0
Median	147.8	3.0	132.9	2.0	121.7	2.0	118.4	2.0	34.6	74.9	108.5	154.9
Mean	148.4	2.8	135.8	2.1	130.2	2.1	128.5	2.1	41.5	76.8	110.6	146.9
3rd Quartile	178.4	3.0	158.7	2.0	154.0	3.0	.:154.0	2.7	49.1	101.1	164.7	188.2
Maximum	316.6	6.0	228.4	5.0	217.4	4.0	217.4	4.0	120.4	157.9	211.2	264.7

Summary of rainfall (mm) for 203 non-debris flow associated storms

	S_{tot}	D_s	SDF_{tot}	$Dsdf$	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	A_1	A_2	A_3	A_4
Minimum	50	1.0	50.0	1.0	50.0	1.0	50.0	1.0	0.0	0.0	0.0	0.00
1st Quartile	67,2	1.0	67.2	1.0	59.6	1.0	59.0	1.0	17.6	39.5	68.5	93.8
Median	89.8	2.0	89.8	:2.0	80.0	2.0	80.0	2.0	32.6	75.5	112.9	163.0
Mean	88.4	2.0	98.2	2.0	87.8	2.0	87.4	2.0	44.3	87.9	129.3	165.7
3rd Quartile	118.5	3.0	117.6	3.0	103.6	2.0	103.6	2.0	58.4	119.6	180.8	214.4
Maximum	316.6	6.0	228.4	6.0	217.4	4.0	217.4	4.0	221.0	325.6	376.8	549.4

APPENDIX B

Storm Date	Start Date	Debris Flow Date	DF	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	ROS	MET
26/02/1980	25/02/1980	NA	0	109.2	3	109.2	3	85	2	85	2	45	60.4	86.2	178.6	1	1
16/06/1980	16/06/1980	NA	0	78.6	1	78.6	1	78.6	1	78.6	1	0.6	36.8	76.6	142.2	0	1
12/09/1980	12/09/1980	NA	0	76.2	2	76.2	2	76.2	2	76.2	2	0	88.9	211.7	221.3	0	2
12/10/1980	12/10/1980	NA	0	65.3	1	65.3	1	65.3	1	65.3	1	0	69.3	159.7	185.3	0	3
01/11/1980	01/11/1980	NA	0	50.3	1	50.3	1	50.3	1	50.3	1	0	0	0	0	1	3
20/11/1980	20/11/1980	NA	0	59.2	1	59.2	1	59.2	1	59.2	1	67.2	142.2	215.8	233.6	0	1
20/11/1980	20/11/1980	NA	0	77	2	77	2	52.8	1	52.8	1	47.4	124.4	196.6	205.4	0	2
20/11/1980	20/11/1980	NA	0	66	1	66	1	66	1	66	1	26.6	93.2	161.4	170	0	3
25/12/1980	25/12/1980	26/12/1980	1	101.6	1	101.6	1	101.6	1	101.6	1	75.6	129	175	218.8	0	1
25/12/1980	25/12/1980	NA	0	97	2	97	2	78	1	78	1	62.6	118.4	194.6	246.3	0	2
25/12/1980	25/12/1980	NA	0	87.2	2	87.2	2	87.2	2	87.2	2	50.8	84.4	149.7	194	0	3
10/01/1981	10/01/1981	NA	0	53.4	1	53.4	1	53.4	1	53.4	1	79.2	128.2	128.2	133.8	0	1
10/01/1981	10/01/1981	NA	0	57	1	57	1	57	1	57	1	42.6	93	93.2	98.7	0	2
06/05/1981	06/05/1981	NA	0	52	1	52	1	52	1	52	1	37.2	73.8	80.8	101.8	0	1
11/11/1981	11/11/1981	NA	0	70	1	70	1	70	1	70	1	10.6	94	150.4	152.4	0	1
23/01/1982	22/01/1982	NA	0	102.4	2	102.4	2	82.4	1	82.4	1	29.4	68	70.4	80	0	1
23/01/1982	23/01/1982	NA	0	62	1	62	1	62	1	62	1	20.8	55.4	67.2	72.2	1	2
12/02/1982	12/02/1982	NA	0	81.8	2	81.8	2	62.4	1	62.4	1	68.8	87.6	163.2	198.8	0	1
12/02/1982	12/02/1982	NA	0	54.6	1	54.6	1	54.6	1	54.6	1	29.9	50.3	86.5	126.1	0	2
13/02/1982	02/12/1982	NA	0	198.8	5	198.8	5	154.6	3	154.6	3	5.4	65.2	220.6	250	1	1
13/02/1982	02/12/1982	NA	0	171.4	5	171.4	5	123.4	3	123.4	3	0	71.8	178	192.4	1	2
09/01/1983	31/08/1983	NA	0	76.6	2	76.6	2	57.6	1	57.6	1	21.6	21.6	25.6	30	0	1
11/02/1983	11/02/1983	NA	0	80.2	2	80.2	2	80.2	2	80.2	2	43.4	103	115.4	115.4	0	2
01/07/1983	01/07/1983	NA	0	56.4	1	56.4	1	56.4	1	56.4	1	91.2	107	134.6	208.8	1	1
01/07/1983	01/07/1983	NA	0	65.4	1	65.4	1	65.4	1	65.4	1	86.7	96.5	135.8	192.2	1	2
01/09/1983	01/09/1983	NA	0	57.6	1	57.6	1	57.6	1	57.6	1	146.2	155.2	184.4	258.2	1	1
01/09/1983	01/09/1983	NA	0	95.6	2	95.6	2	95.6	2	95.6	2	161	162.5	189.5	256	1	2
07/11/1983	07/10/1983	12/07/1983	1	180	5	133	2	118	2	118	2	14.9	36	55.3	106	0	2
07/11/1983	07/10/1983	NA	0	188.4	5	188.4	5	150.4	3	150.4	3	2.2	25.2	62	120.6	0	1
14/11/1983	13/11/1983	NA	0	96.8	3	96.8	3	79.4	2	79.4	2	63.6	200.8	219.6	285.8	0	2

Storm Date	Start Date	Debris Flow Date	DF	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	*ROS*	*MET*
11/02/1984	11/02/1984	NA	0	77	2	77	2	54.2	1	54.2	1	60.8	99.4	112.2	183.3	0	2
01/03/1984	01/01/1984	04/01/1984	1	179.6	4	149.4	3	118.8	2	118.8	2	34.2	34.2	58.2	78.2	1	1
01/03/1984	01/03/1984	NA	0	149.6	2	149.6	2	149.6	2	149.6	2	59	60	75.4	105.2	1	2
09/05/1984	09/05/1984	NA	0	67.4	1	67.4	1	67.4	1	67.4	1	17.2	67.6	67.6	67.6	0	1
09/05/1984	09/05/1984	NA	0	73	1	73	1	73	1	73	1	17.5	69.9	74.9	76.1	0	2
10/08/1984	10/08/1984	NA	0	100.8	3	100.8	3	100.8	3	100.8	3	28.2	28.2	52.6	63.2	0	1
26/04/1985	26/04/1985	NA	0	54.6	1	54.6	1	54.6	1	54.6	1	39.2	64.6	106.7	192.3	0	1
26/04/1985	26/04/1985	NA	0	84.3	2	84.3	2	65	1	65	1	23.5	56.1	78.1	167.6	0	2
26/10/1985	26/10/1985	NA	0	95.4	2	95.4	2	95.4	2	95.4	2	69.6	162	186.4	195	0	1
26/10/1985	26/10/1985	NA	0	115	2	115	2	115	2	115	2	94.2	187.3	226.7	230.1	0	2
26/10/1985	26/10/1985	NA	0	109	2	109	2	109	2	109	2	68.1	165.7	194.4	199.2	0	3
17/01/1986	16/01/1986	NA	0	115.8	3	115.8	3	96.4	2	96.4	2	18.8	46.2	58.2	58.2	1	2
17/01/1986	16/01/1986	NA	0	100	3	100	3	84.2	2	84.2	2	29.7	65.2	73.7	73.7	1	3
23/02/1986	23/02/1986	NA	0	137.8	2	137.8	2	114	1	114	1	15.4	17.4	34.6	87.6	1	1
23/02/1986	23/02/1986	NA	0	105.8	2	105.8	2	105.8	2	105.8	2	8.1	8.5	14.5	52.7	1	3
24/02/1986	23/02/1986	NA	0	151.2	2	151.2	2	151.2	2	151.2	2	7.7	7.7	18.3	58.3	0	2
26/10/1986	25/10/1986	NA	0	103.4	2	103.4	2	87.8	1	87.8	1	13.6	13.6	14.8	48.2	0	1
26/10/1986	25/10/1986	NA	0	91.2	2	91.2	2	72.8	1	72.8	1	13.9	13.9	13.9	45.3	0	2
26/10/1986	25/10/1986	NA	0	114.2	2	114.2	2	91	1	91	1	11.6	11.6	11.8	35.8	0	3
19/11/1986	19/11/1986	NA	0	56.2	1	56.2	1	56.2	1	56.2	1	58.8	85.2	102.6	221	0	1
19/11/1986	19/11/1986	NA	0	68	1	68	1	68	1	68	1	73.6	106.9	124.1	231.2	0	2
19/11/1986	17/11/1986	NA	0	95.2	3	95.2	3	54.2	1	54.2	1	40.2	83.8	103.1	228.9	0	3
22/11/1986	21/11/1986	NA	0	100.6	3	100.6	3	85.2	2	85.2	2	103.4	122	156	281.2	0	1
23/11/1986	22/11/1986	NA	0	95.4	2	95.4	2	95.4	2	95.4	2	144.3	166.9	212	310.6	0	2
23/11/1986	22/11/1986	NA	0	101.6	2	101.6	2	101.6	2	101.6	2	134.2	154	197.6	331.1	0	3
05/12/1986	05/12/1986	NA	0	64.6	1	64.6	1	64.6	1	64.6	1	8.3	41.5	90.1	126.2	0	2
03/02/1987	03/01/1987	NA	0	98.7	3	98.7	3	58.8	1	58.8	1	3.2	33.6	57.6	70.2	1	1
29/05/1987	29/05/1987	NA	0	94.2	2	94.2	2	94.2	2	94.2	2	9	11.4	52	85.2	0	1
01/10/1987	01/10/1987	NA	0	87	2	87	2	87	2	87	2	18.6	105.8	156.2	171	1	3
01/11/1987	01/11/1987	NA	0	60.7	1	60.7	1	60.7	1	60.7	1	15	119.2	169	195.8	1	2
04/05/1988	04/05/1988	NA	0	56	1	56	1	56	1	56	1	73.8	159.6	184.4	209.8	0	1
04/05/1988	04/05/1988	NA	0	80.8	2	80.8	2	64.6	1	64.6	1	54.6	147.4	188	216.4	0	2
04/05/1988	04/05/1988	NA	0	84.2	2	84.2	2	60.2	1	60.2	1	51.1	133.4	153.8	182.4	0	3
13/10/1988	13/10/1988	NA	0	143.6	3	143.6	3	143.6	3	143.6	3	2.2	7	98	131	0	1

Storm Date	Start Date	Debris Flow Date	DF	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	*ROS*	*MET*
13/10/1988	13/10/1988	NA	0	144.2	3	144.2	3	144.2	3	144.2	3	2.6	4.3	90.6	123.4	0	2
07/12/1988	07/12/1988	NA	0	51.6	1	51.6	1	51.6	1	51.6	1	26.6	48.8	53.8	55.6	0	1
11/03/1989	11/03/1989	NA	0	57.6	1	57.6	1	57.6	1	57.6	1	11.6	87.2	116.8	170	0	2
12/03/1989	12/02/1989	NA	0	105.2	3	105.2	3	90	2	90	2	8.2	88.7	112.9	317.4	0	3
20/08/1989	20/08/1989	NA	0	72.2	2	72.2	2	55.4	1	55.4	1	37.8	37.8	69.4	70	0	1
11/09/1989	11/08/1989	10/11/1989	1	154.4	3	132.8	2	132.8	2	132.8	2	120.4	150.6	211.2	264.7	0	2
11/09/1989	11/08/1989	12/11/1989	1	174.9	3	174.9	3	153.9	2	153.9	2	88.8	109.8	155.6	204.2	0	3
11/09/1989	11/06/1989	NA	0	199.2	6	199.2	6	131.4	2	131.4	2	77.2	133.4	191.6	251.6	0	1
10/03/1990	10/03/1990	NA	0	91.6	2	91.6	2	91.6	2	91.6	2	24.4	25.2	68.4	68.4	0	1
10/03/1990	10/03/1990	NA	0	82	2	82	2	82	2	82	2	15.4	15.4	38.2	39	0	3
12/03/1990	12/03/1990	NA	0	52.5	1	52.5	1	52.5	1	52.5	1	57	220	328.4	549.4	0	2
10/04/1990	10/03/1990	NA	0	107.7	2	107.7	2	107.7	2	107.7	2	17.9	17.9	40.7	40.7	0	2
02/09/1990	02/09/1990	NA	0	114	2	114	2	114	2	114	2	40.2	91.6	179	194	1	1
11/09/1990	11/08/1990	11/11/1990	1	197	3	197	3	197	3	197	3	49.4	101.8	127.4	170	0	1
11/09/1990	11/08/1990	NA	0	174.8	3	174.8	3	174.8	3	174.8	3	46.5	145.3	173.5	205.6	0	3
02/10/1990	02/09/1990	NA	0	133.8	2	133.8	2	133.8	2	133.8	2	70.6	120.9	211.9	216.4	1	2
11/10/1990	11/08/1990	NA	0	196.2	3	196.2	3	196.2	3	196.2	3	53.4	161	187.8	233	0	2
22/11/1990	21/11/1990	NA	0	116	4	116	4	75	2	75	2	42	286	329.8	382.2	0	1
22/11/1990	21/11/1990	NA	0	148.8	4	148.8	4	127.2	3	127.2	3	38.6	325.6	374.8	478.8	0	2
23/11/1990	21/11/1990	NA	0	125.7	3	125.7	3	109.7	2	109.7	2	31.4	285.7	330.6	432.6	0	3
11/12/1990	11/12/1990	NA	0	73	1	73	1	73	1	73	1	221	299.6	358.2	401.8	0	2
11/12/1990	11/12/1990	NA	0	75.3	2	75.3	2	55.4	1	55.4	1	196.8	246.9	326.7	359.6	0	3
02/01/1991	31/01/1991	NA	0	68.2	2	68.2	2	51.4	1	51.4	1	3	7	90.1	97.3	1	3
04/03/1991	04/01/1991	NA	0	126	4	126	4	87.6	2	87.6	2	7.8	20.8	23.6	31.6	0	1
04/03/1991	04/02/1991	NA	0	107.2	3	107.2	3	72	1	72	1	14.2	26.4	31.6	68.6	0	2
04/03/1991	04/03/1991	NA	0	89.2	2	89.2	2	89.2	2	89.2	2	20.4	33.4	38.4	53.6	0	3
30/08/1991	30/08/1991	NA	0	60.8	1	60.8	1	60.8	1	60.8	1	80	80	135.8	156.4	0	1
22/01/1992	22/01/1992	NA	0	90.6	2	90.6	2	90.6	2	90.6	2	44.4	108.6	154	173	1	1
22/01/1992	22/01/1992	NA	0	83	2	83	2	83	2	83	2	39.8	95.6	132.5	139.4	1	2
22/01/1992	22/01/1992	NA	0	77.2	2	77.2	2	77.2	2	77.2	2	30.4	81.6	110.4	117.4	1	3
29/01/1992	27/01/1992	NA	0	144	4	144	4	79	2	79	2	116.4	135.8	191.4	230.8	1	2
28/04/1992	28/04/1992	NA	0	86.6	2	86.6	2	68.8	1	68.8	1	32.4	102.6	112.8	156	0	1
23/09/1992	23/09/1992	NA	0	53.2	1	53.2	1	53.2	1	53.2	1	6.8	13.4	59.8	60.6	0	1
23/09/1992	23/09/1992	NA	0	75	2	75	2	52.4	1	52.4	1	5.6	9.7	55.6	56.8	0	2

Storm Date	**Start Date**	**Debris Flow Date**	**DF**	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	***ROS***	***MET***
20/10/1992	20/10/1992	NA	0	56	1	56	1	56	1	56	1	21.2	43.2	50.2	136.2	0	2
24/01/1993	24/01/1993	NA	0	65.8	1	65.8	1	65.8	1	65.8	1	43.6	43.6	43.6	43.6	1	1
24/01/1993	24/01/1993	NA	0	80	1	80	1	80	1	80	1	25.6	25.6	25.6	25.6	1	2
24/01/1993	24/01/1993	NA	0	50	1	50	1	50	1	50	1	31.1	31.1	31.1	31.1	1	3
22/03/1993	22/03/1993	NA	0	61.4	1	61.4	1	61.4	1	61.4	1	41.1	83.5	124.1	124.1	0	2
22/03/1993	22/03/1993	NA	0	56	1	56	1	56	1	56	1	30.6	58.2	81.5	81.5	1	3
13/07/1993	13/07/1993	NA	0	51.8	1	51.8	1	51.8	1	51.8	1	9.4	11.8	57.6	61.8	0	1
12/09/1993	12/09/1993	NA	0	50.4	1	50.4	1	50.4	1	50.4	1	49.4	103.5	138.4	163	0	3
20/11/1993	20/11/1993	NA	0	53	1	53	1	53	1	53	1	72.8	75.5	92.9	114.5	0	2
28/02/1994	26/02/1994	NA	0	122.4	4	122.4	4	104.2	3	104.2	3	20.2	85.8	100.2	100.2	1	1
28/02/1994	27/02/1994	NA	0	140.8	5	140.8	5	77.8	2	77.8	2	31.2	87.3	116.7	116.7	1	2
29/11/1994	29/11/1994	NA	0	70.6	2	70.6	2	53	1	53	1	37.8	88.3	120.1	156	0	2
19/12/1994	15/12/1994	NA	0	167.4	6	167.4	6	64	1	64	1	41.6	54.2	152	182.1	0	2
19/12/1994	17/12/1994	NA	0	101.8	3	101.8	3	54.4	1	54.4	1	37	48	117	138.6	0	3
18/02/1995	18/02/1995	NA	0	67.2	1	67.2	1	67.2	1	67.2	1	43.8	54.6	180.2	181.2	1	1
18/02/1995	18/02/1995	NA	0	54	1	54	1	54	1	54	1	34.3	42.5	163.1	164.1	1	2
18/02/1995	18/02/1995	NA	0	55.2	1	55.2	1	55.2	1	55.2	1	36.8	43.4	129.4	135.2	1	3
11/07/1995	11/07/1995	NA	0	84.8	1	84.8	1	84.8	1	84.8	1	22.6	49.2	88.4	179.8	0	1
11/07/1995	11/07/1995	NA	0	98.8	1	98.8	1	98.8	1	98.8	1	34.8	65.8	97	201.2	0	2
11/07/1995	11/07/1995	NA	0	73	1	73	1	73	1	73	1	17.4	42.5	61.3	128.5	0	3
25/07/1995	25/07/1995	NA	0	60	1	60	1	60	1	60	1	1	1.4	23.4	27.8	0	1
25/07/1995	25/07/1995	NA	0	54.6	1	54.6	1	54.6	1	54.6	1	0.6	0.8	12.2	21.8	0	2
10/09/1995	10/09/1995	NA	0	99	3	99	3	56	1	56	1	56.6	98.9	100.3	100.3	0	2
13/11/1995	13/11/1995	NA	0	52.2	1	52.2	1	52.2	1	52.2	1	158.7	184.5	217.5	261.3	0	2
27/11/1995	27/11/1995	NA	0	80	2	80	2	80	2	80	2	69.2	155.8	310	325.2	0	1
28/11/1995	27/11/1995	NA	0	91.4	3	91.4	3	57.2	1	57.2	1	118.5	218.1	376.8	402.6	0	2
28/11/1995	27/11/1995	NA	0	105.8	3	105.8	3	105.8	3	105.8	3	84.6	153	293.9	306.7	0	3
12/12/1995	12/12/1995	NA	0	50	1	50	1	50	1	50	1	58	175.4	274.8	318.8	0	1
14/01/1996	13/01/1996	NA	0	91.4	2	91.4	2	91.4	2	91.4	2	62.2	120	167.8	207.2	1	1
27/11/1996	26/11/1996	NA	0	89	2	89	2	89	2	89	2	17.8	85.4	133.4	157.6	0	1
27/11/1996	26/11/1996	NA	0	67.2	2	67.2	2	52	1	52	1	11.6	43.7	97.5	115.5	0	2
18/01/1997	16/01/1997	NA	0	141	4	141	4	141	4	141	4	2.8	71.4	143.2	155.2	1	1
29/01/1997	29/01/1997	29/01/1997	1	60.4	1	60.4	1	60.4	1	60.4	1	16.4	157.9	168.4	237.5	1	3
29/01/1997	29/01/1997	NA	0	72.8	1	72.8	1	72.8	1	72.8	1	28.4	178.4	193	259.4	1	1

Storm Date	Start Date	Debris Flow Date	DF	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	*ROS*	*MET*
29/01/1997	29/01/1997	NA	0	55.4	1	55.4	1	55.4	1	55.4	1	25.7	138	148.1	218.5	1	2
18/03/1997	17/03/1997	19/03/1997	1	124.5	3	124.5	3	124.5	3	124.5	3	2.9	48.3	74.1	106.6	1	3
18/03/1997	17/03/1997	NA	0	143.8	3	143.8	3	143.8	3	143.8	3	19.2	85.6	131.4	168.6	1	1
19/03/1997	17/03/1997	20/03/1997	1	140.8	3	140.8	3	117	2	117	2	22.7	72	114	161.8	0	2
07/07/1997	07/07/1997	NA	0	81.1	2	81.1	2	81.1	2	81.1	2	42.6	75.2	128.6	130.4	0	1
07/08/1997	07/07/1997	NA	0	84.8	2	84.8	2	84.8	2	84.8	2	27.4	69.9	145.9	150.5	0	2
16/12/1997	15/12/1997	NA	0	97.8	3	97.8	3	56.6	1	56.6	1	8.4	9.2	95.7	144.7	0	2
20/11/1998	20/11/1998	NA	0	50.6	1	50.6	1	50.6	1	50.6	1	100.8	216	239.3	247.3	0	2
24/11/1998	24/11/1998	NA	0	78.8	2	78.8	2	78.8	2	78.8	2	97.2	288.3	309.7	327.4	0	2
11/12/1998	11/12/1998	NA	0	140.2	4	140.2	4	121.6	3	121.6	3	33.6	69.8	84.8	96.4	0	1
11/12/1998	11/12/1998	NA	0	181.3	4	181.3	4	98.6	1	98.6	1	21.8	40.3	47.9	68.9	0	2
11/12/1998	11/12/1998	NA	0	136.4	4	136.4	4	55	1	55	1	11.4	28.6	40.6	54.6	0	3
13/01/1999	13/01/1999	NA	0	54.6	1	54.6	1	54.6	1	54.6	1	74	78.6	211.4	222.4	1	1
30/10/1999	28/10/1999	NA	0	127.2	3	127.2	3	112.2	2	112.2	2	23.8	23.8	69.2	87	0	1
30/10/1999	28/10/1999	NA	0	106.9	3	106.9	3	90.3	2	90.3	2	32	32	102.2	117	0	2
30/10/1999	28/10/1999	NA	0	125.5	3	125.5	3	107.1	2	107.1	2	24.6	24.6	86.5	95.3	0	3
11/11/1999	11/11/1999	NA	0	57.2	1	57.2	1	57.2	1	57.2	1	100.8	233	256.8	256.8	0	1
11/11/1999	11/11/1999	NA	0	64.6	1	64.6	1	64.6	1	64.6	1	79.1	193	225	225	0	2
11/11/1999	11/11/1999	NA	0	70	1	70	1	70	1	70	1	75.2	210	234.6	234.6	0	3
12/12/2001	12/12/2001	NA	0	81	2	81	2	81	2	81	2	54.8	115.5	144.1	207.1	0	2
13/12/2001	12/12/2001	NA	0	106.4	2	106.4	2	106.4	2	106.4	2	43.6	99.6	132.2	204.6	0	1
21/02/2002	20/02/2002	NA	0	129.2	3	129.2	3	111.2	2	111.2	2	18.8	45.4	74.4	103.8	1	1
21/02/2002	21/02/2002	NA	0	128.6	2	128.6	2	128.6	2	128.6	2	29.4	50.7	80.4	126.2	1	2
21/02/2002	20/02/2002	NA	0	118.1	3	118.1	3	101.1	2	101.1	2	19.7	31.9	47.9	92.4	1	3
01/06/2002	01/06/2002	NA	0	102	3	102	3	80.8	2	80.8	2	28.8	35.6	53.4	203.4	1	1
01/07/2002	01/06/2002	07/01/2002	1	141.5	3	111.7	2	141.5	3	111.7	2	10.8	11.5	34.1	154.9	1	2
01/07/2002	01/06/2002	NA	0	100.2	3	100.2	3	80.2	2	80.2	2	10.7	15.8	46.2	126.2	1	3
18/11/2002	18/11/2002	NA	0	89.8	2	89.8	2	89.8	2	89.8	2	43.4	122.8	123.2	125.8	0	1
30/03/2003	30/03/2003	NA	0	52.8	1	52.8	1	52.8	1	52.8	1	29.1	78.7	189.1	207.1	1	2
16/10/2003	15/10/2003	NA	0	188.1	3	188.1	3	170.6	2	170.6	2	60.4	78.4	78.4	107.6	0	2
16/10/2003	15/10/2003	NA	0	126.7	3	126.7	3	103	2	103	2	46.6	66.2	66.2	74.6	0	3
17/10/2003	15/10/2003	17/10/2003	1	316.6	6	217.4	3	217.4	3	217.4	3	48.2	72.6	72.6	87.4	0	1
20/10/2003	19/10/2003	NA	0	106	2	106	2	84.4	1	84.4	1	219.7	274.7	275.1	275.1	0	2
20/10/2003	19/10/2003	NA	0	151.6	3	151.6	3	151.6	3	151.6	3	153.7	203.1	203.1	203.1	0	3

Storm Date	Start Date	Debris Flow Date	DF	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	*ROS*	*MET*
18/11/2003	17/11/2003	NA	0	113.6	2	113.6	2	113.6	2	113.6	2	53.6	53.6	73.8	170.2	0	1
18/11/2003	16/11/2003	NA	0	146.6	3	146.6	3	122.4	2	122.4	2	28.2	28.2	46.8	179.2	0	2
18/11/2003	16/11/2003	NA	0	138.1	3	138.1	3	119.1	2	119.1	2	22.7	22.7	39.5	203.1	0	3
28/11/2003	27/11/2003	NA	0	81	2	81	2	56.6	1	56.6	1	41.2	185	212.4	212.4	0	1
11/01/2004	11/01/2004	NA	0	60	1	60	1	60	1	60	1	24	77.4	106.8	198.1	0	1
11/01/2004	11/01/2004	NA	0	77	1	77	1	77	1	77	1	20.2	82.2	104.4	173	0	2
11/01/2004	11/01/2004	NA	0	51	1	51	1	51	1	51	1	22	50	68.6	122.5	0	3
29/01/2004	29/01/2004	29/01/2004	1	66.6	1	66.6	1	66.6	1	66.6	1	82.4	99	167.8	184.4	1	1
10/08/2004	10/08/2004	NA	0	50.7	1	50.7	1	50.7	1	50.7	1	32.6	34	63.8	189.2	0	1
12/10/2004	12/09/2004	NA	0	80	2	80	2	80	2	80	2	65	82.6	196.2	251.2	0	2
24/11/2004	23/11/2004	NA	0	99.6	2	99.6	2	99.6	2	99.6	2	34	66.6	112.4	196.4	0	1
24/11/2004	23/11/2004	NA	0	87.2	2	87.2	2	64	1	64	1	43.8	81.8	123.8	221	0	2
24/11/2004	23/11/2004	NA	0	80.5	2	80.5	2	59.7	1	59.7	1	35.1	66.6	103.3	176.3	0	3
17/01/2005	16/01/2005	NA	0	220.8	5	220.8	5	202.8	4	202.8	4	6	6	24.2	61	1	1
18/01/2005	17/01/2005	NA	1	160.2	3	160.2	3	160.2	3	160.2	3	5.6	5.6	8.8	30	1	2
29/09/2005	28/09/2005	NA	0	85.2	2	85.2	2	85.2	2	85.2	2	0	10.6	21.2	25.6	0	1
29/09/2005	28/09/2005	NA	0	96.2	2	96.2	2	96.2	2	96.2	2	0	15.8	27.8	40.4	0	2
16/10/2005	16/10/2005	17/10/2005	1	78.2	2	78.2	2	78.2	2	78.2	2	42	95.7	186.5	189.5	0	1
29/01/2006	29/01/2006	NA	0	55.2	1	55.2	1	55.2	1	55.2	1	68.6	145.8	339.2	422.9	1	1
29/01/2006	29/01/2006	NA	0	59	1	59	1	59	1	59	1	38	92	246.4	352	1	2
11/03/2006	11/03/2006	NA	0	177.6	5	177.6	5	157.3	4	157.3	4	17.8	33.4	62.8	65.8	0	3
11/05/2006	11/02/2006	NA	0	193	5	193	5	141.8	3	141.8	3	20.4	44	84	86.4	0	1
11/05/2006	11/03/2006	NA	0	177.6	5	177.6	5	157.3	4	157.3	4	17.8	33.4	62.8	65.8	0	3
11/06/2006	11/02/2006	06/11/2006	1	228.4	5	228.4	5	210.8	4	210.8	4	33.2	56.8	85.2	86.8	0	2
01/09/2006	01/07/2006	NA	0	120	4	120	4	85.4	2	85.4	2	77.7	175.1	240.5	244.9	1	1
01/12/2006	01/12/2006	NA	0	77.6	2	77.6	2	77.6	2	77.6	2	167.6	229.3	345.5	371.5	1	1
01/01/2007	01/01/2007	NA	0	118.8	2	118.8	2	118.8	2	118.8	2	8.8	74.8	158.2	183.8	1	1
01/01/2007	01/01/2007	NA	0	86	2	86	2	86	2	86	2	5.2	76.8	181.4	201.8	1	2
01/01/2007	01/01/2007	NA	0	76.4	2	76.4	2	76.4	2	76.4	2	13.2	79.1	174.3	199.1	1	3
12/02/2007	12/02/2007	NA	0	93.2	3	93.2	3	75.2	2	75.2	2	0	2.6	58.8	98	0	1
23/03/2007	22/03/2007	NA	0	117.2	3	117.2	3	99.4	2	99.4	2	81.6	167.2	199.9	221.9	1	1
23/03/2007	23/03/2007	NA	0	90.8	2	90.8	2	90.8	2	90.8	2	91.4	235	271.2	281.8	1	2
27/04/2007	27/04/2007	NA	0	59	1	59	1	59	1	59	1	31.4	58.6	83.8	91.2	0	2
03/11/2007	03/10/2007	12/03/2007	1	112.4	2	112.4	2	89.2	1	89.2	1	35	47.4	117.6	155	1	2

Storm Date	Start Date	Debris Flow Date	DF	S_{tot}	D_s	DS_{tot}	D_{sdf}	IR_{tot}	D_{ir}	$IRDF_{tot}$	D_{irdf}	Ant_1	Ant_2	Ant_3	Ant_4	ROS	MET
03/11/2007	03/11/2007	NA	0	85.6	1	85.6	1	85.6	1	85.6	1	24.9	44.9	99.5	150.1	1	1
01/07/2009	01/06/2009	07/01/2009	1	154	2	154	2	154	2	154	2	42.7	77.2	77.2	85.1	1	2
01/07/2009	01/06/2009	07/01/2009	1	100.9	2	100.9	2	100.9	2	100.9	2	21.9	78.3	103.1	123.7	1	3

APPENDIX C

Authors	Date	Topic	Data	Method	Results
Elsner, M., Cuo, L., Voisin, N., Deems, J., Hamlet, A., Vano, J., Mickelson, K., Lee, S., Lettenmaier, D.	2010	Hydrology climate change in Washington	IPCC AR4 A1B and B1 scenario	Variable Infiltration Capacity (VIC), Distributed Hydrology Soil and Vegetation Model	• Winter precipitation will increase, summer precipitation decrease in future • Reductions in snow pack • Soil water equivalent (SWE) will decrease • Enhanced soil dryness
Jakob, M., Lambert, S.	2009	Climate change effects on BC landslides	CGCMI, CGCMII observational data from local rain gauges; IPCC AR4 B1, A1B, A2	Xie-Arkin analysis, frequency distributions, PDFs, power law curves	• 10% increase in antecedent precipitation 2071-2100 compared to 1960-1990 • Short-term precipitation intensity predicted to increase 6% by 2100 • PDO and ENSO stochasticity can complicate predictions
Jakob, M., McKendry, I., Lee, R.	2003	Rainfall intensity in Vancouver	Meteorological Survey of Canada, GVRD stations	Linear regression	• Small increase in short duration spring precipitation 1993-2003 • Significant increase in short term precipitation in 1990s compared to pre-1977 • PDO warm phase may be associated with high intensity precipitation
Mailhout, A., Kingumbi, A., Talbot, G., Poulin, A.	2010	Intensity and season pattern of precipitation in Canada	CGCM3; IPCC AR4 B1, A1B, A2	Model simulations, models compared to observational data	• Greater intensity and frequency of daily and multi-day precipitation (except Prairies) • Annual maximums events predicted to remain unchanged in S. BC (SON), and N. BC decrease in occurrence of summer annual maximum (shift spring/fall) • Reduced return periods with annual maximum events, possible ½ by end of 21st century especially W. coast
Mote, P., Salathé Jr., E.	2010	Future climate in the PNW	IPCC climate models and AR4 B1, A1B, A2 scenarios	Statistical downscaling, multimodel ensembles	• Warming trend throughout the 20th century • 21st century temperature increase between 1.1°C and 3°C compared to 1970-1999 average • 21st century precipitation increase 1-2% annually, however likely a shift to drier spring/summer and wetter winter/fall

Authors	Date	Topic	Data	Method	Results
Murdock, T., Bennett, K., Werner, A.	2007	GVRD historical rainfall analysis	GVRD rainfall data, 7 GCMs	Exceedance per hour thresholds, Sen's method linear model, trend analysis	• Precipitation increase by 1%-5% by mid-21st century • Winter precipitation increase 4%-14%, summer decrease 14%-33% • Warming increase 2.1°C to 2.6°C by mid-21st century • Increase of intensity and threshold exceedence corresponding with winter and spring frontal systems and positive PDO phases
Salathé, E., Leung, R., Qian, Y., Zhang, Y.	2010	Regional climate model projections for Washington	Weather Research and Forecasting model (NCAR), NCAR CCSM3, ECHAM5	Model simulations, model comparison	• Disagreement of predicted winter precipitation over W. Washington between models (CCSM3 decrease) • Temperature warming is amplified by the loss of precipitation, snow, and cloud over the Cascade Range • Small but positive change in precipitation intensity over Washington but pronounced to the north
Salathé, E., Steed, R., Mass, C., Zahn, P.	2008	PNW climate, mesoscale feedback responses to climate change	ECHMA5/MPI-OM, IPCC AR4 A2	Model simulation, model comparison	• Local response to temperature and precipitation in the PNW are influenced by small scale processes • Regional model shows more warming than global model throughout the Cascade Range • Global models show increased autumn precipitation which may be amplified over local terrain
Zhang, X., Wang, J., Zweirs, F., Groisman, P.	2010	Large-scale climate variability on winter maximum precipitation over N.America	18 000 MET stations in Canada, US, Mexico	Composite analysis for each station, extreme value modelling	• PDO and ENSO have significant influence on the scale and distribution of N.American winter daily maximum precipitation • NAO affects the East Coast • ENSO greatly influences S. US, PDO dominates over the Ohio River Valley and northwards