An Investigation into the 2003 Van Trump Creek Debris Flow, Mt Rainier, Washington, United States of America.

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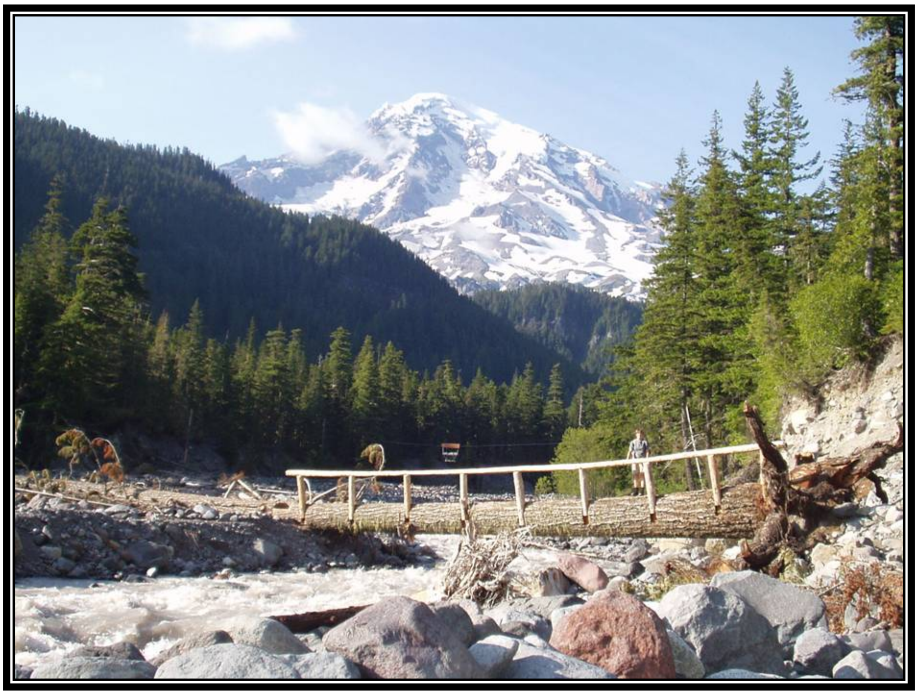

Abstract.

Debris flows are the primary geological hazard from Mt Rainier. Debris flows are mixtures of rock, mud and water that have a high sediment content and move down slope under gravity. These torrents of mud, rock and water pose a considerable risk to the Mount Rainier National Park visitors, employees, and infrastructure. The following study primarily investigates the October 20th -21st 2003 Van Trump Creek debris flow. The 2003 Van Trump Creek debris flow is an archetypal low magnitude, high frequency debris flow. An understanding of this hazard leads to the development of an effective remedial scheme, thereby reducing the risk posed to the local vulnerabilities.

A combination of fieldwork recordings, observations and remote sensing techniques has been used to produce hazard and risk maps for the study area.

The 2003 Van Trump Creek debris flow was triggered by a small rock fall at approximately 3218m, 200m below Camp Hazard. A debris flow only requires a water content of 30 % to flow down hill, and so coupled with an above average precipitation at that time, the rock fall material quickly transformed in to a debris flow. The mass of rock, mud and water increased in volume due to a bulking process (an increase in volume by incorporating sediment from channel banks). Although the 2003 Van Trump Creek debris flow did not travel outside the National Park boundaries, previous large magnitude flow events have reached as far as the Puget Sound, approximately 70 km north west of Mt Rainier.

Avoidance strategies, warning systems, and engineering methods are necessary mitigation schemes that are emplaced at Mt Rainier to reduce the risk posed by low frequency large magnitude flows

The 2003 Van Trump Creek debris flow is not unique to this region and due to the frequency of these low magnitude events, this report recommends the further introduction of some simple educational mitigation schemes, such as instructual warning signs at Van Trump Creek trailhead and at Christine Falls. This report illustrates the importance of educating the local population and tourists about the dangers, the warning signals and what to do in the event of low magnitude debris flows.

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This investigation was only possible with the support and guidance offered by many people.

Firstly I must thank Christopher Crowley for his support on site at Mt Rainier. Secondly to Dr Kevin Scott (Hydrologist, USGS) who supervised my work in America, and who provided opportunities that otherwise would not have been available.

I would like to thank Carolyn Driedger (Outreach Coordinator, USGS) and Anne Doherty (Education Program Manager, NPS) who kindly invited me to take part in the "Living with a volcano in your backyard" teacher training course, which greatly improved my knowledge of educational mitigation.

I must also thank Jim Vallance (Hydrologist, USGS) for inviting me on one of his informative field trips.

I would also like to express my thanks to all the National Park Service (NPS) staff for their enthusiastic support, in particular Barbara Samora (Mt Rainier National Park Resources Manager, NPS) and Paul Kennard (Mt Rainier National Park Regional Geomorphologist, NPS).

Thank you to Paul for guiding me to the Van Trump Glaciers in order to locate the debris flow initiation point.

Finally I would like to thank the staff of the Earth and Environmental Science department at the University of Portsmouth, especially Dr Carmen Solana and Malcolm Whitworth.

Methodology and Objectives.

The objective of this report is to investigate a debris flow that occurred at Mt Rainier on October 20th 2003, which flowed down the Van Trump Creek, located on the south side of the volcano. The report aims to examine the consequences of the debris flow, and evaluate the related hazards, risks and the mitigation strategies emplaced at Mt Rainier. In addition, a hazard remediation scheme is recommended for the Van Trump Creek region.

The fieldwork for this investigation consisted of mapping the route of the debris flow; collecting an array of data on the debris flow using an assortment methods, including the Walman Pebble Count Technique; height and width measurements of the debris fan; cross sections of the flow route; the discharge; the velocities of the debris flow; the behaviour and overall volume of material; analysis of aerial photography and recording observations over the entire study area.

Logistics.

Prior to undertaking this investigation many months of research was carried out in preparation for choosing a suitable study area. During this process I contacted Dr Kevin Scott who assisted me in identifying a suitable study area. The Kautz Creek was originally identified as a potential study area, yet due to the dense forest, large area and lack of trails this proposal was discarded. The 2003 Van Trump Creek debris flow had not been investigated by either USGS or NPS personnel therefore presenting an ideal study opportunity.

A Scientific Research Permit was required and this was acquired prior to the fieldwork. This permit allowed access to the National Park and beyond the designated trails.

The fieldwork was carried out during July 2004, over four weeks. One of those weeks was spent at the White River (north east flank of Mt Rainier) evaluating the Little Tahoma Peak debris avalanche deposits. Dr Kevin Scott provided transport, yet all of the fieldwork was carried out on foot. The trail that followed the Van Trump Creek was well maintained and access to the debris fan was unproblematic.

Health and safety issues included dehydration, sunstroke, debris flows, trip and fall hazards due to loose debris, falling rocks and macro fauna e.g. bears and cougars.

1: Introduction.

1.1: Location.

Mt Rainier is located within the State of Washington in the northwestern United States of America. Situated within the Cascade Range, Mt Rainier is one of 27 volcanoes stretching from Canada to Lassen Peak in California (Figure 1a). Mt Rainier is approximately 70 km south east of Seattle. Mt Rainier is the dominant feature of the Mt Rainier National Park (figure 1b). At 4393m the volcano is the highest in the conterminous United States (Walder and Driedger 1994) and is covered by 88 km^2 of ice and snow (Driedger 1993). Although it is not the most recently active volcano in the Cascade Range it is considered the most dangerous (Scott, Vallance and Pringle 1995). The study area is the Van Trump Creek located on the south side of the volcano from the Van Trump Glaciers to the Nisqually River Valley.

Figure1a: Location of Mt Rainier, USA (modified from Topkina 2001)

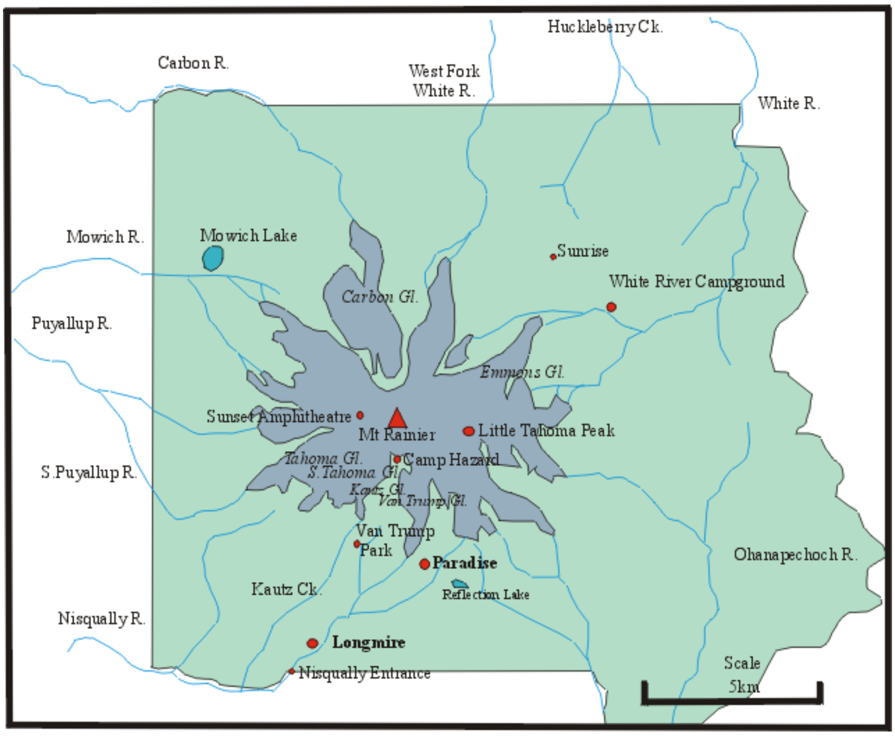


Figure 1b: Map of Mt Rainier National Park (modified from Topinka 1997).

1.2: Geological and Tectonic Setting.

The Ring of Fire is a volcanic zone that encircles the Pacific Ocean. It marks a point of contact between the earth's shifting tectonic plates (Harris 1980). The Cascades in northwest America are a product of the subduction of the Juan De Fuca Plate underneath the North American Plate. As the Juan de Fuca plate descends, it melts. This molten rock then ascends through fissures in the rock above and exits at the surface to form volcanoes (Figure 2). These volcanoes make up the 1126 km long Cascade Range volcanic chain and Mt Rainier stands proud among them.

Mt Rainier is a stratovolcano: it's steep flanks are composed of alternating layers of lava and volcanic rubble: each layer represents an eruptive episode in the life of the volcano.

The volcano sits upon Tertiary volcanic rocks, an intrusion of Granodiorite and Quartz Monzonite that is approximately 17.5-14.1 million years old called Tatoosh Platon (Wood and Kienle 1990). The Tatoosh Range circles the volcano and the white Granodiorite are easily distinguishable from the dark volcanic Andesite produced by Mt Rainier. A geological map of Washington is provided in Appendix 1.

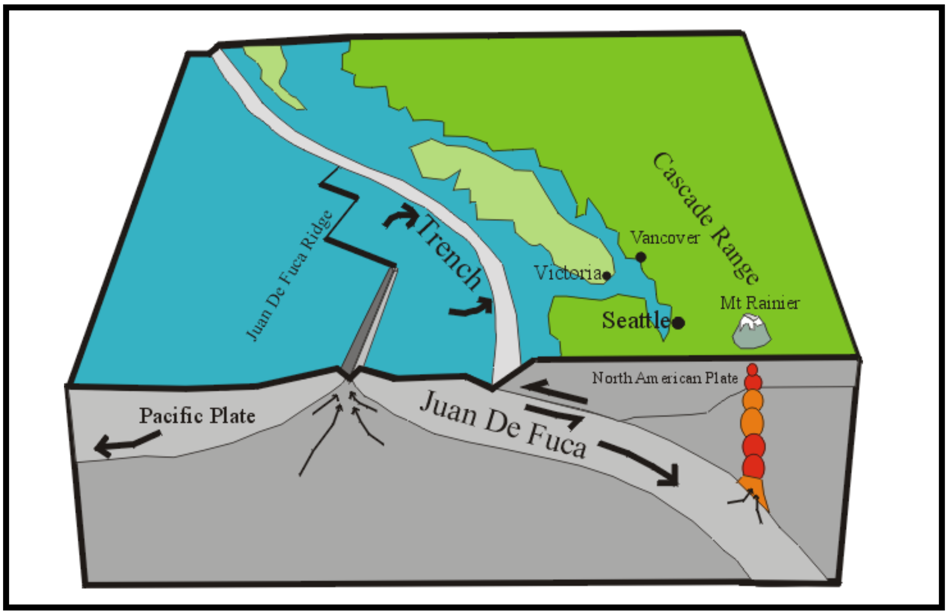


Figure 2: Tectonic setting of Mt Rainier (modified from the geological survey of Canada n.d).

1.3: Eruptive History.

Age/Date	Event	Comment
1894	Small emission of ash.	Produced small lahars.
1820-1850	Minor eruptions of tephra.	Produced small non-cohesive lahars.
600-500BP	White River Eruptive Period.	Eruption may have triggered avalanche of hydrothermally altered rock (Electron mudflow).
1000BP	Deadman Flat Eruptive Period.	Evidence for two pyroclastic flows and ash fall. Large lahars were produced reaching the southern suburbs of Seattle.
2700-1700BP	Summerland Eruptive period.	Highly active; tephra and avalanche induced lahars (Round Pass Mudflow).
2200BP	Eruption: Layer C.	Large eruption produced ash Layer C and National Lahar ($1.5x10^8m^3$) that reached the Puget Sound.
5600-4500BP	Osceola Eruptive Period.	Phreatic and Phreatomagmatic eruption lead to a sector collapse producing both Osceola Mudflow (3.8 km^3) (travelled to Tacoma and south Seattle) and Paradise Lahar.
9600-12000BP	Sunrise Eruptive Period.	Two possible eruptions producing tephra and at least one avalanche induced hydrothermally altered rock lahar.

*BP- Before Present

Table 1: Eruptive history of Mt Rainier (Vallance 2001).

2: Debris flows.

Debris flows are a mixture of rock, mud and water that have a high sediment content and move down slope under gravity (Vallance, Cunico and Schilling 2003).

In this report the terminology of ‘Lahar’ refers to debris flow that is of a large magnitude and in response to volcanic activity, while ‘debris flow’ refers to a low magnitude flow of rock that can occur without volcanic activity (Scott et al 1995).

Debris flows that are low magnitude, high frequency events continue to plague Mt Rainier’s flanks. These mobilised rivers of mud, rock and water increase in volume as they travel along creeks and rivers, bulking material (an increase in volume by incorporating sediment (Scott et al 1995)) from the channel banks. They require a water content of 30% to mobilize although they generally begin as a hyperconcentrated flow or flood (Table 2). They can be initiated by water flowing over loose volcanic or glacial material, a rock avalanche, or glacial outburst. The debris flows rip and pluck boulders, trees and structures, carrying them in a rolling torrent downstream, depositing the load when the gradient shallows and flood plain opens out. Debris flows can travel at speeds of 13m/s (30 mph) and destroy everything in their path either by impact or burial.

There are two types of debris flow: non-cohesive and cohesive. They are classified by their clay content. A non-cohesive flow contains less than 3 – 5 % clay size sediment, while a cohesive flow contains more than 3 - 5 % clay size particles. The clay content means that the two debris flows behave differently in motion. Cohesive debris flows originate from large sector failures and can travel long distances. At Mt Rainier these cohesive debris flows have inundated the Puget Sound low land that is now heavily populated. The non-cohesive debris flows are textually more defined and can travel distances of up to 50 –70 kilometres. The non-cohesive debris flow retains sufficient strength to preserve diagnostic characteristics: convex flow fronts, lateral levees, buoyed dense megaclasts and a highly dispersed clast size (Scott et al 1995). These characteristics will be described in more detail within the case study.

Debris flows can be very destructive, and many factors present at Mt Rainier such as hydrothermally altered weak rock, moraine covered steep slopes, glacial retreat, and high precipitation the debris flow hazard is continuous. Debris flows are smaller and more frequent than lahars from Mt Rainier and are the primary geological hazard within the park (Riedel 1997). On average four are recorded each year (Scott et al 1995). Debris flows pose a risk to employees, tourists and park infrastructure. The 2003 Van Trump Creek debris flow is a prime example of this type of debris flow hazard.

Flow Stage/Type	**Water Content (%)**
Flood	>80%
Hyperconcentrated flow	80-40%
Debris flow	<30%

Table 2: Classification of flows by water content (%) (Scott et al 1995).

3: Other Geological Hazards From Mt Rainier.

The volcanic hazards from Mt Rainier have the potential to cause great harm to the local population and infrastructure, both during future eruptions and intervening periods of repose (Hoblitt et al 1998). A volcano's history can provide a guide to its future behaviour. Past events at Mt Rainier have been catastrophic. If the Osceola Mudflow occurred today many hundreds of people could be killed.

3.1: *Lahars.*

Mt Rainier intercepts precipitation from the Pacific Ocean resulting in high levels of snowfall and rainfall. The perennial snow has produced a cover of approximately 88km^2 of ice and snow and 27 glaciers (Driedger1993). The ice has eroded and shaped Mt Rainier for thousands of years, yet the façade of the volcano has been dramatically morphed by past cataclysmic geological events.

An enormous debris avalanche at Mt Rainier transformed into a large mudflow some 6000 years ago. The Greenwater Mudflow as described by Crandell (1971) cited by Harris (1980) is the earliest identified lahar and transported boulders 9m in diameter and exposed hydrothermally altered rock.

Approximately 4500-5000 radian carbon years ago the largest lahar ever known occurred at Mt Rainier. The weak hydrothermally altered rock at the summit gave way and a massive sector collapse took place. A mass of volcanic rock and debris transformed in to an immense lahar known as the Osceola Mudflow. This event was so large that if it occurred today the flow would envelope at least four settlements and threaten the suburbs of Tacoma and Seattle (Figure 3). A massive volume of 3km^3 of debris spread over a 200km^2 of the Puget Sound lowland. Mt Rainier's summit was lowered and a 3km caldera was produced (Harris 1980).

The same sector collapse is thought to have triggered a second lahar. This lahar initiated above the Nisqually Glacier and travelled over Paradise Park (Scott et al 1995). The Paradise Lahar wave height maximum was 240m at Risksecker point and 70m at Longmire and travelled as far as Ashford 16km distant of the volcano (Scott et al 1995).

The second largest lahar from Mt Rainier, the Electron Lahar initiated from a sector collapse, creating Sunset Amphitheatre. The run out of the lahar is shown in

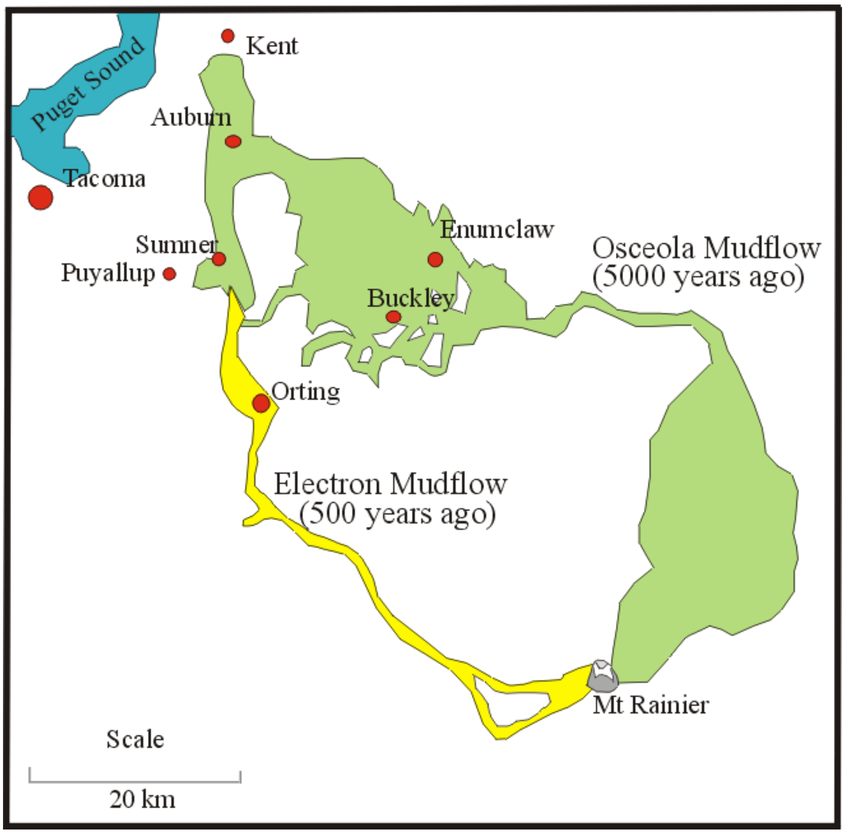


Figure 3: Extent of the Osceola and Electron Mudflows, and the locations of present day settlements (modified from Topinka 1992).

Figure 3. Table 3 illustrates that these lahars are not unique events. Mt Rainier has produced more than 60 during the past 10 000 years (Hoblitt et al 1998).

3.2: *Debris Avalanches*.

Debris avalanches are common at Mt Rainier. Trigger mechanisms include the failure of weakened, over steep hydrothermally altered rock; an intrusion of magma displacing the ground surface; failure of water saturated rock; or the failure of over-steep rock faces by the erosion of glaciers. Debris avalanches can travel at high velocity and their deposits can block channels, causing secondary hazards such as outburst from impounded lakes. A recent major debris avalanche was the 1963 Little Tahoma debris avalanche that initiated above the Emmons Glacier at Little Tahoma Peak (Figures 4 and 5). In the 1960s, increased thermal activity climaxed on the 14th December 1963 when 12.8 million m^3 of hydrothermally altered rock descended from Little Tahoma Peak above the Emmons Glacier.

Age/Date	Name/Location	Comments	Cohesive or Non-Cohesive
1963	Little Tahoma Peak Avalanche.	Avalanche of hydrothermally altered rock, transformed in to debris flow.	Cohesive.
1947	Kautz Creek glacial outburst flood.	Destruction within park boundaries and local to creek.	Cohesive.
1910-1927	Avalanche on Tahoma Glacier.	Produced a small debris flow.	Cohesive.
1500AD	Tahoma Lahar.	To Elbe.	Non cohesive.
530-550 BP	Electron Mudflow.	To Puget Sound.	Cohesive.
1050-1000	1000 year old lahar.	Possibly reached to Puget Sound lowlands.	Cohesive.
1080-1400BP	Cowlitz River.	Three lahars one reaching Packwood.	Non cohesive.
1400BP	Nisqually River.	Lahar reached Elbe.	Non cohesive.
2200-1480BP	Nisqually River.	Three lahars reach Elbe, National and Ashford.	Non cohesive.
2200BP	National Lahar.	Reaches Puget Sound.	Non cohesive.
2900-1480BP	White River.	Six lahars, five reached Puget Sound.	Non cohesive.
Pre-3900BP	Nisqually River.	Large lahar possibly reaching Puget Sound.	Non cohesive.
Pre-3900BP	Cowlitz River.	Three lahars reach park boundary.	Non cohesive.
4500-5000BP	Paradise Lahar.	Paradise River to National.	Cohesive.
Pre-5020BP	White River.	Two lahar run outs possibly reached Puget Sound.	Non cohesive.
No date	Greenwater Lahar.	Main fork White River to Puget Sound lowland.	Cohesive.

Table 3: Lahar events from Mt Rainier (modified from Scott et al 1995).

The debris avalanche reached speeds of 160 km/hr and terminated only 0.5 km from the White River Campground (Crandell and Tahnestock 1965). Figure 6 shows one of the large boulders brought down by this event. This boulder is friable due to its weakened material composition and is morphing in to a hummock. The Osceola Lahar produced similar hummocks (Scott et al 2001) this relationship provides evidence that the Little Tahoma Peak avalanche is a very small version of the sector collapse that occurred 5000 years before and emphasises the fact that Mt Rainier has the potential to repeat its past.

3.3: *Volcanic Gases.*

Volcanic gases from andesitic volcanoes consist of water vapour, carbon dioxide and sulphur compounds. In addition, small quantities of carbon monoxide, chlorine, fluorine, boron compounds and ammonia can be present. The most immediate hazard caused by volcanic gases at Mt Rainier is hydrothermal alteration of the edifice rock. Over a long period of time the hot, acidic water vapour perculates through the volcanic rocks, chemically changing the strong rock into weaker clay and

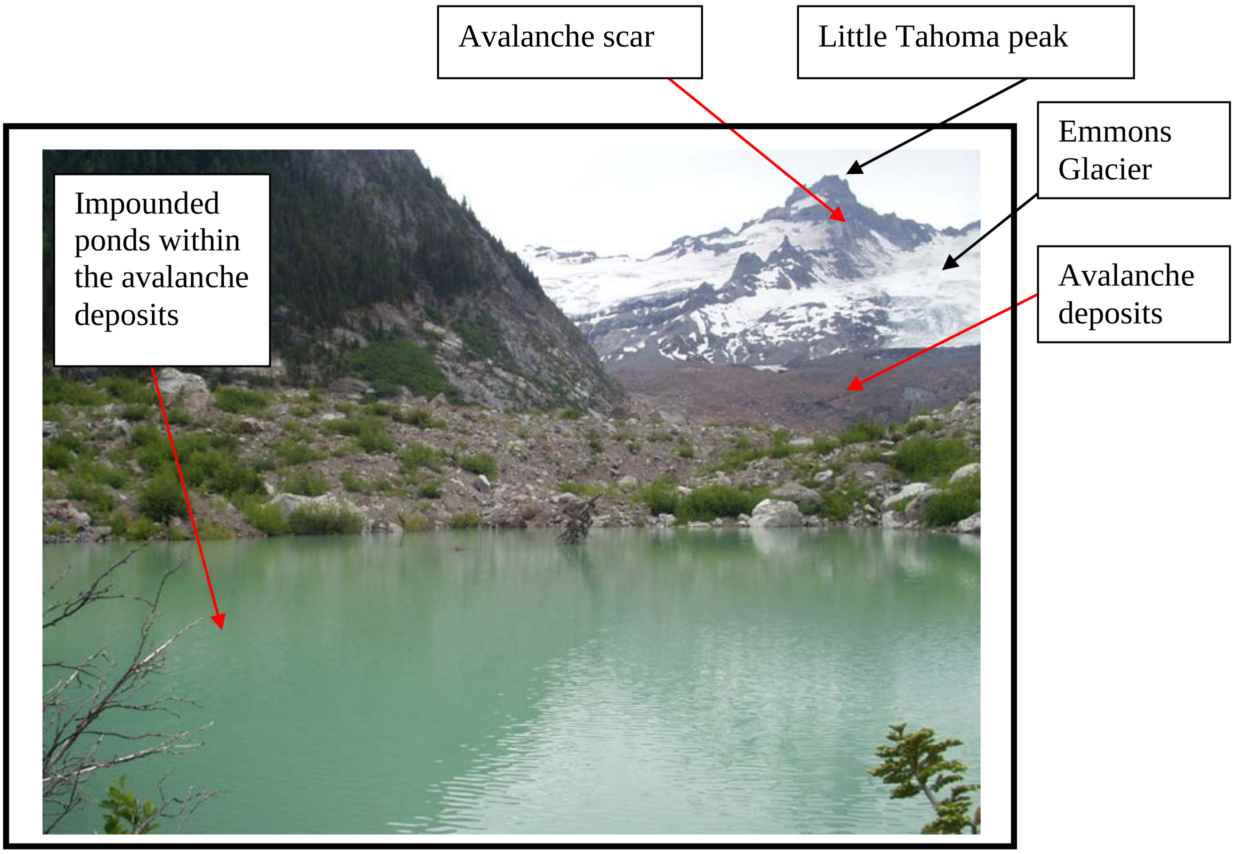


Figure 4: Little Tahoma Peak.

other minerals. The stability of this weakened material is greatly reduced and the potential for rock slope failure increases dramatically.

3.4: *Tephra.*

Tephra particles produced during explosive eruptions can be carried downwind many kilometres and can cover large areas of land. Tephra particles can block out sunlight, restricting visibility and crop growth leading to secondary hazards such as famine. If the particles are inhaled long term respiratory problems can occur. An accumulation of tephra can cause structures to collapse, especially if the tephra is saturated with water. Its abrasive nature is highly hazardous to machinery (Hoblitt et al 1998). In 1980 the eruption of Mt St Helens produced a relatively thin covering of tephra yet the small communities of Spokane, Riztville, and Yakima were vastly disrupted for up to two weeks. Tephra producing eruptions at Mt Rainier are very infrequent compared with the other Cascade Volcanoes. Only eleven eruptions have produced tephra that has affected the region of Mt Rainier.

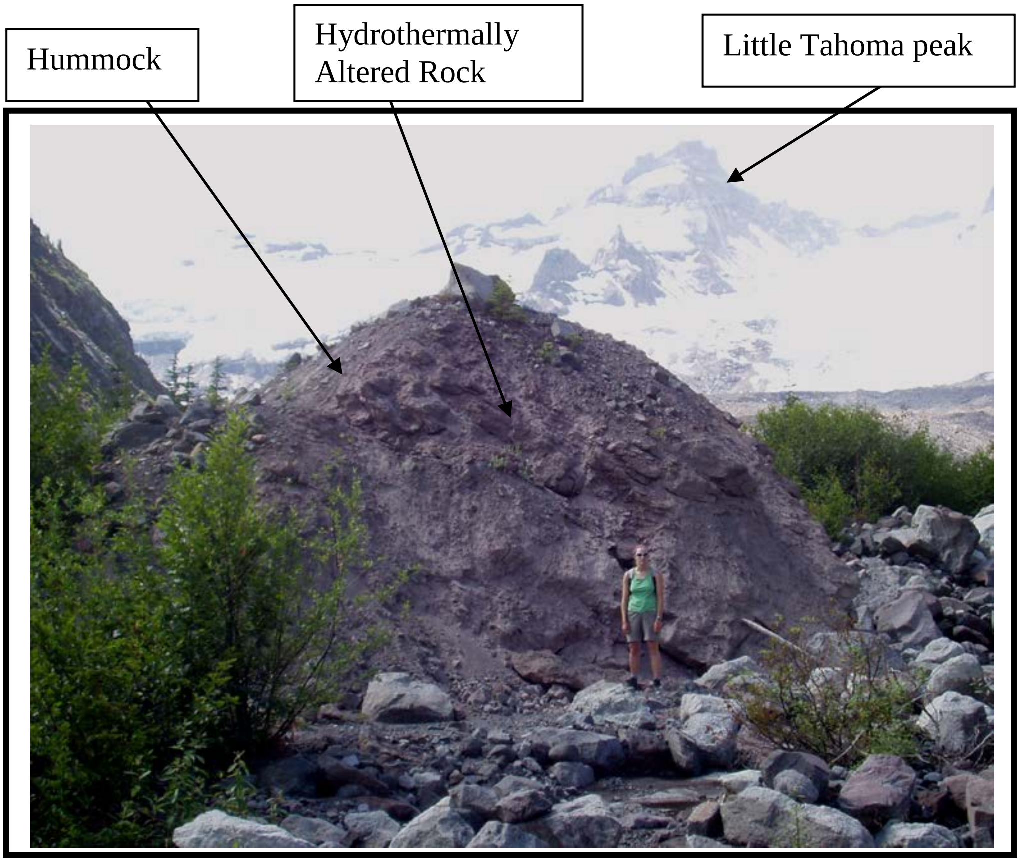


Figure 5: Hummock produced from Little Tahoma Peak rock avalanche.

3.5: *Ballistic Projectiles.*

Ballistic projectiles are large particles, normally greater than 64mm in size that are ejected from the volcanic vent during an eruption. Ballistics are categorised in two main types: Bombs and Blocks. Blocks are solid angular pyroclastic pieces, while Bombs are rounded pyroclastic pieces that are ejected whilst still molten. These particles cause deaths or extreme injury on impact but generally are not launched more than 2 km from the erupting vent. At Mt Rainier ballistic projectiles have been identified in the debris flow or lahar deposits indicating past activity.

3.6: *Pyroclastic Flows.*

Deposits of pyroclastic flow material can be found on flanks of Mt Rainier and those found in the South Puyallup River (12 km south west of the volcanic summit) are approximately 2500 years old and in the White River Valley 1000 years old. Pyroclastic flows are extremely hot mixtures of ejected material and gases that flow down slope at speeds of between 30-300 kph and at temperatures of over 300^{o}C (Hoblitt et al 1998). These flows destroy everything in their way by impact, burial and incineration (see Figure 6).

Figure 6: A pyroclastic flow travelling from the crater of Mt St Helens (Lipman 2002).

3.7: *Lava Flows*.

Mt Rainier is a stratovolcano composed of alternating layers of tephra and lava. The lava flows that make up the large cone consist of andesite. Andesite lava flows are highly viscous and slow moving because they contain up to 60% Silica. Although it is possible to evacuate populations in good time, these lava flows will slowly destroy anything in their path. At Mt Rainier, the main hazard posed from andesitic lava flows would be the subsequent production of lahars and floods created when the hot lava contacts the many glaciers capping the volcano. The most recent lava flow at Mt Rainier occurred some 5000 years ago, reconstructing the present summit cone after the summit collapse that produced the Osceola Mudflow (Harris1980).

4: Case Study: The 2003 Van Trump Creek Debris Flow.

4.1: Location.

Van Trump Creek is situated on the southern flank of Mt Rainier, feeding from the Van Trump Glaciers that have been retreating for many years. This once large glacier system has ablated to form many small patches of glacial ice. The Creek flows over Van Trump Park, an alpine meadow and down through a steep gorge carved into the Granidiorite bedrock. The creek enters the Nisqually River Valley approximately 4.8 km upstream from Longmire Town (Appendix 2).

4.2: Previous Debris Flows at Van Trump Creek.

On August 14th 2001 on the southern side of the volcano a large amount of water from the Kautz Glacier broke the glacial margin and carved a path through the loose glacial moraine that covers the lower slopes of Mt Rainier. The mix of sediment and water entered the western tributary of Van Trump Creek. The released water bulked significantly as it incised the moraine from Van Trump Park to Comet Falls (Vallance, Driedger and Scott 2002). A group of USGS scientists observed later pulses of this debris flow from a helicopter and although this was relatively small debris flow (due to the time of year) there were many tourists visiting the area. The debris flow therefore posed a high risk to the hikers, those at Christine Falls and to highway 706.

Appendix 3 contains the early aerial photograph taken in 1996 which shows that the path of the creek is concealed by lush vegetation. After the 2001 debris flow the creek was scoured and a winding path of rock can be identified from the aerial photograph taken in 2002.

4.3: The 2003 Van Trump Creek Debris Flow Initiation.

During October 20th-21st 2003 an increase in precipitation produced a high runoff from the Van Trump Glaciers. At approximately 3218m a small rock fall occurred and the mixture of dislodged material and precipitation travelled down through the Van Trump Glaciers. At a series of unnamed waterfalls at an altitude of approximately 2000m, the mixture of rock, and water “fire hosed” the unstable glacial moraine (Figure 7a). At the central of the three unnamed waterfalls a large segment of loose moraine was displaced (Figure 7b). This additional moraine transformed the hyperconcentrated flow into a debris flow (Table 2). For approximately 1.5 kilometres the debris flow bulked significantly (Figure 7c).

Mt Rainier edifice rock is affected by hydrothermal weakening. The combination of weakened rock and high precipitation is believed to have triggered the rock fall.

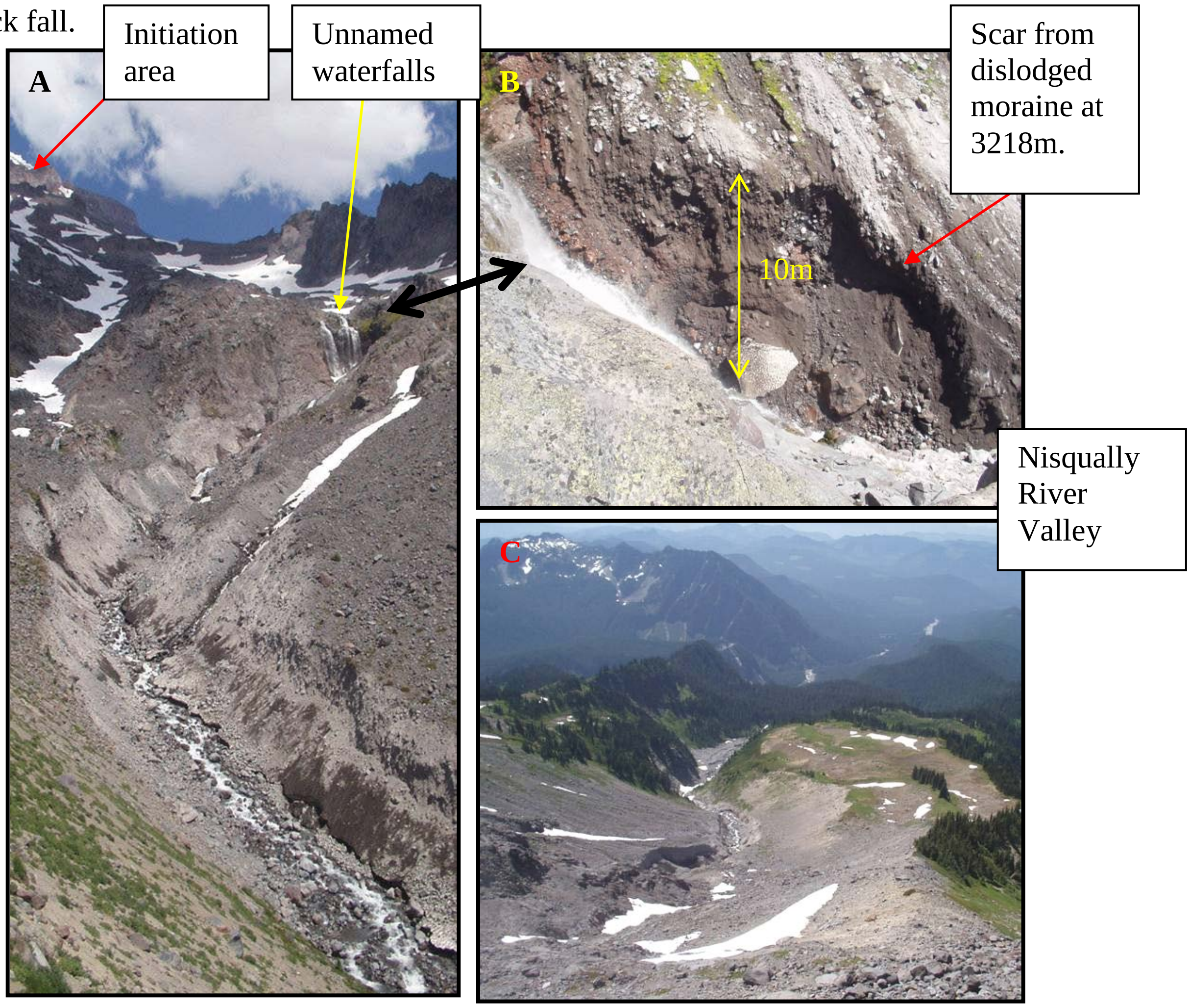


Figure 7: A) The unnamed waterfalls and flow path, B) The "fire hosed" scar, C) Flow route over Van Trump Park.

Climate records modified from NOAA for October 2003 were compared with normal average precipitation records for a thirty year period to illustrate the unusual increase in rainfall and snowfall that occurred in October 2003 as shown in Figures 8 and 9.

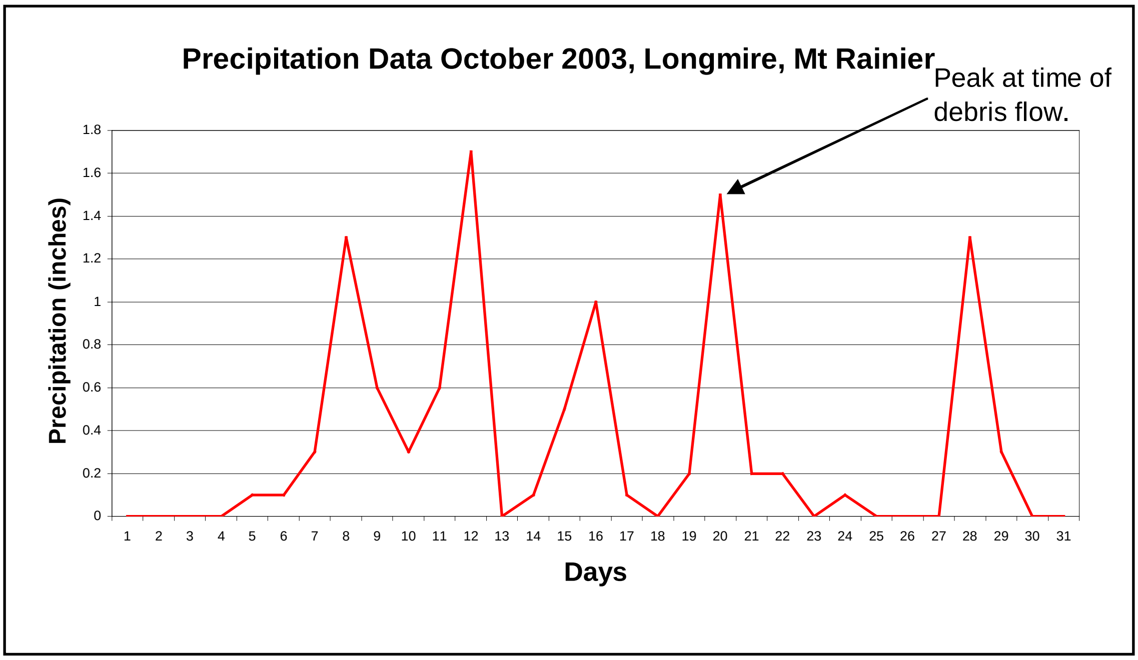


Figure 8: Precipitation data for October 2003 (modified from NOAA).

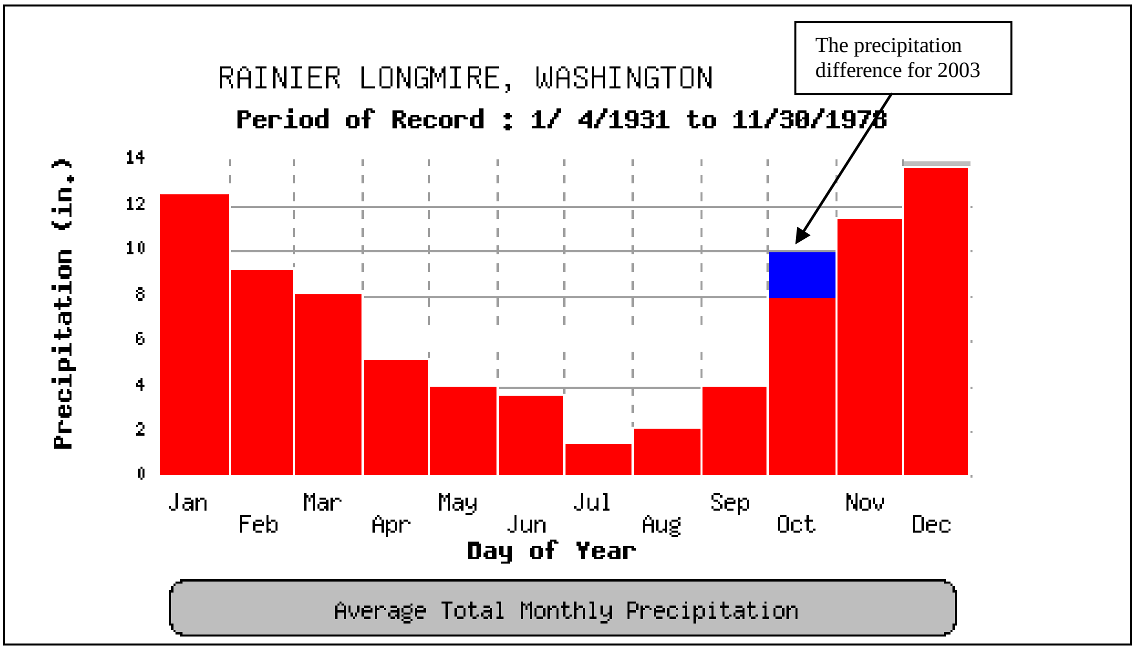


Figure 9: Precipitation data for Longmire from 1931-1978 (modified from Western Regional Climate Centre N.D).

4.4: Velocity.

Debris flows have been known to travel at velocities over 20 m/s (Scott et al 2001) and at similar discharges can travel twice as fast as water flows (Scott and Yuyi 2004). The 2003 Van Trump Creek debris flow travelled at approximately 9m/s as it entered the flat and wide Nisqually River Plain. The approximate velocity of the flow was established by using Equation 1, which incorporates the run up height as the flow hits a vertical surface or as it strikes a tree. For this investigation the height of mud that still remained on many of the dead or dying trees enveloped within the debris flow were recorded. The height at which a flow runs up an object relates to its velocity: the higher the velocity the higher the energy and the higher the run up. The equation relies on clear run up heights, and there are many uncertainties related to this technique. In this case many of the trees measured are situated at the sides of the flow therefore representing a slower velocity than the centre of the flow, and the mud splatter up tree trunks can give a false run up height. According to Iverson et al (1994) cited in Scott and Yuyi (2004) the equation tends to under estimate the flows velocity by nearly 30 %. The resulting velocities are therefore representative of the minimum velocities of the debris flow.

Velocity of Flow Equation:

$$\boxed{V = \sqrt{2gh}}$$

V = Velocity (m/s)

g = Gravitational acceleration = 10m/s

h =Run up height (m)

Equation 1: Velocity of a debris flow (Scott and Yuyi 2004).

Figure 10 illustrates how the debris flow decreased in velocity when the flow reached the wide, low gradient of the Nisqually River Valley. The debris flow lost its energy and deposited its material in a large fan.

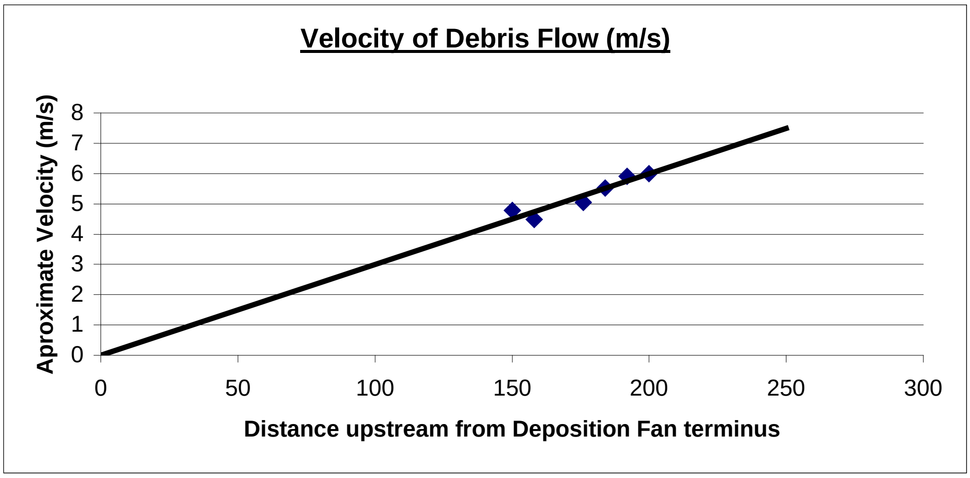


Figure 10: Velocity of the 2003 Van Trump Creek debris flow.

4.5: Cross sections and Discharge.

At different points along the flow route cross sections were recorded, along with the high water mark (the height of the debris flow). Appendix 4 shows all the cross sections these illustrate the growth and decay of the flow. Where the cross sections and velocity of the flow could be calculated or inferred the discharge of the flow can be estimated. The discharges are shown next to the corresponding cross sections. The discharges do not gradually decrease down stream due to the changes in channel topography for example within the gorge the flow is constrained and will increase in velocity and therefore discharge.

4.6: The 2003 Van Trump Creek Debris Flow Volume and Deposition Fan.

The deposition fan can be observed from the photographs taken from Ricksecker Point (Figure 11). The dark volcanic moraine plucked by the debris flow from Van Trump Park contrasts with the white Granodiorite, which has been transported down stream by the Nisqually River. The photographs were used in conjunction with field geomorphological and geomorphographic mapping to provide a precise map of the deposition fan (Appendix 5).

Although photography is a good way to identify the debris fan, winter and spring floodwaters and snow melt from the Van Trump Creek and the Nisqually River will have eroded the fan and some of its material will have been transported downstream. This erosion makes the analysis of the fans volume an approximation, therefore only an estimated volume using measurements in the field and professional judgement was made. Measuring the fan's width, depth and area allowed an approximate volume to be calculated. In addition, an evaluation of the area of maximum bulking gave an idea of the amount of material that had been removed. Figure 12 shows the main area of bulking took place between 2000m and 1500m.

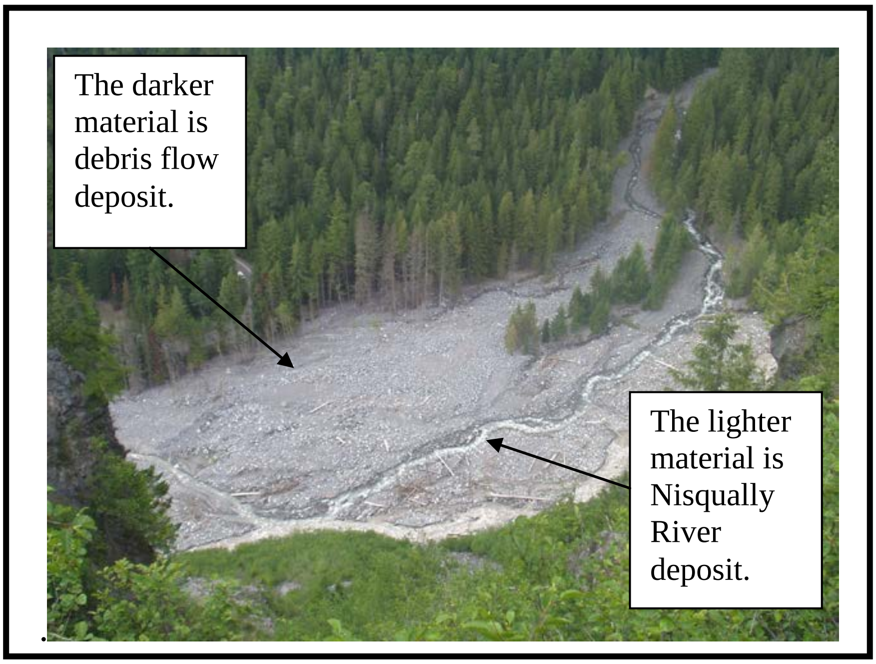


Figure 11: View from Ricksecker Point over looking debris fan.

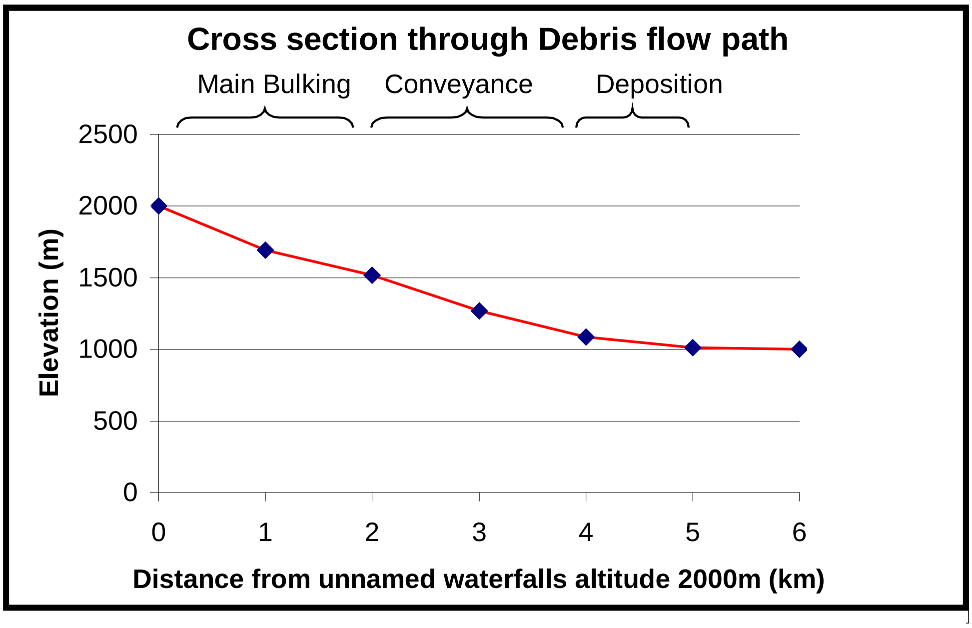


Figure 12: The main bulking and conveyance zones of the 2003 Van Trump Creek debris flow.

The volume of material deposited to form the debris fan is estimated at 200 000m^3. Vallance et al (2002) estimated the volume of the 2001 debris flow fan to be approximately 160 000m^3. This means that the 2003 debris fan is 20% larger than the 2001 debris fan. From field observations the total volume of material removed between the altitudes of 2000m and 1600m is estimated at 350 000 m^3 in 2003, compared with the total volume of debris removed between altitudes 2164m and 2500m in 2001 of approximately 250 000m^3. The 2003 debris flow is almost 30% larger than the 2001 debris flow at this point. From interviews with the National Park Service Maintenance, Climbing, and Trails personnel, the 2003 debris flow was observed to have been a lot larger than the 160 000 m^3 volume 2001 debris flow (Vallance et al 2002). The estimated calculations include a certain error, yet in conjunction with all observations it can be assumed that the 2003 debris was larger in volume than the 2001 debris flow.

4.7: The 2003 Van Trump Creek Debris Flow Behaviour.

Debris flow behaviour has a strong relation to the particle size distribution. The matrix of a debris flow is an essential component when considering whether a debris flow is dominated by viscoplastic behaviour or dominated by granular flow (Scott et al 1995). The two flow behaviours are controlled by the clay content percentage: the viscoplastic behaviour represents a cohesive flow with high clay content whilst the granular dominated flow has a low clay content and is referred to as non-cohesive by Scott et al (1995). This difference not only classifies debris flows but also becomes extremely relevant when modelling debris flow behaviour, thereby anticipating future debris flow characteristics and mitigating against the geological hazard. The plots in Figure 13 represent the sizes of the debris deposited at different points along the flow path. When these plots are compared with a plot representing a size distribution of a generic non-cohesive debris flow based on the National debris flow that occurred 2200 years ago there is a significant similarity. The graph provides evidence that the 2003 debris flow was non cohesive. The data was recorded in the field using the Wentworth Classification and the Walman Pebble Count Technique.

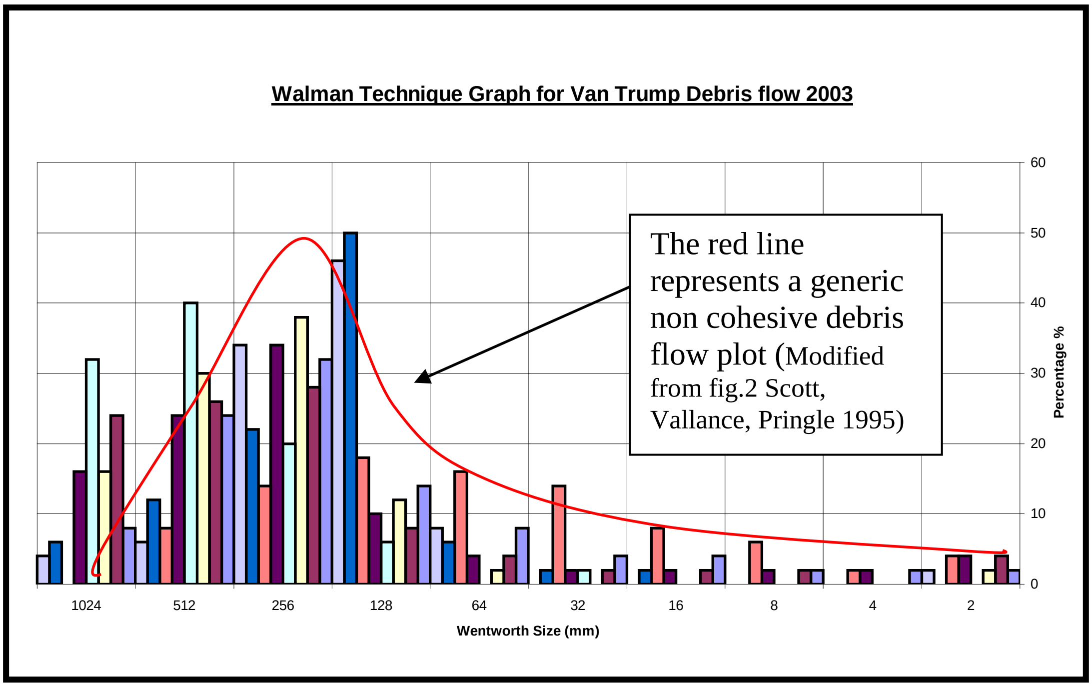


Figure 13: Walman Technique Pebble Count data for the 2003 Van Trump Creek debris flow.

By using this method a range of data could be randomly collected producing a more accurate result (Appendix 6).

The chart enables a fast evaluation of debris size. This chart demonstrates that the 2003 debris flow mainly consisted of large boulders between 256-512mm. There is a lack of fine-grained material below 64mm within the deposits. The lack of smaller material could be due to action of dewatering. Dewatering takes place after the debris flow has deposited is material, when the water held within the debris slowly filters out of the mass. Smaller debris particles will be washed out or will settle in the gaps between the larger boulders. The Walman Technique only records data from the top surface of the debris therefore if the data is recorded a long time after the event the smaller material may not be recorded. In conjunction with the winter floods and snow melt smaller particles may have washed downstream.

4.8: Characteristic Features.

4.81: *Boulder Fronts.*

At the front of a debris flow is a convex tongue of clasts (Scott and Yuyi 2004). A frontal prominence of large clasts was observed during the 2001 Van Trump debris flow and delineated the front of each pulse of debris. Within the deposition fan, terraces of larger clasts can be observed. These are the relic boulder fronts from previous pulses of debris flow. Remnant boulder fronts were observed in the South Tahoma Valley where 23 debris flows occurred between 1967 and 1993 (Walder and Driedger 1994). Boulder fronts can therefore provide evidence that more than one pulse formed during a debris flow event. There was no observed evidence of multiple boulder fronts at the 2003 Van Trump Creek debris flow deposition fan, suggesting that this debris flow consisted of either one main lobe, or a series of smaller pulses that did not produce significant boulder front terracing.

4.82: *Lateral Levees.*

As the boulder front of a debris flow lobe travels down slope, the centre of the lobe travels faster than the edges due to the friction between then bank and the moving debris. This action means that along the edges of a flow an elevated wall of material builds up slowed by the interaction with the bank. This raised wall of debris is called a lateral levee and can be used to trace the lateral extent of a flow. The 2003 deposition fan provides a good example of a lateral levee shown on Figure 14.

Figure 14: Lateral Levee on 2003 Van Trump Creek debris flow deposition fan.

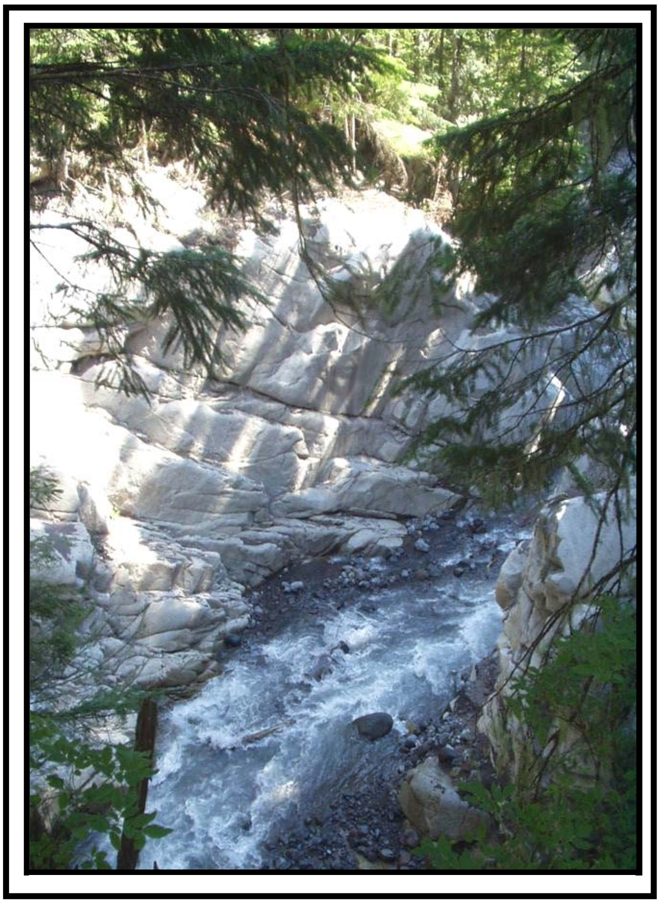


Figure 15: Gorge switch-backs down stream from Christine Falls.

4.83: *Ballistic Clast Projection.*

Within the debris flow grain to grain collision is continuous and aggressive. As a result, clasts are ejected from the moving mass (Scott and Yuyi 2004). Ballistics can be large as demonstrated by the clasts found at Christine Falls look out by the NPS staff who described the clasts as “basket ball” size. The ejection intensifies as the flow impacts a barrier: at Christine Falls, Van Trump Creek changes direction dramatically, producing near 90^{o} switch-backs (Figure15).

4.84: *Buoyed Boulders.*

A debris flow is a powerful mass of moving material so dense that it can carry enormous boulders, not within the flow mass in a rolling action, but sustained on top of the flow. The boulders are then deposited and found at the surface of a deposition fan. Figure 16 shows the potential size that these boulders can reach.

Figure 16: An example of a buoyed boulder at the 2003 Van Trump Creek debris flow deposition fan.

4.9: The Effect of the Debris Flow.

The area affected by the debris flow was relatively small because the flow was constrained by the steep granodiorite gorge. The deep gorge conveyed the debris flow after it left Van Trump Park until just below Christine Falls. Even though at places the gorge is over 20 m deep the flow still spilled from its containment and deposited lateral levees containing rocks with diameters over 2m on the trail, which runs parallel to the creek. At Christine Falls and the Van Trump Creek Falls evidence of the debris flow’s destructive size and nature is clear.

At Van Trump Creek Falls directly down stream from Van Trump Park at an altitude of 1500 m the debris flow had already bulked to a sufficient size that it destroyed a reinforced steel trail bridge. The trail bridge was new and had been flown into place by helicopter earlier that year. The bridge stood 1.8 m above the surface of the normal water level and extended 10.5 m over the creek. The steel beams that made up the bridge weighed approximately 19 kg/m (120 lbs/ft) and were 0.6m in diameter. The whole construction weighed approximately 675 kg (1500 lbs) and had a split cedar façade. It was pinned into two large concrete bases. The remnants of the trail bridge have never been found (Figure 18).

At Christine Falls where the main road (highway 706) leading to the Paradise crosses Van Trump Creek, the road bridge remained intact due to its strong engineering. A wooden trail bridge directly upstream from Christine Falls pictured after the 2001 debris flow was shattered (Figure 17). Parts of the wooden trail bridge can be found in the debris fan in the Nisqually River Plain.

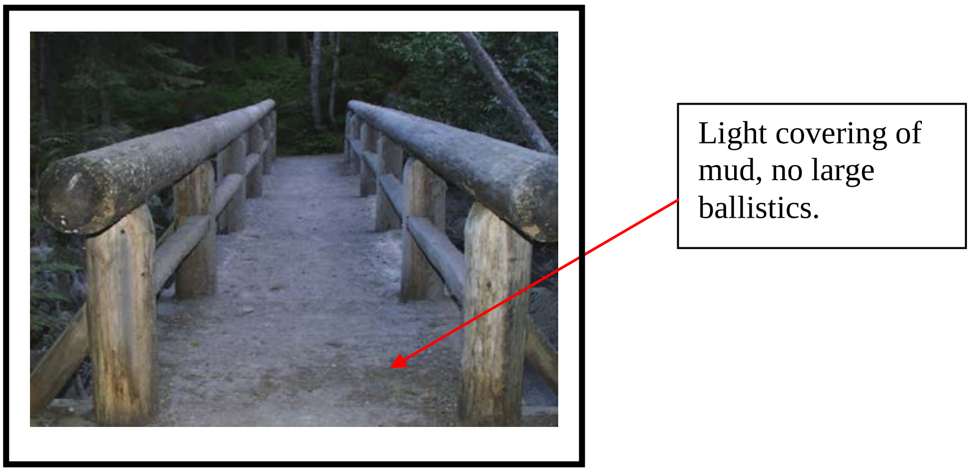


Figure 17: Christine Falls Trail Bridge in 2001, Courtesy of G.Mora 2001(NPS).

Figure 18: A) B) Views of the steel trail bridge early 2003 at Van Trump Creek Waterfalls (curtesey of Carl Fabianai, NPS Trails Foreman); C) D) Views of the same location in 2004.

The trail bridge spanned the gorge above the waterfall some 11.5 m above the normal water level. The destruction of this bridge is evidence that the debris flow was not fully contained by the deep gorge and spilled over, no more so than at Christine Falls. The road bridge at the falls was enveloped by material, not just the fine mud deposits like those left by the 2001 debris flow (Figure 17) but large boulders described by the Maintenance personnel as “the size of basket balls”. These boulders were not only deposited on the bridge but on the look out opposite. As mentioned previously these rocks were projected on to this platform from the torrent below. Using machinery it took over four hours to clear the bridge. Below Christine Falls massive Granodiorite boulders were ripped from the lower gorge. Figure 19 illustrates the size of the plucked bedrock masses.

Figure 19: Granite boulder deposited at the beginning of the 2003 Van Trump Creek debris flow deposition fan.

The 2003 debris flow threatened the main road to Paradise at many points. Not only did it over run the road at Christine Falls, but also down stream only 0.8 km from Cougar Rock Campground. Standing on the road it is clear that the previous debris low in 2001 paved the way for the 2003 event by killing many trees in this area and raising the height of the river bed at this point. The 2003 event rushed down stream and broke the dying trees like match sticks and over spilled on to the road.

The lateral levee in Figure 14 is located at the eastern lateral extent of the debris fan yet during field reconnaissance to the east of this lateral levee debris can still be found in large amounts. This could be evidence that the 2003 debris flow consisted of a number of surges rather than one large flow. Multiple debris flow pulses are dangerous because they can remobilise already deposited material extending the run out of the flow down stream. A centralised levee could be evidence for this multiple debris flow action having occurred in October 2003 yet there is not enough substantial evidence to prove this theory. The eastern debris could have been brought down later during a flood event, during dewatering of the debris fan, or with melt water and reworking of the debris. The 2003 debris flow took place at night and therefore there were no eyewitnesses.

Appendix 5 shows the extent of the 2003 debris deposition fan. Both the 2003 and 2001 debris flows ran out of energy at similar distances within the Nisqually River Valley. This explains why at some places it is possible to identify the 2001 debris flow fan underneath the 2003 debris. The top of the 2001 debris flow fan can be found where tree trunks have been cut off at a certain height, approximately 0.5-1 m above the roots. Figure 20 shows a tree that was killed during the 2001 event and yet remained standing. When the 2003 debris flow inundated the area the weak and brittle tree was pulverized and was ripped near its base. The ripped margin represents a minimum height of the 2001 debris fan, because the base of this tree was encased in 2001 debris which protected the lower trunk and roots, while the exposed tree trunk was ripped away by the 2003 event. This tree is one of many that form a horizontal plane of fractured trunks and deformed small more flexible bushes At this height there is also a change in debris size and compaction of deposits. This distinct change in texture may indicate a transition between the two flows.

A layer of dead pine needles and organic material laid down between 2001 and 2003 would define this terrace of 2001 material under the 2003 debris deposits. However during the field reconnaissance no such layer was discovered. The tree trunk evidence nevertheless delineates two different debris compositions one on top of the other. It is reasonable to suggest that the lower is the 2001 debris while the uppermost is the 2003 debris.

Figure 20: Tree trunk cut by 2003 Van Trump Creek debris flow.

Vallance et al (2002) described how the 2001 debris flow maintained coherence beyond the Wonderland Trail footbridge near Cougar Rock Campground. So although the present debris fan represents where the majority of material was deposited it is reasonable to hypothesise that the 2003 debris flow may have continued down stream transforming into hyper concentrated flows and dissipating in to the stream flow depositing smaller sized debris as far as Longmire. Unfortunately no river gauge data is available for October 2003.

The debris flow has changed the character of the area dramatically. The debris has raised the creek bed up by 1-4 m forcing the rivulet to weave a course through what was previously forest. The Nisqually has been further pinned on to the south bank of its drainage, undercutting this steep bank. This erosion has caused slope instability and failure in many places along the Nisqually River Valley.

The debris itself poses a hazard during the annual floods. The floodwater could remobilise this material producing a hyperconcentrated flow, which can cause significant damage downstream. The Nisqually River bank at Longmire has already suffered from the erosive forces of hyperconcentrated flow events. In 2004 exposed sewage pipes and infrastructure at Longmire were open to erosion and even the road that runs from Longmire to safe high ground (that acts as an escape route for the NPS personnel) is at a higher risk from a future debris flow hazard.

5: Hazard Assessment.

Hazard assessment and the resultant hazard zoned map are vital to planning effective mitigation (Scott et al 2001). Hazard assessment examines the frequency and the undesirable consequence of particular hazard. At Mt Rainier a “worst case” hazard would be a low frequency yet very high consequence event like the Ocseola Mudflow. The 2003 Van Trump Creek debris flow affected national park infrastructure including highway 706 which is the only road from Longmire to Paradise, threatened the town of Longmire, and Cougar Rock campground. Although there were no fatalities or injuries, the debris flow caused an unacceptable economical loss. The high frequency or recurrence of these low magnitude flows enhances the probability that future events will cause destruction and fatalities. A hazard map zones the areas likely to be effected by a similar debris flow. The risk to that area can be calculated from the hazard map and prioritised mitigation strategies can be developed.

According to a recent study (Scott et al 2001) hazard assessment for flow hazards should incorporate these seven stages:

- The frequency (using data from historical events).
- Delineating the areas of inundation.
- Hydraulic modelling (using paleohydrologic case studies).
- Prediction of flow travel times (using data from historical events).
- Identifying areas of low rock strength on edifice.
- Mapping areas of weakened rock by remote sensing techniques.
- Analysing Digital Elevation Models (DEMs) to quantify slope stability.

In assessing the 2003 Van Trump Creek debris flow hazard the following stages were examined: delineating the areas of inundation, identifying areas of low strength on edifice using remoter sensing techniques, and analysis of DEMs to quantify slope stability. The areas of inundation were recorded in the field. The debris flow path was identified and mapped as described previously.

The areas downstream of hydrothermally altered rock are at risk from both small-scale debris flows and cataclysmic lahars. To identify areas of low strength rock (hydrothermally altered rock) within the initiation zone (200m below Camp Hazard) remotely sensed data from a study conducted by Rystrom, Finn, and Descsz-Pan

(2000) was analysed. In 1996 the USGS conducted a high-resolution airborne magnetic and electromagnetic survey at Mt Rainier to determine the extent of altered rock on the edifice. Figure 21 is the electromagnetic resistivity image of Mt Rainier overlaid on a digital elevation model, areas of blue represent regions affected by hydrothermal alteration while areas of red are areas of fresh volcanic rock and ice that is deeper than 150m (Rystrom et al 2000). The Camp Hazard area is a blue zone inferring that the region is dominated by hydrothermally altered rock. The remotely sensed data provides evidence that the rock fall, trigger of the 2003 Van Trump Creek debris flow, could have been due to the failure of hydrothermally altered rock ridges.

Finally, analysing a DEM of the Van Trump Creek can provide an understanding of the topography of the region identifying areas of glacially eroded steep ridges and possible flow routes. Digitising a topographic map of the Van Trump Creek region using ILWIS GIS software created a digital elevation model. The initial process in producing a DEM of the region was to acquire suitable topographic data. For this investigation topographic maps were downloaded from Terraserver (Microsoft Cooperation 2004). This data was then georeferenced within ERmapper so that the software knew the exact location on the earth of each point within the map.

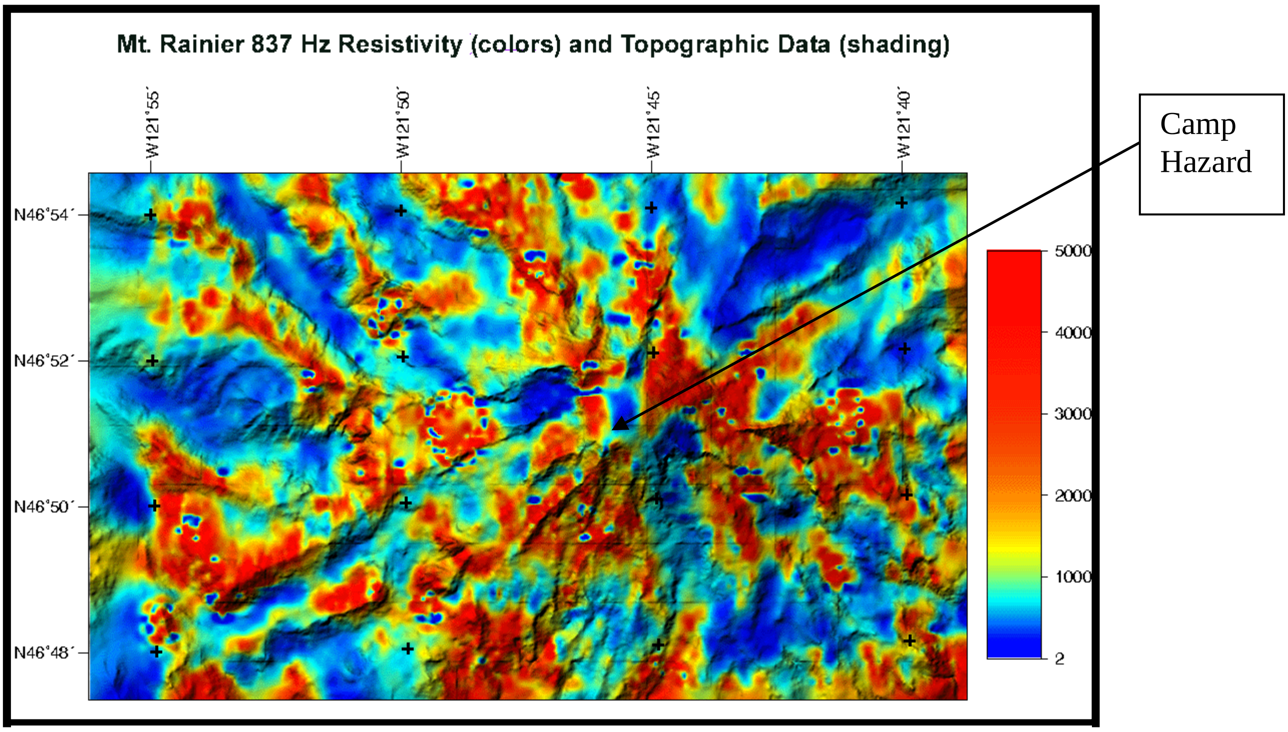


Figure 21: Electromagnetic resistivity data image of Mt rainier (Rystrom et al 2000)

Once the data has been georeferenced ERmapper can orientate the maps exactly. The contours that make up the topographic map were then individually manually digitised on screen within ILWIS GIS programme to produce a trace of the contours, in a colour coded system (Figure 22). This map was then contour interpolated within ILWIS to produce Figure 23. Contour interpolation smoothes the contour heights so that each point on the map is allocated a value according to its nearest contour value producing an image that represents the topography of the region rather than a series of stepped terraces representing where the contours were defined. The final map can then be displayed in greyscale as a shaded map (Figures 24A and B) producing a three dimensional map of the Van Trump Creek. The DEM was then overlaid with a mosaic of aerial photographs taken in 1994. The final map is a three-dimensional representation of the Van Trump Creek region before the 2001 and 2003 debris flow events (Figure 25).

Appendix 7 delineates areas of debris flow hazard for the Van Trump Creek region. The hazard map was created using hazard analysis stages, aerial photographs, field observations and professional judgement. Created in CoralDraw8 the hazard map consists of four zones: high hazard, moderate hazard, low hazard and very low hazard. The high hazard relates to the actual flow path of the 2003 Van Trump Creek debris flows. The moderate hazard delineates areas that may be effected from similar high frequency debris flows, areas of the Van Trump Creek that may be affected by ballistic clast projection or over spill during a debris flow event. Low hazard areas relate to regions that may experience hyper concentrated flow remnants of the debris flow or low gradient areas that could be at risk from successive debris flow pulses. Very low risk relates to areas unlikely to be affected by the debris flow hazard. The immediate area around the initiation zone is categorised as high hazard. The glaciated zone of the edifice is zoned as moderate hazard; a debris flow trigger can initiate at any point in this region, due to the unstable moraine cover, glacially steep rock faces, hydrothermally altered rock, and the possibility of a glacial outburst.

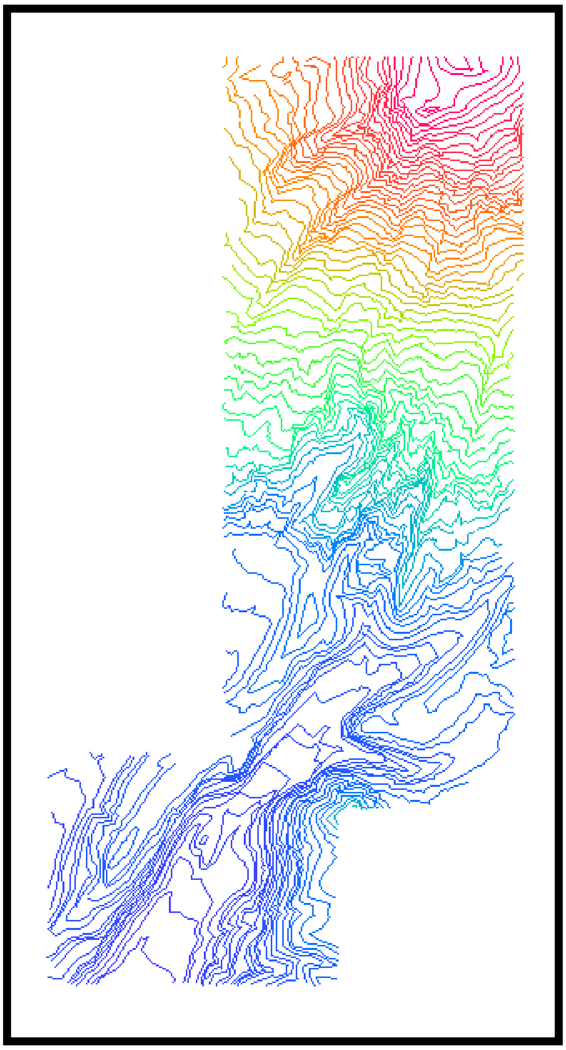


Figure 22: Digitalised contours for the Van Trump Creek region.

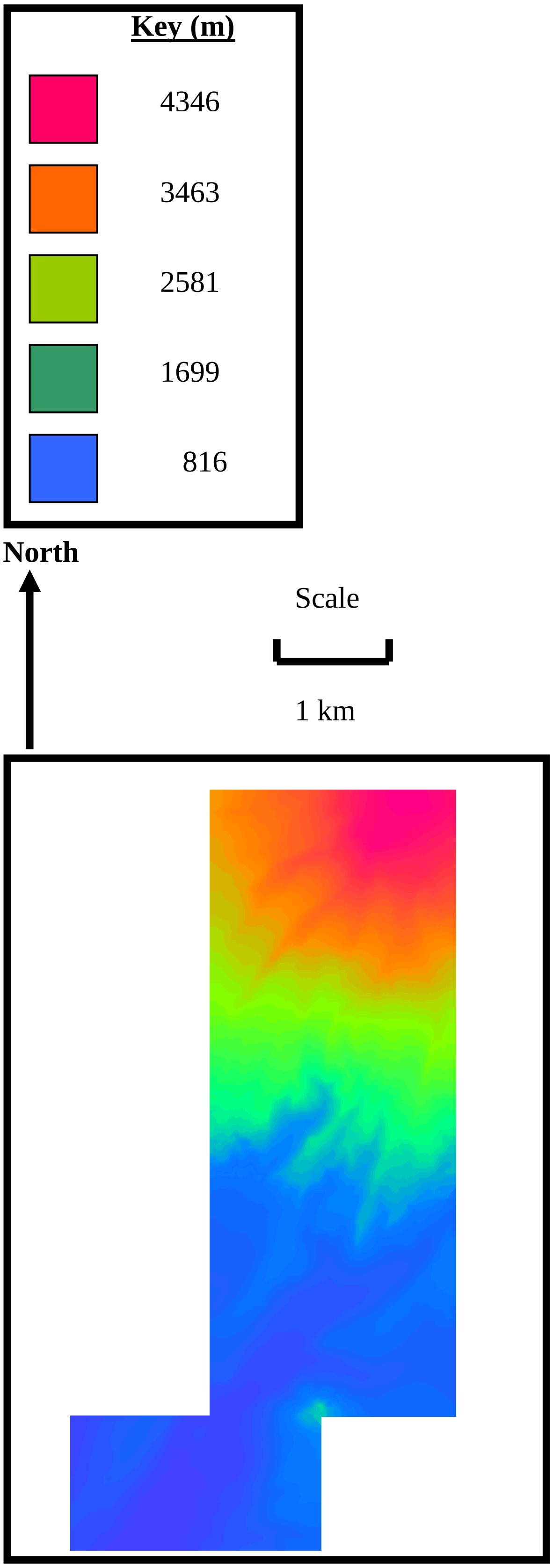
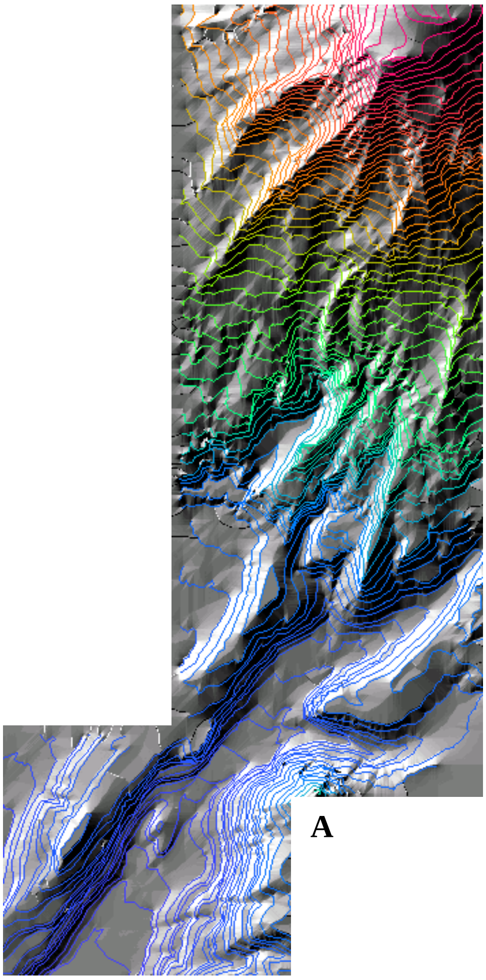
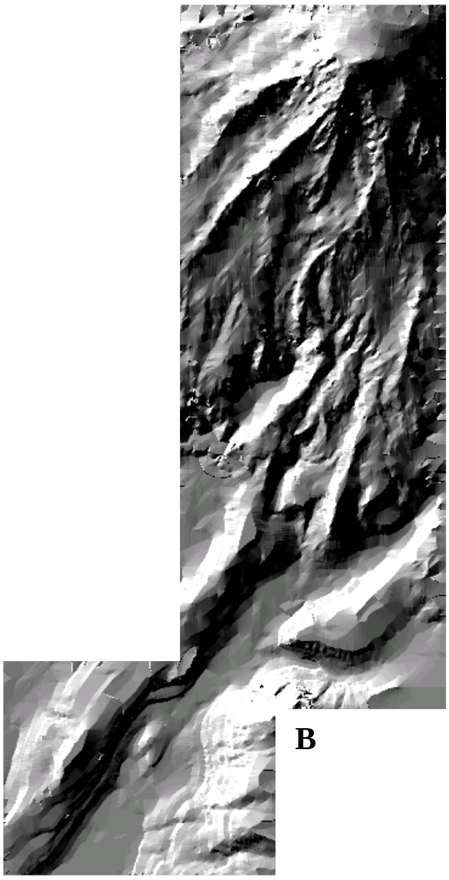


Figure 23: Contour Map after Contour Interpolation.



A



B

Figure 24: A) DEM of Van Trump Creek with contour overlay,
B) DEM of Van Trump Creek
(Scale, Key and orientation same as Figures 22 and 23).

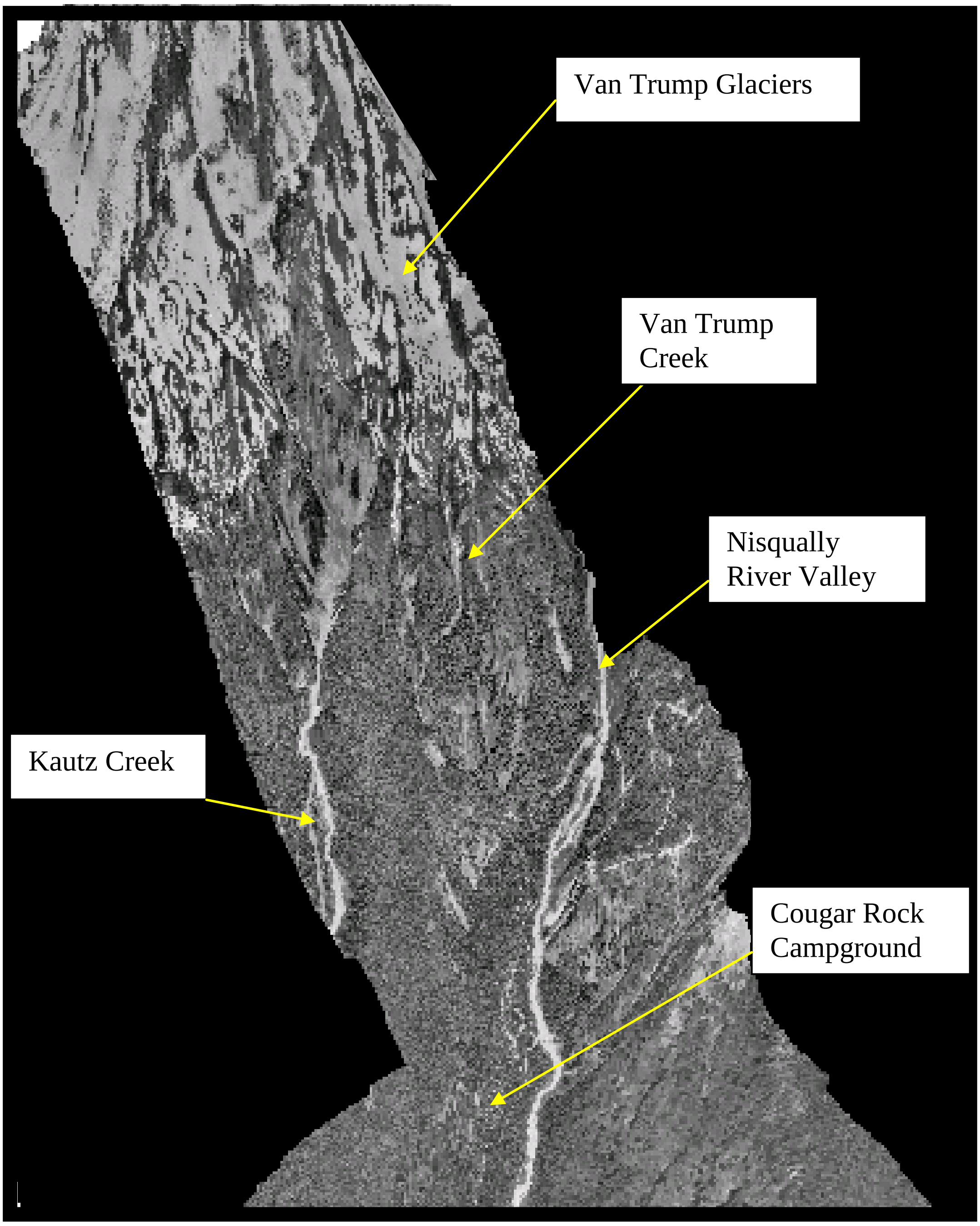


Figure 25: DEM and aerial photograph overlay.

6: Risk Analysis.

Risk analysis is the generic term for methods that support decision making by quantifying consequences and their probabilities of occurrence (Committee on techniques for estimating probability of extreme floods 1988, citied in Scott et al 2001). Both a semi quantitative risk analysis and a risk map are used in this study to evaluate the risk posed by the 2003 Van Trump Creek debris flow.

6.1: Semi Quantitative Risk Analysis.

Riedel (1997) carried out a semi quantitative risk analysis of Mt Rainier. He used a scoring system to analysise 19 sites within the National Park. Riedel used Equation 2 to evaluate risk for each site.

$$\boxed{\text{Risk = Hazard x Value x Vulnerability}}$$

Equation 2: Risk equation (Riedel 1997).

Tables1-3 show Riedel’s scoring system. The debris flow hazard scores were assigned on the recurrence interval of various types of flow taken from Scott Pringle and Vallance (1992).

Hazard = A x B x C x D x E

Hazard	Description	1	2	4	8	16
A	Debris flow inundation level and frequency.	Outside debris flow zone.	Max. debris flow zone.	Case I inundation zone.	Case II inundation zone.	Case III inundation zone.
B	Pyroclastic flow hazard.	Outside pyroclastic flow zone.	Within pyroclastic flow zone.			
C	Regions downstream of hydrothermally altered rock.	Not downstream.	Downstream.			
D	Regions down stream of geologic faults.	Not downstream.	Downstream.			
E	Areas of susceptibility to other geological hazards.	No other geological hazards.	One other geological hazard.	Two or more geological hazards.		

Table 2: Hazard Score System (Riedel 1997).

Value = A x B

Value	Description	1	2	4	8
A	Capital investment and infrastructure.	Primitive day use sites.	Campground facilities, including campground tender station.	Employee housing area or larger administrative facility.	Two or more of 4 point facilities.
B	Number of people concentrated at each site.	Small concentration of visitors or employees.	Large concentration of visitors or employees.		

Table 3: Value Score System (Riedel 1997).

Vulnerability = A x B x C x D x E

Vulnerability	Description	1	2	3	4
A	Geomorphic position.	Valley wall, bedrock bench, or valley divide.	High elevation terrace >11m above floodplain composed of ice age outwash and or Osceola Mudflow.	Low elevation terrace (0-11m) above floodplain.	Floodplains and alluvial fans.
B	Proximity to mountain.	On ridge on non valley site.	Distance of more than 30 km from summit crater.	Distance of 15-30km form summit crater.	Less than 15 km form summit crater.
C	Type of use period as related to diurnal occupation of site.	Day use only.	Overnight and day use.		
D	Type of use period as related to seasonal occupation of site.	Summer use only	All season facility.		
E	Susceptibility to harm.	In structure.	In car.	In tent or on foot.	

Table 4: Vulnerability Score System (Riedel).

Riedel concluded that the top three areas of most at risk from natural hazard within Mt Rainier National Park were White River Campground, Longmire and Cougar Rock campground respectively. The main reasons why Longmire and Cougar Rock scored so highly was because the sites contain numerous sensitive developments, high seasonal populations, proximity to the volcano and the locations of both sites are within the debris flow inundation zones of less than 100 years. Using Riedel's scoring system Christine Falls was evaluated taking into account the past two debris flow events.

From this semi quantitative risk analysis, Christine Falls is the seventh site most at risk out of the 19 sites analysed by Riedel across Mt Rainier National Park. This method of risk analysis is effective in prioritising sites for mitigation, yet is highly subjective

	Hazard	**Value**	**Vulnerability**	**Risk**
A	16	1	3	
B	2	1	4	
C	2		1	
D	2		2.5*	
E	4			
F				
Total	512	1	30	**15 360**

*2.5 Score given as tourists will be in cars and on foot in the area.

Table 5: Christine Falls semi quantitative risk analysis scores.

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6.2: Risk Map.

The risk map is shown in appendix 7. To produce the risk map, the zones on the hazard map have been compared with areas of value or vulnerability (identified using aerial photographs and field observations) for instance Longmire, Cougar Rock Campground, and highway 706. Where the areas of value or vulnerability lie within hazard zones these areas are given a risk rating; for example, Longmire is located partly within a low hazard zone, yet it is an area of high value and vulnerability. Therefore this area is given a rating of high risk.

The very high risk areas are shown in orange. They represent areas that are both directly in the debris flow path and that are sites of high value or vulnerability. Christine Falls is within this zone because it is where highway 706 crosses the flow path, it receives many tourists, and the site includes a car park and look out area. Where highway 706 travels close to the creek these regions are zoned as very high risk because the road is busy in the summer season and remains open through out the winter, the road skirts close to the creek and has been affected by the previous debris flow events. At Van Trump Creek Falls the site is categorised as very high risk because this is the site of the steel trail bridge that was destroyed during the 2003 debris flow. Additionally during the summer season many tourists hike to Comet Falls.

The zone leading to Paradise River is categorised as moderate leading to low risk because this is where the Wonderland Trail crosses the Nisqually River Valley. This is one of most popular trails within the park and as a result has a high tourist density during summer months.

7: Monitoring Debris Flow Events at Mt. Rainier.

The Cascade Volcano Observatory (CVO) has developed a suite of portable monitoring equipment: a portable observatory deployed to evaluate any volcanic hazard in the Cascade Range.

Generally the first warning signs of volcanic unrest are earthquakes. Regional seismic networks work in co-operation with the Pacific Northwest Seismograph Network to detect any seismic occurrences related to the volcanoes. A debris flow can be identified using seismographs. The 2001 Van Trump Creek debris flow created long lasting low-level signals that showed up on three seismographs within the Mt Rainier region network. Analysing the frequency against the time period of trace data produces the spectrogram (Figure 26). The x-axis of the spectrogram represents frequency. There is significant energy in the frequency band 1-6Hz. The average amplitude was low as shown by the spike trace to the right. The spectral amplitude values are converted to colour with deep blues representing low values, ranging through greens and yellows to deep red for the high values (PNSN 2001). Debris flows and lahars produce a lot of ground shaking and unique seismic traces, if these can be picked up by a seismic network, this data can be used to warn populations down valley of the imminent danger. Seismic data was recorded showing the precursor to an eruption in 1985 on Nevado del Ruiz. Unfortunately this data was not fully understood and the warning signs went undiscovered (Bruce 2001).

Lahar and debris flow monitoring relies on historical data and on the identification of the trigger mechanism: whether it is a rock avalanche related to the hydrothermally altered rock, rain on snow events, glacial outburst, or a heating of glacial ice due to a volcanic eruption. The deposits of historical lahar and debris flow events show the potential volume and direction of future flow events.

Recently remote sensing has been introduced to identify debris flow paths and potential flow routes. Aerial photography and satellite imagery can be assessed to identify areas of potential inundation and region at high risk. DEMs can be used to analyse the topography of a region as illustrated previously.

Monitoring the climate data at Mt Rainier is essential in monitoring debris flow hazards. If precipitation levels increase above average or if there are prolonged high temperatures the Mt Rainier NPS issue a debris flow alert to the park.

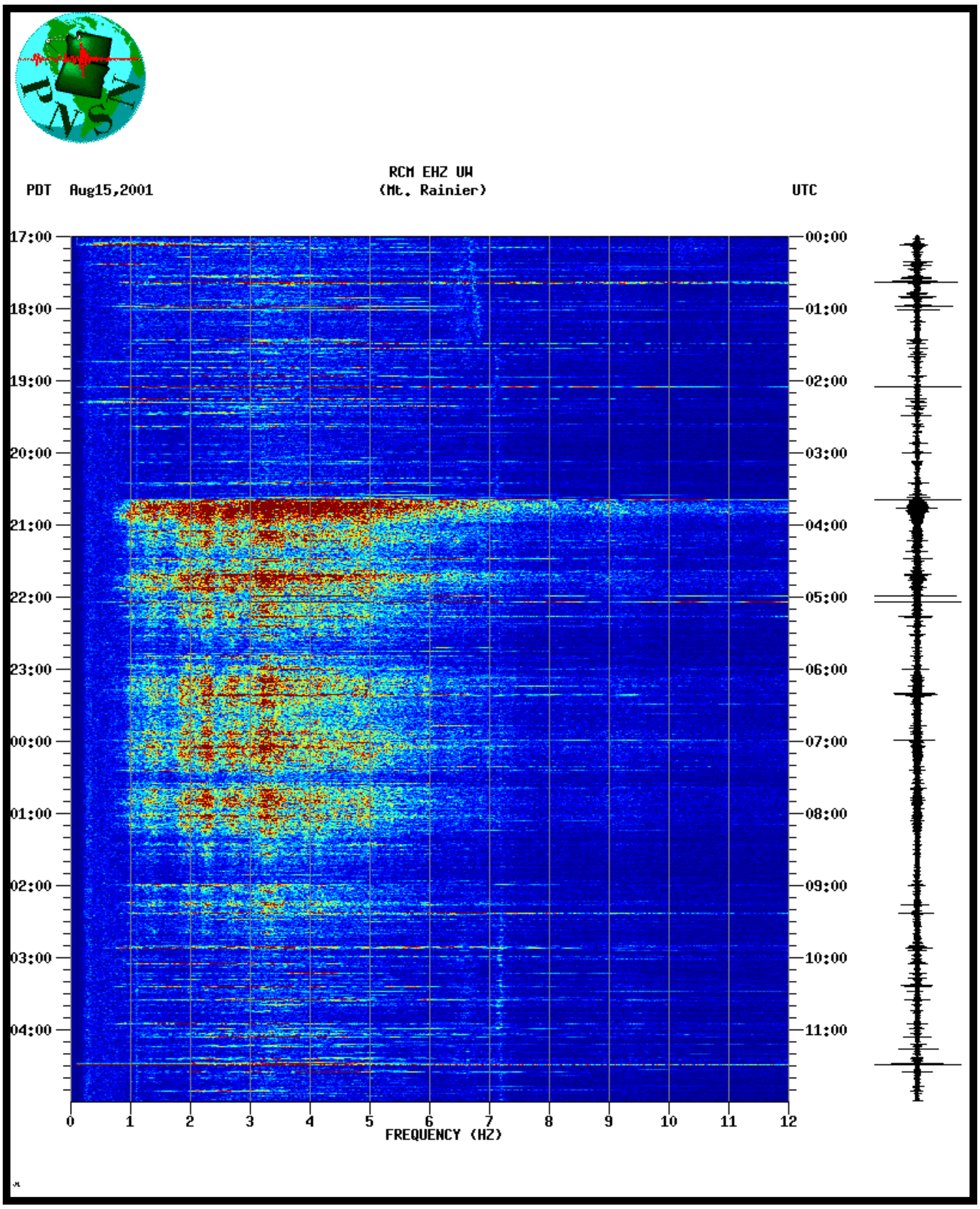

Figure 26: Spectrogram for the 2001 Van Trump Creek debris flow (PNSN 2001).

8: Mitigation.

8.1: Education for Mitigation.

There are more than 1 million people living in the Tacoma-Seattle region that could be at risk from the geological hazards posed from Mt Rainier (Dzurisin, Stauffer, and Hendley 2003) and within the National Park the high influx of tourists all year round increases the risk posed by debris flows (Figures 27 and 28).

To reduce these risks effective monitoring and mitigation strategies must be emplaced. The eruption of Mt St Helens in 1980 and the 1985 Nevado del Ruiz lahar disaster were turning points in volcanic hazard risk management. The David.A.Johnstone Cascades Volcano Observatory (CVO) was established in Vancouver and the Cascades Range became one of the most monitored volcanic ranges in the world. During the designated International Decade for Natural Disaster Reduction Mt Rainier was chosen as one of the 13 “decade volcanoes”, a volcano that for a period of ten years would be monitored and managed to better understand volcanic hazards, raise public awareness and enhance mitigation practices (Topinka 2002). Mt Rainier is now described as a poster volcano, a primary example that educating residents of volcanic hazards can theoretically greatly reduce the risk posed by these hazards.

The most important form of mitigation is educating the people vulnerable to the hazard. As illustrated by the 1985 Nevado del Ruiz disaster (Bruce 2001) if vulnerable local populations do not know the warning signs of an incoming lahar or debris flow and then what to do to protect themselves, no amount of monitoring will help save their lives. The Mt Rainier NPS in conjunction with the USGS have produced an excellent outreach programme to educate the local population and tourists. The NPS and USGS have produced a wide variety of information to raise awareness of the lahar and debris flow hazard within the local population and tourists, ranging from pamphlets, to meetings, to teacher training courses. The most effective mitigation for the Van Trump Creek debris flows is the Education for Self Warning and Evacuation (Scott and Driedger 1998 citied in Scott et al 2001). This is simple advice to vulnerable parties to go to higher ground with out delay if debris flow precursors have been identified (Scott et al 2001). As described previously debris flows produce seismic signals due to the ground shaking from the moving torrent of rock. Additionally the noise produced from a debris flow has been related to the sound of a passing freight train. These precursors can give warning of an oncoming debris flow and initiate simple life saving actions such as getting to high ground.

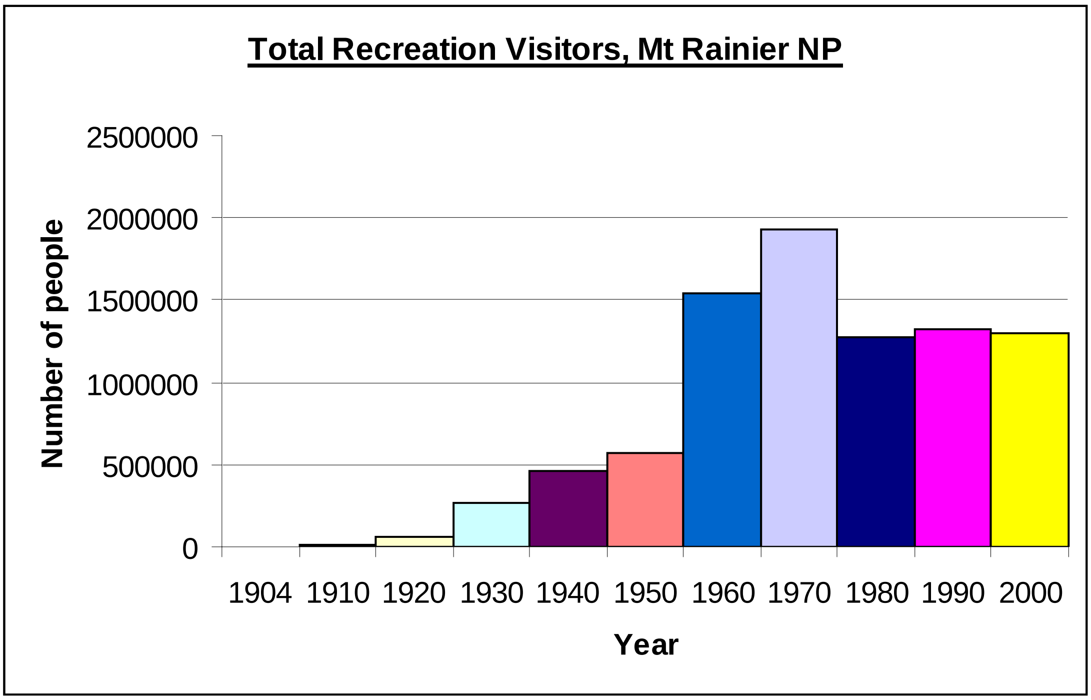

Figure 27: Total recreational visitors to Mt Rainier NP from 1904- 2000 (courtesy of B.Samora NPS)

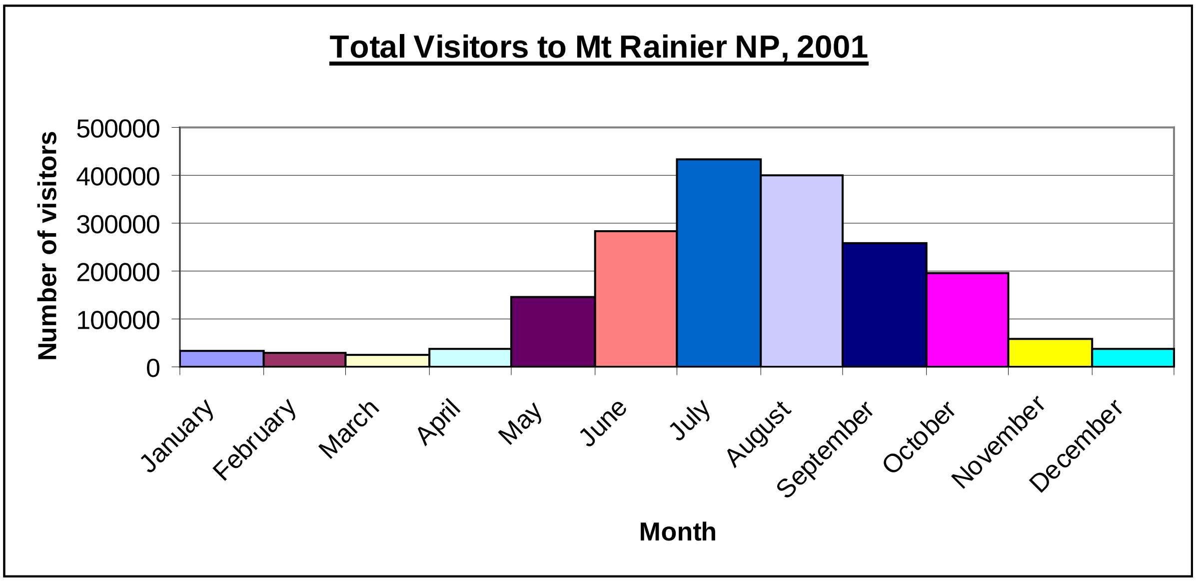

Figure 28: Yearly Visitors to Mt Rainier NP 2001 (courtesy of B.Samora NPS)

8.2: Recommendations for further Mitigation following the 2003 Van Trump Creek Debris Flow.

The people at high risk from debris flows such as the 2003 Van Trump Creek event are hikers following the numerous backcountry trails within the park and tourists at Christine Falls. To raise the awareness of geological hazards the NPS and USGS have placed numerous signs around the National Park (Figure 29). The warning signs presently at the national park offer no advice or instruction. These signs are mainly in camping areas or high visitor areas. There are no warning signs at the Van Trump Creek trailheads, or even at Christine Falls, which is a major tourist attraction with a car park, lookout point and where the Van Trump Creek crosses the main road from Longmire to Paradise. This report therefore recommends that clear signs giving instruction are emplaced at the Christine Falls and the Van Trump Creek trailhead area. Figure 30 is an example of the kind of sign needed in high risk zones within the National Park.

Figure 29: Warning sign presently at Cougar Rock Campground.

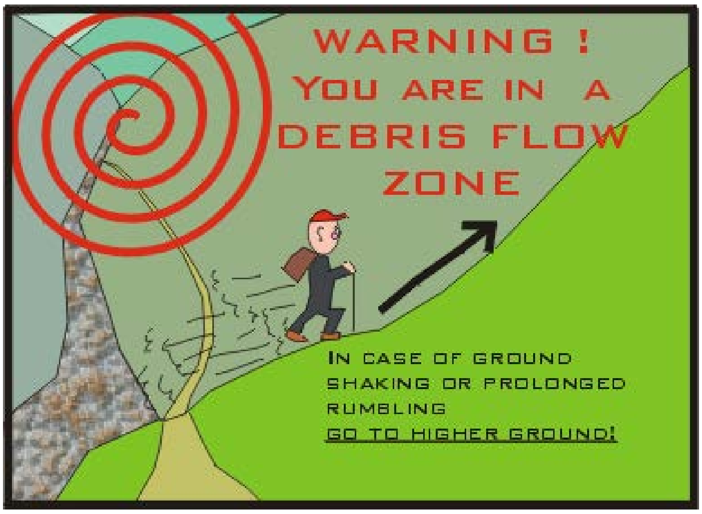

Figure 30: Recommended sign to be placed at the trail heads of the Van Trump Creek and at Christine Falls (modified from Scott et al 2001).

The recommended sign gives both information about how to identify the debris flow hazard and how to reach safety. In addition to these prominently placed instructural signs within the park, leaflets identifying the hazards and evacuation procedures should be given to all people staying over night within the National Park, especially to those who are camping at high risk campgrounds such as Cougar Rock and White River.

Geological Hazard Awareness talks should be incorporated within campground evening lecture series, and should be a prominent activity for the Junior Rangers programme.

If a debris flow alert has been issued by the NPS based on climate data monitoring, park rangers on the Nisqually entrance gates must let each vehicles populace know about the hazard and advise them to read the mitigation advice within the Mt Rainier National Park leaflets and trail map that is automatically given to each tourist as they enter the park.

The 'volcanic hazards' section on the Mt Rainier trail map needs to be in bold and within the main 'precautions' section of the map information, 'Hiking, Walking and Other joys of the Wilderness'.

8.3: Mitigation for High Magnitude Flows from Mt Rainier.

Essential mitigation strategies for lahars include land use planning, Lahar warning systems, engineering structures and evacuation routes. All of these schemes are exist at Mt Rainier.

8.31: *Land use planning.*

Arguably the most effective way to reduce the risk imposed by a lahar, debris flow or any volcanic event would be to remove the aspect of value or vulnerability outlined by Riedel (1997). By not allowing development in areas of high hazard as delineated by a hazard map the risk is removed. Land planning is a complex proposal for Mt Rainier as many settlements already exist on areas of high hazard. Many settlements such as Orting and Longmire are built over debris deposits. Land use planning must therefore reduce further development in areas of high to moderate risk.

8.32: *Lahar Warning System.*

For those settlements already established in areas of high hazard, evacuation plans can be developed. Evacuating populations from flow paths is an economically and socially disruptive procedure (Scott et al 2001). Evacuating a settlement needs to be well planned and must only take place when a flow is definitely approaching. False alarms and evacuations reduce the public trust in advisers and planners, and so the public could ignore future evacuation attempts. Therefore to assure a justified evacuation a warning system must be operational. These can be in the form of trip wires, where a series of wires are strung above potential debris flow routes: when the debris flow snaps these wires a signal is then sent to settlements downstream. Unfortunately this system is open to interference from animals, or human activity. A more accurate warning system is in place at Mt Rainier to warn the cities of Orting, Sumner and Puyallup (Figure 3). The ground shaking produced from a debris flow is unique, predominantly within the frequency range of 30-80 Hz. Acoustic Flow Monitors (AFM) can detect this frequency range. AFMs are solar powered microprocessor-based field computers linked to exploration model geophones (Scott et al 2001). They are installed upstream from settlements and a siren system can be positioned within the urban areas. AFMs can provide the valuable warning and evacuation time for the population to reach high ground before the flow arrives. The towns at Mt Rainier frequently practice for these evacuations and it is believed that due to these detectors the city of Orting will have nearly one hours warning time. If these detectors had been emplaced on Nevado del Ruiz, Amero may have been saved. The populations of these cities at Mt Rainier also need educating so that they can recognise the siren, act quickly and efficiently.

8.33: *Engineered Structures*

To protect existing settlements hard engineering structures may provide a defence against high to low magnitude flows. Sediment dams, reservoirs, diversion barriers are all potential options yet they are expensive and may cause secondary hazards such as water displacement from a reservoir if inundated by a lahar.

Specialised evacuation bridges can be built so that high ground can be reached quickly. The town of Orting is raising funds to build an evacuation bridge for their local school.

9: Discussion.

The future of Van Trump Creek is certain: at some point another debris flow will inundate the creek. Raising public awareness is essential in preventing disaster. As part of the field work for this report a questionnaire was carried out at Longmire to discover the how aware tourists are to the debris flow hazard at Mt Rainier. Appendix 8 gives a break down of the questions and the results. The public awareness was high, 60 % knew that Mt Rainier is affected by geological hazards, and 44% of people knew correctly what to do if a debris flow hazard was imminent. This suggests that the NPS educational mitigation schemes for tourists e.g. leaflets, signs, guided informational tours, are raising geological hazard public awareness effectively. Yet those tourists who knew what to do in the event of a debris flow hazard were questioned, “Where did you acquire this information from?” 37 % replied that the knowledge was commonsense, only 28% had been informed through NPS initiatives. Encouragingly all those who lived locally were aware of the hazards and knew what to do in the event of a debris flow.

The hazard and risk maps overlaid on to a DEM produces an image showing the exact path of the 2003 Van Trump Creek debris flow and its relating hazard and risk zones. This image simply and clearly locates the hazard so that local populations and tourists can identify areas of danger. Using visually stimulating maps such as those overlaid on to DEMs makes it easier for the vulnerable populations to understand the risks and the hazard locations. The three dimensional topographic representation makes it clear that the risk is lower on high ground than in low lying areas, illustrating why it is necessary to reach high ground in the case of a debris flow emergency.

10: Conclusion.

The 2003 Van Trump Creek debris flow was an ideal case study to examine the characteristics and effects of a debris flow of this magnitude. The different methods employed to investigate the debris flow varied in accuracy, from the highly accurate analysis of aerial photographs to the less precise velocity recordings. Overall the data collected for this report is sufficient to illustrate the nature of these frequent geological hazards.

The 2003 Van Trump Creek debris flow was triggered by a rock fall and enhanced by high precipitation. The debris flow was non-cohesive due to a lack of clay content within its composition and was relatively small with a volume of 200 000 m^3. The debris flow entered the Nisqually River Valley travelling at a minimum velocity of 5-6m/s (20kph), however it can be presumed that further upstream within the Van Trump Creek the flow velocity was a great deal elevated. The discharge was varied, with the variation dependent upon the channel topography.

The overall hazard posed by the debris flow can be assumed to be moderate. Due to the time of year visit numbers were decreasing thereby reducing the risk (Figure 28). However the National Park infrastructure that was either damaged or destroyed caused an economical loss for the park which was unacceptable.

The 2001 Van Trump Creek debris flow occurred during the peak of the summer tourist season indicting that these debris flows could occur at any time of year. This report primarily suggests additional instructural signs are posted at the Van Trump Creek Trail head car park and at Christine Falls.

Thousands of people visit Mt Rainier National Park each season, from a study carried out in August 2000, 62% of tourists visit Paradise, the majority of who would have entered the park through the Nisqually entrance travelling along highway 706, past Van Trump Creek and Christine Falls to reach their destination. The most common visitor past time is day hiking with 73% of tourists taking part in this activity. The Van Trump Creek trail is very popular throughout the summer: during this investigation over 50 people were passed on the trail in 5 hours. Raising public awareness about the dangers of debris flow hazards must be paramount for Mt Rainier NPS. It only takes one debris flow event to decimate essential infrastructure within the park and it may only take one more debris flow event to cause fatalities.

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