The Yellow Creek Alluvial Fan Dynamics and Impact to Tourism Infrastructure in the Fox Valley

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Abstract

Alluvial fans are dynamic depositional landforms that are susceptible to abrupt changes influenced by fluctuations in sediment supplies. In paraglacial environments alluvial fans display accelerated aggradation due to the extraordinary influxes of sediment into the system following glacier retreat. This thesis examines how a paraglacial alluvial fan in the Fox Valley has evolved over time, and assess the impact of fan dynamics on tourism infrastructure as well as probabilities of walking track closures. The study area is a significant tourism destination for the West Coast of New Zealand, with the Franz Josef and Fox Glaciers attracting 400,000 visitors to the area each year. Structure from motion (SfM), aerial imagery analysis, experimental physical modelling, binary regression statistics and chronological investigations using a Schmidt hammer, have all been incorporated into the methodology of this research.

The findings of this research identified that between 2015-2017, there had been a mean elevation change of 1.94 m (+/- 30 cm) across Yellow fan, signifying a significant amount of aggradation that impacted the walking track locality. Noticeable changes on other fans within the valley displayed a similar aggrading trend, which has influenced the locality of the active Fox River channel, and has consequently increased the vulnerably of potential damage to infrastructure. The research also indicated that there is a 17.7% chance the glacier walking track could be closed on any given day linking track closure to rainfall events. Overall the significance of this research provides insight into the relationship between the dynamic paraglacial processes within the Fox Valley and impacts on tourism infrastructure.

Acknowledgments

This thesis has been part of a long journey at the University of Canterbury and I would like to thank all the people that have helped me along the way.

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List of Abbreviations

2D	Two – Dimensional
3D	Three – Dimensional
a.s.l	Above sea level
AWS	Automated Weather System
DEM	Digital Elevation Model
DOC	Department of Conservation
DoD	DEM of Difference
GCP	Ground Control Points
GNSS	Global Navigation Satellite System
LINZ	Land Information New Zealand
NIWA	National Institute of Water and Atmospheric Research
NPMP	National Park Management Plan
NZTM2000	New Zealand Transverse Mercator 2000
RTK	Real Time Kinematic Mode
SfM	Structure for Motion
SPSS	Statistical Package for the Social Science
TLS	Terrestrial Laser Scanner
UAV	Unmanned Aerial Vehicle
WCRC	West Coast Regional Council

Terminology

Abandoned channels:	Channels that are no longer connected to mountains or active flow (Denny, 1967)
Aggradation:	Aggradation is the accumulation of sediment in river channel (Mugade & Sapakale, 2015).
Apex:	The highest point of an alluvial fan, which is where the stream emerges from the mountains (Drew, 1873).
Avulsion:	The relatively sudden displacement of a river channel (Jones & Schumm, 1999).
Base:	The term applied to the outermost or lower zone of the fan. This can also be referred to as the fan toe or the distal part of the fan (Blissenbach, 1954; Bull, 1977).
Fan entrenchment:	The downcutting into the fan surface of a channel that is contributing sediment to the fan surface. Entrenchment usually occurs during fan construction (Wasson, 1977)
Fan head:	The area of the fan which is close to the apex (Blissenbach, 1954).
Mid fan:	The area between the fan head and the base of the fan (Blissenbach, 1954).
Paraglacial alluvial fan:	A fan which is a product of an environment in the process of transition from predominantly glacial to predominantly fluvial conditions (Ryder, 1971). Also see section 3.1
***Sheet flow**:*	Is defined as relatively high-frequency, low-magnitude overland flow occurring in a continuous sheet, restricted to laminar flow conditions and is not concentrated into channels larger than rills (Hogg, 1982).
Secondary alluvial fan:	The alluvial fan at the base of a large primary fan, which consists mainly of reworked primary fan deposits (Blissenbach, 1954).
Terminus:	The glacier terminus (snout) is the end of a glacier at any given point in time Kumar, 2011).

Chapter 1: Introduction

1.1. Introduction

Alluvial fans are dynamic depositional systems that develop due to the differences between the upstream and downstream sediment transport capacity of a fluvial system, usually forming at the base of mountain fronts as rivers emerge from constrained catchments onto open plains (Clarke, 2015; Ballantyne, 2002a). They are dynamic landforms that are susceptible to abrupt changes on a geomorphological time scale (decades to centuries), heavily influenced by sediment supply fluctuations that promote stages of aggradation or degradation (Kleinhans *et al.,* 2013). The evolutionary stages of fan development provide considerable indications of environmental change, as development is controlled by fluctuations in climate, tectonics and base level (Nicholas, *et al.*, 2009). Extensive alluvial fan research has been conducted over the last 50 years exploring different depositional environments (e.g. Blissenbach, 1954; Pope & Wikinson, 2005), fan evolution (e.g. Harvey, 2005), time frames of fan development (e.g. White *et al*., 1998) and associated fans hazards (e.g. Jakob & Hungr, 2005). Whist, majority of literature has focused on arid and semi-arid regions (Lecce, 1990), there has been a noticeable shift towards alpine environments due to the dynamic nature of deglaciating landscapes.

Paraglacial landscapes and landforms are defined as 'non-glacial Earth surface processes, sediment accumulation, landforms, land systems and landscapes that are directly conditioned by glaciation and deglaciation' (Ballantyne, 2002a, p. 1938). Upon deglaciation there is a large influx of surplus sediment into fluvial systems from the increase in slope instabilities. Rockslides, rock fall and rock avalanches are all enhanced in both their frequency and magnitude in a paraglacial setting, triggered by the influence of large precipitation events that are associated with these higher altitude locations (Cossart *et al.,* 2008). The evolution of paraglacial alluvial fans are unique with an accelerated period of aggradation immediately following glacial retreat, known as the start of the paraglacial cycle (Ballantyne, 2002b). After deglaciation has been completed and the sediment supplies have been exhausted, the sediment yield rate of the fan will begin to normalise to the rates experienced before deglaciation, known as the end of the paraglacial cycle (Ballantyne, 2003). The life span of the paraglacial cycle is dependent on the amount of sediment available for erosion, geologic nature of the catchment, climate parameters and vegetation cover (Mercier, 2008). The life expectation is limited when sediment sources are exhausted, but this process can be prolonged for several centuries, or millennia, in areas that have sufficient sediment supply (Cossart & Fort, 2008).

Due to the gentle slopes, substantial drainage, good views and height above major river flood plains, alluvial fans have been attractive sites for anthropogenic development in mountainous regions (e.g roading, houses, walking tracks)(Welsh & Davies, 2011). While there are numerous amounts of management techniques available (e.g. levees, floodwalls, debris fences) (Philips & Williams, 2008) for infrastructure security, alluvial fans are dynamic landforms and susceptible to change. While mitigation measures are necessary they often give the illusion of stability and can promote subsequent infrastructural development without the potential hazards (Jakob & Hungr, 2005).

New technologies for assessing topographic changes in geosciences are becoming readably available for researchers. Structure from motion (SfM), is an effective low cost topographic survey tool which was developed in the 1980s (Mackie, 2017). Since 2011, the use of SfM has become increasingly more popular throughout geosciences applications, with the ability to create high spatial resolution topographic outputs within an accuracy of 0.1 m of TLS derived data (Westoby *et al.,* 2012). Due to the short duration and limited applications of this method, the potential for SfM applications is yet to be fully realised (Mackie, 2017).

In this thesis, SfM technology will be used to examine the evolution of a paraglacial alluvial fan and assess the suitability of this method with physical laboratory modelling. The main focus of this thesis is to identify short term and long term changes to the Yellow Creek alluvial fan in the Fox Glacier Valley. In particular, assessing the interaction of fan dynamics and influences on tourism infrastructure within the valley.

1.2. Research Objectives

This thesis will examine the paraglacial landforms within the Fox Glacier Valley. Specifically examining the alluvial fan properties and evolution of Yellow Creek.

The objectives of this research are to;

1) Examine how Yellow Fan has evolved in a paraglacial environment.
2) Investigate the causation of walking track variability, assess the susceptibility of closure and to examine current valley management techniques.
3) Investigate the use of SfM in field based applications and feasibility of using SfM in alluvial fan modelling.

1.3. Thesis Structure

This thesis is organised into seven chapters. The next chapter (chapter two) provides an overview of the Fox Valley study site. Chapter three provides background information of a paraglacial environment, alluvial fan characteristic and relevant literature to this research. Chapter four examines the methodology, data acquisition and processing techniques used for this research. Chapter five provides associated results and interpretations from research carried out. Chapter six provides a discussion of key themes identified within the results to meet objectives of this research and chapter seven provides a summary of key findings and perspectives of future research.

Chapter 2: Study Site

This Chapter provides a general overview of the study site used for this research and provides site specific geologic, geomorphic and climatic parameters.

2.1. The Fox Valley

The Fox Glacier Valley is located within the Westland *Tai Poutini* National Park on the West Coast of New Zealand's South Island (Figure 2.1).This National Park was established in the 1960s and spans over 131,600 hectares including the highest peaks of the Southern Alps, temperate rainforests, and rugged West Coast beaches (Stewart et al, 2016). The Fox Glacier and Franz Josef Glacier are the most well-known glaciers within New Zealand and attract approximately 400,000 visitors to the National Park each year (Wilson et al, 2014). The Westland District Council administers governance to the region, while the Department of Conservation (DOC) is responsible for the running and maintenance of National Park infrastructure and facilities (e.g. walking tracks, car parks and toilet facilities)(DOC 2001;Bosse, 2016). Accessibility to view Fox Glacier is from the glacier walking track within the valley that is regularly maintained by DOC. There are several viewpoints along the track (Figure 2.1b) that have been established to allow for partial track closures if required. The active geomorphology within the Fox Valley as well as rainfall, strongly influences the locality of the walking track (e.g. flooding, maintenance or rockfall), which requires ongoing maintenance and active management.

The Yellow Creek alluvial fan (Figure 2.1c) has been specifically selected as the main focus for this research due to dynamic interactions between fan development and the glacier walking track. The presence of the glacier in the valley has dominated research interest, meaning that paraglacial processes and other landforms have been under researched. The Yellow Creek alluvial fan is fed by Yellow Creek, which has a width of up to 500 m and varies 90 m in elevation up fan from the fan toe (260 m a.s.l) to the apex (350 m a.s.l). The position of Yellow Creek is determined by the presence of a large planar structure, trending NNW-SSE, dipping 55^0 towards the WSW (Hovius, 1995). The Yellow Creek catchment is relatively steep and extends up to approximately 1300 m a.s.l towards the North side of the Fox Valley. Yellow Creek is a tributary to the Fox River which adjoins the Cook River 12.5 km downstream. The majority of sediment transported by Yellow Creek, is eroded from the western side of the catchment, due to an abundance of sediment being supplied by the highly fractured bedrock and material from landslides. Earlier observations by Hovius (1995), indicate that the Yellow Creek catchment prior to the 1960s, experienced intense erosion, where there were large areas of exposed surfaces and minimal vegetation. During the 1960s and 1970s, the catchment was largely subdued to the erosion, which resulted in the construction of the first visitor carpark within the valley near the lower end of the creek. Following increased erosion within the Yellow catchment in the 1980s, a debris fan prompted the relocation of the carpark to its current location.

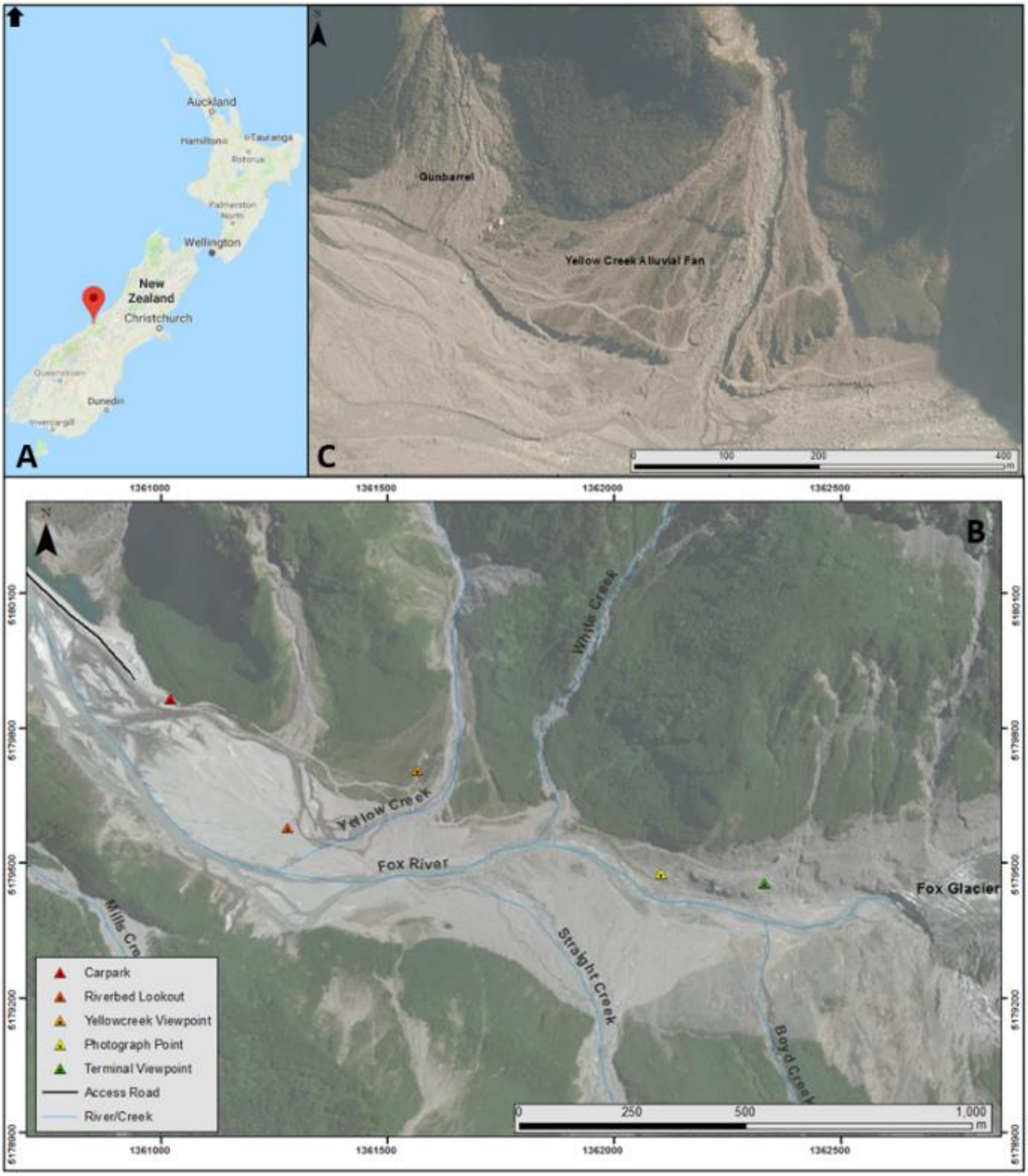


Figure 2.1: *Research study site. A) Location of Fox Glacier within New Zealand. B) The Lower Fox Glacier valley with key features identified. C) The Yellow Creek Alluvial Fan.*

2.2 Geology

New Zealand is a highly active geologic location due to ongoing interactions of the Pacific and Australian plates, which is signified by the active Alpine Fault on the West Coast of the South Island (Coates, 2002). The formation of the Southern Alps occurred in the Late Cenozoic as a result of the Pacific plate colliding with the Indo-Australian Plate, resulting in a tectonic uplift rate of 5-8 mm/yr (Fitzsimons & Veit, 2001). The regional geology of the West Coast is controlled by the by the boundary of the Alpine Fault. East of the fault are successive bands of metasediments, and close to the fault, uplift and erosion are pronounced, where marine sediments are being dragged up from large depths to form highly metamorphosed schist. The lithology within the lower Fox valley is predominately schist with sandstones and mudstones outcropping further up-glacier (Brook & Lukas, 2012).

2.3. Geomorphology

The Fox valley is a glacial valley that has a characteristic U-shaped profile; the valley sides are extremely steep and close to vertical in places along the south side of the valley with glacial striations present on exposed bedrock surfaces in the steepest parts of the valley (Hovius, 1995)., The valley is still occupied by the Fox Glacier, and has a number of large depositional landforms (e.g. alluvial fans and debris fan) and an active outwash plain that is 250 m wide (Hovius, 1995). There are numerous catchments within the valley that are typical of a dendritic drainage system, which all drain into the Fox River (Figure 2.1b). The combination of steep terrain, highly weathered schist and extensive moraine deposits on the valley sides means that the valley slopes are relatively unstable.

2.4. Glacial History

The Fox Glacier is a temperate valley glacier located at $43^{0}30'$S, $170^{0}10'$E. It is New Zealand's fourth largest glacier (Chinn, 2001), starting at 2700 m a.s.l., with an accumulation area that spans 25 km^2, the glacier flows steeply down into the narrow Fox Glacier, terminating at 270 m a.s.l. Currently the glacier is ~12.5 km long (Purdie et al, 2008; Anderson, 2003;Purdie et al, 2014).

Due to a fluctuating climate and warming trends, the Fox and Franz Josef Glaciers have overall been receding up the valley, but have also experienced minor re-advances at with approximately decadal regularity, which research has demonstrated is in part related to climate phenomena like the El Niño Southern Oscillation and regional temperature variability (Fitzharris et al. 2007; Mackintosh et al. 2017) (Figure 2.2) (Coates et al, 1991). As glaciers recede, they not only shorten in length but also thin (Purdie et al, 2015). This combination of shortening and thinning results causes in the surrounding landscape to respond through paraglacial processes, including destabilisation of glacially eroded slopes that were previously supported by larger ice volumes (see section 3.1)(Purdie et al, 2015; Ballantyne, 2002).

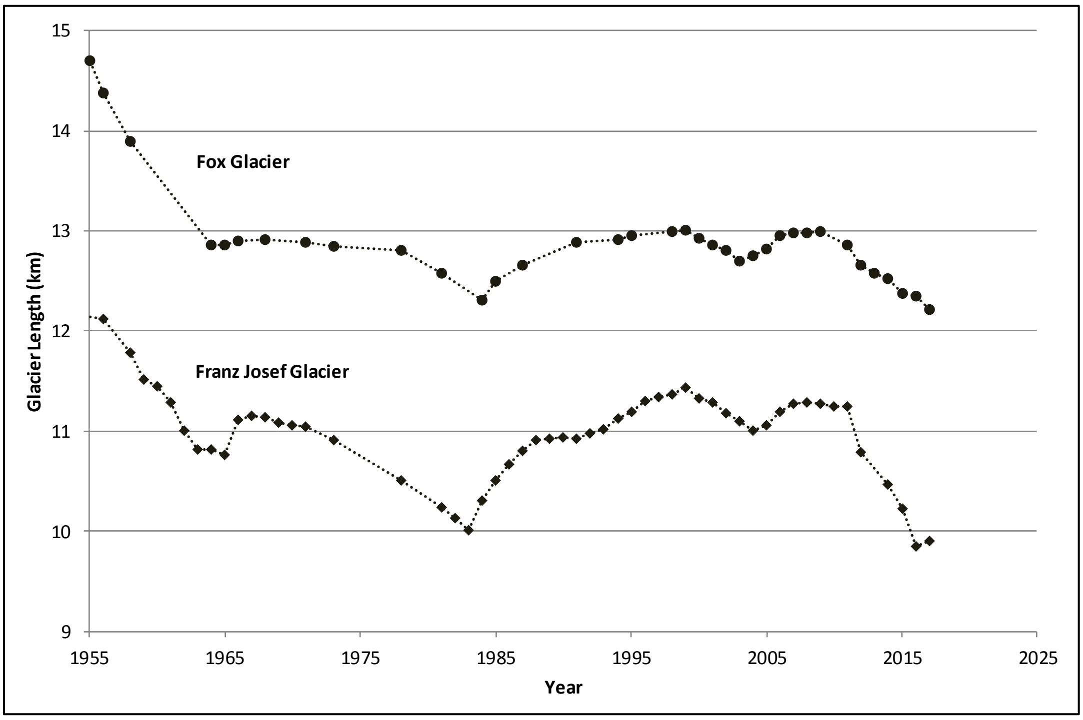


Figure 2.2: *The changes in glacier lengths overtime (Purdie pers. Comm, 2018).*

2.5 Weather and climate

The Westland region of the South Island is deemed the wettest region of New Zealand (Macara, 2016). The spatial distribution of rainfall on the West Coast is dependent on the elevation, exposure to rain bearing airflows from the west, and the orographic effect of the Southern Alps (Figure 2.3) (Henderson and Thompson, 1999; Klik et al, 2015; Macara, 2016). The weather conditions experienced on the west coast are dependent on dominant wind flows. Westerly flows experienced on the West Coast are associated with depressions in the south of the country and generally move towards the east, resulting in heavy rain. Unstable conditions are also associated with westerly flows, due to the change from predominate westerly to a south westerly flow, with dramatic clearances and showers re-developing. Northerly flows form between an anticyclone and a depression, which are usually accompanied by prolonged rainfall that can reach torrential intensities in the Southern Alps. The majority of the rain that occurs on the west coast is from winds that have a northerly component with a mild temperature. Fine weather conditions are associated with south easterly flows (Macara, 2016). Storms frequently occur on the west coast, where large quantities of rainfall are received over 24 hours (eg. 200 mm/day), and result in frequent flood events. In some instances, it is the intensity of rain events on the hourly scale, rather than the total amount of rainfall that can have the great impact on waterbodies (Davies et al, 2011).

Locally, in terms of mean annual rainfall in the Fox valley, there are currently no weather stations as NIWA ceased monitoring in 1994. However, the data gathered between 1966 and 1994 showed a mean annual precipitation amount of 4691 mm (Purdie et al, 2008). The nearest active weather stations are in the Franz Josef, with a mean annual precipitation between 1981 and 2010 is 5751 mm (Macara, 2016).

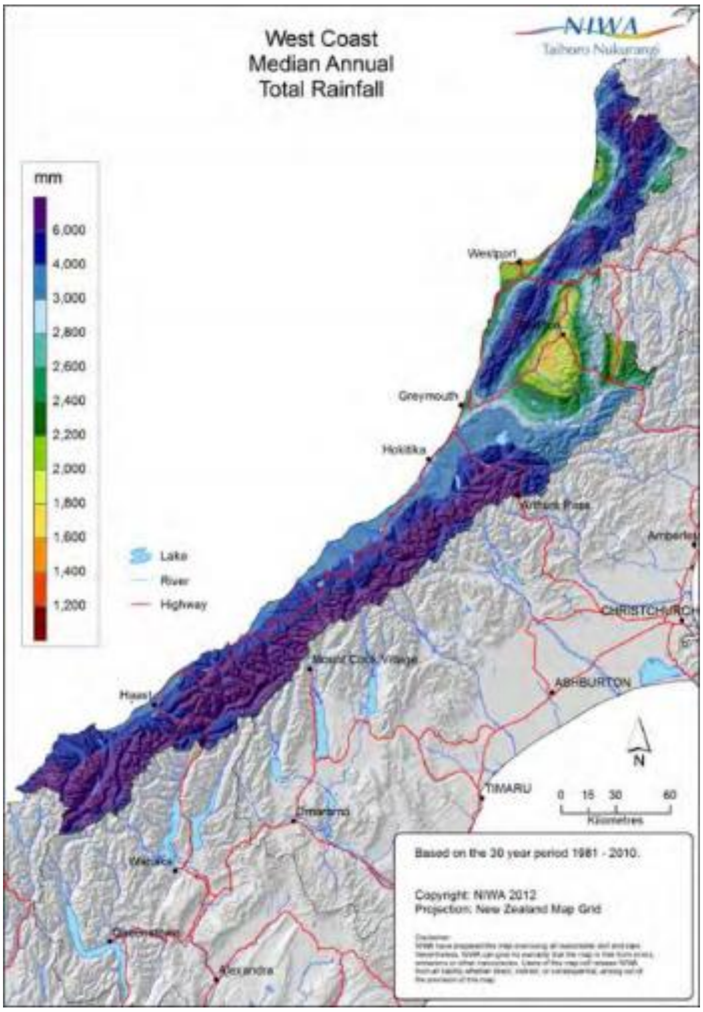


Figure2.3*: Median annual rainfall (1981 -2010) for the West Coast region of New Zealand (Macara, 2016).*

Chapter 3: Background Information

In addition to primary research completed for this thesis, it is also highly valuable to review previous research relating to the specific features discussed throughout. The aim of this chapter is to provide a brief introduction to paraglacial environments, dynamic characteristics of alluvial fans, as well as providing an overview of existing literature within the Fox Valley.

3.1. Paraglacial environments

When the term 'paraglacial' was introduced in the early 1970s, it was used to describe the response of a fluvial system to the rapid sediment adjustments from glacial and non-glacial conditions. Specifically, the large quantities of readily available glacial sediment and the reworking of this sediment during and after deglaciation (Wilson, 2009; Ryder, 1971; Church & Ryder, 1972). Over the past 35 years the meaning of the term has been extended to include adjustments of mountain rock walls and coastal environments (Wilson, 2009; Wyrwoll, 1977; Forbes & Syvitski, 1994). As a result, Ballantyne (2002a, p. 1938) has redefined the term 'paraglacial' to be 'non-glacial Earth surface

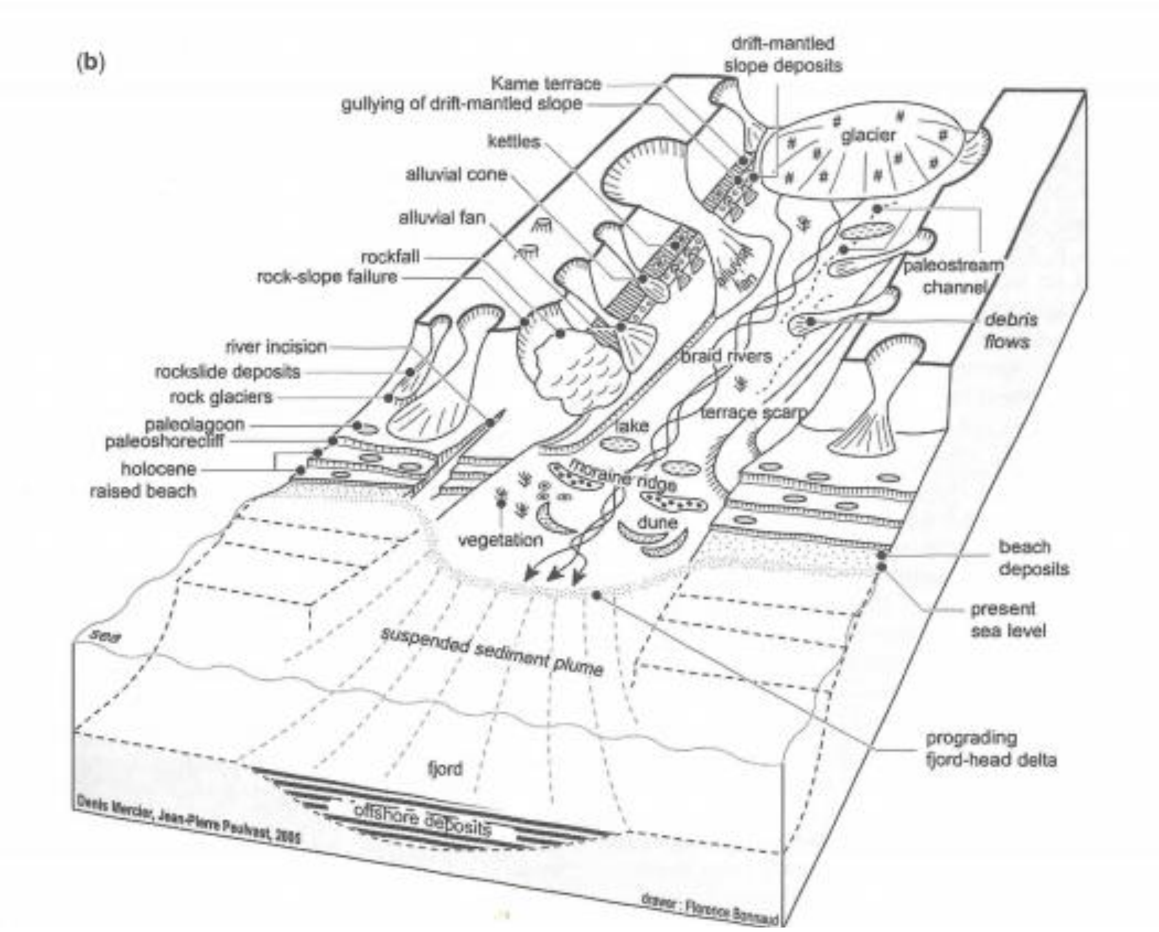


Figure 3.1: *Paraglacial landforms and processes (Mercier, 2007)*

processes, sediment accumulation, landforms, land systems and landscapes that are directly conditioned by glaciation and deglaciation'. This recognising that glaciation and deglaciation impacts a range of geomorphological processes and landscape components as opposed to just the fluvial system (Wilson, 2009). Landforms and land systems that are regarded as paraglacial features include; debris cones, alluvial fans, valley fill deposits, rock slopes, sediment mantled slopes, glacier forefields, glaciolacustrine systems and coastal systems (Figure 3.1) (Slaymaker, 2009).

The paraglacial concept cannot be pinpointed by processes (Ballantyne, 2003), even though the expression of 'paraglacial processes' has been now in common use (Andre, 2009). Rather it focuses on the accelerated conditions of accelerated geomorphological activity after glacier retreat (jakobizaga, 2011). A common discussed feature following deglaciation of a landscape is the supply of additional sediment sources, such as unstable rock walls or glacigenic sediment storages, which are highly susceptible to erosion (Ballantyne, 2002b).

A term commonly used in literature to describe this phenomena is the paraglacial cycle. This is used to describe the extraordinary sediment supply that exceeds the rate of debris produced by weathering in a paraglacial environment (Ballantyne 2002b). It was first discussed by Ryder and Church (1972), in which following deglaciation, sedimentation rates are accelerated with the surplus supply of sediment. Over a sufficient timeframe, once the sediment supplies are exhausted, the sedimentation rates will start to decline and return to background sediment release rates. The timeframe for this sedimentation process, has been widely discussed and has resulted in the creation of numerous sediment exhaustion models (e.g. Ryder & Church, 1972; Harbor & Warburton; 1993; Forbes & Taylor, 1987). As a result, an idealised sediment exhaustion model has been created by Ballantyne (2002b) (Figure 3.2), which assumes that the rates of sediment release is dependent only on sediment availability. That sediment sources are not replenished and that the rate declines exponentially overtime (Iturrizaga, 2011).

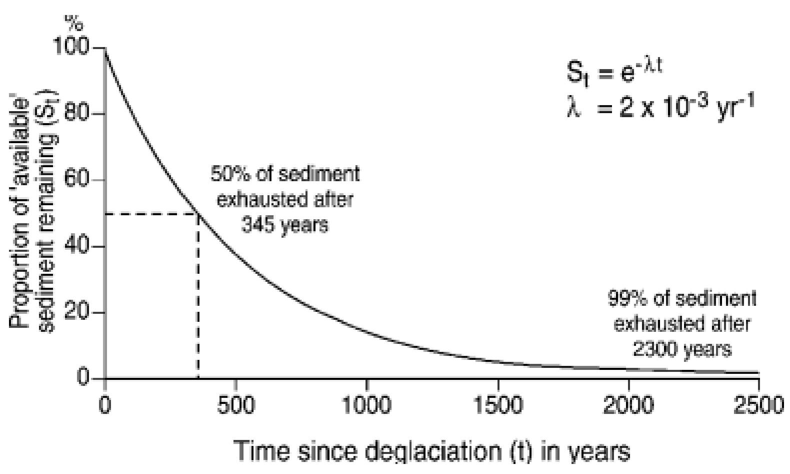


Figure 3.2: *Exhaustion model paraglacial sediment release (Ballantyne, 2002b)*

Sequentially, paraglacial landforms and land systems all have different response and recovery times depending on the spatial scale, making it hard to distinguish an exact overall timeframe (Slaymaker, 2011). Paraglacial environments are landscapes that have been active since the last glacial maximum (Church & Ryder, 1972), which in New Zealand occurred 19000 years ago (Suggate & Almond, 2005).

3.2 Alluvial Fan Characteristics

3.2.1 Alluvial Fans

Alluvial fans are depositional systems that develop due to disparity between the upstream and downstream sediment transport capacity of a fluvial system (Clarke, 2015). The term alluvial fan has been used to describe these landforms, due to the fan like shape produced and the contributing fluvial process (Figure 3.3). Other processes that may contribute to fan formation include, debris flows and snow avalanches. Debris flow activity on fans is highly sporadic and irregular based on the availability of unconsolidated materials and occurrence of intense rainfall within a catchment (Beaty, 1990). A complex fan formation, also known as a composite fan may incorporate a range of sediments from mudflows, debris flows or glaciofluvial, lacustrine, fluvial and aeolian derived processes (Ballantyne, 2002a).

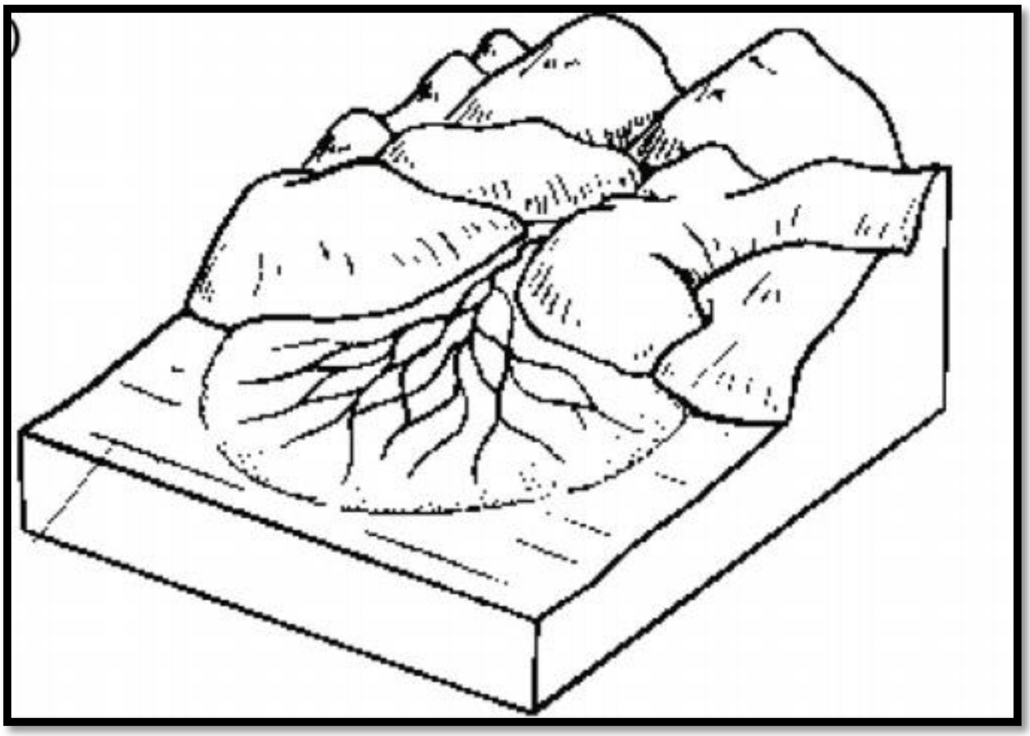


***Figure 3.3**: a conceptual diagram of an alluvial fan (Rachocki, 1981).*

Fan

deposits characteristically exhibit parallel bedding, generally low roundness, although can increase down fan in some instances and a decreasing particle size towards the fan base (Rachocki, 1981). Fans have also been distinguished to have a slope generally less than 15^0, but are often less than 5^0, anything steeper than 15^0 could be considered a debris cone (Ballantyne, 2002a).

3.2.2 Fan dynamics

Alluvial fans are dynamic landforms, the evolution of which is determined by both external (allogenic) environmental parameters (e.g. climate, tectonics, drainage basin size and base level change), and internal (autogenic) process-form feedbacks (e.g. the change between sheet flow and channelized flow states) (Clarke, 2015; Nicholas et al, 2009). Development of alluvial fan systems has long been investigated within the geomorphological and sedimentological literature, however, it can be often difficult to isolate the influence of each contributing environmental parameter (Hartley *et al.,* 2005). Alluvial fan physical modelling has been largely used within literature to try establish relationships and observe the evolutionary processes of fan development (e.g. Clarke, 2015; Clarke *et al.,* 2010; Hooke, 1968; Schumm et al., 1987). However, the understanding of autogenic controls on alluvial fan evolution remains limited, in particular the relationship between flow width and depth and sediment transport and how these may alter in response to changes in fan morphology (Clarke *et al,.* 2010).

Climatic changes appear to be the primary control of fan development, with periods of excess sediment supply leading to fan sedimentation through aggradation and progradation (Harvey, 2005). This is a result of the fluvial system readjusting to changes in precipitation, solar energy inputs, changes in base level and changes in vegetation (Kleinhans *et al.*, 2012). Paraglacial alluvial fans form as a response to a change of climate, where there is ample sediment available (see section 3.1). They experience initial aggradation at high rates due to the large sediment input, followed by incision and terrace development as sediment inputs decline and the base level is lowered by regional uplift (Ballantyne, 2002a).

Stabilisation of fans occur when either the main channel becomes entrenched in the fan, or the sediment ceases to be supplied, which is signified by the establishment of vegetation (Carryer, 1966). Many alluvial fans that exhibit fanhead trenches can still aggrade in their distal zones but are stable up fan (Harvey, 2002). Late stages of fan development are largely influenced by the maturity of the fan and the beginnings of features that occur in the late stages of fan development (e.g. effects of varying base levels, tectonic movements, slumping of unconsolidated material and secondary alluvial fans)(Blissenbach, 1964).

3.2.3 Hydrology and Channel Dynamics

The fluvial system is a complex response system with two main components, the morphological system of channels, floodplains, deltas and the cascading system of the flow of water (Piegay & Schumm, 2005). The channel dynamics on alluvial fans are similar to and often compared to a braided river system (Blair & McPherson, 2009). Fans have three different zones of hydraulic processes (Figure 3.4), zone one is the main channel zone near the apex, signified by one active channel that is usually incised signifying stability of the upper fan. Zone two is the braided zone where the channels are unstable and create multiple smaller channels that are prone to avulsion episodes. Zone three is the sheetflow zone found far down the fan, where the flow spreads laterally and is very shallow (French, 1987).

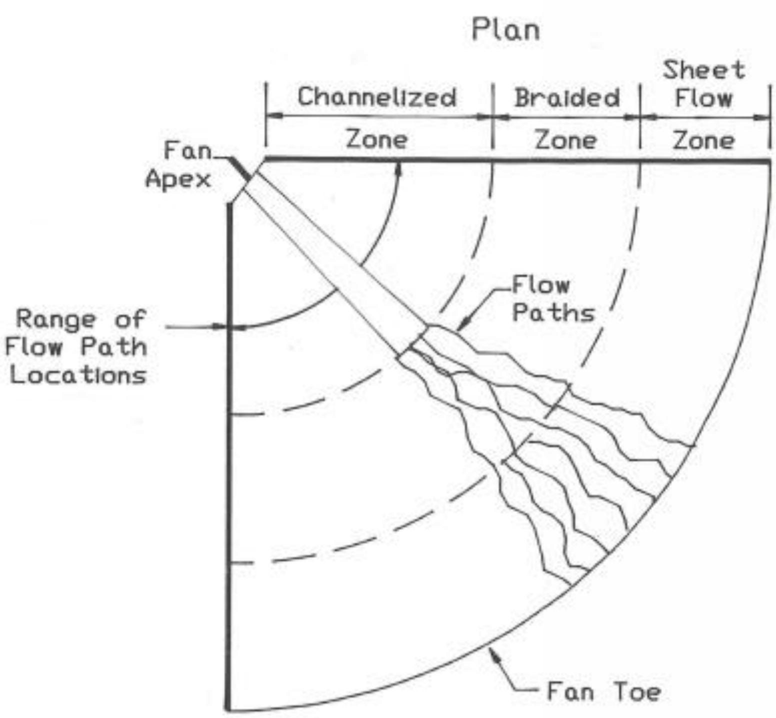


Figure 3.4: *The different flow zones on an alluvial fan (French, 1989).*

3.2.4 Alluvial Fan Environments

Alluvial fans are commonly found in arid and semiarid regions with tectonically active mountains, resulting in an abundant supply of sediment (Lecce, 1990). However, alluvial fan development is not confined to these particular areas and can occur in humid temperature regions, alpine environments, the humid tropics, paraglacial, periglacial, Arctic and Antarctic environments (De Haas et al, 2015; McPherson, 2009; Harvey, 2011). Extensive alluvial fan research has been carried out over the last 50 years. However, some alluvial fan environments have been more intensively research compared to others, the formation of alluvial fans remains similar, and it is just the scale of the fan that is different (Lecce, 1990). Many different studies suggest that processes leading to fan deposits differ little between humid and arid environments or between arctic and subtopic environments. Fans from periglacial regions were also found to be relatively similar to fans developed in other climates, although periglacial fans have been largely understudied (De Haas *et al.,* 2015).

McEwen *et al.,* (2011), suggests that a small amount of alluvial fan research had been completed on explaining alpine fan morphology and development in terms of nature, magnitude, frequency and the dynamics of different process regimes. The majority of studies done on an alpine environment (e.g. Krostaschuk *et al.,*1986; Decaulne *et al.,* 2007; Hornung *et al.,* 2010; Crosta & Frattini, 2004; Cavalli & Marchi, 2008; Marchi *et al.,* 2010) focus on glacier-fed fan development, whether this be as a result of glaciation or deglaciation (e.g. paraglacial processes). For example, Horung *et al.,* (2010), explored the relationship between sediment fluxes and the development of a fan during the Holocene in Switzerland, concluding that the sediment fluxes had declined overtime reflecting reductions of sediment production within the source catchment (paraglacial cycle).

3.2.5 Influence on Evolution and Shape Variations

The factors that influence fan morphometry are; the supply of water, sediment from the feeder catchment and allogenic environmental parameters (Al-Farraj & Harvey, 2005). More specific factors identified by Kochel (1990) and Weissmann & Fogg (1999) that affect the fan morphology include;

- The nature of dominant depositional processes (e.g. fluvial, hyper concentrated flood flow, debris flow)
- Frequency of depositional events
- The rate of recovery or revegetation of hillslopes and fan surfaces following deposition events
- Source basin lithology
- The degree of topographic restriction or the deposition site where fans are constructed

- Post deposition modifications of fan sediments by other geomorphic processes (e.g. the cutting of the fan toe by an active river at the base of the fan)
- Sequences that form in response to changes in accommodation space caused by base level or base profile changes

3.2.6 Time scale

The time scale of fan development are largely varied and largely dependent on availability of sediment. Most alluvial fans were formed during the last glacial age, with more recent fan development occurring in paraglacial environments (see section 3.1), although frequent debris flows can form steep and small alluvial fans (Ono, 1990). For example, alluvial fan development in north and central Japan occurred mainly in the early half of the last glacial age, between 90000 and 40000 years ago, where the fans formed through glacial/interglacial climatic changes when there was an abundance of sediment available (Ono, 1990).

3.3 Hazards

3.3.1 Alluvial Fan Hazards

A natural hazard results from climatic, tectonic or other geomorphic events of natural processes that continuously reshape the landscape in order to maintain the equilibrium between endogenous and exogenous processes, therefore they are not isolated events but tend to recur (Kritikos, 2013). Predominate hazards associated with alluvial fans are flooding and debris flow events. Alluvial fan floods typically do not exhibit the same predictable behaviour compared to normally encountered river floodplains. This is due to unpredictability of flow paths and large availability of sediment within the catchment (Philips & Williams, 2008). The FEMA (1989) has identified the following characteristics of flood and debris hazards which are commonly associated with alluvial fans;

- High velocity flows that can produce significant hydrodynamic forces on structures.
- Significant erosion/scour
- Inundation of the fan area
- Flash flooding
- Unpredictable flow paths with the potential of channel avulsion
- Hydrostatic and buoyant forces
- Large sediment influxes and deposition depths from a single debris flow event

3.3.2 Glacier Hazards

Hazards associated with glaciers include sea-level rise, landslides and mass movements (see section 3.3.3), changes to streams and glacier outburst floods (Clague, 2013). The melting of glaciers contributes to the current sea level rise of about 3 mm/yr., if all the glaciers were to disappear sea level would rise by several tens of centimetres, but would still have a detrimental effect on low lying coastal areas (Larsen *et al.,* 2007). Glacier outburst floods occur when large bodies of water become trapped, within, beneath or at the margins of glacier and subsequently drain suddenly causing down valley floods (i.e. Jökulhlaups) (Clague, 2013).

3.3.3 Paraglacial Hazards

Hazards in paraglacial environments include rockslides, rock fall and rock avalanches due to the landscape relaxation processes immediately following ice retreat in areas associated with glaciation (Hewitt, 2006). The unloading pressure on the material results in an increase in instability, due to the steep slopes and geological parameters associated with different rock types and jointing. Rockslides, rock fall and rock avalanches are all enhanced in both their frequency and magnitude in a paraglacial setting, triggered by the influence of large precipitation events that are associated with these higher altitude locations (Cossart *et al.,* 2008). For example, from August 20-23, 2005, in the European Alps, a large storm with extremely high rainfall intensities caused major river erosion, flooding events and triggered landslides, debris flows and rock fall (Hilker *et al*., 2009).

3.4 Anthropogenic Influences

3.4.1 Urbanisation on Alluvial Fans

Alluvial fans are commonly used as sites for development in mountainous regions. This is due to their gentle slopes, substantial drainage, good views, and they are generally above the flood range of major rivers (Welsh & Davies, 2011). Despite the positives around developing infrastructure on fans, there are dynamic landforms and have associated hazards. For Example, the town of Antofagasta (Chile), experienced a significant flooding event from 42 mm of rain that fell within three hrs. Subsequently, 100 people were killed and extensive damage was caused (Mather & Hartley, 2005). In New Zealand, Aoraki/Mount Cook village is situated on the Black Birch fan. In the 1960s an upgrade was needed on the oxidation ponds and they were built out of sight on the fan. As a result this required river control work to keep the Black Birch stream to the southern side of the fan, which gave the illusion of stability and promoted subsequent infrastructural development. The stream is continuously constrained by earth works to prevent avulsion (Jakob & Hungr, 2005).

3.4.2 Typical mitigation structures

The dynamic nature of alluvial fans provides numerous floodplain management challenges due to the unpredictability of flow paths and delivery of large amounts of sediment (see section 3.3.1) (Welsh & Davies, 2011). Typical mitigation structures identified by Phillips & Williams (2008) for alluvial fan management include the following;

- Levees and floodwalls
- Channelization or straightening of the main channel
- Debris and detention basins
- Drop structures
- Debris fences
- Local diles
- Street orientation
- Elevating structures
- Floodplain zoning.

Protection measures that provide whole fan protection include levees, channelization, detention basins and debris basins or dams (FEMA, 1989). While these management techniques are widely used, they are designed for long term solutions on urbanised fans (Phillips & Williams, 2008).

3.5 Tourism in the Fox Valley

3.5.1 Tourism to the Area

The Westland *Tai Poutini* National Park is home to the Franz Josef and Fox glaciers and is one of the South Island's most iconic tourism destinations (Wilson *et al*., 2014). In 2013, a total 418,466 international tourists visited the wider West Coast region. The majority of whom visited the glaciers, with 283,374 tourists staying on overnight trips in the West Coast region (Statistics New Zealand, 2014). A survey conducted by Wilson *et al* (2014) found that majority of visitors visited both glaciers, whist the remainder were just going to visit one of the two. Over the past four decades fundamental challenges have arisen for Nature-Based tourism industries due to climate change (Espiner *et al.,* 2017). Nowhere in New Zealand are these changes most evident than at the Fox and Franz Josef Glaciers (Wilson *et al*., 2014). For example, in 2013/2014, the increase in slope instability from the retreat of both the Franz Josef and Fox Glaciers, resulted in the suspension of walk on glacier guided tours. Currently, the only way to access the glaciers is from air, which is highly weather dependant and provides continuous challenges for tourism satisfaction and businesses in the area (Stewart *et* *al.,* 2016). Tourism in the Westland area is increasingly significant for the surrounding townships and livelihoods of locals. A survey completed by Stewart et al (2016), found that the glaciers are perceived as a high commodity and extremely influential to the area. For example two stakeholders responses where; 'the glaciers are first and foremost the reason why people stop at Franz and Fox' (DOC), 'if the glaciers were not here, these towns would not be either' (Franz Josef activity operator) (Stewart *et al.,* 2016).

3.5.2 Current Management Plans

In accordance with the New Zealand National Park act 1980 and policy for National Parks 1983, the Westland *Tai Poutini* National Park Management Plan (NPMP) 2001-2011 was established for the management of the park. Under the jurisdiction of the plan it is DOCs responsibility to ensure all objectives are meet and maintained. For example, in section 4.3.13a of the management plan, DOC must inform park visitors and concessionaries of potential natural hazards in the park in order to create an awareness and understanding of natural hazards, whist it is still recognised that visitors will be primarily responsible for their own safety (DOC, 2001). This is currently achieved within the valley through the use of hazard warning signs (Figure 3.5) and visitor information boards through recommendations from Espiner (1999).

Figure 3.5*: Rockfall hazard sign used within the Fox Valley (Dyer, 2017)*

In a response to the Franz Josef and Fox Glacier recession, DOC undertook a partial review of the *Tai Poutini* NPMP (DOC, 2013). The review sought stakeholder feedback on ongoing issues (e.g. aircraft access, extending access roads, upgrading walking tracks) to help compensate for increased distances to the glacier termini. The amendment that was released sought to balance the aspirations of commercial businesses accessing the glacier, alongside recreational groups who were concerned about increasing disturbance from aircrafts and vehicles (Stewart *et al*., 2016; DOC, 2013).

The flexibility of the 2001- 2011 NPMP was identified in the 2012 review as to not being flexible enough to cope with the current speed of the glacier changes. When the plan was first approved in 2001, it was not anticipated how dramatic the rate of glacier retreat would be and subsequent problems with losing walking access to the glacier (DOC, 2013). Subsequent adaptive management strategies have been incorporated in the amended 2014 NPMP and include the use of 'near terminal' terminology as descriptive end points of the routes. Enabling appropriate end points to be selected when walking tracks are constructed maximises visitor safety and enables the track end points to change the glaciers retreat or advance. The construction of the walking tracks within the valley has also been specified to be unsurfaced, to ensure that ongoing maintenance and reinstatement of tracks is at a minimum following flooding events (DOC, 2013).

Chapter 4: Methodology Data Acquisition and Processing

This chapter provides details of the methodological approach used including a description of the research methodology, data acquisition in the Fox valley, processing of data and associated limitations.

4.1 Structure from Motion (SfM)

4.1.1 General Method Overview

Over the last decade a technological revolution in geomatics has transformed the way digital elevation modelling has been incorporated with geomorphological terrain analysis (Westoby *et al.,* 2012). Geosciences frequently use three-dimensional (3D) topographic information to quantify landforms and landform properties, specifically conceptualising changes from observations and the use of numerical models (Carrivick *et al.,* 2016). Through new methods of acquiring topographic data, technological advancements, higher quality spatial resolution, and the ability to match the scale of topographic data with the spatiotemporal scale provide greater details of landform morphology (Carrivick *et al.,* 2016). This enables the quality of digital elevation models (DEMs) to have larger spatial extents, improved accuracy and greater resolution outputs (Westoby *et al.,* 2012). Current topographic data survey methods such as traditional ground surveying, terrestrial laser scanning (TLS), and remote sensing provide a substantial digital output. However, these methods are often restrictive for data acquisition with high costs or lack practicality in rugged environments.

A new topographic tool, Structure for Motion (SfM), creates high resolution 3D models from a series of overlapping offset two-dimensional (2D) images (Figure 4.1) with appropriate processing software (Mackie, 2017). SfM compatible software, such as Agisoft Photoscan, 123D Catch/ReCap and Autodesk ImageModler, use algorithms to identify and pixel-match features based on luminance and colour gradients from overlapping digital images, as well as calculating camera orientation and location from the different positions of multiple matched features (Carrivick *et al.,* 2016). However, SfM only provides relative camera locations and scene geometry, which as a result, the generated point cloud output is in an arbitrary coordinate system. To create spatially relevant SfM derived outputs, image collection is required and images must be processed in conjunction with a georeferencing system (i.e. ground control points (GCPs)) (Szeliski, 2011). Successful georeferencing and scaling of the point cloud requires a minimum of three GCPs with XYZ coordinates (Carrivick *et al.,* 2016).

Gruen (2012) states that the pixel matching phase of a SfM workflow is the most important function and is affected by image quality, lighting conditions and surface characteristics (i.e. texture). In agreement, Mosbrucker *et al.,* (2017) has identified that in terms of SfM accuracy for camera collaboration, point density, and DEM outputs, it is the pixel- level detection within the source imagery that is key. When working in the physical environment and at large scales, lighting conditions, changes in shadow length, surface albedo, and distribution of camera positions can also affect the quality of 3D models produced (Carrivick *et al.,* 2016). Westoby *et al.,* (2012) and Gienko and Terry (2014), found that the accuracy of SfM derived 3D models is highly correlated with the number of points used to reconstruct a surface (i.e. point density).

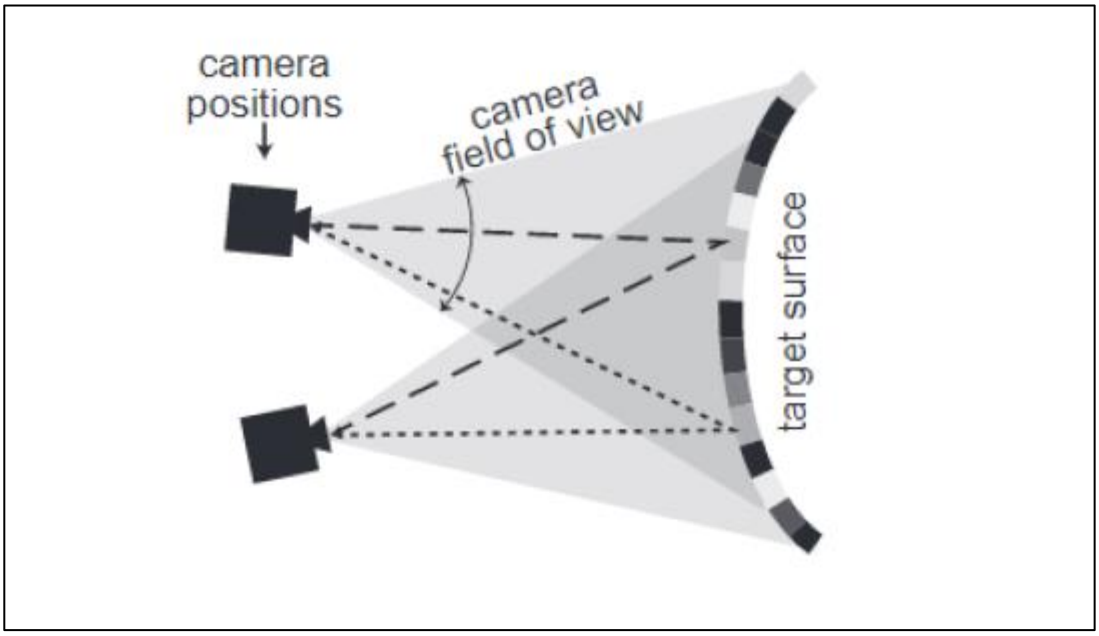


Figure 4.1: *An example of how SfM works with camera positions in regards to overlapping of 2D imagery. Multiple images are captured from a range of angles and positions of the targeted surface to ensure optimal imagery overlap (Bemis et al., 2014).*

SfM is a relatively low-cost and effective method that can capture complex topography in a variety of environments. Additionally, data acquisition for SfM is easy with multiple techniques available (e.g. Ground base hand-held device, Unmanned Aerial Vehicle (UAV), helicopter). The method can be applied over a great range of spatial scales (10^{-2} to 10^{6} m^2), where the accuracy of a survey in some circumstances is comparable to that from modern TLS. Associated disadvantages with using SfM include errors arising from the control of the surveyor; the post field collection processing, which as a result the survey output is not known until a later date and dependant on number of imagery, the processing time can be a long process (Carrivick *et al.,* 2016).

The relevance of using SfM for this research is based on the advantages associated with this method and previous geomorphic applications of SfM. SfM derived DEMs have been used to investigate landslide displacement, landslide expansion, identifying flow kinematics such as flow rate, scarp erosion and sediment accumulation (Niethammer *et al.,* 2011; Lucieer *et al.,* 2014). SfM is the primary method used within this research and will be used to address objectives one and three.

4.1.2 Data Acquisition

Acquisition of imagery for SfM processing took place on the 15th November 2017, with the use of a DJI Phantom 4 drone (Figure 4.2). For the purpose of undertaking an airborne survey of Yellow Creek alluvial fan, the flight paths were pre-planned using the Map Pilot application compatible with DJI software. This ensured optimal use of flying time in accordance to battery life and to allow the entire fan to be included. Five flight paths were established across Yellow Creek (Figure 4.3), with a flying height of 60m from each take-off location to optimise imagery overlapping for a more detailed SfM output with post-field processing. Prior to completing the flights, seven yellow ground targets were randomly distributed across the fan to provide ground control (Figure 4.4). Each GCP target was surveyed with a Trimble R8 Global Navigation Satellite System (GNSS) using the real time kinematic mode (RTK) in a New Zealand Transverse Mercator 2000 (NZTM2000) coordinate system. The GNSS base station was set up on the lower reaches of the fan in conjunction with a base control set up at

Figure 4.2*: DJI Phantom 4 drone used for airborne survey of the Yellow Creek alluvial fan.*

the Land Information New Zealand (LINZ) benchmark in the Fox village (at the junction of Cook Flat road and SH6).

Operating a drone within a National Park requires some flight restrictions to be observed (http://www.caa.govt.nz/rpas/), in particular, with the large amount of helicopter flights in the valley, the drone could not be flown during the early evening until all scheduled flights had been completed in the valley. Completing the drone survey in the early evening meant that there was a low amount of foot traffic in the valley, reducing the risk of possible incidents or disturbance of visitors. Due to the early evening drone survey, lighting conditions were dull and have the potential to impact on pixel matching.

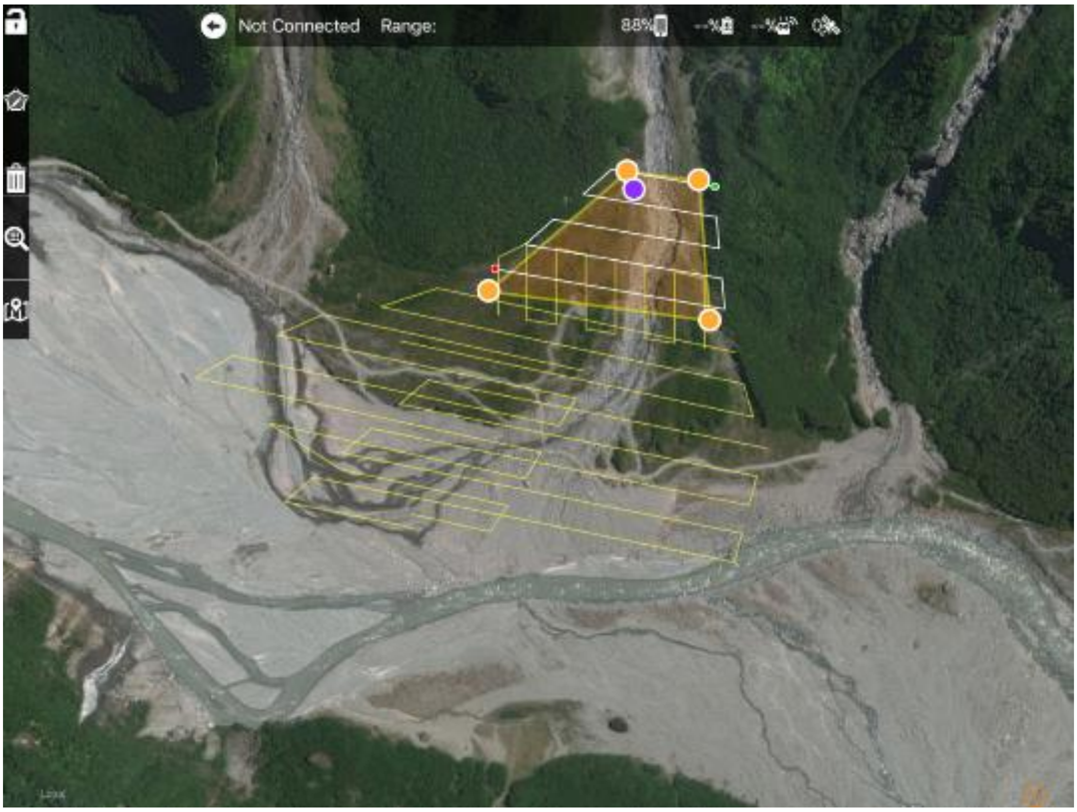


Figure 4.3*: Screenshot of completed flight paths for drone survey from Map Pilot. The first flight path has been highlighted in orange with the orange dots representing the boundary of flight one. The purple dot within the image displays the drone location. The green dot represents the starting point for imagery capture and the red dot represents the finishing location for that particular flight.*

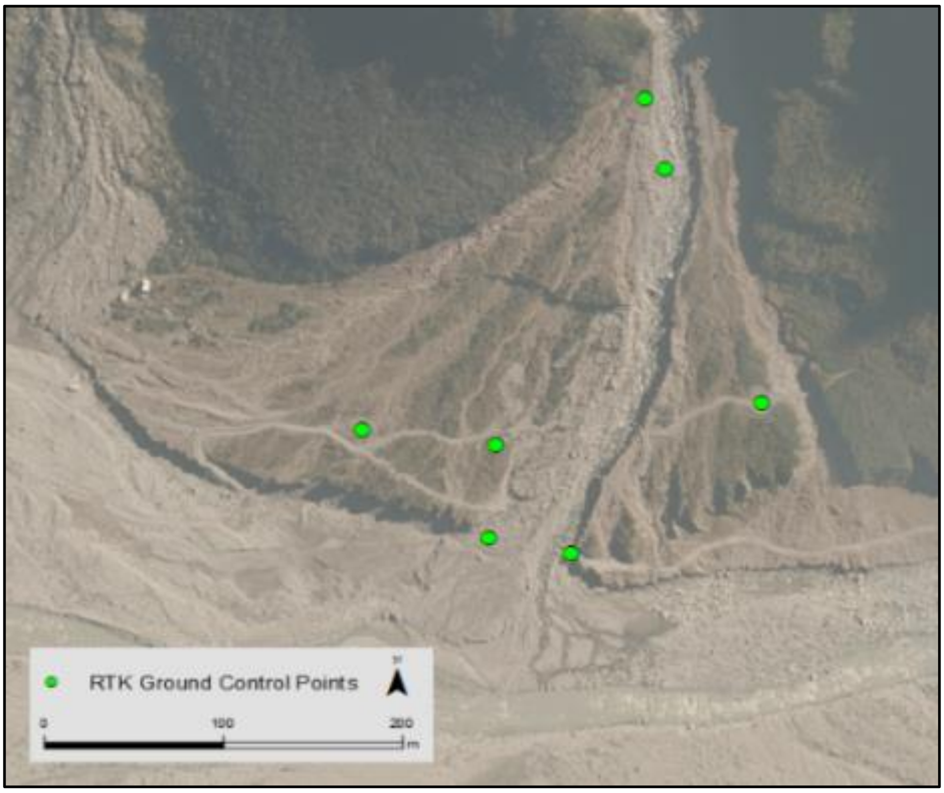


Figure 4.4: *Mapped ground control points used for drone survey.*

A DEM from November 2015 was supplied by Dr Sam McColl (Massey University) from previous work in the valley (Figure 4.5). The Fox2015 DEM was also generated by SfM, being produced from an aerial survey of the whole Fox valley using helicopter mounted cameras. The survey was completed in NZTM2000 at ellipsoidal heights using the same base control of the LINZ benchmark in the Fox village.

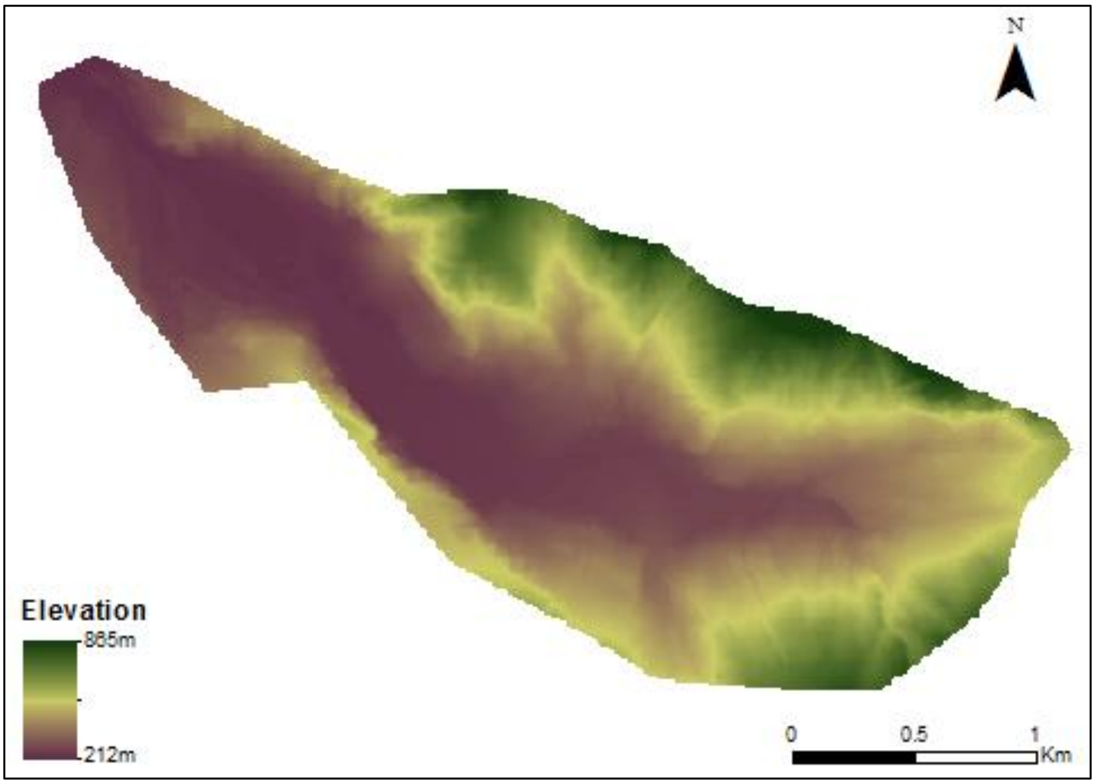


Figure 4.5: *Fox Valley November 2015 DEM supplied by Dr Sam McColl.*

4.1.3 Data Processing and Associated Limitations

The processing of data was completed using Agisoft PhotoScan professional v1.2.6 (64 bit) and ArcMap 10.4.1. The workflow of processing the drone captured imagery to a SfM derived DEM output is summarised in Figure 4.6. In terms of accuracy, the photo alignment was processed on a high setting to generate 323,545 points for the point cloud and subsequently 58,616,898 points for the dense point cloud, producing a high quality DEM. From the 7 GCPs distributed on the fan (Figure 4.4), only 4 points were identified within the imagery and used for the SfM processing. The GCPs that were not used were within close proximity of other GCPS, which can cause issues with processing alignment if the point distribution is not great enough, so as a result they were disregarded.

To be able to use the November Fox2015 DEM to generate an appropriate DEM of difference with the November Fox2017 DEM, the height projection for the Fox2015 DEM was first adjusted from height above ellipsoid to orthometric height. The Fox2015 DEM was first input into ArcMap 10.4.1, where using the clipping tool, it was reduced to the Yellow Creek fan area. Coordinates for each corner were extracted and converted into meters above sea level using the LINZ online coordinate conversion tool (http://apps.linz.govt.nz/coordinateconversion/index.aspx?Advanced=1).
The selected coordinate input and output were both set to NZTM, with the height coordinate systems set to Ellipsoidal for the input and New Zealand Vertical Datum 2009 for the output.
The average offset height of 12.253 m (Table 4.1), was subtracted from the clipped Fox2015 DEM using the raster calculator tool, thus converting the heights into orthometric.
With the completed height conversion, the raster calculator tool was used to subtract the Fox2015 DEM from the Fox2017 DEM to generate a DEM of difference to establish fan evolution over a two year period.

Table 4.1: *Coordinates (NZTM) used for height conversion of Fox2105 DEM using the LINZ conversion tool.*

Easting	Northing	Ellipsoid Height	Converted Orthometric Height	Difference
1361264.985	5180007.234	417.556	405.354	12.202
1361840.455	5179998.503	540.67	528.396	12.274
1361272.129	5179420.652	256.544	244.31	12.234
1361833.31	5179427.002	274.77	262.469	12.301
				12.253

Processing limitations associated with this methodology include;

- The height conversion of the Fox2015 DEM.
- Possibility of DEM alignment discrepancies between Fox2015 and Fox2017
- GCP accuracy of with Trimble, vertical and horizontal estimates are 8cm and 5cm respectively.
- Associated SfM processing errors with the x-axis (5.55 cm), y-axis (4.20 cm), z-axis (1.47 cm) and total error (7.11 cm). Individual error estimations of each GCP used within the estimations provided in the Yellow Creek processing report (Appendix A).

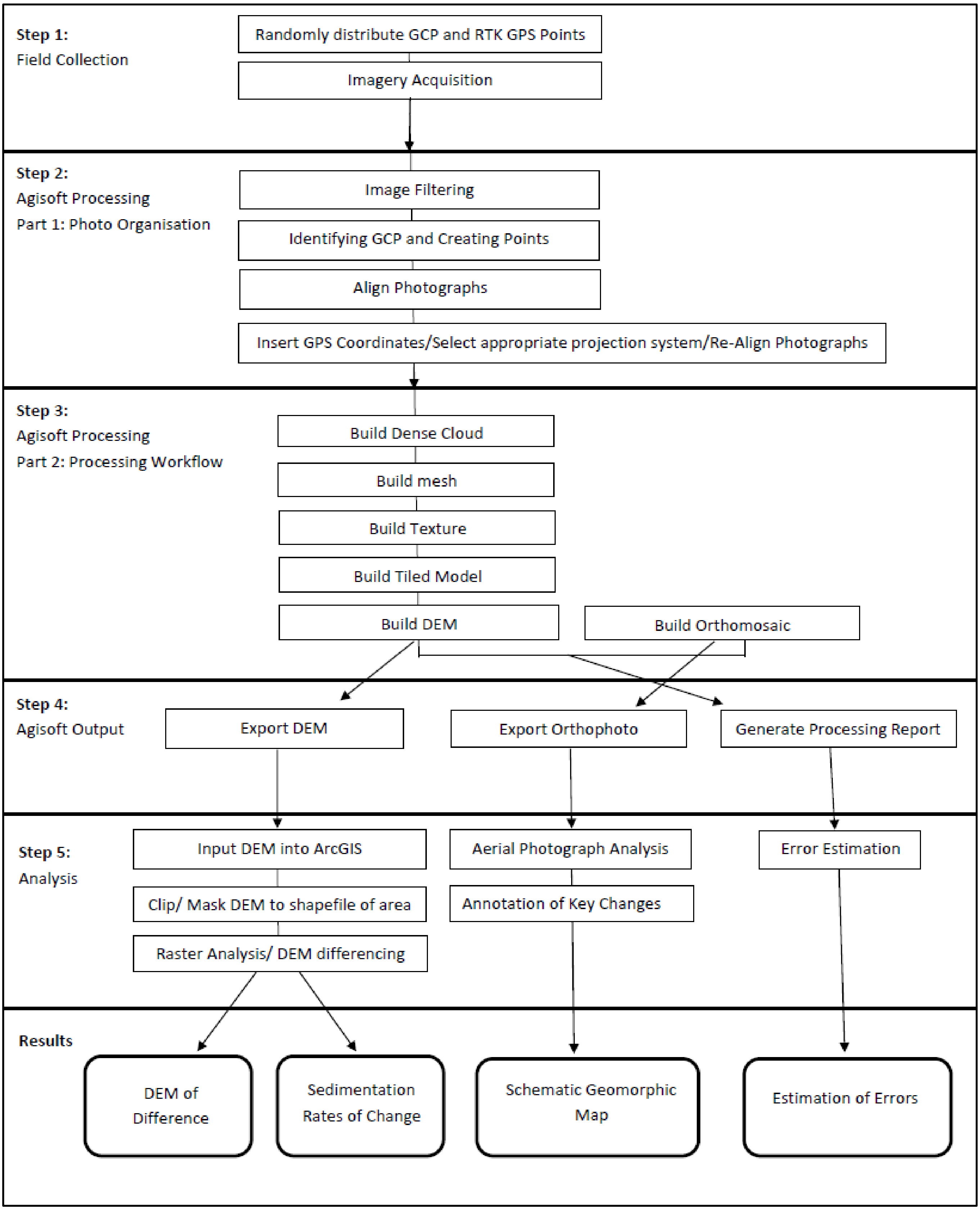


Figure 4.6: *Overall SfM workflow, adjusted from Mackie (2017).*

4.3 Aerial Photograph Analysis

4.3.1 General Method Overview

Digital photogrammetry is well used in geosciences across a variety of spatial scales, including a combination of aerial and ground-based platforms to assess the rapidly changing surfaces of, for example, glaciers, braided rivers, coastal systems and landslides (Carrivick *et al.,* 2016). With the increasing availability of open source data and high resolution aerial imagery, the use of aerial imagery is valuable for interpretation of past environments and geomorphic changes (Gomez *et al.,* 2015). This method was used in conjunction with SfM to address objectives one and two in this research.

4.3.2 Data Acquisition

Acquisition of photographs of the Yellow Creek alluvial fan and other landforms of interest within Fox valley was performed on each site visit to the Fox valley. The photographs acquired within the valley were used for the analysis of small scale changes and feature identifications, whereas the aerial photographs acquired were used to identify larger scale landform and valley changes.
The acquisition of aerial photographs used within this research include imagery from Google Earth with the available timeline function, LINZ, New Zealand basemap imagery through ArcGIS, three web cameras operating in the valley and personal imagery captured and provided by Prof. Stefan Winkler (University of Würzburg) and Dr Trevor Chinn (Alpine & Polar Processes Consultancy/Lake Wanaka). Currently there are three Snowgrass Solution web cameras operating in the fox valley installed and utilised by Fox Glacier Guiding and DOC (http://www.snowgrass.co.nz/cust/fox_glacier/index.html). The cameras are situated on the surrounding slopes to capture images from the lower and middle regions of the valley and glacier. The camera utilised for this research is the lower valley camera, where six different locations are captured at regular intervals daily. The locations captured include; Yellow Creek, Straight Creek, Gun barrel and the carpark, which are sites of significant interest in this research. Imagery from the web cameras were collected at appropriate monthly intervals or after large weather events.

4.3.3 Data Processing and Limitations

Data analysis has been completed by comparing the collected imagery identifying and annotating key indicators of geomorphic change over time on Yellow Fan and the Fox Valley as a whole, for example sediment deposition and erosion. Imagery captured within the valley was orientated by using key landmarks e.g. walking track marker posts or large boulders, to be able to make observational comparisons of change over time. Aerial imagery provided an overview of the valley allowing analysis of track changes, channel avulsions, areas that experienced episodes of accretion or erosion after a significant rainfall event and establishment of vegetation.

A number of limitations of aerial photograph analysis at this study site need to be highlighted. Due to the location of the site being so close to the Main Divide there is a lack of imagery over a continuous timescale. The rugged terrain surrounding the valley, isolated locality of Fox Glacier within a National Park, minimal infrastructure and low population in the surrounding area limits the practicality of regular aerial surveys. The weather on the West Coast is extremely variable. As a result, capturing imagery from the web cameras was not always viable due to cloudy or raining conditions. The visible spectrum of Google Earth imagery captured by satellites is similarly influenced by cloud coverage, impacting image clarity and availability. While aerial photograph analysis is a method widely used, earlier imagery is not to the same pixel quality standards as present day, thus making it difficult to establish small scale observational changes.

4.4 Sedimentological and Chronological Investigations

4.4.1 General Method Overview

To address research objective one, a number of methods investigating the geochronology and sediments on Yellow fan were undertaken. They include the use of the Schmidt hammer, clast analysis and notations of depositional features observed on the fan.

The Schmidt hammer yields an inexpensive and instant measure of bedrock and boulder surface hardness. It is widely used for estimating the mechanical properties of rock material (Aydin & Basu, 2005). Geomorphic research frequently uses the Schmidt hammer for relative surface exposure dating on a wide range of different landforms through the Holocene and sometimes beyond. Its application based on the relationship between the degree of surface weathering and the time period a rock surface has been exposure to the atmosphere (Goudie, 2006). The rebound value (R-value) retrieved by the Schmidt hammer is measured on a scale between 0 and 100 and provides a measure for the magnitude of the rebound when a spring-loaded plunger impacts on the rock surface with a calibrated energy (Stahl *et al.,* 2013; Goudie, 2006; Shakesby *et al.,* 2006). Subsequently, the R-value can be used to compare the relative age of different surfaces tested as it should theoretically reflect the time-dependant surface weathering if applied on the same rock type (Stahl *et al.,* 2013). Previous alluvial fan research conducted by White *et al.,* (1998), has displayed the use of determining relative ages of fan segments using the Schmidt hammer, which is the objective of applying this method to the Yellow Creek alluvial fan.

Clast shape is an important source of information as it reflects both the physical properties of the source material and subsequent modification by weathering, erosion and transport (Benn & Ballantyne, 1994). Many methods of clasts analysis are in use, however, Benn and Ballantyne (1993), suggested to standardise clast analysis using the Sneed and Folk ternary diagrams as it provides a sufficient representation of clast shapes without bias or distortion in comparison to other diagrams. As described by Graham and Midgley (2000), the Sneed and Folk (1958) diagram employs a triangular plot where the ratios of the long, intermediate and short orthogonal axes of a particle are plotted (Figure 4.7). This method is used in glacial environments to determine if sediments have been transported actively in the zone of traction at the glacier bed or passively transported englacially or supraglacially (Graham & Midgley, 2000; Bennet *et al.,* 1997). As determined by Brook and Lukas (2012) and Evans *et al.,* (2010), when determining the origin and transport history of clasts, a single lithology should be used. Thus, minimising the ambiguity within a data set making it difficult to determine different transport histories.

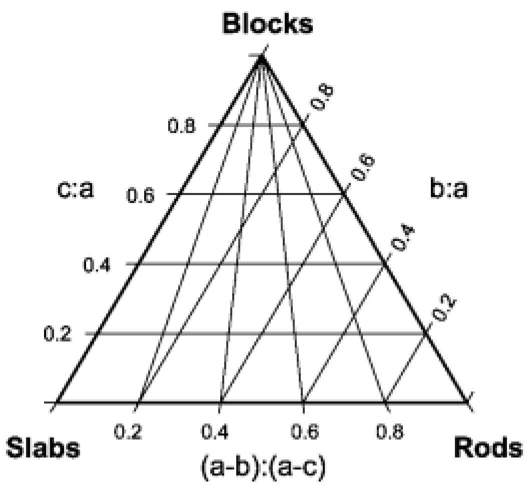


Figure 4.7: *A Sneed and Folk diagram used to plot a particle's shape using the three axes a,b and c. Letter a,b and c represent the long, intermediate and short orthogonal axes of each particle respectively (Graham & Midgley, 2000)*

4.4.2 Data Acquisition

Data acquisition took place on the 27th and 28th February 2017 with the Schmidt hammer and clast analysis sites indicated in Figure 4.8. As well as the sites indicated in Figure 4.8, additional observations were made at each site to identify general depositional features, evidence of channel reactivation and identifying sediment supply.

A mechanical L-type Schmidt hammer (with an impact energy of 0.735 Nm was used for measurements (Proceq, 1997). At each site, 10 schist boulders were selected at random with five rebound measurements collected on each boulder. All measurements were taken perpendicular to the foliation avoiding quartz veins, moss, lichens and fractured covered patches. On large boulders that did not move during sampling were tested.

A clast shape box was used to measure the long, intermediate and short orthogonal axes of each clast. At each clast analysis site, 50 small to large pebble samples were collected and measured at random from the outcrops surface to ensure remobilised clasts were not incorporated. The roundness of each clast was also recorded using the visual classification approach of Krumbein (1941) and Power (1953).

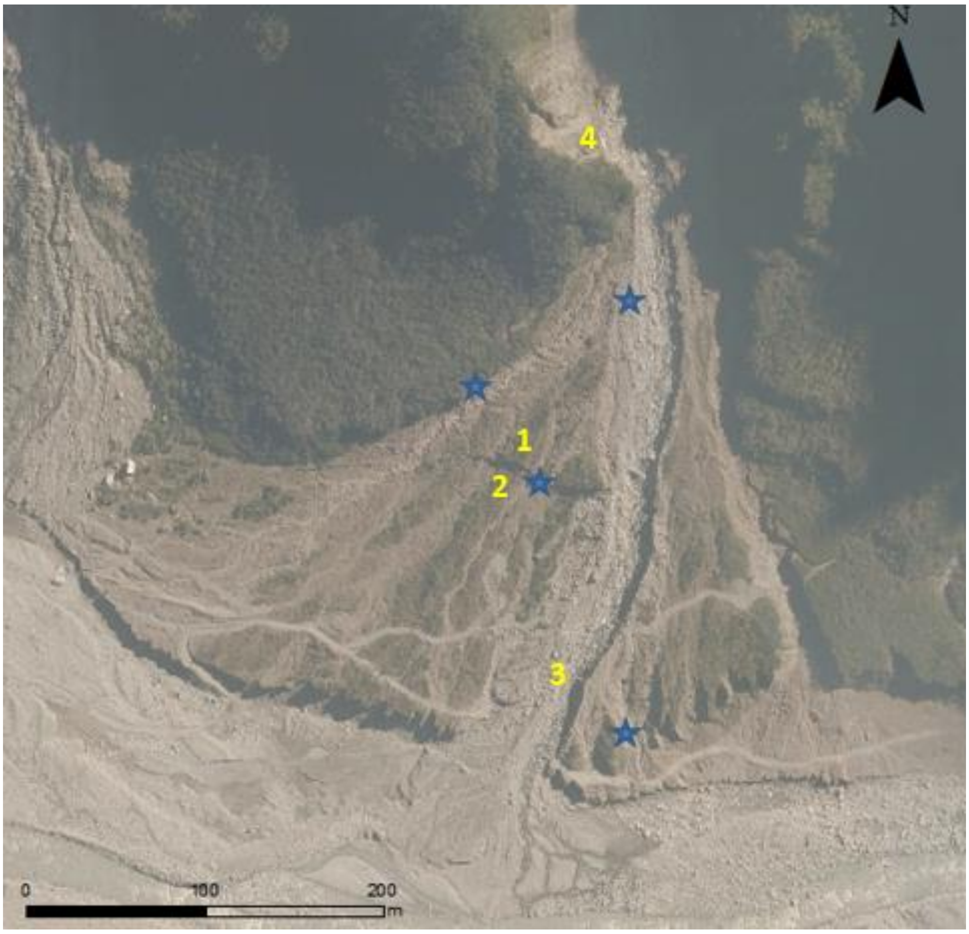


Figure 4.8: *Schmidt hammer and clast analysis sites. Schmidt hammer sites indicated by yellow numbering and clast analysis sites indicated by blue stars.*

4.4.3 Data Processing and Limitations

The processing of the Schmidt hammer data involved calculating the average of each of the 10 individual boulders was calculated as well as an overall average for the site, the standard deviation and the 95% confidence interval. Limitations of using this method include the possibility of rebound measurements collected from boulders that had been remobilised and that this particular alluvial fan is too young to exhibit age differences of significant range detectable by the resolution achievable by the instrument.

The processing of clast measurements was completed in Microsoft Excel using the Sneed and Folk triangular diagram, Tri-plot v1.4.2 retrieved from (http://www.lboro.ac.uk/microsites/research/phys-geog/tri-plot/). The measured axes were entered into the shape spread sheet were the ratios are projected automatically onto the triangle diagram.

It is acknowledged that some sampling bias may exists with clast selection as it was at random and there was no systematic sampling executed. Due to samples being pulled out of the outcrop, some of the original selected samples would not detach, and as a result another sample was selected.

4.5 Meteorological and Track Closure Analysis

4.5.1 General Method Overview

To better understand the role that rainfall has on environmental management and fan dynamics (research objective two), investigations of the relationship between rainfall and track accessibility have been explored. Due to the large amounts of rainfall (5751 mm/yr (Macara, 2016)) and variable weather the Fox valley receives (see section 1.2.4), DOC regularly maintain accessibility to the terminal viewpoint and in some instances have to close the track for safety reasons.

4.5.2 Data Acquisition

The rainfall data was acquired from the national climate database from the National Institute of Water and Atmospheric Research (NIWA) (https://cliflo.niwa.co.nz/). The two rain gauges closest to the Fox valley from the national climate database are located in the nearby Franz Josef valley (stations 4060 and 24926). Stations 4060 at a height of 155 m provides daily rainfall information from 2001- 2016, and 24926 at a height of 80 m provides daily rainfall information from 2003 to present. Both station's daily rainfall amounts were extracted and downloaded. DOC also provided rainfall data from 2009-2016, which was used to supplement the NIWA data.

Track closure information acquired from DOC provided the following information from the 11th May 2001 until the 29th may 2017;

- Date
- Fox Glacier access status
- Access road status
- View point location and associated distance from the glacier
- Staff member that completed the daily valley check (eg. Ranger 1).

The Fox Glacier track access status provides notes on the conditions of the walking track and includes other specific information such as rockfall events or areas to monitor. The view point distance provided information indicating where the available viewpoint to look at the glacier is on a particular day (Table 4.2).

Table 4.2: *Fox Glacier viewpoints used by DOC along the valley walking track*

Viewpoint Location	Distance From The Glacier (m)	Description
Terminal	450	The closest viewpoint to the glacier, located at the top of a slope
Photograph Point	500	The viewpoint is after the White Creek footbridge
Yellow Creek	750	An old viewpoint location in the middle of Yellow Creek fan
Riverbed lookout	1000	Within the valley riverbed, has an information board on the valley
Carpark	1500	The furthest Viewpoint to the glacier on the walking track

4.5.3 Data Processing and Limitations

Due to the availability of three rain gauges close to the study site, an assessment of reliability was first completed to establish which rain gauge information would be most appropriate to use. The rain gauge information from Fox Valley has a strong positive relationship with an R-squared value of 0.9 against the Franz Josef rain gauges. As a result, the Franz Josef rain gauges were used for this study, due to the availability of a larger data set and the daily rainfall amounts are sourced from a calibrated and maintained automated weather system (AWS) and therefore should be more accurate.

The two weather stations at Franz Josef both overlap the walking track data series from DOC, however, no individual station covers the whole time period 2001-2017. Station 24926 is currently still used by NIWA and the most appropriate station to use for the study. To establish a complete rainfall data set for the time frame (2001- 2017), a linear regression analysis was conducted between stations 4060 and 24926 to subsequently estimate 2001-2003 rainfall values from the 4060 station data (Figure 4.9).

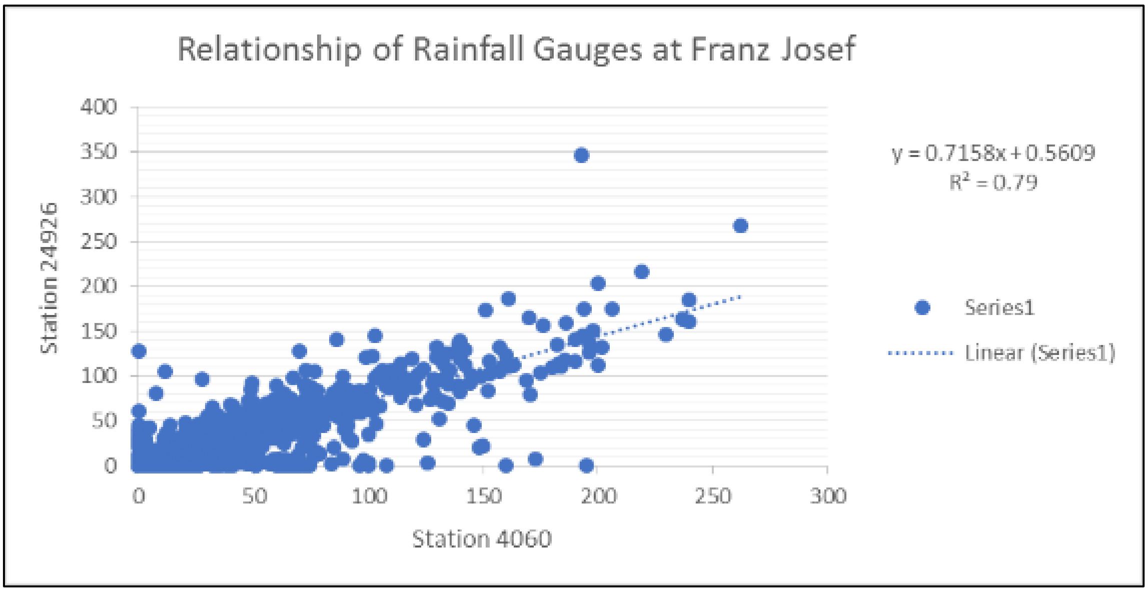


***Figure 4.9**: Linear regression between weather stations 24926 and 2060. The output equation has been used to establish rainfall values for the 24926 station, during 2001-2003 from applying the equation to original 4060 values.*

The walking track accessibility data was assessed and classified by totalling the daily viewpoint locations for each year (Appendix B), as well as classifying if the track was open or closed (1= open, 0= closed). The track was allocated open if the track was at the terminal view point and was allocated closed if the track was at photograph point, riverbed lookout, Yellow Creek, the carpark or closed for any given day. Allocation of open and closure locations has been based on the ability to view the glacier. Due to the glaciers current position, the terminal viewpoint is consistently the best location for visitors. Whilst other locations may provide a glimpse of the glacier, this is largely weather dependant. The daily rainfall amount and track allocation was then analysed in IBM SPSS using a binary regression, assessing the predictability and relationship of rainfall against tack closure with the Nagelkerke R square value (0 -1). The Nagelkerke R square value is similar to a normal R squared value, where the relationship is stronger the closer the value is to 1. Additionally, for each day the track was closed cumulative rainfall totals for 48 hrs and 72 hrs prior to closure, were calculated to assess relationships of cumulative rainfall against track closure.

It is important to note that the position of the glacier view point has changed over time with glacier recession and the terminology used for view point locations. As a result, the distances for the viewpoints stated are only specific to present day locations. Previous viewpoints have been categorised as the following; 1960 moraine or two minute walk with carpark, five minute walk with riverbed lookout and White Creek with photograph point. It is acknowledged that there is missing data for days in both the NIWA rainfall data set and the DOC valley check spreadsheet, however, due to the large data set the missing data accounts for an insignificant amount of days.

While the relationship between the DOC and Franz Josef daily rainfall amounts is substantial, some discrepancies may exist due to localised weather effects.

The daily valley checks are done by different DOC staff, so there is likely to be variability within the details provided. Perspectives on conditions will be variable and on occasions, multiple checks per day were completed in the valley due to fast changing conditions. As a result, the waking track may have been open in the morning but closed later in the day. For the purpose of this research, if the valley was closed at any stage during the day, the whole day has been recorded as closed.

It is acknowledged that the causation of track closures is not entirely due to rainfall, and includes rockfall events and track maintenance. Which has subsequently been included for calculating likelihood of closure, but will be disregarded for rainfall analysis.

4.6 Experimental Alluvial Fan Lab Modelling

4.6.1 General Method Overview

Experimental physical models have been used in alluvial fan research for over 50 years, with experiments covering aspects of fan evolution and morphology, flow dynamics with regards to avulsion, flood hazard simulation, sequence stratigraphy, and identifying autogenic indications (Clarke, 2015).The use of physical models is becoming increasingly important to forecast fan behaviour for predicting the effects of anthropogenic causes to natural environmental variables that influence fan evolution, such as changes in the upstream sediment supply from the likes of damming, and the restriction of natural flooding processes by artificial levees (Reitz & Jerolmack, 2012). It is virtually impossible to observe the influence of autogenic mechanisms on fan evolution solely with field techniques. In a natural environment it is difficult to isolate internal from external forcing. The typical time scale of fan change is usually too long and the preservation of stratigraphic profiles is limited (Clarke *et al.,* 2010). Using physical models provides a scaled representation of the formation and evolution of landforms in controlled environments, where identification of relationships or features can be determined, which would have otherwise remained hidden (Clarke *et al.,* 2010; Schumm *et al.,* 1987). The use of physical modelling in this research is to assess current management techniques used on Yellow Creek and associated implications for fan development

(Objectives one and two), as well as assess the viability of SfM in physical modelling (Objective three).

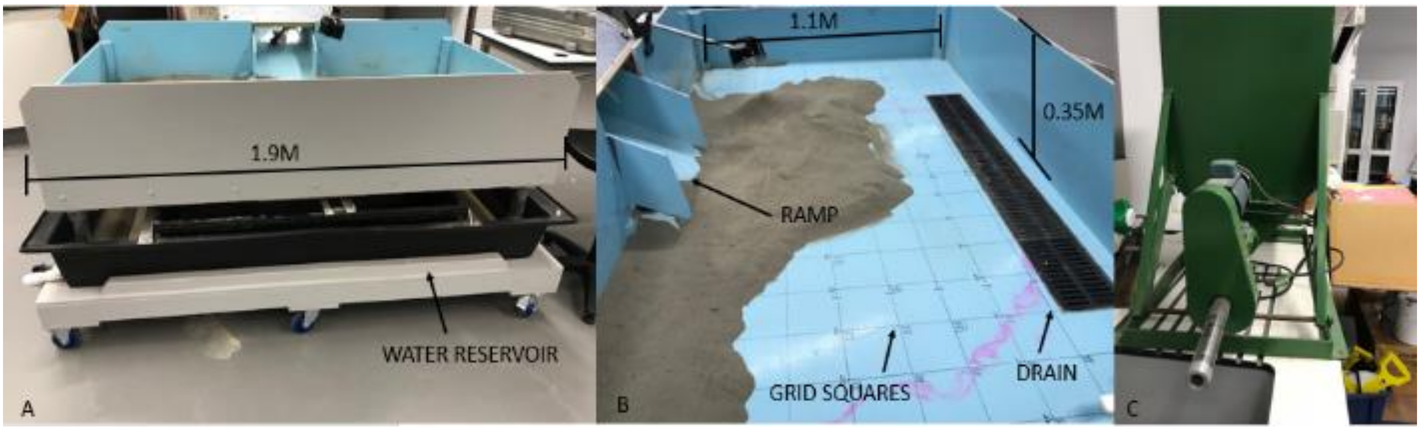


Figure 4.10: *a) Sandbox used for experiments. b) Inside view of sandbox, grid squares are 10 x 10 cm. c) Sediment feeder used.*

4.6.2 Data Acquisition

The series of lab models used for this research were completed in the Physical Geography Lab at the University of Canterbury. The alluvial fans were created in a sandbox with a ramp (at an angle of 27.7 ^{0}), allowing sediment water to mix together and deposit at the base of the ramp (Figure 4.10). Sediment and water ratios used for different scenarios are summarised in Table 4.3, grain size distribution used in the models was -0.75 to 2 phi. Ten alluvial fans were created, seven of which were built for 15 minutes at speed 20 (ml/s^{-1}), two for 30 minutes and one for 120 minutes at speed 30 (ml/s^{-1}). The sediment and water supply were stopped at 5 or 10 minute intervals to capture photographs for SfM processing. To capture the photographs used for SfM an Apple Iphone7 was used. In regards to assessing the management techniques used by DOC, two models were run with time lapse cameras recording and set to speed 30. One model demonstrated the use of stop banks on an alluvial fan, whereas the second model looked at the deposition characteristics with a rock wall features at the toe (Figure 4.11).

Finally, a model to simulate an alluvial fan developing over 'dead ice' was executed to explore the changes in fan shape post ice melting. This involved, building the fan for 20 minutes at a speed of 30, placing blocks of ice into the middle of the fan, and continuing to build the fan until the ice was covered with sediment. Time-lapse cameras were placed to film the changes over time.

Figure 4.11: Some of the alluvial fan models run. A) 15-minute model. B) 30-minute model. C) Stop bank model D) Rock wall model.

4.6.3 Data Processing and Limitations

The data processing for the lab simulations is similar to the SfM process workflow in Figure 4.6, however, step 5 required a different analysis approach. With majority of fan simulations stopped at 5 or 10 minute intervals, a DEM was created for each stage of development for the 10 alluvial fans specified in section 4.6.2. The SfM derived DEMs for each fan, were put into ArcMap 10.4.1 and georeferenced to overlap one another. The ramp structure was used as the referencing feature due to remaining in the same location throughout simulations. Raster analysis was completed by using the raster calculator to create DoD (DEM of difference) to establish sediment changes. Screenshots were taken from the time-lapse cameras, specifically on the models that were used to assess management techniques on the fan and dead ice. The time lapse screenshots and other imagery

Table 4.3: *Table showing flow and sediment rates used for modelling, the water and sediment rates were repeated 5 times to get an average rate (Q represents the water discharge and Qs represents the sediment supply rate (all values are to 2dp)).*

Trial	Q(ml/s^{-1}) set to speed 20	Q (ml/s^{-1}) set to speed 30	Qs (g/s^{-1})
1	11.43	21.16	2.64
2	11.11	21.23	2.63
3	10.42	20.37	2.68
4	10.74	19.86	2.68
5	10.23	20.04	2.68
Average	10.79	20.53	2.66

collected of management models were used for interpretation of changes experienced and how these relate to Yellow Creek. One of the challenges with using lab models is accurately representing real-world scales. Compared to existing modelling experiments, the duration of fan building was still in the sheet flow stage in most instances, were the changes were occurring more rapidly compared to real-world changes. The structures implicated on the fan were not to proportional scale, however, the overall objective of assessing how structures interact and endure fan evolution can still be acknowledged. In terms of SfM errors, the lighting in the lab and reflectivity of the water in the sand box may create some issues in terms of pixel matching, impacting on the accuracy of DEMs.

Chapter 5: Results

This chapter presents the results and interpretation of the Yellow Creek alluvial fan properties investigated in chapter 4. The structure of this chapter is aligned with chapter 4. The fan changes obtained from SfM and aerial photography are presented first, followed by walking track location changes, sediment properties of the fan, meteorological influence on the valley, and lab modelling results.

5.1 Structure from Motion

5.1.1 Interpretation of Fan Changes between 2015 and 2017

The changes in elevation experienced on Yellow Creek fan between November 2015 and November 2017 are shown in Figure 5.1. The average elevation change is 1.94 m (+/- 30 cm), resulting in a mean elevation rate of 0.97 m/y^{-1}. Between 2015 and 2017, the fan has experienced large areas of aggradation. Across the vegetated areas of the fan (Figure 5.2), small changes of 1-2 m are noticeable. This is likely to have occurred from changes in vegetation growth, or movement of boulders through reactivated abandoned channels (Figure 5.1). The largest area of aggradation is in the active channel (Figure 5.2). The fan apex has experienced large accretion, where sediment has settled out of suspension and deposited alongside the banks (Figure 5.3). On the east side of Yellow Creek, there is a significant area of accretion, but, this is not a natural occurrence. As DOC is actively managing Yellow Creek, the fan morphology has been influenced by human modification. In this instance, a stop bank has been made to prevent channel avulsion towards the east side of the fan to protect the glacier walking track (Figure 5.4). The area of the fan that has experienced the greatest erosion is within the channel. This is likely to be the result of sediment excavated by DOC for stop bank material and re-deposition of material from large rainfall events. The west side of Yellow Creek is affected by the predominant accretionary development of the secondary fan due to the instigated stop banks (see section 5.2.1). The immediate areas around the slump and erosional scarps (between the different fan development stages (Figure 5.2)), on the fan show large changes in height (Figure 5.1). This could be the result of material becoming loose within the outcrop and subsequently fallen and deposited at the base of the scarp. Or could have been created from a shadowing effect from when the DEMs were created. Dependant on the angle of image capture, the scarps could have created shadows and subsequently caused discrepancies between the two DEMs.

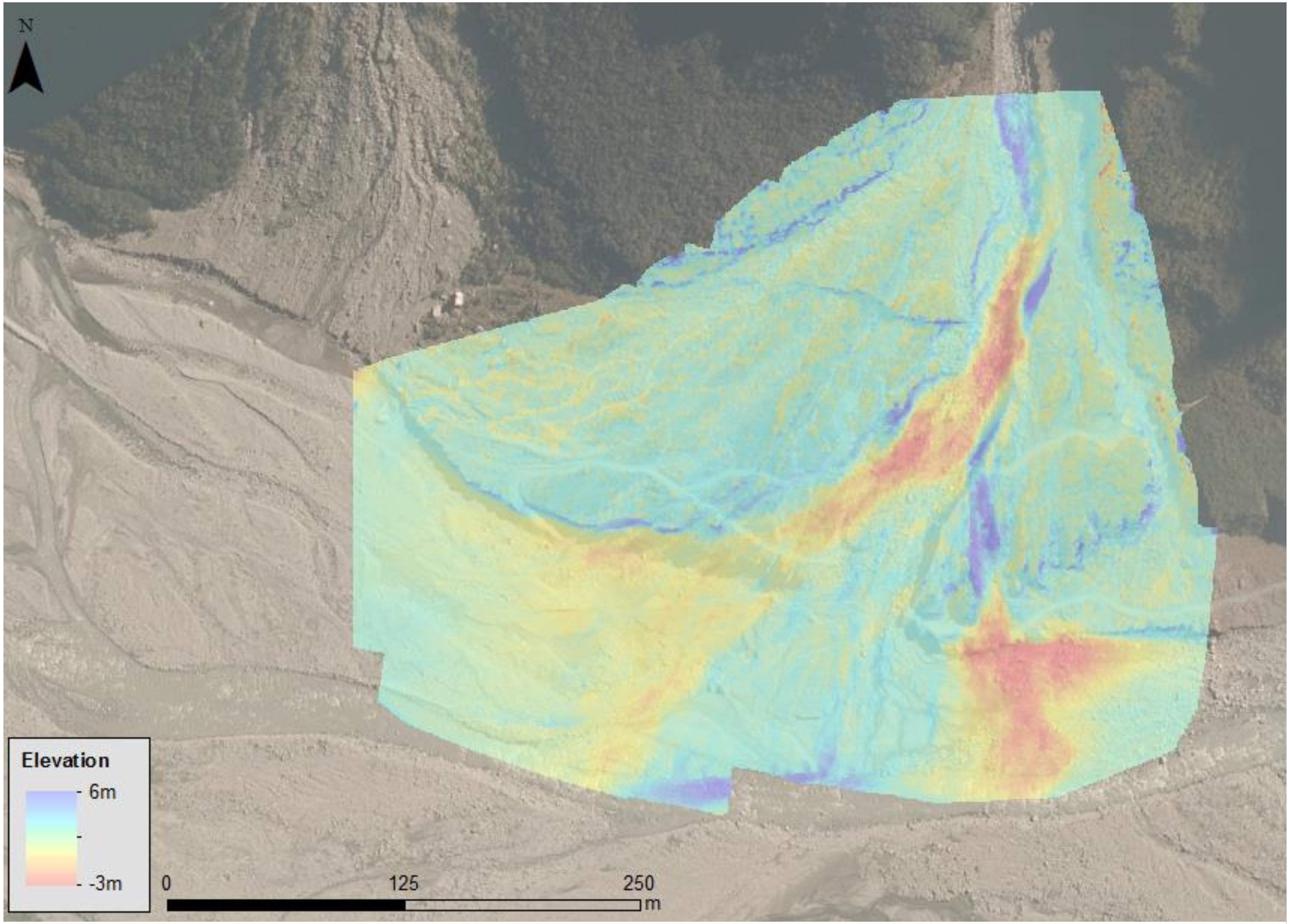


Figure 5.1: *The sediment changes on Yellow Creek fan between November 2015 and November 2017.*

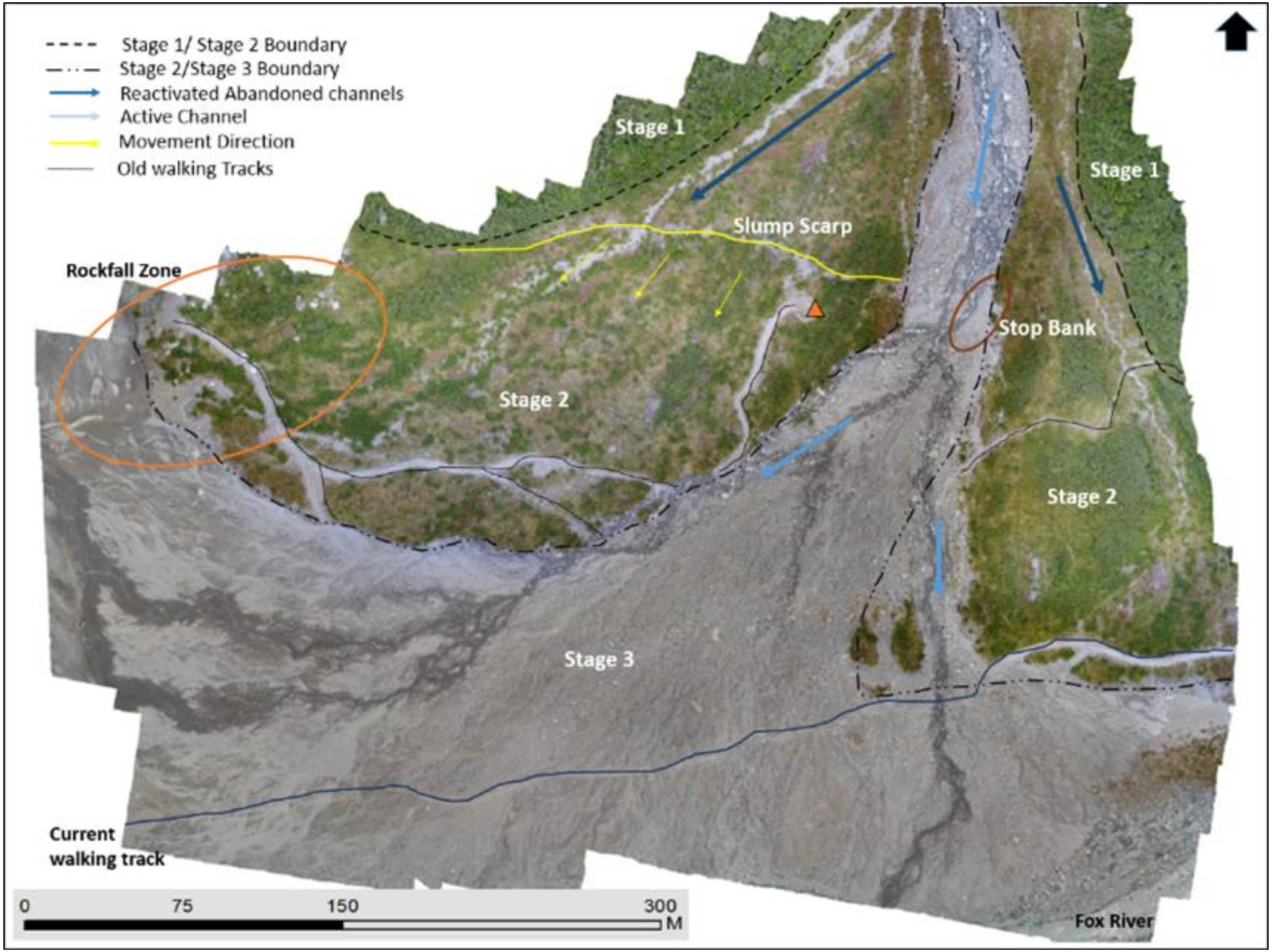


Figure 5.2: Identified features on Yellow Fan.

Figure 5.3: *Sediment accumulation on the West side of Yellow Creek near the fan apex. A) Captured within the active channel looking down fan. B) Captured within the active channel looking up towards the apex. Captured August 2016.*

Figure 5.4*: Evidence of anthropogenic influences on sediment distribution. Captured August 2016.*

5.2 Aerial Photograph Analysis

5.2.1 Long Term Fan Changes

SfM analysis showed that the majority of the fan has aggraded over time. Historically the fan has experienced several sediment fluctuations, due to erosive and passive episodes from the Fox River (Figure 4.6). As the Fox Glacier experiences phases of advancement and retreat (see section 2.4), the influx of sediment into the valley system influences the location of the active Fox River channel from the formation of paraglacial landforms (e.g. alluvial fans). Yellow Creek in 2004 (Figure 5.5a), shows a dominating phase of aggradation indicated by limited vegetation, fresh sediment deposition and no evident channel entrenchment. With the lack of vegetation and stability, the main channel will be largely prone to avulsion events (Piégay & Schumm, 2005). The North side of the valley constituted as the dominant side for sediment accumulation in 2004, with the Fox River largely protruding to the south side of the valley after Straight Creek. There is evidence of a flooding event with a large erosional scarp cutting the fan toes of Yellow Creek, Straight Creek and Gunbarrel. Successive erosional scarps are evident in Figure 5.6b, that indicates another erosion event. However, The South side of the valley has recovered faster, with noticeably larger aggradation of Straight Creek. The large hummocky topography near the carpark is a large area of debris-covered ice that previously became detached from the glacier. The dead ice has disappeared since 2004 from the outwash plain, with the last remnants close to the car parks gone by 2007 (Purdie *et al.,* 2014).

Over the last 10 years, by contrast, Yellow creek has experienced some dramatic changes (Figure 5.5). The upper fan has stabilised with large areas of established vegetation and distinct channel entrenchment through the middle of the fan. The fan has experienced significant erosion from 2004 onwards creating large erosional scarps. There is evidence of channel reactivation on either side of the fan with fresh sediment deposition.

One distinctive feature is a slump that has been forming on the top half of the west side of the fan. This slump has a large scarp that has slightly increased in height during the last two subsequent years (Figure 5.1). The formation of the slump has formed from either; a large seismic event in the area, a large erosive event of the fan toe causing the fan to slump forward on a bedding plan, or from the melting of potentially debris covered ice from underneath the fan (see section 6.1.3). Following large erosion events on Yellow fan, subsequent fan development has occurred with the formation of a secondary fan.

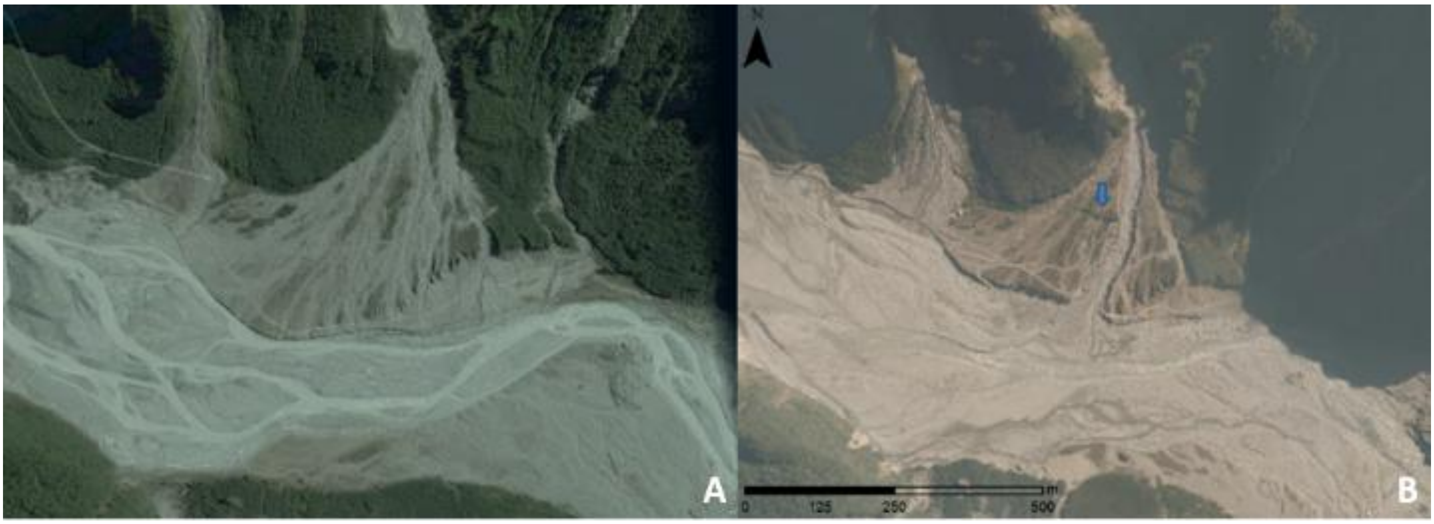


Figure 5.5: *A) Yellow Creek fan in 2004 (Google Earth, 2018). B) Yellow Creek fan in 2015. The blue arrow in the image is indicated the scarp that has formed (LINZ, 2018).*

5.2.2 Short Term Fan Changes (2015 – 2018)

The short term changes from both Straight Creek and Yellow Creek fans are shown in Figure 5.6. The main channel of Fox River is directed towards the North side of the valley, due to the large aggradation of Straight Creek. Yellow Creek also influences the course of the main channel with the fan encroaching on the river, but the predominant influence of the fan is on the northern side (near the carpark). The Yellow Creek and White Creek fans have experienced several erosional events within this short time frame. Large erosional scarps are evident on the fan toes, specifically in relation to more recent events (Figures 5.6c & 5.6d). The most recent flooding event that occurred on the 1st February 2018, has caused significant damage within the lower valley. A large amount of material has been eroded away from the North side of the valley, whist the South side has experienced sediment deposition (Figure 5.6d). The toe of Straight fan has experience small amounts of erosion with a significant amount of red coloured boulders eroded away. The red-coloured boulders are covered in a red coloured algae called '*Trentepohlia',* which takes a few years to establish under stable conditions (John *et al.,* 2002). Thus the red boulders are a sign of short term stability. The avulsion of the river further to the North side of the valley has created sediment deposition around the fan toe of Straight creek. Subsequently the smaller channel would be expected to be filled by sediment from Fox River because of low energy flow and from Straight Creek.

The walking track has changed over this time frame, with the track moving progressively up the Yellow fan (Figures 5.6b & 5.6c). A section of the track that was considered relatively stable (see

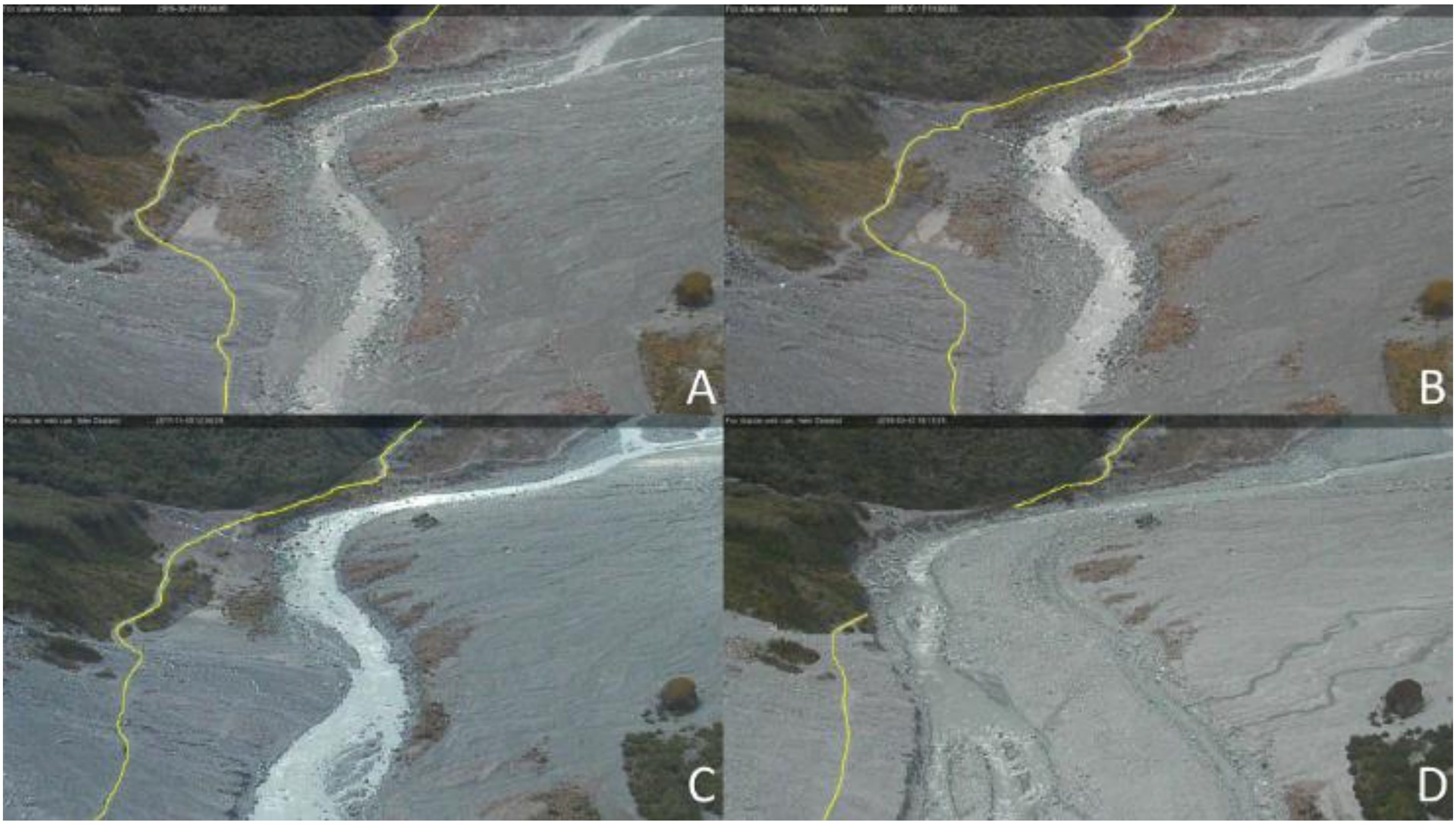


Figure 5.6: *Short term changes of the glacier side of Yellow fan in the lower Fox valley. The location of the active walking track is represented in yellow. A) Image captured 27 August 2015. B) Image captured 20 September 2015. C) Image captured 10 November 2017. D) Image captured 12 march 2018. (SS, 2018)*

Section 5.2.3) has been significantly eroded (Figure 5.6d). The location of the old walking track on Yellow fan has also been eroded away, leaving just the remnants of the most recent walking track.

The short term geomorphic changes of the carpark side of Yellow Creek fan and Gunbarel are shown in Figure 5.7. The carpark side of Yellow fan is the most dynamic area of the fan regarding sediment accumulation and rockfall. Gunbarel has been continuously active during the observed time frame, with large boulders sprawling onto Yellow fan and the outwash plain. A large levee was constructed near the base of Gunbarel to protect the walking track from rockfall events (Figure 5.7b). The active flow of Yellow Creek is on the west side of the fan, which is reflected by the fan shape and growth direction. The active flow has most recently avulsed towards the East side (Figures 5.7c & 5.7d). This change is highly likely to have been influenced by anthropogenic factors with the construction of the new walking track. Yellow fan has had predominate aggradation throughout this time frame. As previously shown on Figure 5.7, the fan has also experienced several erosional events. The most recent event has resulted in the Fox River channel avulsing to the North side of the valley in this particular location. As a consequence, this has caused significant erosion of the North side of the valley with the levee eroded away and both Gunbarel and Yellow fan toes cut. The walking track has significantly changed over this time frame (Figure 5.7). The most recent walking track has been constructed to stay above the river floodplain and adjoins the remnants of an older walking track.

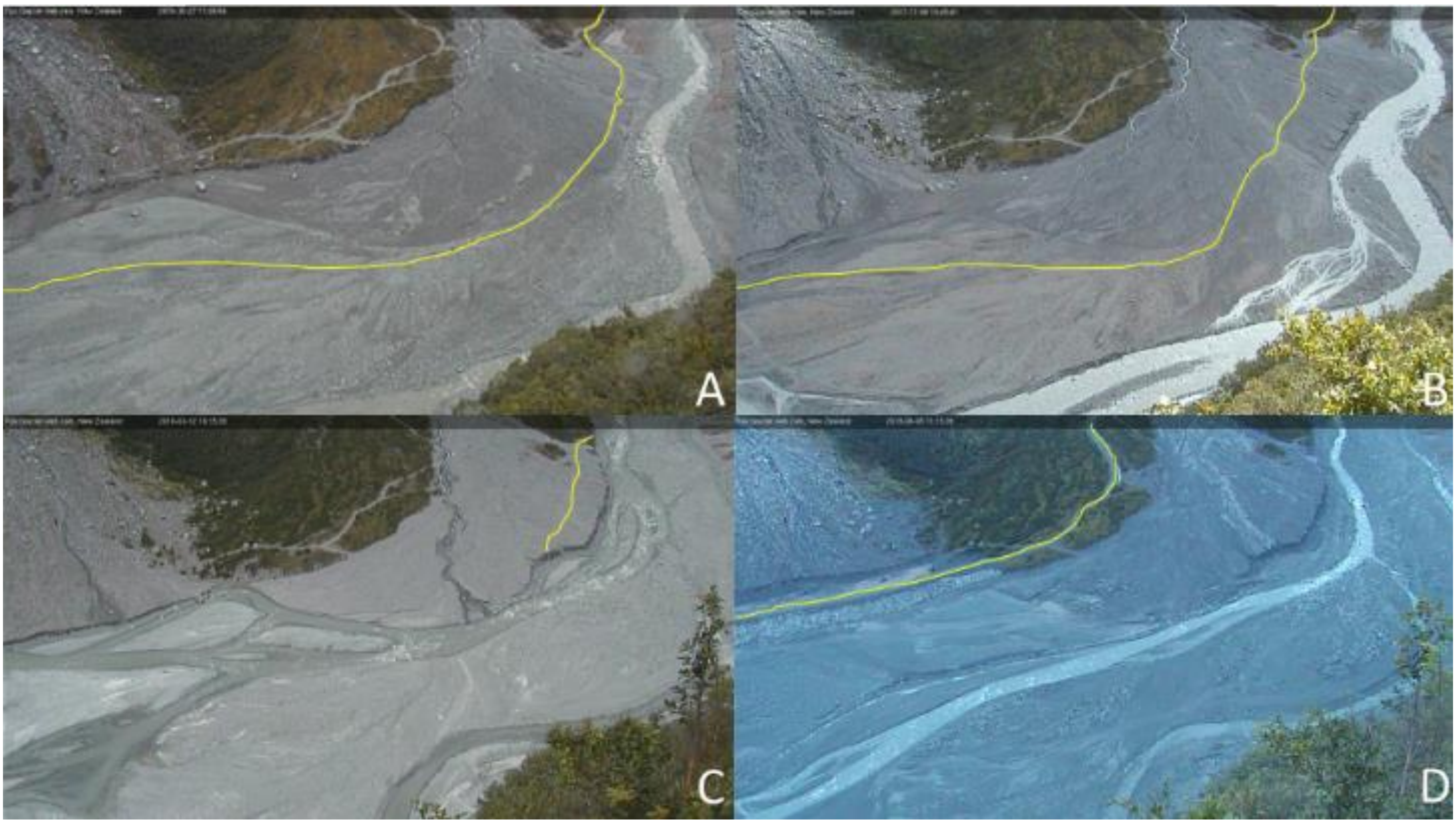


Figure 5.7: *Short term changes of the carpark side of Yellow fan in the lower Fox valley. The location of the active walking track is represented in yellow. A) Image captured 20 August 2015. B) Image captured 10 November 2017. C) Image captured 12 March 2018. D) Image captured 5 June 2018. (SS, 2018).*

5.2.2 Walking Track Changes

The Fox Glacier walking track is frequently visited all year round. The detailed course of the track has to be adjusted frequently due to rockfall or flooding events. Without a complete record of track locations for the 2001-2017 time period, the use of available aerial photographs enabled track locations to be established for 2004, 2014 and 2015, with the 2017 location established with GPS. The Walking track length has varied over time with response to the changes of the glacier terminus. The 2004 track displayed the shortest track with the glacier viewpoint, at that time, close to the base of the slope of the current glacier viewpoint (Figure 5.8). Tracks in 2014, 2015 and 2017, all ended at the current glacier viewpoint location at the top of the slope, with the part of the track closest to the glacier remaining relatively constant throughout with minimal track variations. Track changes have largely be observed between the carpark and glacier side of Yellow Creek (Figure 5.8). Slope instability and reactivation of rockfall events on Gunbarrel since 2015 have resulted in track adjustments onto the active Fox River flood plain. The valley is susceptible to flooding during large rainfall events and the risk of meltwater outbursts from the glacier, DOC are constantly adjusting the track to lower risk areas. Aggradation that has occurred on the fan has proven to constitute a sufficient argument for track migration up the fan (Figure 5.9).

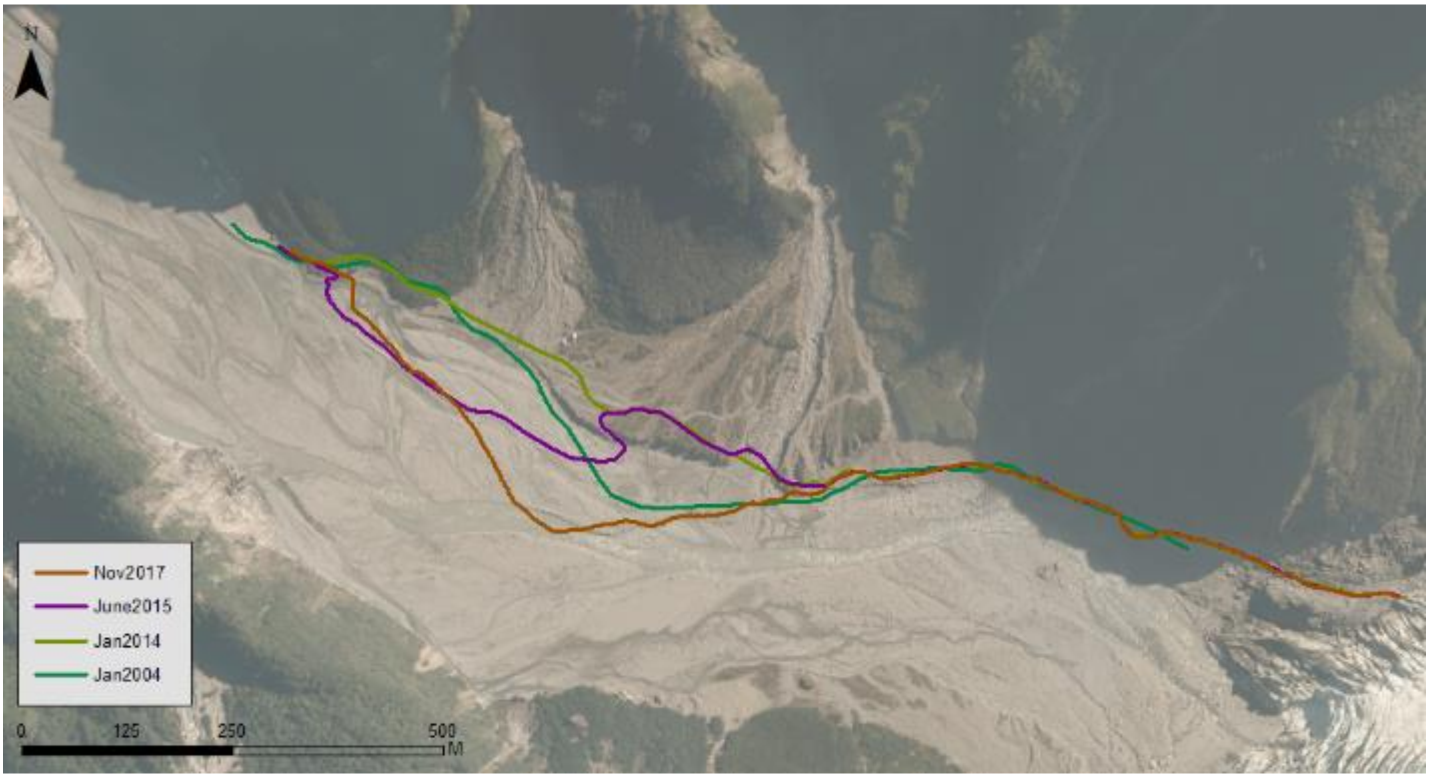


Figure 5.8: *Fluctuations of the Fox Glacier walking track over time.*

The track locations can also provide some details on previous geomorphic environments in the valley. The 2004 walking tracks reflects a relatively stable Gunbarrel and fan aggradation with the wider track around Yellow Creek. The 2014 track reflects a relatively stable Gunbarrel and Yellow Creek. In 2015, the position of the track reflects instability in the Gunbarrel area, attributed to a large avoidance zone and a stable Yellow Creek as the 2015 track adjoins the original 2014 track. Likewise in 2017, the position of the track reflects an unstable Gunbarrel similar to the 2015 track, however, displays a large amount of aggradation attributed to a wider track around Yellow Creek.

Figure 5.9: *Walking track adjustments made up fan. This photo has been taken on the previous walking track, looking towards the new adjusted location away from the Fox River. Captured in March 2017.*

5.2.3 Valley changes

The lower valley, has experienced large amounts of aggradation in response to the retreat of Fox Glacier over the last several decades. The steep slopes and surrounding catchments have transported a significant amount of material into the valley. Availability of material is largely dependent on the sediment supply within the surrounding catchments. Mills Creek, Yellow Creek, Straight Creek and Boyd Creek all currently display highly erosive catchments through the lack of vegetation and large sediment abundance, due to landslides. Of these tributaries, the Straight Creek, Yellow Creek and Mills Creek currently have the most significant impact on the lower valley system, with each associated fan experiencing substantial aggradation, which has influenced the position of the Fox River. Mills Creek has experienced the most amount of change most recently. Where large fluxes of sediment have been transported down the system, resulting in the damage to walking track infrastructure (river walk look out and chalet lookout tracks) and immersed vegetation from substantial fan development (Figure 5.10). Subsequently development of the Mills Creek fan has forced the Fox River to the northern side of the valley floor, which consequently is towards the valley access road. The areas of the valley experiencing large aggradation will continue to impact on the location of the Fox River, which will be problematic for existing infrastructure.

Figure 5.10*: Mills Creek alluvial fan that has developed over top of existing vegetation.*

5.3 Sedimentological and Chronological investigations

5.3.1 Field Observations

The fan is well established with an incised apex and three distinctive stages of development identified. The fan is fundamentally an alluvial fan, displaying the concave shape and has a slope of 9^0. The sediment size ranges from a clay to a boulder and the deposits are grain supported and non-cohesive as there is a very small amount of clay. The predominant lithology on the fan is schist. Majority of the material becomes progressively finer down fan, with the largest boulders observed at the fan apex. Depositional features observed on the Yellow Fan include;

- Reactivation of abandoned channels (Figure 5.11)
- Imbrication, present on natural levees (Boulder berms) and within outcrops from previous depositional events (Figure 5.12a)
- Deposition of rockfall from Gunbarrel (Figure 5.2)

- Slump (Figure 5.11b)(Figure 5.2)

Figure 5.11*: A) An example of a reactivated channel on the fan, indicated with a fresh deposit of sediment. B) Slump scarp on fan. The scarp is 2 m in height and the material is regularly reworked through gullies that were old abandoned channels. There has been a fresh deposit, with the blue arrow indication direction of flow.*

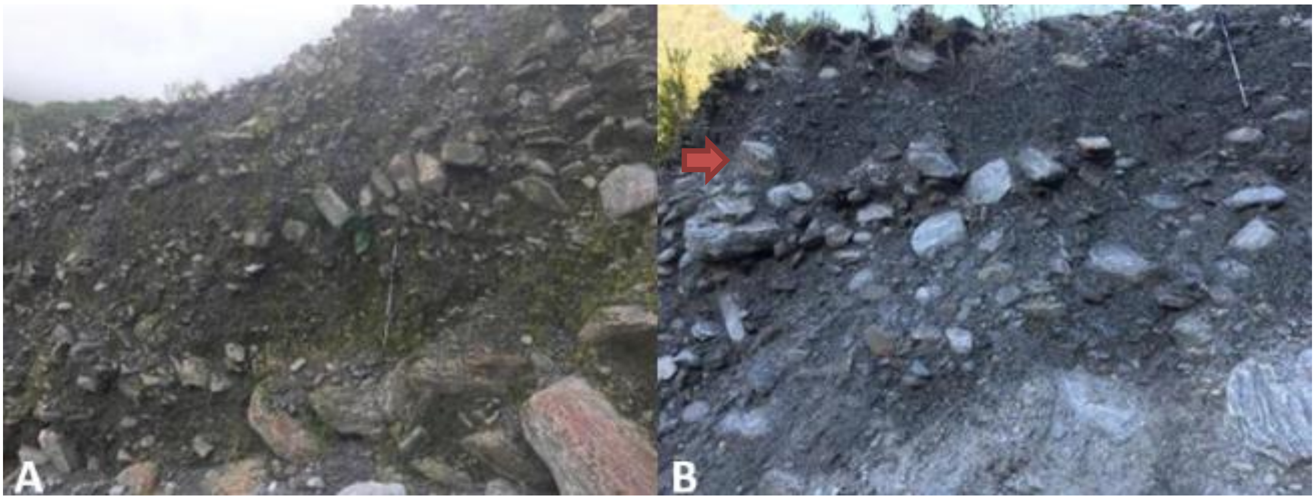


Figure 5.12*: Deposition features on yellow creek A) imbrication. B) Low energy deposit, indicated by the red arrow.*

The Yellow creek fan is comprised of fluvial and debris flow deposits. Fluvial processes are the dominant feature on the fan with large amounts of imbrication, finer material is at the top of the deposit and the material becomes finer towards the fan toe. Due to the Fox Valley experiencing large storm events or frequent heavy rainfall events and being a steep catchment, debris flows are common. Debris flow deposits are represented by a larger material at the top with no evident layering or depositional features, moderate to poor sorting and the deposits have mixed clasts orientations (Welsh & Davies, 2011). An outcrop on the west side of fan from stage two, has a low energy deposit (Figure 5.12b). This deposit appears to be flat, has no imbrication, but does display laminated normally graded sediments, which is indicative of a glaciolacustrine deposit (Cofaigh & Dowdeswell, 2001).

The slump feature that is located on in the east side of the fan (Figure 5.2) has fresh material along the base of the scarp. This indicates two features, the first of which is the accumulation of reworked material from old abandoned channels above the scarp, or material has become unstable and detached from the outcrop (Figure 5.11b). Secondly, the areas along the scarp that have fresh material, with no apparent abandoned channels or gullies nearby, demonstrate the growth of the slump.

5.3.2 Clasts analysis

Clast analysis on the Yellow fan showed that the deposits are predominantly fluvially derived with four out of the five sites, having sub-rounded clasts and one site having slightly more sub-angular clasts (Table 5.1). The site that displayed slightly more angular clasts was the outcrop at the slump, where the clasts are less susceptible to weathering compared to the other sites that were within gullies, which subsequently would be expected to be more sub-rounded due to fluvial processes. The shape of the clasts are shown in Figures 5.13 and Table 5.2. The dominant shapes of the clasts are platy, bladed or elongate, due to the dominant schist lithology of the clasts.

The general mean size of the sediment across the fan is decreasing in the down fan direction. There are several larger boulders found down fan, however, the area is susceptible to debris flows and rockfall (Figure 5.2) that have caused deposition.

Table 5.1: *Clast roundness from each outcrop on Yellow Fan.*

Outcrop	Roundeness average	Class interval (Powers, 1953)	Classification
1	0.35	0.25-0.35	SA
2	0.37	0.35-0.49	SR
3	0.37	0.35-0.50	SR
4	0.39	0.35-0.51	SR
5	0.4	0.35-0.52	SR

Table 5.2: *The shape of each clast from four outcrops on Yellow Fan.*

Sneed & Folk classes	Outcrop 1		Outcrop 2		Outcrop 3		Outcrop 4	
	Count	%	Count	%	Count	%	Count	%
Compact	0	0	2	4	2	4	1	2
Compact-Platy	4	8	3	6	2	4	3	6
Compact-Bladed	1	2	0	0	5	10	1	2
Compact-Elongate	2	4	0	0	1	2	2	4
Platy	12	24	12	24	6	12	10	20
Bladed	13	27	9	18	22	44	14	28
Elongate	4	8	7	14	4	8	4	8
Very-Platy	5	10	7	14	3	6	5	10
Very-Bladed	7	14	5	10	5	10	9	18
Very-Elongate	1	2	5	10	0	0	1	2

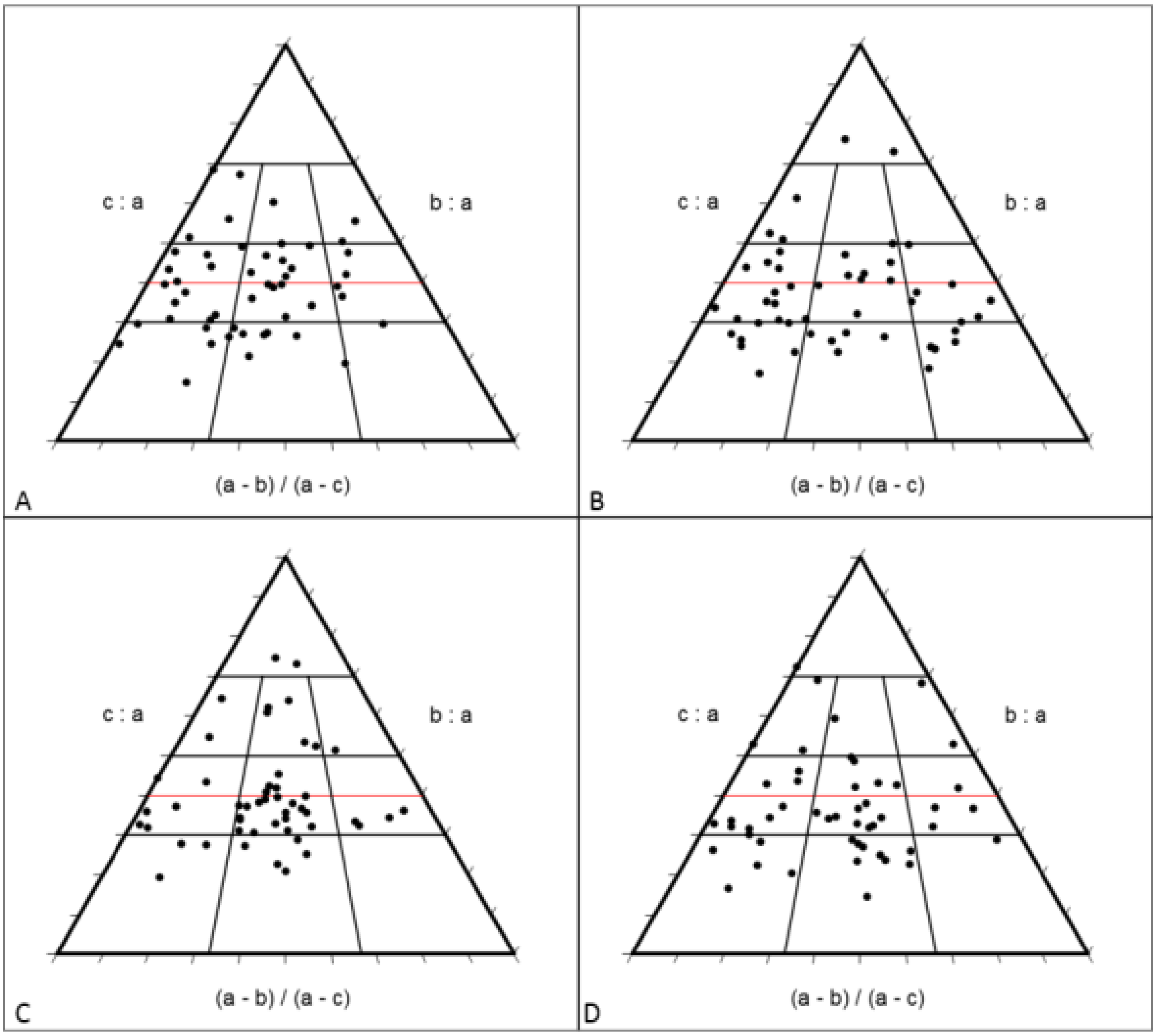


Figure 5.13: *Tri-plot diagrams for the shape of each clast from four different outcrops on Yellow Fan. The red line on each plots is the* C_{40} *index. A) Is an outcrop that is from stage one of the fan. B) Is towards the apex and is from stage two of the fan. C) is the slump and is from stage two of the fan. D) Is from the bottom of the erosional scarp between stage two and three of the fan.*

5.3.3 Chronological investigations

To establish the evolutionary stages for the development of the Yellow Creek Fan, a Schmidt hammer was used and the results are displayed in Table 5.3. Due to the fan being relatively young, relative age dating for the different development stages have not been possible. Instead the results have been used to reinforce identified depositional stages of the fan (Figure 5.2). Historic imagery and interpretations of the valley indicate that the fan has been developing since the 1950s (see Section 2.1). Stage one of fan development (Figure 5.2) includes the upper most section of the fan below an old lateral moraine. The distinction of this stage has been from the dense well-established vegetation, erosion scarps above stage two and small rebound value (39.44) (Table 5.3). Stage two of fan development has been defined by less substantial vegetation, old walking tracks, and erosional scarps above stage three. Stage two of the fan has a large post depositional slump feature that has formed within the last 10 years (Figure 5.2). The slump on stage two can be confirmed to have been post depositional feature that has formed with the bottom half of stage two subsiding downward the Fox River. The rebound values from above and below the slump (Table 5.3), produced relatively similar values (46.26 & 46.22) indicating that material was deposited at the same time. Stage three has been identified as the current fan development stage, with freshly deposited material, lack of vegetation, active channel and highest rebound value indicating less weathering has occurred (50.6) (Table 5.3).

***Table 5.3**: Schmidt hammer measurements (n) taken, with the average (n) displayed reinforcing the difference development stages of Yellow fan.*

Outcrop Number	Description of surface	Average N	Standard deviation	95% confidence interval
1	Upper surface of scarp	46.26	6.50	1.80
2	Lower surface of scarp	46.22	7.27	2.01
3	Lowest, new surface	50.6	7.13	1.98
4	Upper most surface	39.44	8.88	2.46

5.4 Meteorological conditions and track closure analysis

5.4.1 Track accessibility

Based on the closure criteria established in section 3.5.3, on any given day, visitors to the Fox Valley have a 17.7% chance that the glacier viewpoint is not accessible. Whilst this closure is an overall estimate, some years have experienced more viewpoint variability than others (Figure 5.14). The year with the least amount of days allowing visitors to the glacier viewpoint is 2009, followed by 2008, 2010 and 2014. From the 11/9/08 – 28/9/09, there was no days that allowed a visitor to the terminal viewpoint, due to series of rockfall and flooding events that required a significant amount of track maintenance. The three months that have received the highest rainfall amounts have been identified for 2008, 2009, 2010 and 2014 (Table 5.4). There is a positive relationship between high 3-monthly rainfall totals and long periods of track closure. Months that receive small amounts of rainfall can also have an impact on track access. This is partially due to large amounts of rainfall occurring over a short period of time. For example, the month of May 2012 received 218 mm total rainfall, half of which fell across 3 days, resulting in the track being closure for 4 days.

Rockfall events in the valley occur majority of the time from large amounts of rainfall. However, if the material in the valley is unstable, rockfall is not always associated with heavy rain events. It may only take a small amount of rainfall to trigger the material. An example of this can be demonstrated

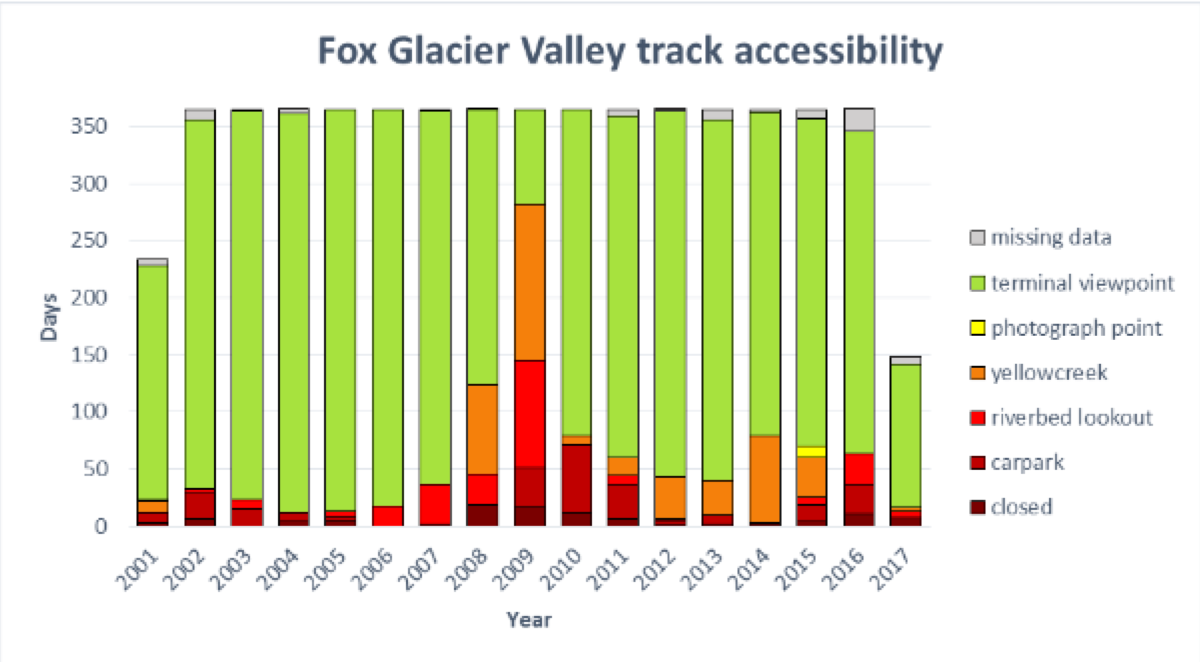


Figure 5.14: *The number of days at each viewpoint location from track restrictions for the Fox Glacier walking track from 11th May 2001 until the 29th May 2017.*

by the rockfall hazard monitoring within the valley undertaken by DOC. On the 23rd April 2010, 30 rocks, described in the hazard event register as 'TV/basketball' sized (i.e. 30-150 cm in diameter), fell down Gunbarel with an associated 6.4mm of rainfall received. Seven days prior to this event, only 1.5 mm of rainfall had fallen, establishing that the conditions prior to this event were dry.

Apart from flooding and rockfall, other reasons for the walking track closures or restrictions in Figure 5.14, include;

- High side streams/ high water levels
- Icy/Ice grit conditions
- Morning mower
- Roadworks on the access road to the carpark
- Ongoing track maintenance with heavy machinery in the valley

It is acknowledged that there may be outliers within the data due to human error in recording the daily track status.

Table 5.4: *The three highest monthly rainfall totals for the four years that displayed the highest viewpoint variability.*

Year	Month	Total rainfall (mm)
2008	September	882
	November	937
	December	566
2009	April	1024
	August	1086
	December	746
2010	January	911
	September	843
	December	1168
2014	January	689
	April	653
	November	934

5.4.2 Rainfall and track closure relationships

The binary logistical regression between rainfall and track closure statistically shows a weak relationship with a Nagelkerke R square value of 0.063. The model could only match 6.1% of the predicted track closures for daily rainfall, 9.7% for 48 hours and 14.5% for 72 hours of rainfall. The ability to determine any threshold value for rainfall and closure in this environment is difficult, due to the high frequency and large amounts of rainfall in the area. In some instances, the valley would receive over 150 mm in day, in which the track would still remain open to the terminal viewpoint. Thus, making it extremely difficult to determine a daily threshold value for predicting track closure from a valley management perspective. The establishment of the probability the track would remain open was then adopted using the logit model (Equation 5.1).

$$y = 1 - (1/(1 + \exp(-(constant + variable\ x\ RF))))\ x\ 100 \qquad (5.1)$$

The parameters for this model are defined by the following; Y= the probability the walking track will be closed, the constant is the intercept output from the binary regression model as well as the variable using the SPSS output (Table 5.5). RF refers to the rainfall amount, which is either the cumulative rainfall amount for 24, 48 or 72 hours. Equations 5.2, 5.3 and 5.4 have been used to determine the probability outputs.

$$y = 1 - (1/(1 + exp(-(1.809 - 0.019\ x\ 24hr))))\ x\ 100 \qquad (5.2)$$

$$y = 1 - (1/(1 + exp(-(1.998 - 0.016\ x\ 48hr))))\ x\ 100 \qquad (5.3)$$

$$y = 1 - (1/(1 + exp(-(2.174 - 0.015\ x\ 72hr))))\ x\ 100 \qquad (5.4)$$

Table 5.5*: SPSS variables in equation output from binary regression model. Values used in to calculate track closure probabilities in the logit model are indicated by the red circle.*

Variables in the Equation

	B	S.E.	Wald	df	Sig.	Exp(B)
[a] rainfall_daily	-.019	.001	212.561	1	.000	.981
Constant	1.809	.041	1939.116	1	.000	6.105
rainfall_48hours	-.016	.001	339.747	1	.000	.984
Constant	1.998	.046	1920.917	1	.000	7.371
rainfall_72hours	-.015	.001	443.127	1	.000	.985
Constant	2.174	.050	1906.537	1	.000	8.795

The probabilities of the Fox Glacier walking track being closed with each specified rainfall amount are shown in Figures 5.15, 5.16 and 5.17. The probability the walking track is closed increases as the amount of rainfall increases. For example, if the Fox Valley receives 100 mm of rainfall over 24 hours, there is a 50% chance that the walking track will be closed to visitors compared to a 30% chance of being closed with 50 mm of rainfall (Figure 5.15). The probability of track closure then decreases for the same amount of rainfall that has been received over a longer duration (e.g. 100 mm in 24 hours vs 48 hours). For example, 100 mm rainfall received over 24 hours has a track closure probability of 50%, which then decrease to 40% if the 100 mm has accumulated over 48 hours (Figure 5.16), and to 30% for accumulation over 72 hours (Figure 5.17).

The probabilities generated from the logit model, provide a realistic representation for the probability the glacier walking track will be closed on any given day. For example, when there has been no rainfall, there is still a 10 – 15% probability the walking track could be closed (Figure 5.15). This is due to the fact that subsequent track closures can occur following rain events for track maintenance, which coincides with the 17.7% probability that on any day, visitors may not have access to the terminal viewpoint.

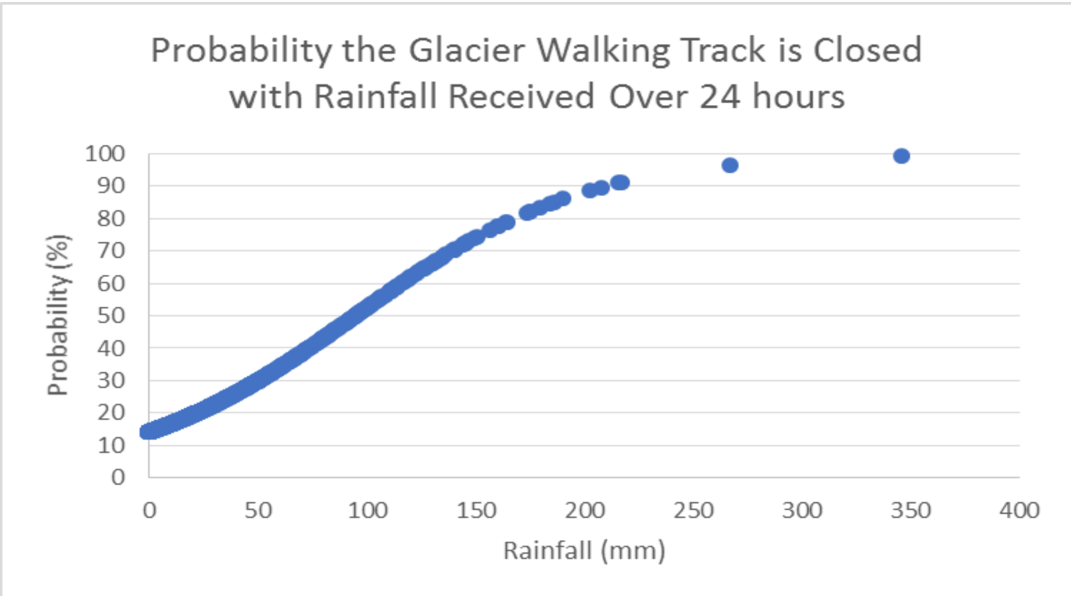


Figure 5.15: *Probability the Fox Glacier walking track will be closed from rainfall received over 24 hours. The rainfall data is representative from 2001-2017.*

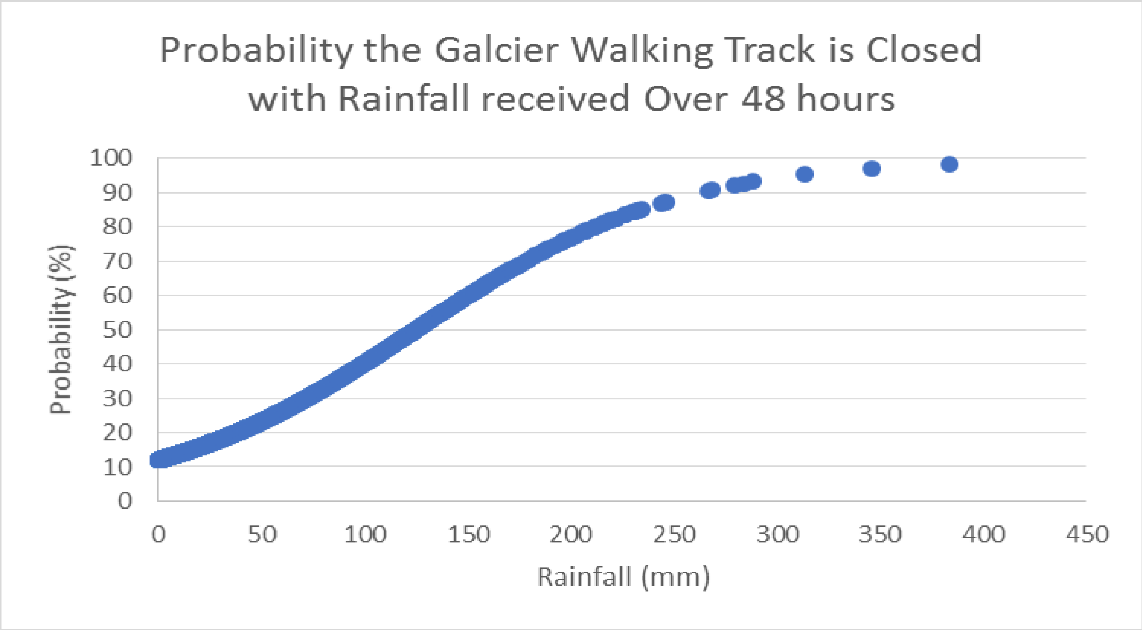


Figure 5.16: *Probability the Fox Glacier walking track will be closed from rainfall received over 48 hours. The rainfall data is representative from 2001-2017*

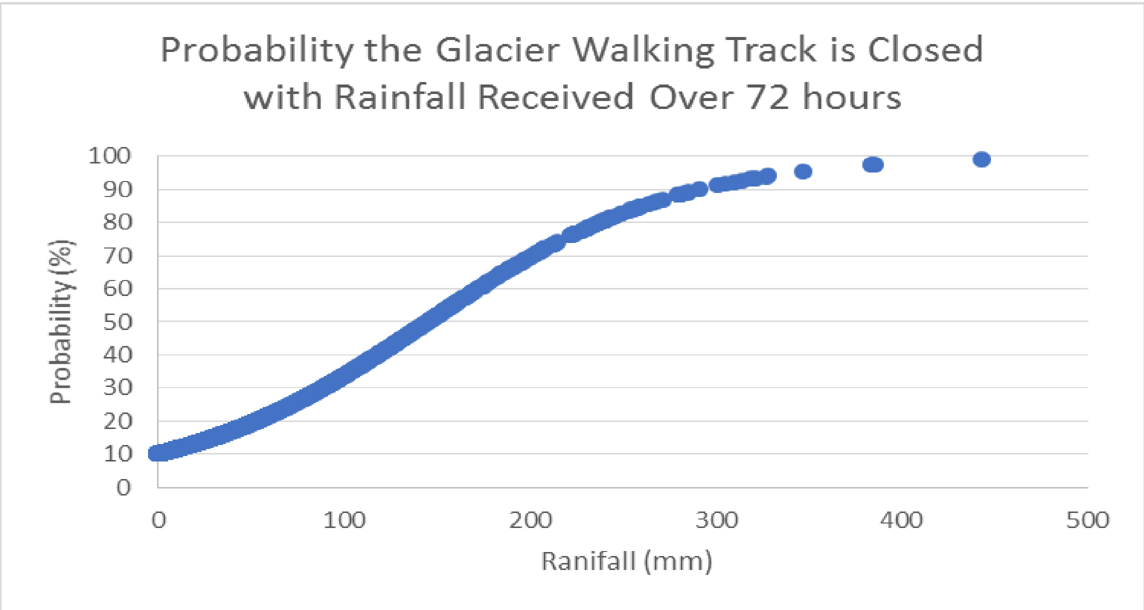


Figure 5.17: *Probability the Fox Glacier walking track will be closed from rainfall received over 72 hours. The rainfall data is representative from 2001-2017.*

5.5 Experimental alluvial fan lab modelling

5.5.1 Simulation of fan management and evolution

The models completed in the lab were used to anticipate fan evolution based from management techniques used in the Fox Valley. Stop banks on Yellow Creek have been used to direct the flow towards the true right hand side of the fan (Figure 5.2). With the stop bank installed at an angle, the energy from the active channel erodes away the stop bank until it is breached and the channel can flow in its natural state (Figure 5.18). Whilst the lab fan is not to the correct scale of the Yellow fan, it successfully demonstrates what has been observed in the valley. Sediment aggradation has been directed towards the true right hand side of the fan, until recently where active channel has avulsed towards the left hand side. Avulsion of Yellow Creek has occurred from two possible scenarios. The first scenario is from the gradual erosion of the stop bank overtime or due to a large rainfall event where a debris flow has demolished the stop bank. Given the natural flow conditions of Yellow Creek the most likely situation to cause avulsions is from a debris flow or flooding events.

A more recent management technique applied by DOC, involved the creation of a levee in front of Gunbarrel to minimise rockfall runout on to the walking track. The height of the levee dissipates out towards Yellow Fan, which has the potential to alter sediment deposition from Yellow Creek in large storm events. The lab modelling displayed that sediment deposition would occur around the levee and within the dugout depression, with the potential to erode the end closet to the active channel (Figure 5.19). As a result, this could impact on the functionality of the levee as a rockfall mitigation technique and provide ongoing maintenance with removal of the material that accumulated in the depression.

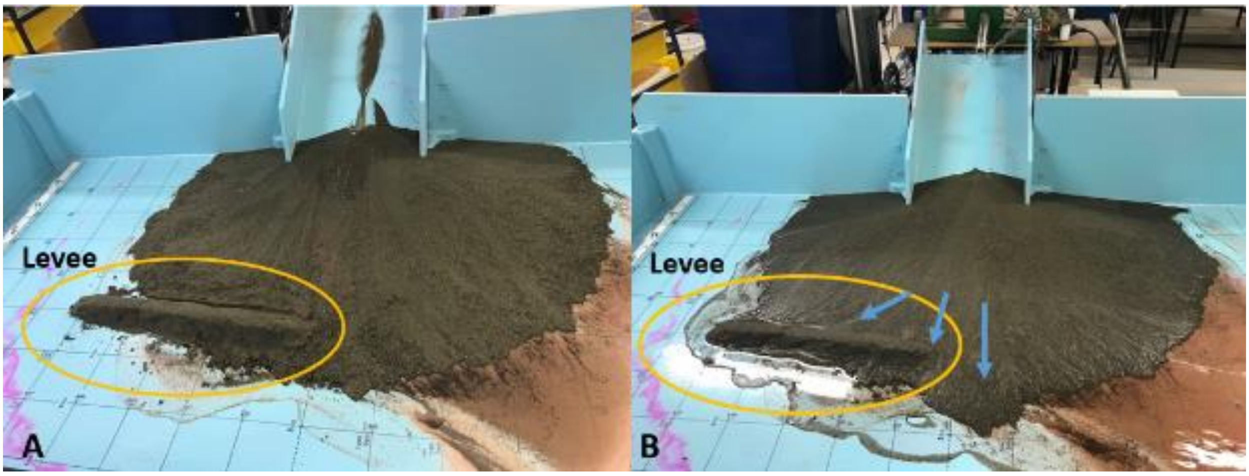


Figure 5.18: *Lab modelling for stop bank scenario with A) demonstrating before interaction with the active channel and B) demonstrating an eroded stop bank after channel avulsion. Flow and deposition indicated with blue arrows.*

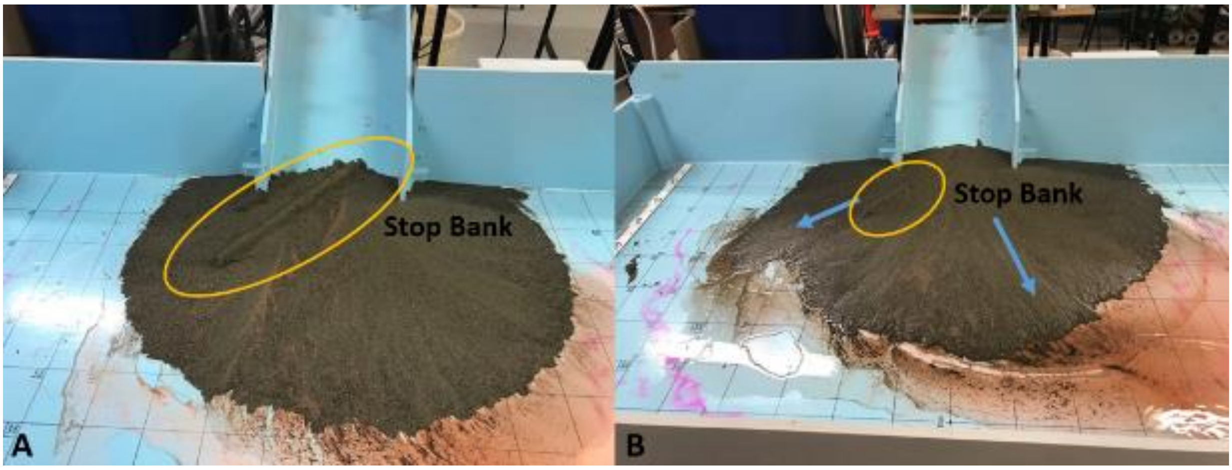


Figure 5.19: *Lab modelling for levee scenario with A) demonstrating before sediment deposition and B) demonstrating post sediment deposition. Flow and deposition indicated with blue arrows.*

5.5.1 SfM and lab modelling

The digital elevation models produced via SFM processing of the experimental fans all had large errors meaning that they were not suitable for assessing the use of SFM at a laboratory scale (Table 5.6). The errors in Table 4.4 are from one development stage, with the addition of combining the DEMs together, DoDs produced in ArcGIS would create too larger uncertainty given the size of the model. Factors for the uncertainty were derived from the lack of imagery overlap, high reflection of light on residual water, the clarity of imagery and interference from the ramp structure (e.g. Impacting on deposition and difficulties with image capture around the structure). Due to time constraints, these issues were not able to be resolved. For further investigation and improvements into using SfM in physical modelling, several steps should be taken into account. Firstly, the duration each simulation is run for should be increased, thus allowing for larger amounts of sediment accumulation in between SfM surveys to reduce errors. Increase the number of images taken whilst using a higher resolution camera for better pixel matching. Allow for the residual water to decrease to reduce the reflectivity as well as the sandbox placed in a more light appropriate area. Lastly, the sandboxed used in this experiment, may need the ramp structure adjusted so it has less interference with future SFM modelling.

Table 5.6: *Associated errors produced from the SfM processing report for one of the alluvial fan models.*

X error (m)	Y error (m)	Z error (m)	XY error (m)	Total error (m)
4.3894	1.97924	0.359942	4.815	4.82843

Chapter 6: Discussion

This chapter presents a discussion and analyses of the findings of this research and their wider application to the management of the Fox Valley.

6.1 Formation Sequence of the Yellow Creek Alluvial Fan

6.1.1 Rate of Change

Since the 1800s, Franz Josef and Fox Glaciers have retreated by 3 km in length and 3–4 km^2 in area, with the greatest overall loss occurring between 1934 and 1983 (Purdie *et al.,* 2014). Following several small glacier advances since the 1990s (Figure 2.2), the glaciers are currently in a retreat phase. Alpine catchments, such as the Fox catchment, are sensitive to climate change and human impacts, which can be reflected within the geomorphology (e.g. deglaciation, aggradation and mass movements) (Carrivick *et al.,* 2013). The Fox Valley, displays the following paraglacial features as a response to the morphogenic readjustment of the valley; rockfall, rock-slope failures, debris flows, alluvial fans, kettles (near the glacier terminus) and a braided river (Figure 3.1) (Mercier, 2008).

Over the last two years, aggradation from the Yellow Creek and Straight Creek alluvial fans has affected the Fox Valley. The average elevation of Yellow Fan has changed by 1.94m (+/- 30cm) and it is unknown how much the Straight Creek Fan has changed. More recently, due to the different positions of the fans within the valley, it would be expected that Straight Creek Fan would have experienced more aggradation. This is because the fan is younger, lacks vegetation, lacks channel incision (i.e. the fan is unstable), has a continuous supply of sediment, and the landscape is responding to the effects of deglaciation (Figure 6.1) (Church & Ryder, 1972).

Figure 6.1: *Straight Creek alluvial fan, within the Fox Valley.*

Yellow Fan is currently in a stable period, with established vegetation, incised channels and has distinguishable evolutionary stages (Figure 5.2). It is likely the Yellow Fan developed during the last century between the 1940s-1950s dependent on the position of Fox Glacier at the time (Figure 6.4). The Yellow Creek catchment has a continuous supply of sediment from several landslides that have occurred over time. These landslides had a width of up to over 100 m, and depths of several tens of meters, which Hovis (1994) identified to contain tens to hundreds of thousands of cubic meters of material. While this observation was made several decades ago, there is still a substantial supply of material available within the catchment (Figure 6.2).

When predicting the duration of sediment supply within a paraglacial system, Ballantyne (2003), describes the sediment supply to have a negative exponential function. The life time of the paraglacial cycle depends on the amount of sediment available for erosion, climatic parameters, geographic location and geologic nature of the catchment and vegetation cover (Mercier, 2008). After deglaciation has been completed and the sediment supplies have been exhausted the paraglacial cycle ends (Ballantyne, 2003). Cossart and Fort (2008), note that the life expectation of a paraglacial land system is limited. However, system adjustment can be prolonged for several centuries, or millennia, in areas that have sufficient sediment supply. In the Fox Valley, there is a sufficient sediment supply from the valley side walls and surrounding catchments typical in a paraglacial environment. Although, Carrivick and Rushmer (2008), suggest that the glaciofluvial discharges across the Fox Glacier outwash plain are insufficient for transporting paraglacial inputs

Figure 6.2: *The Yellow Creek catchment, captured looking up catchment from the fans apex. Vegetated landslides within the catchment have been indicated by the orange circle.*

from the valley side walls (e.g. alluvial/debris fans). This means that the Fox Valley is transport limited and consequently a net aggradation zone. Episodes of aggradation are currently viewed in the valley, except when there are large storm events or subsequent glacier ice collapse events, where large influxes of material has entered the outwash plain. These events are apparent from imbricated boulder bars marginal to the main outwash plain (Carrivick & Rushmer, 2009). As the Fox Valley is a net aggradation zone, further fan development will occur until the next big storm event, which will result in fluxes of sediment down the Fox River.

6.1.2 Paraglacial Alluvial Fans

The importance of studying paraglacial landforms and sediments have been identified by Carrivick and Rushmer (2009) for three main reasons;

- To understand the controls on water and sediment fluxes is important for management and conservation in glaciated regions.
- To predict the future response of water and sediment from climate change.
- To accurately understand geologic, geomorphic and sedimentological records in deglaciated regions.

However, to gain a full understanding of a paraglacial environment, landforms should not be treated as binary features, but instead assessed as an interconnected landscape (Campbell & Church, 2003). This has been taken into account within this thesis. Paraglacial alluvial fans act as a sediment storage system and are classified as a primary paraglacial system (Ballantyne, 2002b). Generally, paraglacial fans will contain large amounts of till deposits, if the surrounding catchment is steep hillslopes (Campbell & Church, 2003). On Yellow Fan, there are noticeable till deposits that have been reworked, as well as a large amount of eroded bedrock. Channel avulsions are common on Yellow Fan, which are a response to episodic flood events (McEwen *et al.,* 2011).

6.1.3 Possibility of Detached Ice underneath Yellow Fan

A distinctive feature on the Yellow Fan is a slump in the mid-fan region (Figure 5.2). The development of the slump began on the west side of the fan between 2010–2014, where it has continually increased to up to 2 m in height. There are a few possible scenarios for the creation of slump feature on the fan. Firstly, this slump may have formed from a large seismic event. Given the close proximity to the alpine fault, this is feasible. However, there has been no recent seismic activity in the area to coincide with the slump. Secondly, the slump could be an alluvial fan terrace. Colombo (2005), suggests that segmented geometry on alluvial fans or several morphological breaks on the fans upper surface can indicate a terrace. These could have formed as a complex response to a change of an external variable (e.g. base level, climate, vegetation). Chronological investigation of the fan, has found that the upper slump segment and lower slump segment of the fan were deposited at the same time (see section 5.3.3). As a result, the slump is not a terrace.

The most probable causation of the slump is from the melting of debris covered detached glacial ice from underneath the fan. From the 1950s glacial retreat, a large amount of debris covered ice became detached and remained in the valley beside the carpark until 2012 (Figure 6.3). If there is sufficient debris cover on glacial ice, it acts as an insulator and slows down the rate of ablation (Mihalcea *et al.,* 2006; Brook *et al.,* 2013). A study by Purdie *et al.,* (2014), discussed the fluctuation of the length of Fox Glacier, and identified potential areas that were reported to have had detached debris covered ice (Figure 6.4). The 1955 glacial retreat is when the ice was likely to have become detached and gradually buried underneath Yellow fan from aggradation. Mercier (1997), suggested that once the glacier retreats, leaving behind lateral moraines, the landscape can reshape quickly and the debris from the surrounding slopes can burry deposits of detached ice. Due to the formation of the Yellow Fan likely to have started around this period, it is highly likely that the fan could have formed over top of detached ice. Future investigations could be carried out on the fan with a thermal camera to detect if there is if any remnant ice remains buried under the fan, which would indicate the area will continue to experience slumping until all the ice has melted.

Figure 6.3: *Debris covered detached ice located beside the carpark. Photo captured from Yellow fan looking towards the carpark (Chinn, 2004).*

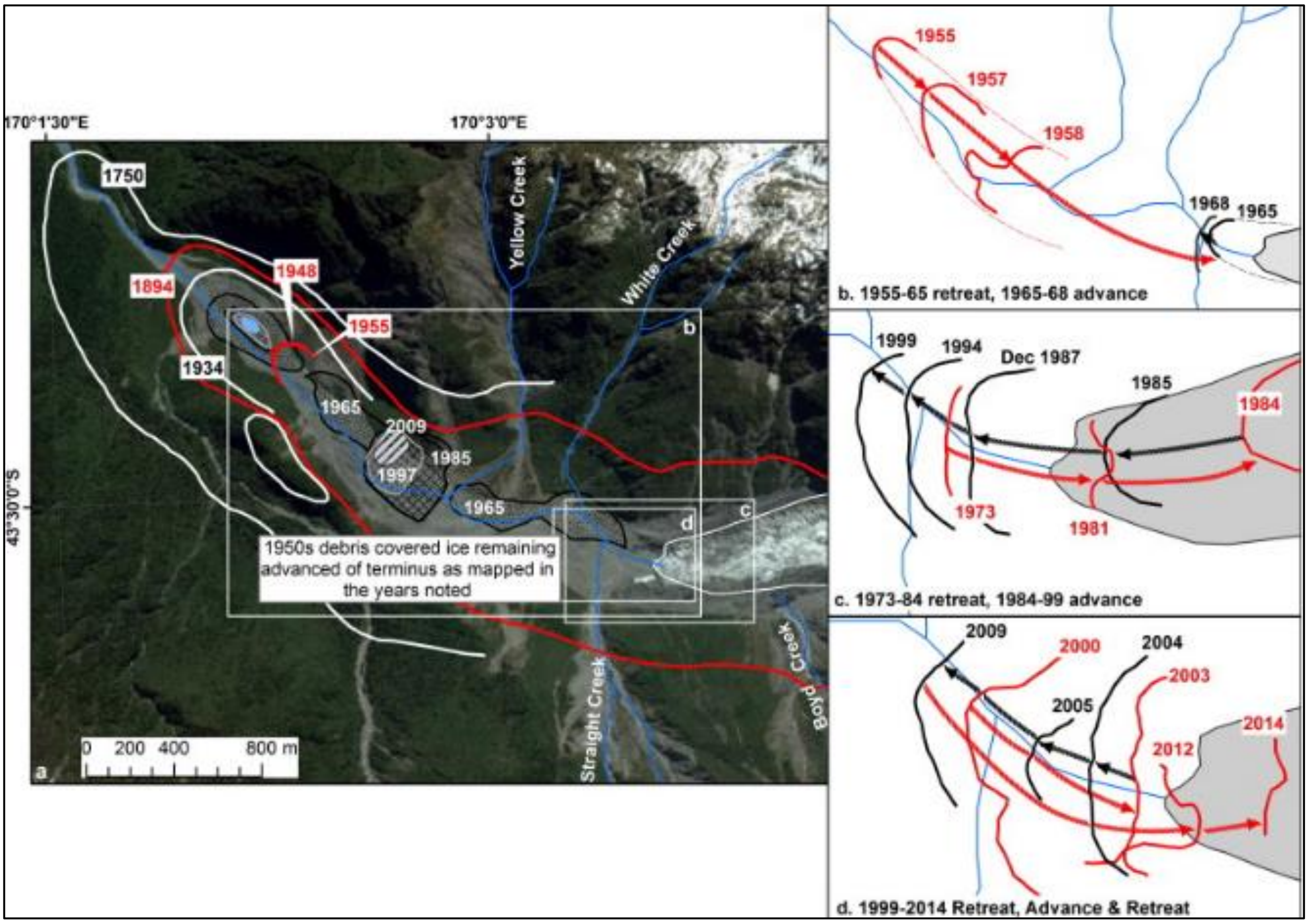


Figure 6.4: *Historic lengths of advance and retreat of Fox Glacier (Reproduced from Purdie et al., 2014, Figure 4, p48).*

6.2. Rainfall and the Impact on Track Closure

6.2.1. The Relationship of Track Closure and Rainfall

Establishing a relationship between track closure and rainfall is important given the frequency and amount of rainfall received in the area. On average, Franz Josef township receives 185 days of rainfall (>1 mm) per year with the mean annual rainfall for Franz Josef totalling 5751 mm. December has the highest monthly rainfall average of 659 mm (Figure 6.5) (Macara, 2016). As summer and spring receive the largest amounts of rainfall, management concerns arise around walking track accessibility during the peak tourist season. The walking track within the valley is vulnerable to flooding, rockfall and debris flow episodes (Figure 4.9). All of which require maintenance that can interrupt accessibility to the glacier terminal viewpoint. Storms that occur during summer months have the highest erosivity impact on material, further enhancing slope instabilities and erosion of material. On average these storms are 2.1 times more erosive than those that occur in winter (Kilk *et al.,* 2015). Large rainfall amounts are also associated with these storms resulting in flooding of main rivers. For example, in March 1982, 650mm of rain was recorded over 72 hours in the Franz Josef Valley, causing the Wahio River to flood (Benn, 1990). The recurrence of storm events producing over 600 mm of rain in 72 hours is thought to be once every few years and storms producing 200 mm in 24 hours occur about once a year (McSaveney & Davies, 1998). At Fox Glacier, the largest amount of rainfall accumulation recorded over 72 hours was 450 mm (Figure 5.17).

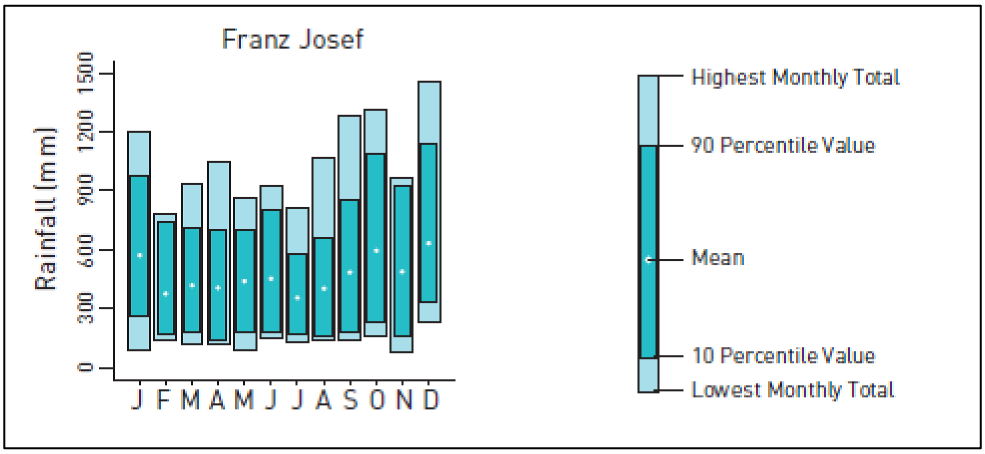


Figure 6.5: *Monthly rainfall averages from 1981- 2010 for Franz Josef (Macara, 2016).*

Whilst the binary regression model produced a weak relationship between track closure and rainfall (see section 5.4), the probabilities of track closure in Figures 5.15, 5.16 & 5.17 show that there is a relationship. When there is an increase in the amount of rainfall, the probability of the walking track being closed also increases. This is valuable information for those responsible for the management off public access into the valley, as it allows managers to anticipate whether the walking track is going to be closed. However ideally, establishing a trigger value for track closure would be required. A study completed by Bosse (2016) explored the recurrence interval for heavy precipitation events in the Otira Valley, to determine a threshold rainfall value to trigger walking track closures. Bosse (2016) concluded that DOC should close the track to the public before, during or after a rainfall event greater than 300 mm over 24 hours. Although the Otira Valley receives large amounts of annual rainfall, like Westland (Figure 2.3), this trigger value seems surprisingly high. When anticipating track closure before a rainfall event, an overestimation would be better than an underestimation, causing the least amount of inconvenience if the conditions were not as bad as first anticipated and the track was closed. Such an approach would be feasible in the Fox Valley, where daily track checks are completed and can be reassessed throughout the day, which is not the case for other tracks around New Zealand. Future research could focus on establishing storm recurrence intervals for the Fox Valley area. This would be beneficial to help establish a track closure trigger value in conjunction with the probabilities of track closure with specific rainfall amounts.

6.2.2. Climate Change

Glaciers are sensitive indicators of climatic variations on all time scales from inter-annual variations and decadal to millennia-long glaciations (Purdie *et al.,* 2014). This sensitivity is reflected in dramatic length fluctuations at Franz Josef and Fox Glaciers during recent decades (Figure 2.2) (Purdie *et al.,* 2015). With the mean global temperature expected to rise between 1.8 and 4 ^{0}C over the next 100 years (IPCC, 2013), it is expected that deglaciation will continue. By 2090, the West Coast is expected to have 30 extra days per year where the maximum temperature exceeds 25 ^{0}C and the overall mean temperature rise is between 0.6 and 3.2 ^{0}C (Table 6.1)(MfE, 2018). Other climatic impacts from climate change are as follows; an increase in rainfall (Table 6.1) and an increase in extreme rainfall events, an increase in the frequency of westerly winds, an increase in intensity of storm events, and an increase risk of flooding and landslides (MfE, 2018). Moreover, the duration of snow cover is likely to decrease as well as a significant decreases in seasonal snowfall, which is likely to have detrimental impacts on New Zealand glaciers (Purdie *et al.,* 2015).

Table 6.1: *Predicated seasonal changes of temperate and rainfall by 2090 (MfE, 2018)*

Spring	• 0.6°C to 2.5°C temperature rise • 4 to 9 per cent more rainfall in Hokitika
Summer	• 0.6°C to 3.2°C temperature rise • 2 to 4 per cent more rainfall in Hokitika
Autumn	• 0.7°C to 3.1°C temperature rise • 2 to 5 per cent more rainfall in Hokitika
Winter	• 0.7°C to 3.1°C temperature rise • 8 to 29 per cent more rainfall in Hokitika

With the current management challenges experienced with rainfall and walking track accessibility to view Fox Glacier, climate change impacts will likely result in more track closures. A study completed by Anderson *et al.,* (2008), has predicted that under a mean climate change scenario (0.7- 1.4 ^{0}C), the Franz Josef Glacier will retreat 5 km and lose 38% of its mass by 2100. With the predicted ongoing deglaciation, the valley will remain in a high sediment yield phase in the paraglacial cycle. This will cause the valley to be continually susceptible to ongoing changes for the foreseeable future. For example, large fluxes of sediment will continue to enter the valley system through rock-slope failures, rock-mass movements and debris cone/alluvial fan formations (Ballantyne, 2002b). Increases in rainfall and storm intensities will continue to influence slope, where debris flows and rockfall events will be more frequent.

6.2.3 Impacts on Tourism

Currently, the Westland *Tai Poutini* National Park experiencing rapid environmental change, increasing the potential that the tourism viability of its glacier attractions will diminish overtime (Stewart *et al.,* 2016). In the 2013/2014 summer season, glacial tourism experienced a major setback with guided walks on the lower glacier surface being suspended due to increased slope instability and rock fall susceptibility around the glacier terminus. As a result, visitors can now opt to pay for a helicopter hike to walk onto the glacier, or view the glacier for no cost from the terminal viewpoint in the valley (Stewart *et al.,* 2016). A study completed by Wilson *et al.,* (2014), within the Fox Valley surveyed visitors to get an indication of overall satisfaction of their glacial experience. At the time of the survey in 2013, the terminal viewpoint allowed visitors to walk within 200 m of the glacier.

Surveying was completed across five days, in which one of the five days only allowed visitors to the 600 m Yellow Creek viewpoint after heavy rain had increased rockfall risk. Only 30% of respondents that could reach the 200 m terminal viewpoint were satisfied with how close they got to the glacier. Whist 24.9% of respondents that could only reach the 600m Yellow Creek viewpoint were satisfied with how close they were able to get the glacier with 93.8% expecting to be able to get closer. Over the last decade, the retreat of Fox Glacier has resulted in the terminal viewpoint becoming further away from the terminus. For example, from 2013, the terminal viewpoint was 200 m from the terminus compared to 2017, where the terminal viewpoint was 450 m from the terminus. Whilst the current terminal viewpoint of Fox Glacier provides substantial views, the expectations and satisfaction of visitors may not always be achieved. Particularly, if the viewpoint becomes increasingly further away from the glacier or if the walking track accessibility is limited (e.g. visitors are restricted to another viewpoint further down valley). The steep slopes and unstable debris up valley will make any future viewpoint relocations up valley highly unlikely. As a result, the distance between the terminal viewpoint and terminus will increase, which may have a negative impact on tourist satisfaction over the next few decades.

On any given day there is a 17.7% chance that the glacier walking track will not be open to the terminal viewpoint (See section 5.4.1). As discussed in section 5.2.1, the months that receive the highest amounts of rainfall are December and January (Figure 6.5). Which coincides with the peak tourist season in New Zealand, due to it being summertime (see section 3.5.1). On the 1st of February 2018, ex-tropical cyclone Fehi, hit the West Coast causing substantial flooding in the Fox valley and subsequent damage to infrastructure (Figure 6.6). As a result the access road and glacier were closed for a minimum of two months. When an event like this occurs, it is highly likely to cause economic loss to the local communities. However, as there is only helicopter access to be able to go on the glacier, this specific event would have had a less economic impact. In terms of helicopter accessibility onto the glacier, this is largely weather dependent, so summers that experience frequent rainfall events, will impact the number of people that can be accommodated by such tours. While tourism in the Westland region is largely dependent on natural features and can be heavily impacted by weather conditions, Espiner *et al.,* (2017) suggest that the region has displayed resilience to the current changing conditions and the tourism industry has been sustained despite vulnerabilities (e.g. natural disasters, changing climate and glacier accessibility).

Difficulties that arise with managing a popular area that is extremely hazard prone, is an individual's perception of a hazard and associated risk. Whilst tourism is a necessity for the area, the safety of the visitors is extremely important. A hazard can be defined as a set of circumstances which may

Figure 6.6: *A section of the Fox Glacier access road that was washed out from flooding (Huffadine, 2018).*

cause harmful consequences and risk is the likelihood of becoming harmed by a hazard (Espiner, 1999). Due to the large influx of tourists into the area, mitigation measures are important tools to prevent harm to individuals. This includes reducing the track accessibility if needed. While tourists may not have a good experience if the walking track is closed, they may not be aware of or have been exposed to these specific hazards before.

6.3 Management in the Fox valley

6.3.1 Assessment of Current Management Practises

As discussed in section 3.5.2, DOC is responsible for the management of the Fox Valley. One of the biggest challenges with managing such an active landscape, is that one extreme event (e.g. flooding, landslide or earthquake) can causing long term or permanent changes to the landscape, which in turn, causes on-going management challenges. For example, currently in the Fox valley, the activation of rockfall from the Gunbarrel, has created on-going management issues for visitor safety. Similar challenges are currently being faced in the Kaikoura region where ongoing issues with the slope stability and accessibility of State Highway one following the Kaikoura earthquake in Month, Year (KDC, 2017). Thus, requiring the need for a high adaptive management strategy from environmental managers and surrounding users of the environment (Stewart *et al.,* 2016).

The current monitoring in the Fox valley undertaken by DOC includes; a hazard register (e.g. rockfall), daily valley checks (e.g. track conditions) and daily rainfall, from a rain gauge that is regularly checked. NIWA had an AWS in the Fox valley until 1994 when monitoring was ceased as a result of on-going issues (Purdie *et al.,* 2008). The West Coast Regional Council (WCRC) is responsible for monitoring river conditions (e.g. river level, flow) on the West Coast. Several river monitoring programmes have been established on the major rivers on the West Coast, but due to resource constraints, not all rivers are monitored. The closest river to the Fox River that is monitored is the Waiho River near Franz Josef (WCRC, 2013). Due to the lack of monitoring at Fox, determining a flooding frequency pattern can be difficult. While the Franz Josef and Fox Glacier catchments are often regarded as having somewhat similar morphologies (e.g. Anderson *et al.,* 2008; Purdie *et al.,* 2008), Carrivick and Rushmer (2009) have identified different river characteristics between the Waiho and Fox Rivers. Thus, making it difficult to determine a reliable flooding reoccurrence intervals in the Fox Valley (WCRC, 2013). The Fox Valley is prone to aggradation and is confined by a smaller outwash plain so is transport limited, whereas the Franz Josef is the complete opposite and has a greater transport capacity in flood events (Carrivick & Rushmer, 2009).

Current management structures within the valley include; the use of hazard signs and information boards advising the visitors of their surroundings (Espiner, 1999), rockwalls and rockfall fallout pits to actively mitigate against rockfall, as well as stop banks to protect walking track infrastructure. The use of stop banks on Yellow Creek has enabled aggradation on the west side of the fan as well as protecting the walking track. While the purpose of these structures is to provide protection for the visitors along the walking track, it is important to explore any implications these structures may have on natural system evolution. The issue of using stop banks on Yellow Fan is that the fan is highly dynamic and prone to debris flows. As seen in section 5.2.1 and 5.2.2, the stability of the main Yellow Creek channel fluctuates. As the material builds up within the channel, the active stream becomes less channelized and more dynamic, resulting in avulsion episodes (Jones & Schumm, 1999).

The rockwall feature that was established in front of the Gunbarrel at the beginning of 2017 (Figure 6.7), provides some protection to the walking track from and active rockfall. The rockwall was approximately 100 m in length and had a dissipating height from 8.5 – 3.7 m towards Yellow Fan. The dug out region in the northern side of the wall (Figure 6.7a), was 9.15 m wide and 1.6 m deep. This mitigation feature will successfully protect the track, but will need ongoing maintenance to ensure it functions properly. Issues that will arise without continued maintenance will result in the

Figure 6.7: *Rockfall mitigation used in front of Gunbarel. A) The rockfall fallout pit. B) The rockwall dissipating towards Yellow Fan. C) Large area of rockfall.*

build-up of material within the dugout, that will create a ramp-like structure, that boulders could bounce off and subsequently fly or roll over the wall if momentum was sufficient (Evans & Hungr, 1993). The amount of rainfall and sediment deposition will dictate how frequently the pit will need to be dug out in order for this structure to remain effective.

Over the duration of this research, this rockwall structure has been eroded away from a large flooding event in the valley, as a result of a large storm that occurred in February. However, this does not make this information invalid, as DOC has installed a similar type of structure (Figure 6.8), which will still require ongoing maintenance. Whilst DOC is continually completing maintenance work within the valley, large amounts of the work completed are unplanned. For example, between July 2016 and February 2017, 3025 hours of work was logged (e.g. daily valley check, planned track changes), of which, 375 hours were unplanned (O. Kilgour – Personal communication 26/3/17). The dynamics of a geomorphically active area make it difficult to manage for the long term. Due to the constant changes in the landscape and large supply of sediment still readily available (Ballantyne, 2002b), it is sensible to implement structures that are effective, low cost and short term. Thus allowing for an adaptive management strategy and planning for the unknown (Stewart *et al.,* 2016).

6.3.2. Vulnerability of the area

As discussed, the Fox Valley is a highly dynamic paraglacial environment, which is influenced by the availability and instability of sediment (Slaymaker, 2011). Due to the large amounts of rainfall received in the valley, the stability of the valley sides are increasingly susceptible to erosion and mass movement events (WCRC, 2013). Welsh and Davies (2011), identified Yellow Creek and Bullock Creek in the Fox Glacier valley to be vulnerable to debris flow events based on their catchment and climate criteria's. Prior work completed in the valley by Hovius (1995), identified the following vulnerabilities within the Fox Valley;

- Large rock avalanches from the Undercite Creek Catchment and adjacent steep rock faces.
- Reoccurring debris flow and mudflows from the Yellow Creek catchment
- Instability of channel sides below the Yellow Creek Fan
- Slope instability between White Creek and the glacier terminal, both above and below the glacier walking track
- Occasional debris flows from an unnamed catchment to the North West of the upper Yellow Creek catchment.
- Debris avalanching in the lower valley from Gunbarrel

Hovius (1995) concluded that Undercite Creek was the greatest area of concern, given the vulnerability to the access road and carpark infrastructure. Since this study, DOC has successfully managed the large rock avalanches from Undercite and has adopted the same technique for managing Gunbarrel (Figure 6.8).

Figure 6.8: *A) Gunbarrel with current management technique. B) Undercite Creek management technique (SS, 2018)*

Chapter 7: Conclusion

7.1 Objectives Revisited

This research successfully identified the evolutionary stages of the Yellow Creek fan (Objective 1), and developed some probability estimates linking track closure to rainfall events (Objective 2). Objective 3, to assess the feasibility of using SfM in alluvial fan modelling, was only partially realised, and although the research here was successful within the field more work is required in order to assess the use of SfM with physical modelling.

7.2 Future Research Opportunities

From this research, important questions regarding the behaviour and future stability of the Fox Valley have been highlighted. While there exists a reasonable body of research on paraglacial environments, the high sediment yields produced within the Fox Valley, create challenges for valley management. The popularity of glacier tourism and subsequently large visitor numbers to the Fox Valley, means that a more in depth investigation to establish flooding reoccurrence intervals would be desirable for future management planning. Future research opportunities in the Fox Valley include the following;

- The establishment of a flow meter or a river monitoring programme, to assess maximum flow conditions and sediment transport capacities of the Fox River.
- Investigating reoccurrence intervals for flood frequency and maximum rainfall events, to establish trigger values for track closure and to estimate the life span of mitigation structures.
- To investigate further into tourism and visitor satisfaction from previous studies complete (e.g. Stewart *et al.,* 2016; Wilson *et al.,* 2013), identifying issues with the increasing distances between the glacier terminus and terminal viewpoint.

Due to time constraints and other limitations that have been specified in section 5.5.1, the SfM alluvial fan modelling was only partially successful. Future research into using this method in a laboratory would be beneficial as it is an effective low cost method that is becoming increasingly more popular (Carrivick *et al.,* 2016).

7.3 Summary

The key findings of this research have been summarised below;

- The Yellow Fan has developed in three stages, which has most likely to have begun immediately following the 1950s retreat of Fox Glacier. This conclusion was determined through a combination of photographic analysis and chronological investigations (see section 6.1).
- There has been predominant aggradation on Yellow Fan between 2015 and 2017, with an average elevation change of 1.94 m (+/- 30 cm).
- The slump on Yellow Fan has formed from the melting of debris covered ice that had become detached from the glacier during the 1950s retreat (see section 6.1).
- On any given day, there is a 17.7% chance that the Fox Glacier walking track will be closed due to heavy rainfall, rockfall or track maintenance.
- The amount of rainfall received in the valley significantly impacts on the walking track accessibility. When there is an increase in the amount of rainfall, the probability of the walking track being closed also increases.
- December receives the highest monthly rainfall, which coincides with the peak tourist season and consequently has the potential to impact tourism in the area. A recent example of this was on the 1st of February 2018, ex-tropical cyclone Fehi, caused damage to infrastructure in the valley, subsequently restricting valley access for two months.
- Adaptive management strategies are needed in a paraglacial environment. The high sediment yield and constant changes that occur make it difficult to establish longer term infrastructure or mitigation measures for hazards within the valley.
- Finally, the use of SfM was successful in the field, however, was not in a laboratory environment due to user errors and requires future investigation.

8. References

Al-Farraj, A., & Harvey, A. M. (2005). Morphometry and depositional style of late Pleistocene alluvial fans: Wadi al-bih, northern UAE and Oman. *Geological Society Special Publication, 251*, 85-94. Doi:10.1144/GSL.SP.2005.251.01.07

Anderson, B., Lawson, W., & Owens, I. (2008). Response of Franz Josef Glacier Ka Roimata o Hine Hukatere to climate change. *Global and Planetary Change*, *63*(1), 23-30.

André, M. F. (2009). From climatic to global change geomorphology: contemporary shifts in periglacial geomorphology. *Geological Society, London, Special Publications*, *320*(1), 5-28.

Aydin, A., & Basu, A. (2005). The Schmidt hammer in rock material characterization. *Engineering Geology, 81*(1), 1-14. Doi:10.1016/j.enggeo.2005.06.006

Ballantyne, C. K. (2002a). Paraglacial geomorphology. *Quaternary Science Reviews, 21*(18), 1935-2017. Doi: 10.1016/S0277-3791(02)00005-7

Ballantyne, C. K. (2002b). A general model of paraglacial landscape response. *The Holocene, 12*(3), 371-376. Doi:10.1191/0959683602hl553fa

Ballantyne, C. K. (2003). Paraglacial landform succession and sediment storage in deglaciated mountain valleys: Theory and approaches to calibration. *Zeitschrift Fur Geomorphologie, Supplementband, 132*, 1-18

Ballantyne, C. K., & Benn, D. I. (1994). Paraglacial slope adjustment and resedimentation following recent glacier retreat, Fåbergstølsdalen, Norway. *Arctic and Alpine Research, 26*(3), 255-269. Doi:10.2307/1551938

Beaty, C. B. (1990). Anatomy of a White Mountains debris-flow - the making of an alluvial fan. In Rachocki, A., & Church, M. A. (Ed.), *Alluvial fans: A field approach* (69-89). New York; Chichester, West Sussex, England; Wiley.

Bemis, S. P., Micklethwaite, S., Turner, D., James, M. R., Akciz, S., Thiele, S. T., & Bangash, H. A. (2014). Ground-based and UAV-based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology. *Journal of Structural Geology*, 69, 163-178.

Benn, D. I., & Ballantyne, C. K. (1993). The description and representation of particle shape. *Earth Surface Processes and Landforms, 18*(7), 665-672. Doi:10.1002/esp.3290180709

Benn, D. I., & Ballantyne, C. K. (1994). Reconstructing the transport history of glacigenic sediments: A new approach based on the co-variance of clast form indices. *Sedimentary Geology, 91*(1-4), 215-227. Doi:10.1016/0037-0738(94)90130-9

Benn, J. (1990). *West Coast River Flood History 1846 -1989*. 1-69.

Bennett, M. R., Hambrey, M. J., & Huddart, D. (1997). Modification of clast shape in high-arctic glacial environments. *Journal of Sedimentary Research, 67*(3), 550. Doi:10.1306/D42685CC-2B26-11D7-8648000102C1865D

Blair, T. C., & McPherson, J. G. (2009). Processes and forms of alluvial fans. In *Geomorphology of desert environments* (pp. 413-467). Springer, Dordrecht.

Blissenbach, E. (1954). Geology of alluvial fans in semiarid regions. *Geological Society of America Bulletin*, *65*(2), 175-190.

Bosse, D.W. (2016). *An Assessment of Tramper Safety in the Southern Alps New Zealand: The Upper Otira Valley Walking Track.* Professional Masters Dissertation, Department of Geological Sciences, University of Canterbury, 1- 10.

Brook, M. S., & Lukas, S. (2012). A revised approach to discriminating sediment transport histories in glacigenic sediments in a temperate alpine environment: A case study from Fox Glacier, New Zealand. *Earth Surface Processes and Landforms, 37*(8), 895-900. Doi:10.1002/esp.3250.

Brook, M., Hagg, W., & Winkler, S. (2017). Contrasting medial moraine development at adjacent temperate, maritime glaciers: Fox and Franz Josef Glaciers, South Westland, New Zealand. *Geomorphology, 290*, 58-68. Doi:10.1016/j.geomorph.2017.04.015.

Brook, M.S, Hagg, W., Winkler, S (2013). Debris cover and surface melt at a temperate maritime alpine glacier: Franz Josef Glacier, New Zealand. *New Zealand Journal of Geology and Geophysics*, 56 (1):27-38.

Bull, W. B. (1977). The alluvial-fan environment. *Progress in Physical Geography, 1*(2), 222-270. Doi: 10.1177/030913337700100202

Campbell, D., & Church, M. (2003). Reconnaissance sediment budgets for Lynn valley, British Columbia: Holocene and contemporary time scales. *Canadian Journal of Earth Sciences, 40*(5), 701-713. Doi:10.1139/e03-012

Carrivick, J. L., & Rushmer, E. L. (2008). Inter- and intra-catchment variations in geomorphology: An example from Franz Josef glacier and fox glacier, New Zealand. *Arctic, Antarctic, and Alpine Research, 41*(1), 18-36. Doi: 10.1657/1938-4246(07-099)[CARRIVICK]2.0.CO;2

Carrivick, J. L., Geilhausen, M., Warburton, J., Dickson, N. E., Carver, S. J., Evans, A. J., & Brown, L. E. (2013). Contemporary geomorphological activity throughout the proglacial area of an alpine catchment. *Geomorphology, 188*, 83-95. Doi:10.1016/j.geomorph.2012.03.029

Carrivick, J., Smith, M., & Quincey, D. (2016). *Structure from Motion in the Geosciences*. Ames, Iowa; Chichester, West Sussex, SQ, UK: Wiley Blackwell.

Carryer, S. J. (1966). A note on the formation of alluvial fans. *New Zealand Journal of Geology and Geophysics, 9*(1-2), 91-94. Doi:10.1080/00288306.1966.10420197

Cavalli, M., & Marchi, L. (2008). Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. *Natural Hazards and Earth System Science*, *8*(2), 323-333.

Church, M., & Ryder, J.M. (1972). Paraglacial sedimentation: A consideration of fluvial processes conditioned by glaciation. *GSA Bulletin, 83*(10), 3059-3072. Doi: 10.1130/0016-7606(1972)83[3059:PSACOF]2.0.CO;2

Clague, J. (2013). *Encyclopedia of natural hazards*. 400-404, New York;Dordrecht;: Springer. doi:10.1007/978-1-4020-4399-4

Clarke, L. E. (2015). Experimental alluvial fans: Advances in understanding of fan dynamics and processes. *Geomorphology, 244*, 135-145. Doi:10.1016/j.geomorph.2015.04.013.

Clarke, L., Quine, T. A., & Nicholas, A. (2010). An experimental investigation of autogenic behaviour during alluvial fan evolution. *Geomorphology, 115*(3), 278-285. Doi:10.1016/j.geomorph.2009.06.033.

Coates, G. 2002: *The Rise and Fall of the Southern Alps*. Christchurch: Canterbury University Press.

Cofaigh, C. Ó., & Dowdeswell, J. A. (2001). Laminated sediments in glacimarine environments: diagnostic criteria for their interpretation. *Quaternary Science Reviews*, *20*(13), 1411-1436.

Colombo, F. (2005). Quaternary telescopic-like alluvial fans, Andean ranges, Argentina. *Geological Society Special Publication, 251*, 69-84. Doi:10.1144/GSL.SP.2005.251.01.06

Cossart, E., Braucher, R., Fort, M., Bourlès, D. L., & Carcaillet, J. (2008). Slope instability in relation to glacial debuttressing in alpine areas (Upper Durance catchment, southeastern France): evidence from field data and 10Be cosmic ray exposure ages. *Geomorphology*, *95*(1-2), 3-26

Cossart, E., Braucher, R., Fort, M., Bourles, D., & Carcaillet, J. (2008). Slope instability in relation to glacial debuttressing in alpine areas (upper durance catchment, southeastern france): Evidence from field data and be-10 cosmic ray exposure ages. *Geomorphology, 95*(1-2), 3-26. doi:10.1016/j.geomorph.2006.12.022

Crosta, G. B., & Frattini, P. (2004). Controls on modern alluvial fan processes in the central Alps, northern Italy. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *29*(3), 267-293.

Davies, H., Weber, P., Lindsay, P., Craw, D., & Pope, J. (2011). Characterisation of acid mine drainage in a high rainfall mountain environment, New Zealand. *Science of the Total Environment, 409*(15), 2971-2980. Doi:10.1016/j.scitotenv.2011.04.034

De Haas, T., Kleinhans, M. G., Carbonneau, P. E., Rubensdotter, L., & Hauber, E. (2015). Surface morphology of fans in the high-Arctic periglacial environment of Svalbard: Controls and processes. *Earth-Science Reviews*, *146*, 163-182.

Decaulne, A., Sæmundsson, Þ., Jónsson, H. P., & Sandberg, O. (2007). Changes in deposition on a colluvial fan during the upper Holocene in the Tindastóll Mountain, Skagafjörður district, North Iceland: preliminary results. *Geografiska Annaler: Series A, Physical Geography*, *89*(1), 51-63.

Denny, C. S. (1967). Fans and pediments. *American Journal of Science*, *265*(2), 81-105.

Department of Conservation (DOC). (2001). Westland *Tai Poutini* National Park Management Plan 2001 – 2011, Amended 4 April 2014 *West Coast Conservancy Management Plan Series, 3*, 1-155.

Department of Conservation (DOC). (2013). *Draft Westland Tai Poutini National Park Management Plan partial review.* Retrieved from https://www.doc.govt.nz/Documents/getting-involved/consultations/current-consultations/west-coast/draft-westland-plan-partial-review.pdf

Derbyshire, E., & Owen, L. A. (1990). Quaternary alluvial fans in the Karakoram Mountains. In Rachocki, A., & Church, M. A. (Ed.), *Alluvial fans: A field approach* (27-53). New York; Chichester, West Sussex, England: Wiley.

Drew, F. (1873). Alluvial and lacustrine deposits and glacial records of the Upper-Indus Basin. *Quarterly Journal of the Geological Society*, *29*(1-2), 441-471.

Espiner, S. (1999). *The use and effect of hazard warning signs: Managing visitor safety at Franz Josef and Fox Glaciers.* (No. 108). Wellington, N.Z: Department of Conservation.

Espiner, S., Orchiston, C., & Higham, J. (2017). Resilience and sustainability: A complementary relationship? Towards a practical conceptual model for the sustainability-resilience nexus in tourism. *Journal of Sustainable Tourism, 25*(10), 1385-1400. Doi:10.1080/09669582.2017.1281929

Evans, D. J. A., Shulmeister, J., & Hyatt, O. (2010). Sedimentology of latero-frontal moraines and fans on the west coast of South Island, New Zealand. *Quaternary Science Reviews, 29*(27), 3790-3811. Doi:10.1016/j.quascirev.2010.08.019.

Evans, S. G., & Hungr, O. (1993). The assessment of rockfall hazard at the base of talus slopes. *Canadian Geotechnical Journal*, *30*(4), 620-636.

Federal Emergency Management Agency, (FEMA). (1989). *Alluvial Fans: Hazards and Management.* Retrieved from*, https://www.fema.gov/media-library/assets/documents/2955*

Fitzharris, B., Clare, G.R. & Renwick, J. 2007: Teleconnections between Andean and New Zealand glaciers. *Global and Planetary Change*, *59*, 159-174.

Fitzsimons, S. J., & Veit, H. (2001). Geology and geomorphology of the european alps and the southern alps of new zealand: A comparison. *Mountain Research and Development, 21*(4), 340-349. doi:10.1659/0276-4741(2001)021[0340:GAGOTE]2.0.CO;2

Forbes, D. L., & Taylor, R. B. (1987). Coarse-grained beach sedimentation under paraglacial conditions, Canadian Atlantic coast. In *Glaciated coasts* (pp. 51-86).

Forbes, D.L. & Syvitski, J.P.M. (1994). Paraglacial coasts. In Carter, B., Woodroffe, C. D., & IGCP Project 274. (1994). *Coastal evolution: Late quaternary shoreline morphodynamics*. Cambridge; New York: Cambridge University Press.

French, R. H. (1987). Developments in water science. hydraulic processes on alluvial fans.

Gienko, G. A., & Terry, J. P. (2014). Three-dimensional modelling of coastal boulders using multi-view image measurements. *Earth Surface Processes and Landforms, 39*(7), 853-864. Doi:10.1002/esp.3485

Gomez, C., Hayakawa, Y., & Obanawa, H. (2015). A study of Japanese landscapes using structure from motion derived DSMs and DEMs based on historical aerial photographs: New opportunities for vegetation monitoring and diachronic geomorphology. *Geomorphology*, 242: 11-20.

Goudie, A. S. (2006). The Schmidt hammer in geomorphological research. *Progress in Physical Geography, 30*(6), 703-718. Doi:10.1177/0309133306071954

Graham, D. J., & Midgley, N. G. (2000). Graphical representation of particle shape using triangular diagrams: An excel spreadsheet method. *Earth Surface Processes and Landforms, 25*(13), 1473-1477. Doi: 10.1002/1096-9837(200012)25:13<1473::AID- ESP158>3.0.CO;2-C

Gruen, A. (2012). Development and status of image matching in photogrammetry. *The Photogrammetric Record, 27*(137), 36-57. Doi:10.1111/j.1477-9730.2011.00671.x

Harbor, J., & Warburton, J. (1993). Relative rates of glacial and nonglacial erosion in alpine environments. *Arctic and Alpine Research, 25*(1), 1-7. doi:10.2307/1551473

Harvey, A. M. (1997). The role of alluvial fans in arid zone fluvial systems. *Arid Zone Geomorphology: Processes, Form and Change in Drylands*.

Harvey, A. M. (2002). Effective timescales of coupling within fluvial systems. *Geomorphology, 44*(3), 175-201. Doi: 10.1016/S0169-555X(01)00174-X

Harvey, A. M. (2005). Differential effects of base-level, tectonic setting and climatic change on quaternary alluvial fans in the northern great basin, Nevada, USA. *Geological Society Special Publication, 251*, 117-131. Doi:10.1144/GSL.SP.2005.251.01.09

Harvey, A. M., Mather, A. E., & Stokes, M. (2005). Alluvial fans: geomorphology, sedimentology, dynamics—introduction. A review of alluvial-fan research. *Geological Society, London, Special Publications*, *251*(1), 1-7.

Henderson, R. D., & Thompson, S. M. (1999). Extreme rainfalls in the Southern Alps of New Zealand. *Journal of Hydrology (New Zealand), 38*(2), 309-330.

Hewitt, K. (2006). Disturbance regime landscapes: Mountain drainage systems interrupted by large rockslides. *Progress in Physical Geography, 30*(3), 365-393. doi:10.1191/0309133306pp486ra

Hewitt, K. (2006). Rock avalanche dams on the transHimalayan Upper Indus Streams: a survey and assessment of hazards-related characteristics. *Italian Journal of Engineering Geology and Environment*, *1*, 61-65.

Hilker, N., Badoux, A., & Hegg, C. (2009). The swiss flood and landslide damage database 1972-2007. *Natural Hazards and Earth System Sciences, 9*(3), 913-925. doi:10.5194/nhess-9-913-2009

Hogg, S. E. (1982). Sheetfloods, sheetwash, sheetflow, or...?. *Earth-Science Reviews*, *18*(1), 59-76.

Hornung, J., Pflanz, D., Hechler, A., Beer, A., Hinderer, M., Maisch, M., & Bieg, U. (2010). 3-D architecture, depositional patterns and climate triggered sediment fluxes of an alpine alluvial fan (Samedan, Switzerland). *Geomorphology*, *115*(3-4), 202-214.

Hovius, N., New Zealand. Department of Conservation. West Coast Conservancy, & New Zealand. Department of Conservation. (1995). *A geological hazard assessment for the lower fox valley, anno 1994.*Report no. 121. Wellington, N.Z: Dept. of Conservation.

Huffadine, L. (2018). 200m washout closes access to Fox Glacier. https://www.stuff.co.nz/the-press/news/west-coast/101125270/200m-washout-closes-access-to-Fox-Glacier

IPCC (2013). Contribution to the IPCC Fifth Assessment Report. *Climate Change*, 36.

Iturrizaga, I. (2011). Paraglacial Landscape Transformations. *Encyclopaedia of Earth Sciences Series: Encyclopaedia of Snow, Ice and Glaciers,* 817-822.

Jakob, M., & Hungr, O. (2005). *Debris-flow hazards and related phenomena*. New York; Berlin; Chicester, UK; Springer.

John, D. M., Whitton, B. A., & Brook, A. J. (2002). *The freshwater algal flora of the British Isles: An identification guide to freshwater and terrestrial algae*. New York: Cambridge University Press.

Jones, L. S., & Schumm, S. A. (1999). Causes of avulsion: an overview. In *Fluvial sedimentology VI* (Vol. 28, pp. 171-178). Spec. Publ. Int. Assoc. Sedimentology.

Kaikoura District Council (KDC). (2017). 2017-2018 the draft annual plan consultation document.

Kilgour, O. Personal Communication, March 26, 2017

Kleinhans, M. G., Ferguson, R. I., Lane, S. N., & Hardy, R. J. (2013). Splitting rivers at their seams: Bifurcations and avulsion. *Earth Surface Processes and Landforms, 38*(1), 47-61. doi:10.1002/esp.3268

Klik, A., Haas, K., Dvorackova, A., & Fuller, I. C. (2015). Spatial and temporal distribution of rainfall erosivity in New Zealand. *Soil Research, 53*(7), 815-825. Doi:10.1071/SR14363.

Kochel, R. C. (1990). Humid fans of the appalachian mountains. 109-129.

Kostaschuk, R. A., MacDonald, G. M., & Putnam, P. E. (1986). Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada. *Earth Surface Processes and Landforms*, *11*(5), 471-484.

Kritikos, T. (2013). Geomorphic hazard analyses in tectonically-active mountains: application to the Western Southern Alps, New Zealand.

Krumbein, W.C. (1941): Measurements and geological significance of shape and roundness of sedimentary particles. *Journal of Sedimentary Petrology* 11, 64 – 72.

Kumar, A. (2011). Paraglacial Landscape Transformations. *Encyclopaedia of Earth Sciences Series: Encyclopaedia of Snow, Ice and Glaciers,* 1154.

Land Information New Zealand (LINZ). (2018). https://data.linz.govt.nz/set/4702-nz-aerial-imagery/

Larsen, C. F., Motyka, R. J., Arendt, A. A., Echelmeyer, K. A., & Geissler, P. E. (2007). Glacier changes in southeast alaska and northwest british columbia and contribution to sea level rise.*Journal of Geophysical Research - Earth Surface, 112*(F1), F01007. doi:10.1029/2006JF000586

Lecce, S.A. (1990). Chapter 1: The Alluvial Fan Problem. *Alluvial fans: A field approach*. New York; Chichester, West Sussex, England: Wiley.

Lucieer, A., de Jong, S.M. & Turner, D. (2014) Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. *Progress in Physical Geography,* 38, 97–116.

Lukas, S., Benn, D. I., Boston, C. M., Brook, M., Coray, S., Evans, D. J. A., Graf, A., Kellerer-Pirklbauer, A., Kirkbride, M. P., Krabbendam, M., Lovell, H., Machiedo, M., Mills, S.C., Nye, K., Reinardy, B., Ross, F.H., & Signer, M. (2013). Clast shape analysis and clast transport paths in glacial environments: A critical review of methods and the role of lithology. *Earth-Science Reviews, 121*, 96-116. doi:10.1016/j.earscirev.2013.02.005

Macara, G.R. (2016). The Climate and Weather of West Coast. *NIWA Science and Technology series,* 72, 1 - 38.

Mackie, K. (2017). *Ground-based Structure-from-Motion and High Resolution Proglacial Valley Dynamics.* Honours Dissertation in Geography, University of Manchester, 1- 62.

Mackintosh, A.N., Anderson, B.M., Lorrey, A.M., Renwick, J.A., Frei, P. and Dean, S.M. 2017: Regional cooling caused recent New Zealand glacial advances in a period of global warming. *Nature Communications*, *8*, 1-13.

Marchi, L., Cavalli, M., & D'Agostino, V. (2010). Hydrogeomorphic processes and torrent control works on a large alluvial fan in the eastern Italian Alps. *Natural Hazards and Earth System Sciences*, *10*(3), 547.

Mather, A. E., & Hartley, A. (2005). Flow events on a hyper-arid alluvial fan: Quebrada Tambores, Salar de Atacama, northern Chile. *Geological Society Special Publication, 251*, 9-24. Doi:10.1144/GSL.SP.2005.251.01.02

McEwen, L. J., Owen, G., Matthews, J. A., & Hiemstra, J. F. (2011). Late Holocene development of a Norwegian alpine alluvial fan affected by proximal glacier variations, episodic distal undercutting, and colluvial activity. *Geomorphology, 127*(3), 198-215. Doi:10.1016/j.geomorph.2010.12.016

McSaveney, M. J., & Davies, T. R. H. (1998). Natural hazard assessment for the township of Franz Josef Glacier and its environs. *Client Report B*, *43714*.

Mercier, D. (1997). L'impact du ruissellement sur les moraines latérales du glacier du Roi. *Norois*, *175*(1), 549-566.

Mercier, D. (2008). Géosystèmes paraglaciaire et parapériglaciaire: Concepts, échelles temporelles et distribution spatiale. *Geomorphologie: Relief, Processus, Environnement,* (4), 223-234.

Merkuryeva, G., Merkuryev, Y., Sokolov, B. V., Potryasaev, S., Zelentsov, V. A., & Lektauers, A. (2015). Advanced river flood monitoring, modelling and forecasting. *Journal of Computational Science, 10*, 77-85. Doi:10.1016/j.jocs.2014.10.004

Mihalcea, C., Mayer, C., Diolaiuti, G., Lambrecht, A., Smiraglia, C., & Tartari, G. (2006). Ice ablation and meteorological conditions on the debris-covered area of Baltoro glacier, Karakoram, Pakistan. *Annals of Glaciology*, *43*, 292-300.

Ministery for the Environment (MfE). (2018). Climate change projections for the West Coast region. Retrieved from http://www.mfe.govt.nz/climate-change/how-climate-change-affects-nz/how-might-climate-change-affect-my-region/west-coast.

Mosbrucker, A. R., Major, J. J., Spicer, K. R., & Pitlick, J. (2017). Camera system considerations for geomorphic applications of SfM photogrammetry: Camera system configuration to optimize SfM imagery. *Earth Surface Processes and Landforms, 42*(6), 969-986. Doi:10.1002/esp.4066.

Mugade, U. R., & Sapkale, J. B. (2015). Influence of Aggradation and Degradation on River Channels: A Review. *Int. J. of Engineering and Technical Research*, *3*(6), 209-212.

Mukerji, A. B. (1990). The Chandigarh Dun alluvial fans: An analysis of the process-form relationship. *Alluvial Fans. A Field Approach.* John Wiley and Sons, Chichester, 131-149.

Nicholas, A. P., Clarke, L., & Quine, T. A. (2009). A numerical modelling and experimental study of flow width dynamics on alluvial fans. *Earth Surface Processes and Landforms, 34*(15), 1985-1993. doi:10.1002/esp.1839

Niehammer, U., Rothmund, S., Schwaderer, U., Zeman, J. & Joswig, M. (2011) Open source image-processing tools for low-cost UAV-based landslide investigations. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 38* (1), C22.

Ono, Y. (1990). Alluvial fans in japan and South Korea. In Rachocki, A., & Church, M. A. (Ed.), *Alluvial fans: A field approach* (91-107). New York; Chichester, West Sussex England: Wiley.

Philips, B. M., & Williams, D. T. (2008). Design Considerations for Confining and Guiding Levees on Alluvial Fans. In *World Environmental and Water Resources Congress 2008: Ahupua'A,* 1-10. Doi: 10.1061/40976(316)203

Piégay, H., & Schumm, S. A. (2005). *System approaches in fluvial geomorphology.* Doi:10.1002/0470868333.ch5

Pope, R. J. J., & Wilkinson, K. N. (2005). Reconciling the roles of climate and tectonics in late quaternary fan development on the Spartan piedmont, Greece. *Geological Society Special Publication, 251*, 133-152. Doi:10.1144/GSL.SP.2005.251.01.10

Powers, M. C. (1953). A new roundness scale for sedimentary particles. *Journal of Sedimentary Research*, *23*(2), 117-119.

Proceq. (1997). Schmidt Hammer operating instructions. Proceq SA, Zurich.

Purdie, H. L., Brook, M. S., Fuller, I. C., & Appleby, J. (2008). Seasonal variability in velocity and ablation of Te Moeka o Tuawe/Fox glacier, South Westland, New Zealand. *New Zealand Geographer, 64*(1), 5-19. Doi:10.1111/j.1745-7939.2008.00123.x

Purdie, H., Anderson, B., Chinn, T., Owens, I., Mackintosh, A., & Lawson, W. (2014). Franz Josef and Fox glaciers, New Zealand: Historic length records. *Global and Planetary Change, 121*, 41-52. Doi:10.1016/j.gloplacha.2014.06.008

Purdie, H., Gomez, C., & Espiner, S. (2015). Glacier recession and the changing rockfall hazard: Implications for glacier tourism*, New Zealand Geographer, 71*(3), 189-202. Doi:10.1111/nzg.12091

Rachocki, A. (1981). *Alluvial fans: An attempt at an empirical approach*. John Wiley & Sons.

Reitz, M. D., & Jerolmack, D. J. (2012). Experimental alluvial fan evolution: Channel dynamics, slope controls, and shoreline growth. *Journal of Geophysical Research: Earth Surface, 117*(2) Doi:10.1029/2011JF002261.

Ryder, J. M. (1971). Some aspects of the morphometry of paraglacial alluvial fans in south-central British Columbia. *Canadian Journal of Earth Sciences, 8*(10), 1252-1264. Doi: 10.1139/e71-114.

Schumm, S. A., Mosley, M. P., & Weaver, W. E. (1987). *Experimental fluvial geomorphology*. New York: Wiley.

Shakesby, R. A., Matthews, J. A., & Owen, G. (2006). The Schmidt hammer as a relative-age dating tool and its potential for calibrated-age dating in Holocene glaciated environments. *Quaternary Science Reviews, 25*(21), 2846-2867. Doi:10.1016/j.quascirev.2006.07.011

Slaymaker, O. (2011). Criteria to distinguish between periglacial, proglacial and paraglacial environments. *Quaestiones Geographicae, 30*(1), 85-94. Doi:10.2478/v10117-011-0008-y

Sneed, E. D., & Folk, R. L. (1958). Pebbles in the lower Colorado River, Texas a study in particle morphogenesis. *The Journal of Geology, 66*(2), 114-150. Doi:10.1086/626490

Snowgrass Solutions (SS). (2018). Fox Glacier webcams http://snowgrass.co.nz/cust/fox_glacier/

Stahl, T., Winkler, S., Quigley, M., Bebbington, M., Duffy, B., & Duke, D. (2013). Schmidt hammer exposure-age dating (SHD) of late quaternary fluvial terraces in New Zealand. *Earth Surface Processes and Landforms, 38*(15), 1838-1850. Doi:10.1002/esp.3427

Statistics New Zealand. 2014. *International Visitor Survey: Place Visited* West Coast RTO) YE Dec 2013. Retrieved from: http://nzdotstat.stats.govt.nz/wbos/index?DataSetCode=TABLECODE7574 (Accessed 27 May 2014)

Stewart, E. J., Wilson, J., Espiner, S., Purdie, H., Lemieux, C., & Dawson, J. (2016). Implications of climate change for glacier tourism. *Tourism Geographies, 18*(4), 377-398. Doi:10.1080/14616688.2016.1198416

Suggate, R. P., & Almond, P. C. (2005). The last glacial maximum (LGM) in western south island, New Zealand: Implications for the global LGM and MIS 2. *Quaternary Science Reviews, 24*(16), 1923-1940. doi:10.1016/j.quascirev.2004.11.007

Szeliski, R. (2011) *Computer Vision: Algorithms and Applications*. Springer, London.

Wasson, R. J. (1977). Last-glacial alluvial fan sedimentation in the Lower Derwent Valley, Tasmania. *Sedimentology*, *24*(6), 781-799.

Weissmann, G. S., & Fogg, G. E. (1999). Multi-scale alluvial fan heterogeneity modeled with transition probability geostatistics in a sequence stratigraphic framework. *Journal of Hydrology, 226*(1), 48-65. doi:10.1016/S0022-1694(99)00160-2

Welsh, A., & Davies, T. (2011). Identification of alluvial fans susceptible to debris-flow hazards. *Landslides, 8*(2), 183-194. Doi:10.1007/s10346-010-0238-4

West Coast Regional Council (WCRC). (2013). West coast regional council: Natural Hazards Review.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. (2012). 'Structure-from-motion' photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology, 179*, 300-314. Doi:10.1016/j.geomorph.2012.08.021

White, K., Bryant, R., & Drake, N. (1998). Techniques for measuring rock weathering: Application to a dated fan segment sequence in southern Tunisia. *Earth Surface Processes and Landforms, 23*(11), 1031-1043. Doi: 10.1002/(SICI)1096-9837(1998110)23:11<1031::AID-ESP919>3.0.CO;2-G

Wilson, J., Stewart, E., Espiner, S., & Purdie, H. (2014). *'Last chance tourism' at the Franz Josef and Fox glaciers, Westland Tai Poutini National Park: Stakeholder perspectives*. University of Canterbury. Geography.

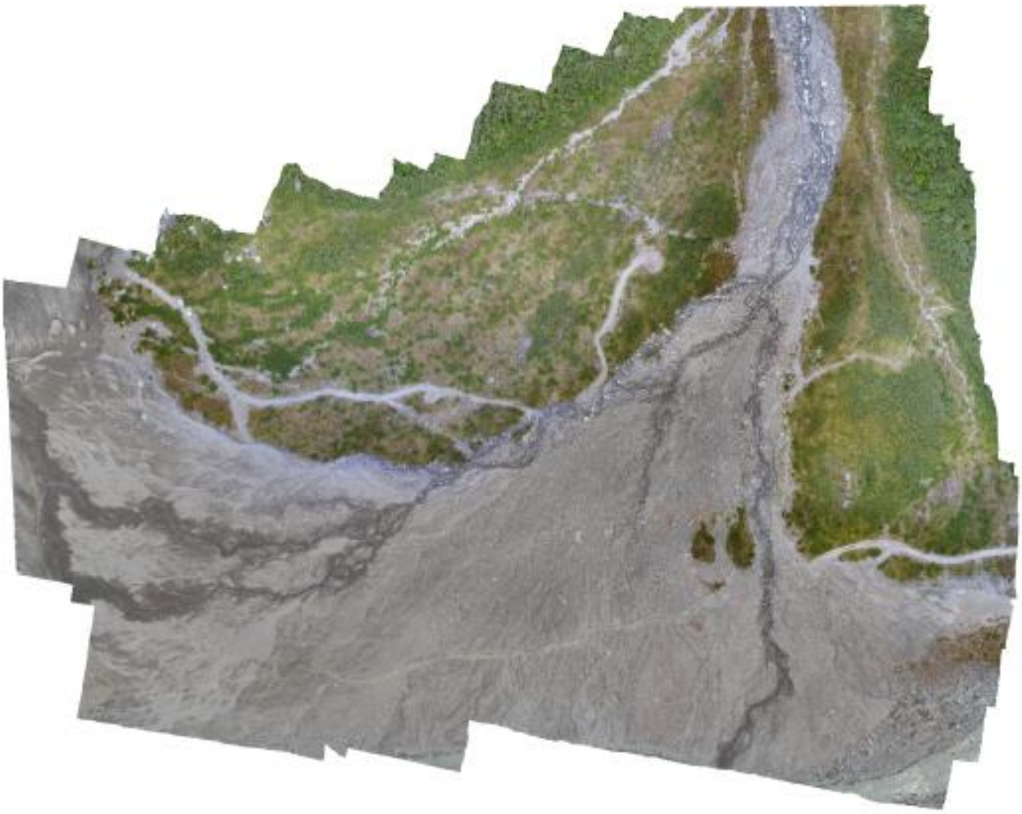
Wilson, P. (2009). Rockfall talus slopes and associated talus-foot features in the glaciated uplands of Great Britain and Ireland: periglacial, paraglacial or composite landforms? *Geological Society, London, Special Publications*, *320*(1), 133-144.

Wyrwoll, K. H. (1977). Causes of rock-slope failure in a cold area: Labrador-Ungava. *Geological Society of America Reviews in Engineering Geology*, *3*, 59-67.

Appendix A: SfM Processing Report

Yelow creek fan nov 2017

Processing Report
24 January 2018



Survey Data

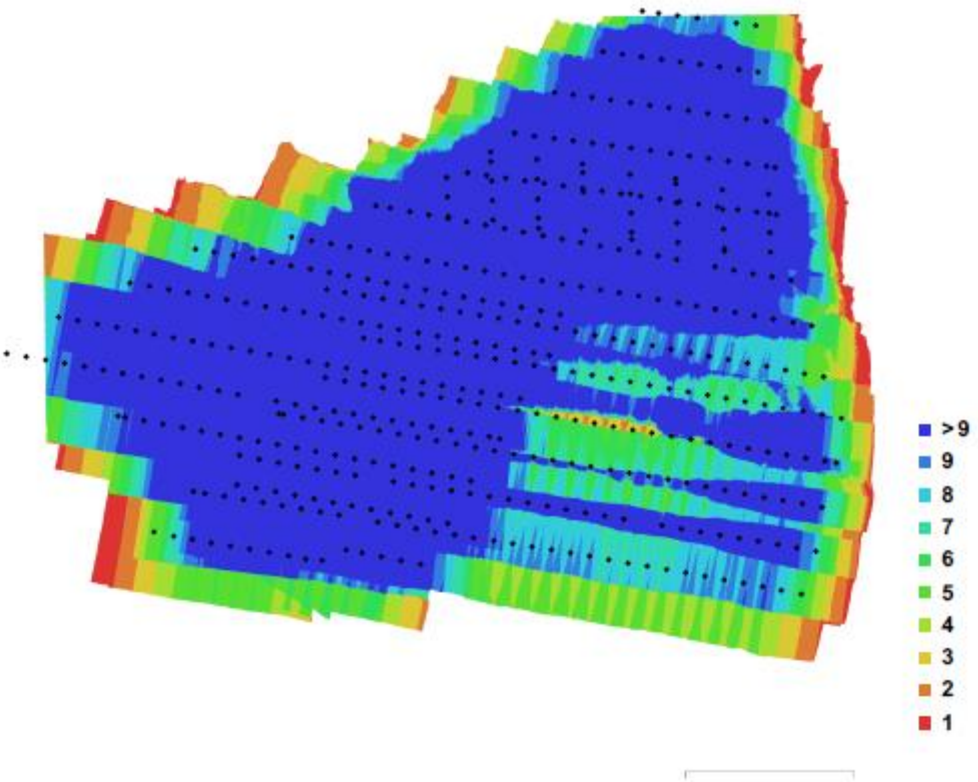


Fig. 1. Camera locations and image overlap.

Number of images:	459	Camera stations:	458
Flying altitude:	57.5 m	Tie points:	323,545
Ground resolution:	1.43 cm/pix	Projections:	1,702,786
Coverage area:	0.141 km²	Reprojection error:	0.459 pix

Camera Model	Resolution	Focal Length	Pixel Size	Precalibrated
FC6310 (8.8 mm)	5472 x 3648	8.8 mm	2.41 x 2.41 μm	No

Table 1. Cameras.

Camera Calibration

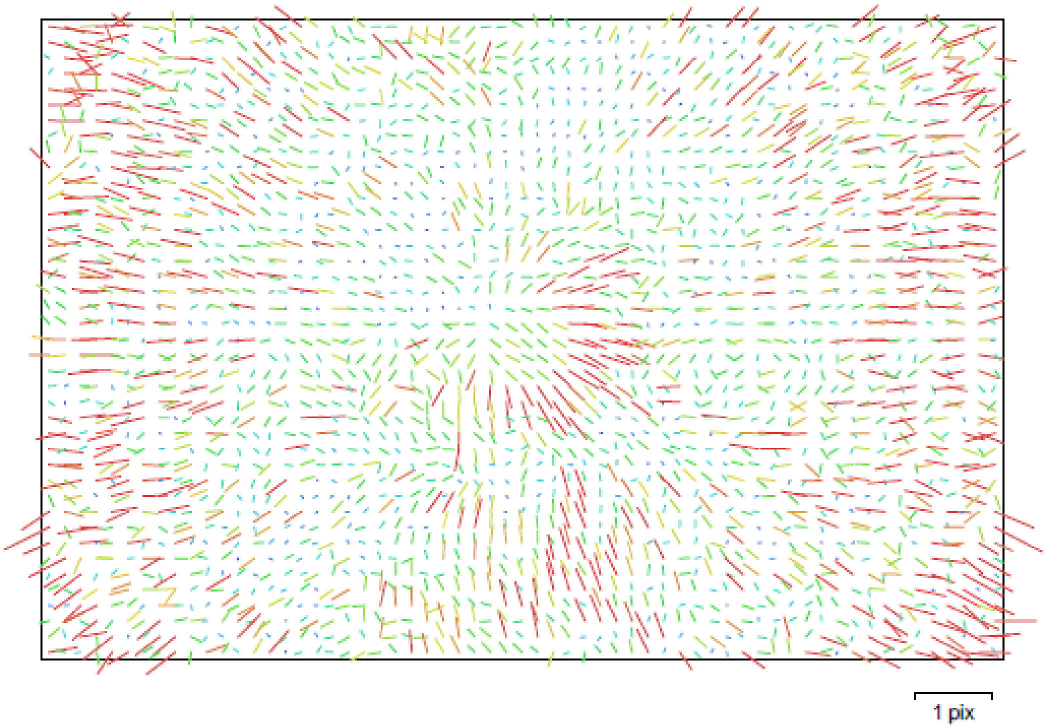


Fig. 2. Image residuals for FC6310 (8.8 mm).

FC6310 (8.8 mm)
459 images

Resolution	Focal Length	Pixel Size	Precalibrated
5472 x 3648	**8.8 mm**	**2.41 x 2.41 μm**	**No**

Type:	Frame	F:	3648
Cx:	22.3613	B1:	-0.0517932
Cy:	19.4978	B2:	-0.222687
K1:	0.00680092	P1:	0.00187524
K2:	-0.0452716	P2:	-3.29867e-05
K3:	0.0844452	P3:	0
K4:	-0.0510543	P4:	0

Ground Control Points

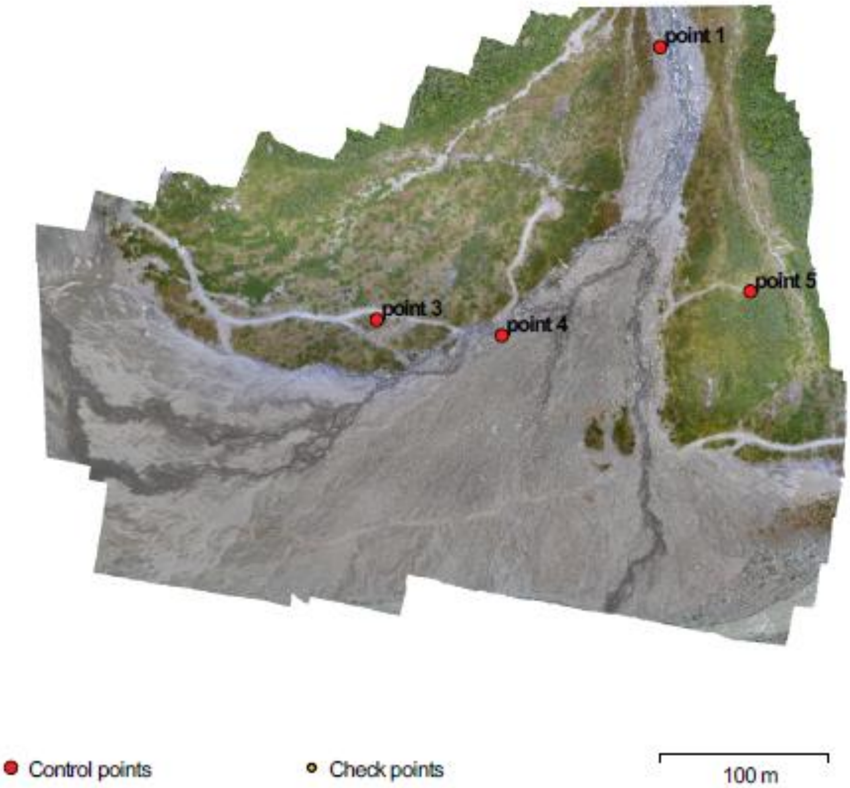


Fig. 3. GCP locations.

Count	X error (cm)	Y error (cm)	Z error (cm)	XY error (cm)	Total (cm)	Image (pix)
4	5.54486	4.20331	1.46812	6.95797	7.11117	0.684

Table 2. Control points RMSE.

Label	X error (cm)	Y error (cm)	Z error (cm)	Total (cm)	Image (pix)
point 1	-0.316066	4.99948	1.42748	5.20888	0.986 (6)
point 3	-1.98433	3.41934	-0.137213	3.95579	0.592 (6)
point 4	8.77903	-4.91177	1.18255	10.1289	0.574 (8)
point 5	-6.47095	-3.13989	-2.27302	7.54312	0.241 (3)
Total	**5.54486**	**4.20331**	**1.46812**	**7.11117**	**0.684**

Table 3. Control points.

Digital Elevation Model

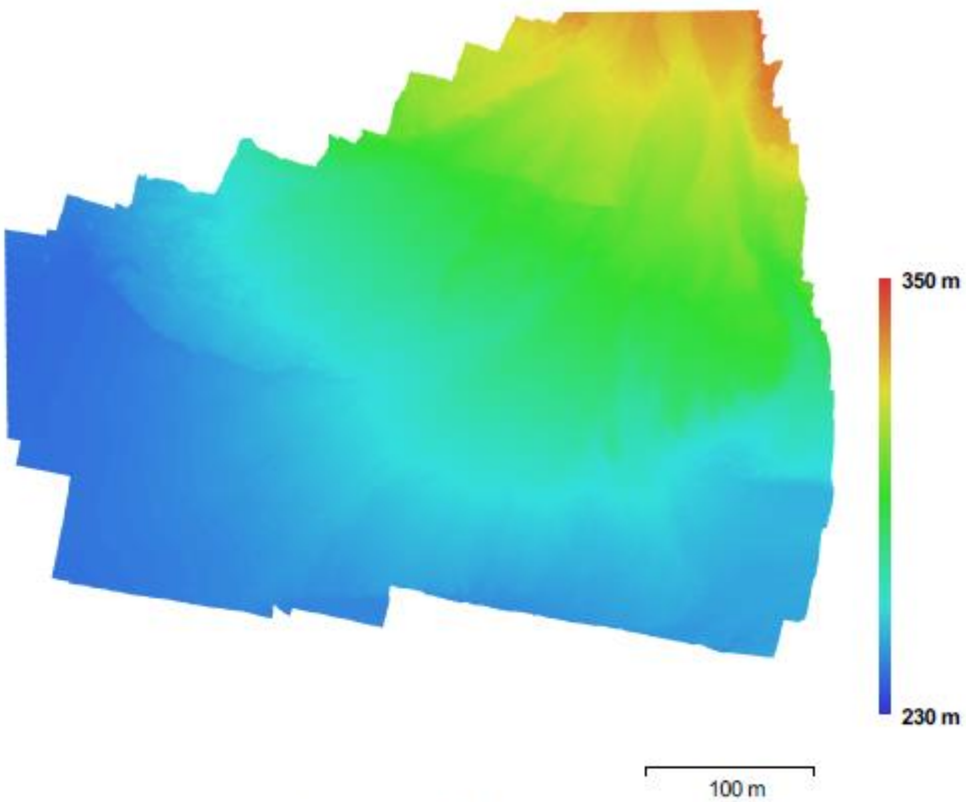


Fig. 4. Reconstructed digital elevation model.

Resolution:	5.71 cm/pix
Point density:	306 points/m²

Processing Parameters

General	
Cameras	459
Aligned cameras	458
Markers	4
Coordinate system	NZGD2000 / New Zealand Transverse Mercator 2000 (EPSG::2193)
Point Cloud	
Points	323,545 of 354,362
RMS reprojection error	0.176541 (0.458875 pix)
Max reprojection error	0.529967 (25.9178 pix)
Mean key point size	2.52635 pix
Effective overlap	5.66041
Alignment parameters	
Accuracy	High
Pair preselection	Disabled
Key point limit	40,000
Tie point limit	4,000
Constrain features by mask	No
Adaptive camera model fitting	Yes
Matching time	5 hours 22 minutes
Alignment time	7 minutes 3 seconds
Dense Point Cloud	
Points	58,616,898
Reconstruction parameters	
Quality	Medium
Depth filtering	Aggressive
Depth maps generation time	3 hours 9 minutes
Dense cloud generation time	26 minutes 57 seconds
Model	
Faces	3,907,781
Vertices	1,958,189
Texture	4,096 x 4,096, uint8
Reconstruction parameters	
Surface type	Arbitrary
Source data	Dense
Interpolation	Enabled
Quality	Medium
Depth filtering	Aggressive
Face count	3,907,782
Processing time	56 minutes 13 seconds
Texturing parameters	
Mapping mode	Generic
Blending mode	Mosaic
Texture size	4,096 x 4,096
Enable color correction	No
Enable hole filling	Yes
UV mapping time	5 minutes 19 seconds
Blending time	2 minutes 12 seconds
Tiled Model	
Reconstruction parameters	
Source data	Dense cloud
Tile size	256
Processing time	1 hours 46 minutes
DEM	
Size	9,837 x 7,468
Coordinate system	NZGD2000 / New Zealand Transverse Mercator 2000 (EPSG::2193)
Reconstruction parameters	

Source data	Dense cloud
Interpolation	Enabled
Processing time	2 minutes 20 seconds
Orthomosaic	
Size	33,975 x 27,731
Coordinate system	NZGD2000 / New Zealand Transverse Mercator 2000 (EPSG::2193)
Channels	3, uint8
Blending mode	Mosaic
Reconstruction parameters	
Surface	DEM
Enable color correction	No
Processing time	10 minutes 54 seconds
Software	
Version	1.2.6 build 2834
Platform	Windows 64 bit

Appendix B: Track Closure Data

Table 6: Track closure data for 2006

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	50	348		
Riverbed Lookout	700		17	
Photograph Point	500			
Yellow Creek Viewpoint	600			
Carpark	1200			
Closed				
Missing Data				

Table 7: Track closure data for 2007

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	50	328		
Riverbed Lookout	700		34	
Photograph Point	500			
Yellow Creek Viewpoint	600			
Carpark	1200			
Closed			2	
Missing Data				1

Table 8: Track closure data for 2008

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	50	241		
Riverbed Lookout	700		27	
Photograph Point	500			
Yellow Creek Viewpoint	600		79	
Carpark	1200			
Closed			18	
Missing Data				1

Table 9: Track closure data for 2009

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	50	83		
Riverbed Lookout	700		94	
Photograph Point	500			
Yellow Creek Viewpoint	600		137	
Carpark	1200		34	
Closed			17	
Missing Data				

Table 10: Track closure data for 2010

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	100	299		
Riverbed Lookout	700		8	
Photograph Point	500			
Yellow Creek Viewpoint	600		16	
Carpark	1200		30	
Closed			6	
Missing Data				6

Table 11: Track closure data for 2011

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	200	321		
Riverbed Lookout	700		1	
Photograph Point	500			
Yellow Creek Viewpoint	600		37	
Carpark	1200		3	
Closed			2	
Missing Data				2

Table 12: Track closure data for 2012

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	200	316		
Riverbed Lookout	700			
Photograph Point	500			
Yellow Creek Viewpoint	600		30	
Carpark	1200		8	
Closed			2	
Missing Data				9

Table 13: Track closure data for 2013

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	200	283		
Riverbed Lookout	700			
Photograph Point	500			
Yellow Creek Viewpoint	600		76	
Carpark	1200		1	
Closed			2	
Missing Data				3

Table 14: Track closure data for 2014

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	100	286		
Riverbed Lookout	700			
Photograph Point	500			
Yellow Creek Viewpoint	600		8	
Carpark	1200		59	
Closed			12	
Missing Data				

Table 15: Track closure data for 2015

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	450	283		
Riverbed Lookout	1000		26	
Photograph Point	500			
Yellow Creek Viewpoint	600			
Carpark	1500		26	
Closed			11	
Missing Data				20

Table 16: Track closure data for 2016

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	450	126		
Riverbed Lookout	1000		6	
Photograph Point	500			
Yellow Creek Viewpoint	750		3	
Carpark	1500			
Closed			7	
Missing Data				6

Table 17: Track closure data for 2017, data represents 1st January – 29th May

Track Viewpoint	Distance from the Glacier (m)	Open (1)	Closed (0)	
Terminal Viewpoint	200	287		
Riverbed Lookout	700		7	
Photograph Point	500		10	
Yellow Creek Viewpoint	600		35	
Carpark	1200		14	
Closed			4	
Missing Data				8