Shallow Fluid Movement in the Hanging Wall of the Alpine Fault

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By

ALEX SIMS
Abstract

New Zealand’s best example of large-scale fault processes is the Alpine Fault, which is currently the focus of national and international investigation. Numerical models show that thermal, stress, and hydraulic anomalies associated with the topology of the Southern Alps are likely to be significant at depths of 1000–1500 m near the Alpine Fault (Allis & Shi, 1995), conditions that influence how the fault evolves and produces earthquakes (McCaig, 1988). However, there is little empirical data on the hydrological conditions and fluid-flow within the rock mass adjacent to the Alpine Fault. The objective of this research was to enhance understanding of how meteoric fluids permeate the fault zone, and the over-arching aim was to quantify rates and patterns in the infiltration of meteoric water into uplifted schist bedrock adjacent to the Alpine Fault. Measurements were made in the Tartare Tunnel, located ~2km from the Franz Josef Township and adjacent to the Alpine Fault. Tunnel Discharge and water temperature were measured between April 2012 and January 2013, while water samples were taken at various time throughout 2012 and analysed for major ions and two stable isotopes: \( ^{18} \text{O} \) and D.

Differences in the total volume of water infiltrated, transmission time of water from the surface to the tunnel, and peak tunnel discharge were observed between the April to August and August to January periods. Snow on the surface was thought to be an important control on infiltration; reducing infiltration in the winter months and increasing it during the spring melt period. A conceptual model involved a log-normal distribution of fractures to explain patterns of groundwater movement in the rock mass surrounding the tunnel. Groundwater flow was predominantly percolation leading to movement of fluid into storage between April and August. Between September and January, however, elevation of the water table was variable, and at times intersected the tunnel, inducing lateral groundwater movement in the hillside. Temperature analysis indicated that the rock surrounding the tunnel was saturated between September and January and that the abundance of fluid lowered rock temperature. Chemical analyses suggested that the eastern portion of the rock mass above the tunnel was more permeable than the western part. Stable isotopes indicated that the recharge signal peaks in summer—a pattern attributed to the role of snowmelt—and that infiltrating water did not isotopically exchange with the host rock.
The results of this research show the role of snow in controlling rates and patterns of infiltration toward the Alpine Fault. Further research into the movement of water from the surface towards deeper parts of the Alpine fault is required, and will provide insight into the triggering of landslides, earthquakes and the behaviour of the rock mass during seismic events.
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List of Abbreviations and Symbols

Abbreviations

DE Discharge Event
ADE Anomalous Discharge Event
SMBM Soil Moisture Balance Model
R\text{Direct} Direct Recharge
C Root Constant
RC Runoff Coefficient

Symbols and Units

1\text{ s}^{-1} \quad \text{litres per second}

m^3 \quad \text{Metres cubed}

m^3\text{ s}^{-1} \quad \text{Metres cubed per second (cumec)}

J\text{ cm}^{-3}\text{ K}^{-1} \quad \text{Joules per centimetre cubed per degree Kelvin}

\si{^\circ}\text{C} \quad \text{Degrees Celsius}

mm \quad \text{Millimetre}

km \quad \text{Kilometres}

\text{^{18}}\text{O} \quad \text{Oxygen 18 stable isotope}

D \quad \text{Deuterium, stable isotope of hydrogen}
Chapter 1: Introduction

Fluid in fault zones is an important control on the frictional properties of faults, influencing both the initiation and the propagation of rupture (Scholz, 1990). As well as determining effective stress levels in rock masses, fluid has been postulated to modify the permeability, strength and seismic properties of a major fault zone throughout its stress cycle (Sutherland et al., 2012). The Alpine Fault, the major transpressional boundary between the Pacific and Australian tectonic plates, is an example of a major fault zone in which fluid is expected to play an important role (Stern et al., 2001; Sutherland et al., 2012). The infiltration of meteoric water toward the Alpine Fault is the focus of this research.

As a consequence of on-going collision between the two tectonic plates, the region is characterized by mean uplift rates in excess of 10 mm yr$^{-1}$, leading to the formation of the 480 km long mountain range, the Southern Alps, just to the east of the Alpine Fault (Adams, 1981). The rapid uplift rate results in a steep geothermal gradient that has been measured at 62.6 ± 2.1 °C km$^{-1}$ (Koons, 1987; Sutherland et al., 2012). At depths exceeding 15 km, collision between the two plates leads to continuing deformation and metamorphism of the schist bedrock. The extreme heat and pressure generated at these depths results in dewatering reactions, in which metamorphic fluid is liberated from the compressed rock (Allis and Shi, 1995; Craw and Koons, 1986; Koons et al., 1998; Upton et al., 1995). Density differences drive the warm metamorphic fluids upwards by a process known as buoyancy-driven flow.

At the surface, the mountain range intersects the dominant westerly air flow. When warm, saturated air reaches the Southern Alps it is forced upwards and cools adiabatically. As a result the Southern Alps may experience a high annual rainfall that exceeds 10,000 mm yr$^{-1}$ in many places. The rainfall decreases rapidly to the east and the precipitation map is characterized by steep rainfall gradients (Griffiths and McSaveney, 1983; Woods et al., 2006). Consequently there is an abundance of water to flow into the crust. While the depth to which this fluid penetrates is variable, fluid inclusions in calcite veins exhumed along the fault zone indicate that it is in excess of 5 km (Craw, 1997; Jenkin and Fallick, 1994).
The concurrent downward percolation of meteoric waters and upward migration of metamorphic fluid are thought to result in a large scale convective cell beneath the mountain chain. Evidence for the mixing of the two fluid end-members has been observed in numerous hot-springs that discharge fluids at temperatures in excess of 50 °C (Reyes, 2010; Reyes and Britten, 2007).

The influence of fluid on the continued evolution of the Alpine Fault and the Southern Alps at both the geological and historical timescales is the topic of considerable current research interest. A better understanding of the diverse processes in major fault zones is required in order to quantify seismic hazard worldwide. The link between movement of fluid at hydrological timescales and behaviour of the rock mass at geological timescales is an emerging area of geophysical research, and lies at the junction of hydrology, geology and rock mechanics. The processes that control fluid circulation in the Southern Alps span large spatial and temporal scales, presenting significant challenges to the researcher who attempts to quantify components of the system. Sub-components of this system— such as fault processes, thermally-driven flow, shallow fluid circulation and, in particular, the infiltration of meteoric water— involve a variety of geophysical and environmental processes, but generally operate at small spatial and temporal scales. While meteoric water has been identified as one of the two primary inputs to the broader model of circulation (Craw, 1997; Templeton et al., 1998; Upton et al., 1995), little is known about how much of that fluid enters the crust. Quantifying the amount of precipitation that enters the bedrock from the atmosphere is necessary if we are to understand the role that fluid plays in the evolution of the Alpine Fault, the alteration of the rock mass surrounding the fault, and the influence of saturated rock masses on landslides.

One major complicating factor in understanding the flow of fluid in the rock mass adjacent to the Alpine Fault is that it is repeatedly subject to large earthquakes, and is highly fractured. The degree and distribution of fracturing are highly heterogeneous, implying that infiltration of meteoric water will follow a similar pattern. Fracture systems are complex and are often characterized by fractures of varying aperture with a variety of orientations. As a result quantifying the rocks storage capacity and preferential fluid flow paths is difficult.
The scope of this research is limited in space and time. The study focused on the area adjacent to the Alpine Fault, along the foothills of the Southern Alps and at an elevation generally less than 500 m. The temporal frame of the study was nine months, when storm events constituted the main mode of water delivery. Rainfall events were variable in duration, but are usually in the order of a few days.

The over-arching aim of this research was to make a first attempt to quantify rates and understand patterns of the infiltration of meteoric water into the uplifted schist bedrock adjacent to the Alpine Fault. Three particular aims were defined in relation to this over-arching aim;

- To characterize the response of groundwater to rainfall events;
- To characterize the permeability of the schist rock mass that controls the movement of groundwater;
- To identify sources of infiltrating water and observe any changes in sources of groundwater during the study period;

### 1.1 Thesis Structure

#### 1.1.1 Chapter 2: Research Context

The thesis begins by situating shallow fluid movements in a broader spatial context: large-scale fluid circulation beneath the Southern Alps. Section 2.2 details the thermal consequences of rapid uplift on the Alpine Fault where increased rock temperatures have led to an array of hydrogeological phenomenon. The evidence for two distinct sources of subsurface fluids— meteoric water and metamorphic fluids— are also examined. The review then identifies the gaps in current understanding of fluid circulation beneath the Southern Alps, as well as the infiltration of meteoric water and its interaction with the Alpine Fault. With an understanding of the influence of fluid in the evolution of the Alpine Fault and the techniques used to observe shallow circulation, the review moves to section 2.5 to outline the three main elements of shallow fluid circulation: the arrival of meteoric water during storm events, the influence of rain and snow on infiltration patterns, and controls on the permeability of the schist rock mass adjacent to the Alpine Fault. These three elements correspond closely to the three particular aims outlined above. The distinction between saturated
and un-saturated fluid flow is vital to the interpretation of infiltration and groundwater flow patterns. Therefore definitions of each, as well as important differences in driving forces, are discussed in section 2.7.

Having discussed the broader context of the research and the specific elements of shallow fluid circulation to be investigated in this research, the methods employed to make empirical measurements of infiltration and groundwater movement are discussed. Many of the techniques used to track large scale fluid circulation, such as isotopic analyses, conceptual modelling and the use of tunnels, are equally as useful when analysing shallow fluid circulation. Finally section 2.11 summarises gaps in our understanding of shallow fluid circulation and situates the current research in the literature.

1.1.2 Chapter 3 & 4: Research Strategy and Field Site

The third chapter of this thesis relates to the main research gap— the lack of empirical estimates of infiltration— its broad context and how the research aims will be addressed.

The Tatare Tunnel, 2 km east of the Alpine Fault surface trace and Franz Josef Township, affords a unique opportunity to measure subsurface flow in an area ideally suited to examining shallow fluid infiltration. The tunnel is located on the western flanks of the central Southern Alps, where uplift rates of 12 mm yr\(^{-1}\) (Cooper and Norris, 1994) and steep topography enhance shallow fluid circulation. Patterns of infiltration and groundwater flow are likely to be readily observed in such an environment. The 354 m long Tatare Tunnel was excavated through Alpine Schist and lies directly above the Alpine Fault, making it ideally situated to intercept meteoric water percolating toward the fault. Discharge measurements in the Tatare Tunnel provide an ideal way to integrate the heterogeneous flow through the overlying rock mass into a single signal. In order to simplify analyses of the discharge record, discharge events — being periods of pronounced increase in tunnel discharge in response to rainfall — were defined. A discharge event served as the basis for further modelling and is outlined below. Relationships between the rainfall and discharge signals during a discharge event could then be used to make inferences about the rock mass surrounding the tunnel.
The structural geology of the tunnel is presented and summarised in chapter four. Schistosity and fracture patterns are major controls on the rate and direction of fluid movement in the rock mass and are given the most attention in this chapter. Observations in the tunnel are considered in the light of local and regional forces acting on the hillside.

As well as discharge measurements, the research makes use of chemical, isotopic and temperature analyses in an examination of the interaction of fluid and rock to understand how the residence time of fluid in the rock influences patterns of tunnel discharge. These further analyses were expected to shed light on the pathways that fluid takes between the surface and tunnel, and how the ratio of fluid to rock volume may change during a discharge event.

1.1.3 Chapters 5 - 7: Field Methods and Data Analyses

Chapter 5: outlines how discharge data was collected during the study period, as well describing the placement of temperature sensors inside the tunnel and the sampling schemes implemented to collect groundwater samples from the tunnel. Chapter 6: details the sampling scheme used to collect water samples at the Tatare Tunnel. Chapter 7: focuses on how flow data collected at the Tatare Tunnel was analysed. It outlines the criteria used to define discharge events and the techniques used to quantify patterns of rainfall and discharge. Finally, section 7.4 outlines the assumptions and procedures used to model patterns of infiltration during discharge events.

1.1.4 Chapters 8 & 11: Flow Results, Modelling and Residence Time

The results and preliminary interpretation of them are divided into three sections: flow, modelling, and residence time. This division is based on the three ways that the research for this thesis investigated the dynamics of infiltration.

Discharge measurements at the tunnel are used in conjunction with rainfall receipts at Franz Josef to characterize the tunnel’s response to rainfall events. The chapter examines the relationships between rainfall metrics, the transmission time of water through the rock mass, and the magnitude of response in the tunnel. Having described and interpreted patterns of rainfall and discharge, Chapter 9: presents the results of two modelling trials: a soil moisture balance model (SMBM), and an infiltration model
designed to identify discharge events that do not conform to patterns established earlier in the chapter.

With the temporal pattern of discharge established (flow results and modelling chapters), the results of chemical and temperature analyses, takes a closer look at the movement of fluid through the surrounding rock mass. A single discharge event was sampled in greater detail in May 2012 in order to characterize fluid-rock interaction during infiltration. Finally, temperature measurements for the entire study period are presented. Records from a large, intermittently-flowing fissure are compared with tunnel air temperature measurements and the temperature of water flowing from the tunnel outlet.

While chemical and temperature analyses shed light on fluid flow pathways and infiltration patterns during discharge events, the two also supplemented flow measurements by partitioning relative discharge along the tunnel. Taken as a whole the data provides a detailed picture of shallow fluid circulation in the rock mass surrounding the Tatare Tunnel.

1.1.5 Chapter 12: Discussion of Findings and Conceptual Model

The discussion chapter draws together findings of flow and residence time, and presents a conceptual model of fluid flow in the rock mass surrounding the tunnel. The model is developed in two stages: the observed rainfall-discharge patterns are related to physical characteristics of the rock mass and, secondly, the model is expanded to encompass changes in flow patterns across the entire study period. From its focus on processes the model addresses each of the particular aims and shows the relationship between atmospheric, surface and sub-surface processes.

Finally, the chapter places the study period in a broader context by comparing mean monthly rainfall and cumulative tunnel discharge to the rainfall record at Franz Josef between 2002 and 2012.

The thesis concludes with a summary of what the research revealed about the over-arching and particular aims outlined at the beginning of this chapter.
Chapter 2: Fluid Circulation Beneath the Southern Alps

This chapter begins by reviewing current understanding of large scale fluid circulation and evidence for the infiltration of meteoric water. Section 2.5 outlines three elements that control shallow fluid circulation, and evidence for each is presented: storm events as drivers of infiltration; the two sources of infiltrating fluid (rain and snow) and the permeability of the rock mass adjacent to the Alpine Fault. Section 2.7 describes the important differences between saturated and un-saturated flow in rock masses and the substantial differences in groundwater movement associated with each type of flow. Having outlined the body of theory that informs the research, the review turns (section 2.8) to the methods employed by researchers to investigate sub-surface fluid flow in a variety of settings. Three important approaches are considered: surface observations, boreholes and tunnels. Section 2.9.4 then discusses how chemical and temperature analyses can be used to aid the interpretation of data gathered by any of the three means cited above. Section 2.10 describes the role of modelling in drawing different types of observation together to shed light on processes that control patterns of infiltration and groundwater movement in the rock mass surrounding the Tatare Tunnel.

2.1 Large Scale Fluid Circulation Beneath the Southern Alps

There are important feedback loops between uplift, deformation and meteoric water (Cox et al., 2012b). The formation of the Southern Alps, and patterns of fluid circulation below them, result from uplift on the Alpine Fault. Interaction between fluids that circulate below the Southern Alps and the Alpine Fault have received attention recently (e.g. (Cox et al., 2012b; Stern et al., 2001; Sutherland et al., 2012; Townend et al., 2010)). Fluids are hypothesized to play an important role in the earthquake cycle of the Alpine Fault, potentially influencing nucleation and patterns of slip when earthquakes are initiated (Sibson, 1992; Sutherland et al., 2012).

The theorized convection cell that drives the circular motion of fluid at geological timescales is the most important distinction between large-scale fluid circulation beneath the Southern Alps and shallow fluid circulation in the upper 1 km of the crust.
(Templeton et al., 1998). The presence of a convection cell determines what happens to
the infiltrating fluid, the upwelling fluid and how the two interact.

Three factors control regional scale fluid flow beneath the Southern Alps: rapid uplift
and its thermal consequences, the upward migration of metamorphic fluid and the
downward percolation of meteoric fluid. All are influenced by, and interact with, the
Alpine Fault.

2.2 Alpine Fault: Uplift and Thermal Consequences

The 480 km long Alpine Fault that marks the western edge of the Southern Alps is one
of the world’s longest and straightest transpressional plate boundaries (Townend et al.,
2010). The fault, which regularly ruptures in $M_w$ eight earthquakes (Boese et al., 2012),
is late in its approximately 200-400 year cycle of stress accumulation and subsequent
rupture (Sutherland et al., 2012). Oblique collision between the Pacific and Australian
plates results in high uplift rates that peak at approximately 12 mm yr$^{-1}$ (Cooper and
Norris, 1994; Koons and Craw, 1991). The high uplift rate elevates shallow rock
temperature and leads to the steep geothermal gradient measured by Sutherland et al.
(2012) at $62.6 \pm 2.1 ^\circ$C km$^{-1}$. The rapid uplift of rock from depths in excess of 15 km
brings hot rock close to the surface. The theorized temperature and pressure distribution
beneath the Alps comes from modelling by Allis et al. (1979) and Allis and Shi (1995)
and the patterns that they predicted for the Southern Alps are supported by further
modelling efforts by Foster and Smith (1989). The principal of buoyancy driven flow,
where differences in fluid density due to thermal expansion act as a driver of fluid flow,
derpins much of Foster’s (1989) modelling. Further modelling conducted by Foster
and colleagues sheds light on the ratios of topographically and thermal driven flow in
mountain systems (Foster and Smith, 1988a; Foster and Smith, 1988b). Modelling
indicates that the downward movement of infiltrating fluid perturbs the flow path of an
upwelling fluid and, as a result, hot springs are concentrated in mountain valleys.

An abundance of thermal springs in mountain valleys of the Southern Alps (Reyes,
2010; Reyes and Britten, 2007) provides support for the model of Allis and Shi (1995).
The hot springs, some emanating from deep reservoirs with temperatures greater than
60 $^\circ$C, provide a means of studying fluid circulating to depths otherwise unobservable
by more traditional means of investigation.
Heat indicated at the surface by elevated isotherms as well as minor contributions to rock temperature from shear heating along the Alpine Fault (Johnston and White, 1983; Sutherland et al., 2012), provides the upward driver of fluid circulation. Hydrothermal gold deposits in the central Southern Alps and its eastern flanks indicate that re-distribution of meteoric and metamorphic fluid by heat has been occurring across the entire Southern Alps for at least 5 million years (Craw, 1992; Craw, 1997; Craw and Koons, 1986).

Fluid from two sources moves along the steep thermal gradients: metamorphic fluid generated by dewatering reactions at depth, and surface infiltration of meteoric water.

### 2.3 Fluid Sources

At depths in excess of 10 km, where the pressure regime is lithostatic (total pressure is the weight of the overlying fluid plus the weight of the rock overburden), compression of hydrous minerals leads to the generation of metamorphic fluid. The metamorphic fluid expelled from rock is driven upward by the large heat gradient and re-distribution of pressure due to changes in rock volume (Dipple and Ferry, 1992; Upton et al., 1995; Wickham et al., 1993; Young, 1993). Metamorphic fluids are one of two primary components of convective circulation beneath the Alps. The relative abundance of the stable isotopes of Strontium ($^{87}$Sr and $^{86}$Sr), Oxygen ($^{18}$O) and Deuterium ($^2$H) present in uplifted calcite veins and in fluid inclusions verify that metamorphic fluids are major contributors to the convective cell beneath the Southern Alps (Templeton et al., 1998).

While upwelling metamorphic fluids are evident on geological timescales, most observations of shallow hydrothermal activity (evident in the mineral deposits and hot springs of the region) suggest that the infiltration of meteoric fluid is also a major driver of the convective cell (Craw, 1992; Craw, 1997; Craw and Koons, 1986).

Evidence from exhumed calcite veins and fluid inclusions indicates that meteoric water is pervasive to depths of 5 km and capable of descending below the brittle-ductile transition depth, approximately 15 km below the surface (Jenkin and Fallick, 1994; Templeton et al., 1998). Furthermore, the $^{18}$O and $^2$H signatures of water issuing from hot springs in the region suggest that meteoric water mixes with metamorphic fluids throughout the upper 5 km of the crust (Cox et al., 2012a; Reyes, 2010; Reyes and Britten, 2007). The timeframes that characterize the infiltration and movement of
meteoric water are far more variable than those for metamorphic fluids. Hydrothermal deposits and calcite veins with meteoric fluid inclusions from eastern Otago suggest that the infiltration of meteoric water is not simply a contemporary phenomenon (Craw, 1992; Craw and Koons, 1986; Davies et al., 2011). Cox (2012) observed cooling of the Copland Hot Spring in the central Southern Alps during rainfall events, and attributed an abrupt drop in the temperature of them to the infiltration of meteoric fluid. Coupled with the sheer volume of annual rainfall on the western flanks of the Southern Alps (Anderson et al., 2006; Woods et al., 2006), the evidence cited above indicates that in the upper 1 km of the crust downward infiltration of meteoric water is the dominant component of fluid circulation. Figure 2.1 shows the convective cell schematically.

2.4 Meteoric Water and the Alpine Fault

Research conducted during the Deep Fault Drilling Programme (DFDP) has revealed the extent to which meteoric fluid can alter the > 50m thick zone of intensley crushed rock bounding the Alpine Fault’s principal slip surface (Sutherland et al., 2012). The alteration of crushed fault rock by infiltrating meteoric water in the shallow crust was observed in the drill hole and supports the interpretation of several authors (e.g. (McCaig, 1990; Sibson, 1992; Warr and Cox, 2001)) that fluid acts as a major control on the nucleation of earthquakes and, through modification of the frictional properties of the fault plane, the rate of slip on the fault once an earthquake is initiated.
Figure 2.1: The two main elements of the convection cell beneath the Southern Alps, buoyancy-driven flow from the release of metamorphic fluid, and gravity-driven flow of meteoric water. The fluid mixes and is trapped in calcite veins. Figure adapted from Allis et al. (1995).

The permeability of the rock mass adjacent to the Alpine Fault not only determines the ease with which meteoric fluid reaches the fault, but also the behaviour of the rock mass once the fault ruptures. Saturation of the schist rock mass adjacent to the Alpine Fault acts as a major control on landslide initiation and the capacity of the landscape to buffer the effects of a large storm event (Barth, 2013; Henderson and Thompson, 1999).

The fate of meteoric water that infiltrates the crust can be considered under these processes: first, water may continue to percolate downwards towards the water table, eventually mixing with upwellling metamorphic fluid; secondly, the water may remain in storage within the rock mass for some time; and, thirdly, the water may be expelled back to the surface by springs and in the baseflow of a river. At any one time, a certain amount of meteoric water will be percolating downwards, moving into storage or being discharged at the surface by some means. Infiltration of meteoric water forms a smaller, more spatially confined, circulation cell. Shallow fluid circulation is distinct from the concept of infiltration as it incorporates the lateral flow of groundwater once it enters the crust and the potential discharge of fluid at the surface. The term ‘shallow fluid
circulation’ encompasses a range of processes affecting the Alpine Fault and is used in this thesis. Although shallow fluid circulation exerts a strong influence on the Alpine Fault and the surrounding landscape, very little is known about current rates and patterns of fluid movement, but the major factors that control the system can be identified. The following section outlines current levels of understanding regarding the infiltration and movement of meteoric water in the shallow crust along the flanks of the Southern Alps.

### 2.5 Shallow Fluid Circulation

This section covers the three main elements of shallow fluid circulation: storm events as drivers of infiltration; the different sources of infiltration (rain and snow) and the effects they have on patterns of infiltration and groundwater flow; and, finally, how the permeability of the rock mass interacts with the first two elements to control groundwater movement. To the author’s knowledge no one study incorporates the above three elements to develop an understanding of rates and patterns of infiltration in the Southern Alps. The majority of published studies focus on long-term changes in meteoric water infiltration or the role of surface water hydrology. The emphases of this research are infiltration of meteoric water into the schist rock mass adjacent to the Alpine Fault and movement of water once it enters the crust. Mechanisms for the return of meteoric water to the surface, such as springs and river baseflow, are not considered.

#### 2.5.1 Storm Events: Delivery of Meteoric Water

The main divide of the Southern Alps is orthogonal to the westerly winds that bring warm, moist air from the Tasman Sea (Griffiths and McSaveney, 1983; Henderson and Thompson, 1999; Sinclair et al., 1997; Stuart, 2011). The topographic barrier of the Alps forces air upwards, inducing heavy rainfall that is estimated to peak at ~ 10,000 mm yr\(^{-1}\) west of the main divide at an altitude of approximately 800 m (Anderson et al., 2006; Griffiths and McSaveney, 1983; Henderson and Thompson, 1999; Woods et al., 2006). Orographic precipitation distinguishes the flanks of the Southern Alps from low-lying areas, and results in a steep west-east rainfall gradient. Griffiths and McSaveney (1983) was one of the first to measure the steep rainfall gradients of the Southern Alps, and described them as typical of temperate alpine environments. Henderson (1993)
used similar methods to emphasize the role of storm events in recharging the region’s aquifers.

Much of the precipitation available to infiltrate the rock mass adjacent to the Alpine Fault arrives as pulses during storm events. Characterisation of rainfall patterns is difficult because the temporal distribution of rainfall is random and, like many sparsely populated mountain regions, the density of rain is low. As a result there is considerable uncertainty about the spatial distribution of rainfall in steep, mountainous catchments throughout the Alps (Goovaerts, 2000; Kerr, 2009). The receipt of large amounts of rain in a short time, high spatial variability in rainfall intensity, and low density rain-gauge networks mean that quantifying the amount of meteoric water that arrives during a storm event is difficult.

Several authors have directly or indirectly quantified infiltration during a storm event (e.g (Craw, 2000b; Manga, 1999; Padilla et al., 1994; Walton-Day and Poeter, 2009), and the most commonly reported observation is that infiltration rates are spatially variable. Surface runoff is higher during intense rainfall events, a factor compounded by the steep topography of mountain regions. Furthermore, flow of groundwater, often over large distances during a storm event, complicates the interpretation of discharge hydrographs and can make identifying ‘new’ infiltrating water difficult. It follows that infiltration of meteoric water adjacent to the Alpine Fault is likely to occur during storm events and that measurements of infiltration are likely to be affected by the lateral movement of groundwater. While storm events are the primary means by which meteoric water is delivered to the surface, the form in which it arrives (as rain or snow) may cause patterns of infiltration to deviate from patterns of rainfall.

2.5.2 Sources of Infiltration Fluid

Precipitation may also reach the earth’s surface as snow, and in temperate alpine regions, such as the Southern Alps, snowfall is strongly seasonal (Chinn, 1995a; Kerr, 2009; Stuart, 2011). Compared to rainfall, snow is more variable in its spatial distribution, is subject to significant redistribution post-deposition (e.g. by wind drift and avalanching) and can remain in storage for long periods. In the Southern Alps, snowline elevations mirror the orographic precipitation gradient, lie at an average elevation of ~1800 masl, and vary regionally (Chinn, 1995a).
Aside from physical state, the most important difference between snow and rainfall is that snow can be stored in a catchment for long periods of time. The storage of snow, which can lie several meters deep in elevated regions, introduces a large time delay between precipitation and infiltration. For water derived from snow to infiltrate the crust, it must first be converted to its liquid phase, a process which requires an additional energy input. Increases in air temperature and 'rain-on-snow' effects have both been shown to induce melt in studies of glacier mass-balance (Anderson and Mackintosh, 2006; Anderson and Mackintosh, 2012a; Ishikawa et al., 1992). An energy increase in the form of increased solar radiation or an increase in air temperature or, an increase in snowpack temperature due to precipitation falling directly on it (Anderson and Mackintosh, 2012a; Marcus et al., 1985) are the two main processes that initiate large-scale melt of a snowpack, and the dominance of one over the other has been contentious for some time. Increases in air temperature during the spring months are the major driver of seasonal snowmelt (French and Binley, 2004; Stahli et al., 2004) and the resulting increase in discharge observed in snow-dominated catchments (Gardener et al., 2010). The vast majority of these measurements have been made in the context of studies on glacial mass balance. While large ice masses complicate interpretations through feedback mechanisms, the theoretical basis for predicting snowmelt initiation remains sound. The presence of snow means that not only rainfall but also increases in temperature and changes in solar radiation influence the infiltration of fluid into the crust (Stahli et al., 2004).

2.6 Estimates and Controls of Permeability

So far two inputs to shallow fluid circulation have been considered: precipitation during storm events, and snowmelt. The proportion of meteoric water that actually infiltrates the crust is controlled by the permeability of the soil and the rock mass beneath.

2.6.1 Surface Controls

As a soil becomes increasingly saturated during a precipitation event, void spaces become occupied by fluid and the ability of the medium to absorb water decreases (Schwartz and Zhang, 2003). During a storm event two main changes in the rate and pattern of infiltration occur: (1) as a storm progresses and the soil tends toward saturation, the total volume of fluid that can enter the soil per unit of time decreases
and; (2) as the soil approaches saturation, the time taken for a unit of water entering the soil to reach a depth decreases. The soils of the Westland region are thin (< 1 m) and subject to frequent storm events (Barth, 2013). Low soil-storage capacity and frequent rainstorms mean that the regions soils rapidly transmit rainfall to the rock mass below and have little influence on the total volume of infiltration (Graham et al., 2010; Scott, 2004).

Snow on the surface and ice immediately on or below the soil horizon have been identified as potential fluid-storage mechanism (see section 2.5.2). However, seasonal variations in snow and ice have been observed to not only store fluid, but also to reduce the volume of infiltration (French, 2003; Harris, 2001). Dobinski (2011) reviewed the effect of season variations in ice cover and permafrost beneath the soil horizon. True permafrost is unlikely to form in soils on the western flanks of the Southern Alps, but ice accumulation beneath the surface may occur in response to reduced winter temperatures and lesser availability of water in the region. Much of the rock mass adjacent to the Alpine Fault lies at elevations where seasonal ice and snow play a significant role in the storage and infiltration of fluid (Chinn, 1995a; Dobinski, 2011; Healy, 2010). In the area adjacent to the Alpine Fault the presence of snow and ice is thought to be an important control on patterns of infiltration, both in terms of volume and temporal distribution.

2.6.2 Rock Mass Controls and Permeability

While the physical structure of the soil and the presence or absence of snow and ice are initial controls on patterns of infiltration, the structure of the underlying rock mass exerts a strong influence on infiltration into uplifted basement rocks (Smerdon et al., 2009). There are variations in topography, slope and rock fracturing between sedimentary, volcanic and metamorphic rocks (Ingebristen and Sanford, 1998), and a large body of literature concerning rock mass controls on infiltration in different geological settings exists (e.g. (Lui et al., 2004; Masset and Loew, 2010; Peters and Klavetter, 1988; Wang and Narasimhan, 1985). The most relevant examples come from work undertaken in the Cromwell Gorge, Otago, New Zealand where the rock type and structural setting is similar to that of the rock mass adjacent to the Alpine Fault.
Substantial investigations into rates and patterns of infiltration, groundwater storage and movement were conducted during remedial works to stabilize large creeping landslides in the schist slopes above Lake Dunstan between 1990 and 1992 (Macfarlane, 1992). The geology of the schist rock mass of the Cromwell Gorge is similar to the rock mass adjacent to the Alpine Fault neat Franz Josef township, and the structural controls on infiltration and fluid movement are also expected to be similar. The investigations, which utilized seismic, drill-hole and surface observations as well as tunnel excavation identified several key features that influence infiltration and groundwater movement (Beetham, 1992; Gillon, 1992; Macfarlane, 1992);

1. The presence of shear zones, many of which were cemented with low-permeability fault gouge and surrounded by highly fractured rock;

2. Perched aquifers, some of which stored large volumes of fluid; (the bases of perched aquifers were usually sealed by crush and shear zones);

3. The toppling of over-steepened schist forms sharp step-like topography beneath the soil horizon and in zones of relaxation.

These steps serve as sites where water may pool, an effect that has been shown to drastically increase localised, direct groundwater recharge (Graham et al., 2010; Hayashi et al., 2003; Horton, 1940; Olofsson, 1994).

Shear zones within a rock mass can act as barriers to fluid flow when the dominant direction of groundwater flow is orthogonal to low-permeability gouge (Evans and Foster, 1997; Sibson, 1992; Sutherland et al., 2012). Shear zones obstruct flow and store fluid, but the highly fractured rock that surrounds them may enhance local permeability of the rock mass. Together, these features illustrate the highly variable nature of rock mass permeability and the importance of small shear zones in controlling groundwater movement in schist.

The Amethyst Tunnel which has been cut through schist, adjacent to the Alpine Fault, mirrors observations made in the Cromwell Gorge. Discontinuous crush zones within the rock mass served as barriers to flow and provided a significant storage mechanism for infiltration (E. Savage, University of Canterbury, pers. comm. 5/03/2012). Shear and crush zones exert a major control on fluid flow at larger scales. However, at the scale of the hillside, where large shear zones may be absent, patterns of infiltration and
fluid flow are largely dictated by networks of inter-connected fractures (Miller and Dunne, 1996).

2.6.3 Fracture Networks

Networks of fractures can transport orders of magnitude more fluid than porous media (Caine, 2003; Ingebritsen et al., 1992). The study of flow through fractures is a broad field of inquiry, and here its scope is limited to factors that likely control fluid movement in Alpine Schist.

The rock mass adjacent to the Alpine Fault is repeatedly subject to large earthquakes generated on the Alpine Fault and in other active faults in the region (Cox et al., 2012b). As a result, the abundance of rock fractures and their permeability may be higher than in the schist that lies further to the east (Craw, 1992; Reyes, 2010; Reyes and Britten, 2007). High values of permeability were measured during bore-hole tests at the Amethyst Tunnel site, and the measured value of $1-3 \times 10^{13}$ m$^2$ suggests that the mountains adjacent to the fault are relatively permeable (J. Townend, Victoria University, pers comm). While faults can serve as regional barriers to flow, rock masses within and adjacent to major fault zones worldwide have been shown act as major conduits of fluid flow (Manga and Chia, 2008; Sibson, 1996; Sibson, 2001). Observations of rock properties near major faults suggest that the rock mass adjacent to the Alpine fault is likely to show enhanced permeability because it is regularly subject to earthquakes (Cox et al., 2012a; Craw and Koons, 1986; Manga and Chia, 2008; Sibson, 1992; Sibson, 1996; Stern et al., 2001; Sutherland et al., 2012).

In addition to the formation of fractures by the passage of seismic waves, fracture abundance, orientation and aperture are determined by the orientation of the regional stress field (NRC, 1996). Boese et al. (2012) used first motion analyses of earthquakes to determine a maximum horizontal principal stress orientation of $115 \pm 10^\circ$ in the vicinity of the Alpine Fault. Regional stress orientations interact with discontinuities within the rock mass to form fractures. In the case of schist adjacent to the Alpine Fault, any discontinuities are likely to have formed during earlier stages of ductile deformation (Little et al., 2002a). As well as regional compressive stress, the flanks of the Southern Alps are subject to topographic and erosion-induced stresses of varying orientation. A decrease in overburden near the surface results in parallel jointing near
the surface, or an increase in the aperture of joints and faults orientated parallel to the surface (Miller and Dunne, 1996). Furthermore, the confining stress that prevails in a shallow rock mass favours fracturing. Marechal et al. (1999) and Masset and Loew (2010) attributed increased inflow of water near a tunnel portal to this 'weathered zone' of increased fracture density. Savage (1985) and Miller and Dunne (1996) found that steep topography is capable of inducing tensile jointing in ridges/hill slopes, even under regional compression.

The stresses induced by topography and the unloading of the crust by removal of the overburden results in spatially variable fracture patterns (Little et al., 2002a; Miller and Dunne, 1996). At the scale of a hillside in the Southern Alps, little research has been conducted on mapping fracture patterns, primarily due to dense forest cover and the expense of bore holes in mountainous areas. Despite that, fracture patterns can be expected to reflect regional stress orientation, with more localised effects of topography dominating at any one site. Like patterns of fracture orientation, the apertures of fractures are also highly variable.

2.7 Saturated and Unsaturated Flow Dynamics

Transmission of fluid through a rock mass occurs in one of two ways: by percolation through the unsaturated zone, or as flow through the saturated zone. While the focus of this review is not on the mechanics of saturated and unsaturated flow, the interpretation of data collected by the methods outlined in sections 2.9.1 to 2.9.4 must reflect substantial differences in patterns of groundwater movement between the two zones. The division between saturated (phreatic) and un-saturated (vadose) flow is indicated by elevation of the water table (Schwartz and Zhang, 2003).

Saturation of a rock mass signifies that additional inputs of water are accommodated through a rising water table or by flow of water to un-saturated areas. Below the water table, all voids within the rock will be occupied by fluid and the pressure at any point will be greater than an atmosphere. In a saturated rock mass, fluid flow from areas of high hydraulic head to low hydraulic head, is proportional to the gradient and the permeability of the rock mass. Transmission of recharge signals in the saturated zone is achieved by two mechanisms; by the actual flow of water, or by hydrostatic fluid pressure waves (Gueguen, 2004; Streltsova, 1976). Pressure-wave velocities have been
observed at 1000 times faster than the physical flow of water (Rasmussen, 2000) meaning the response of a saturated system to external forcing may be equally rapid. Equations of saturated flow are used in modelling programmes to predict the distribution of hydraulic head under different recharge scenarios. The mechanics of saturated flow are well understood, and an infiltrating fluid must often pass through a substantial volume of un-saturated rock before reaching the water table.

Infiltration and groundwater movement in the un-saturated zone are fundamentally different than in the saturated zone, in that voids in the rock mass are occupied by fluid as well as air. The negative pressure head between the water table and the surface leads to two important phenomena that perturb patterns of groundwater flow observed in the saturated zone: capillary action, being the upward migration of water along this pressure gradient, and adhesion, the strong inter-molecular forces binding water to fracture walls that inhibit drainage of the rock mass to a dry state (Gray and Hassanizadeh, 1991). Given that the unsaturated zone may be partially saturated, recharge is achieved through a combination of hydrostatic pressure waves and the percolation of water. Celia et al. (1990) and Wang and Narasimhan (1985) noted that the effects of capillary action and adhesion are not constant over time but are saturation-dependant. Compared with flow in the saturated zone, percolation through the un-saturated zone may result in substantially slower fluid transmission times and retention of large volumes of fluid in only partly occupied pore spaces. Therefore, patterns of infiltration and groundwater movement may be differ significantly above and below the water table.

2.8 Measurement Challenges andAttempts to Overcome Them

Evidence for large scale fluid circulation usually comes from uplifted bedrock and exhumed veins of precipitated minerals. The output of models of landscape evolution provide a means by which to interpret field observations (Adams, 1981; Craw, 1997; Koons, 1987; Upton et al., 1995). Such techniques are unsuitable for measuring aspects of shallow fluid circulation as the system operates on a shorter timescale. The following section reviews the methods used to observe and characterize rates and patterns of meteoric infiltration. While outlining aspects of shallow fluid circulation is straightforward, to obtain empirical measurements of rainfall, infiltration and
groundwater movement presents major challenges. These challenges have been met by a variety of means and will be discussed in the following two sections.

### 2.9 Sampling Methods in the Shallow Crust

To sample subsurface processes is expensive and to design a sampling scheme that captures the spatial heterogeneity of shallow circulation is challenging. The up-scaling of sub-surface point measurements to bulk rock mass properties is one of the greatest challenges in hydrogeology (Bierkens, 1998). The three main methods used to obtain information are discussed here: surface observations, boreholes and tunnels. These methods provide ways to access the subsurface environments, so that analytical tools such as water chemistry and temperature analyses can be used to interpret the actual empirical data (such as flow measurements). Merging the various forms of empirical data, often taken at different spatial and time scales, into a complete picture of shallow fluid circulation can be achieved by the use of numerical or conceptual models (discussed in section 2.10).

#### 2.9.1 Outcrops and Surface Samples

Surface observations are cost effective ways to collect information about subsurface flow. At the outcrop scale, measurements of fracture spacing, density, aperture and orientation have been used to infer the permeability of the rock mass (Bierkens, 1998). The majority of surface measurements taken in the Alpine schist have been in outcrops around the Alpine Fault. Fracture patterns observed in these outcrops are strongly influenced by fault zone processes and are not representative of the average permeability of alpine schist (Korup et al., 2005; Sutherland et al., 2012). To gather data on the distribution of fractures in rock outcrops is difficult, but measurements of mean strike and dip of regional schistosity— being the parallel bands of foliation formed during metamorphism— are frequently made (e.g. (Cooper and Norris, 1994; Cox and Warr, 2001; Little, 2009; Little et al., 2002a)). The strike and dip of schistosity are major structural controls on fluid flow and have been shown to enhance fluid flow in a limited set of directions (Gillon, 1992; Macfarlane, 1992; Masset and Loew, 2010). As well as on the surface, schistosity strike and dip have often been measured in tunnels (covered in section 2.9.3), in mine drifts and from borehole logs (section 2.9.2).
Measurements of spring discharge at the surface are used to infer actual patterns of groundwater flow, as well as bulk permeability or the flow paths that control them. Spring discharge hydrographs have been interpreted by several authors (e.g. (Kresic and Bonacci, 2010; Manga, 2001; Soulsby, 1999)) and provide a useful tool for inferring flow paths and rock mass permeability. Amit et al. (2002) used spring recession curves to infer differences in permeability between karst and chalk aquifers in Israel, and further work by Bonacci (1993) and Padilla et al. (1994) used recession curve analyses — with other catchment parameters, such as area and slope — to estimate the permeability of karst aquifers. Analyses of spring recession curves provide a way to distinguish high-volume, quick-flow paths through interpretation of flow through low permeability fracture sets or the rock matrix. Manga (1999) used spring discharge hydrographs in fractured rock to relate patterns of discharge with seasonal shifts in groundwater flow. While the vast majority of spring discharge analyses have been conducted in karst areas — primarily due to the abundance of springs in limestone — the techniques are applicable to studying flow in a variety of fractured rock lithologies. By comparing the timing and rate of spring discharge with precipitation patterns one can infer rock mass permeability and flow paths.

2.9.2 Boreholes

Although surface measurements are inexpensive, and allow for a broad spatial coverage, they have the obvious disadvantage of not sampling changes in rock mass properties with depth. Surface erosion processes, stress conditions and rock storage properties have been shown to change significantly with depth (Bloomfield, 1996; Finkbeiner et al., 1997). Core logging and examination of the borehole wall allow fractures to be located at depth, while instrumented boreholes fitted with water level loggers, temperature sensors and water chemistry sensors provide information on the short term nature of infiltration and groundwater movement. Boreholes fitted with water-level loggers allow elevation of the water table to be monitored and groundwater movement to be inferred. Healy (2002) used changes in water table elevation to estimate rates of infiltration, while others used changes in water pressure in response to rainfall receipts to infer rates and patterns of infiltration (de Vries and Simmers, 2002; Gleeson et al., 2009; Harper, 1975). Information from boreholes can also be used for direct calculation of the permeability of the host rock through slug tests: addition of a
known volume of water and monitoring its drainage from the borehole. Packer tests — the pressurization of the borehole to monitor the movement of fluid through the surrounding rock mass — are also useful (Healy, 2010; Heath, 1993).

Instrumented boreholes allow investigation of subsurface processes with time. The heavily-instrumented borehole 1B of the Deep Fault Drilling Programme (DFDP), at Gaunt Creek, South Westland, has provided a wealth of information on fluid movement in the hanging wall of the Alpine Fault and its interaction with the Alpine Fault (Sutherland et al., 2012). Slug tests conducted in the bore hole allowed calculation of permeability of the footwall mylonites (sheared rock) at $10^{-14}$ m$^2$, a value similar to that calculated for the Amethyst Tunnel site ($1.3 \times 10^{-13}$). In addition, sensitive instruments have shown that the water table responds to rainfall events and distant earthquakes (R. Sutherland, GNS Science, pers. comm. 28/10/2012).

The advantages of boreholes over surface observations are numerous, although their limited lateral extent means they may only poorly characterize the horizontal distribution of fluid flow. Tunnel and mining excavations are analogous to horizontal drill holes and have the advantage of integrating infiltration over large lateral distances.

2.9.3 Tunnels

The most substantial body of literature relating to the use of tunnels for studies of subsurface fluid flow comes from large tunnelling projects in the European Alps. Analyses of inflows into deep alpine tunnels by Rybach (1995) and Masset and Loew (2010) were sensitive to the influence of the tunnel on the regional water table, and the hydraulic connections between the shallow rock mass and regional flow cells. Masset and Loew (2010) measured flow rates from seeps and fissures along several kilometres of the Gotthard Tunnel, Switzerland and were able to calculate hydraulic conductivity of the surrounding rock mass and account for its spatial features.

Flow measurements have been widely complemented by isotope and temperature measurements taken along the length of a tunnel as a way to sample water passing through different amounts of overburden (Marechal et al., 1999; Marechal and Etcheverry, 2003; Pastorelli, 2001). Marechal and Etcheverry (2003) analysed the $^{18}$O and D signatures of inflowing tunnel waters and found that meteoric water (in this case snowmelt) infiltrated through the rock mass to depths exceeding 1 km. Similar
approaches involving temperature measurements of tunnel inflows have allowed maps of contact time between water and rock, and showed infiltrated meteoric water tended to re-distribute large amounts of heat in the massif (Marechal and Perrochet, 2001; Rybach and Pfister, 1994).

Shimojima et al. (1993) monitored seepage into a shallow mountain tunnel in Japan and used flow data to infer fluid pathways in the surrounding rock mass. Further work utilized flow measurements, the electrical conductivity of inflowing water, and measurements of CO₂ concentrations to define the relative amount of matrix and fissure flow in the rock mass, as well as the degree of rock mass saturation (Shimojima et al., 2000). Investigations in mountain tunnels not only show the utility of tunnel flow measurements in shallow and deep circulation settings, but how isotopic, temperature and chemical measurements can be used to refine conceptual flow models (Loew et al., 2007; Marechal and Etcheverry, 2003; Pastorelli, 2001; Rybach and Pfister, 1994; Shimojima et al., 2000; Zhang and Franklin, 1993).

2.9.4 Water Sampling and Temperature Analyses

The chemical, isotopic and heat signatures that waters inherit during shallow fluid circulation shed light on the flow paths, the type and volume of rock the fluid comes into contact with, and the duration of water-rock contact time.

Section 2.3 discussed the use of stable isotopes to determine sources of fluid sampled from within the crust. After sufficient contact time, pressure and heat, stable isotopes in meteoric water exchange with the surrounding rock, and that exchange is expressed as a pronounced shift in \(^{18}\)O values (Jenkin and Fallick, 1994; Upton et al., 1995), although the hydrostatic regime of the shallow crust (Sibson, 1992), contact time, pressure and temperature may be insufficient to permit isotopic exchange between fluid and rock. However the \(^{18}\)O and D concentrations of infiltrating water can be used to infer the source of shallow fluids and the degree of mixing between different fluid sources (Purdie et al., 2010; Sharp, 2007). The preferential nucleation of heavy water isotopes (\(^{18}\)O and D) means that precipitation that falls as snow is relatively depleted in light isotopes (Sharp, 2007). Although variable in this regard, precipitation that falls as rain will plot as slightly negative values on the New Zealand Meteoric Water Line (NZMWL), while snow shifts down the NZMWL to even more negative values.
(Marechal and Etcheverry, 2003; Sharp, 2007). The isotopic signature of groundwater not only indicates whether or not the fluid has exchanged with the host rock, but if the fluid entered the system as rainfall or snowmelt. The signature may also be the result of mixing between the two end members. Given that the elevation of snowfall may be easily predicted, the proportion of rain or snow informs conceptual models on flows that feed the groundwater sampling site. In shallow fluid circulation systems, stable isotopes have the advantage of preserving their source-state signature for long periods of time.

Stable isotopes can be excellent means for distinguishing fluid sources, but the low temperatures and pressures encountered in the shallow crust mean that they provide little information on residence time or the extent of water rock-contact. Dissolution of minerals from fracture surfaces imparts a signature on circulating waters, and major ion analyses of appropriate groundwater samples allow this signature to be characterized (Kim, 2001). Analysis of major ions in schist-derived groundwater was successfully used by Craw (2000b) and Rosen (1998) to distinguish flow paths and to infer the extent of chemical weathering initiated by the circulating waters. The chemical evolution identified by Craw (2000a and b) is comparable to the chemical reactions likely to occur in the Alpine Schist adjacent to the Alpine Fault.

Studies of chemical signatures in high rainfall, mountainous environments conducted by Davies et al. (2011) suggest that even in highly saturated environments where water-rock contact time may be low, schist imparts a discernable chemical signature on infiltrating waters. Research into the chemical reactions and weathering paths of schist conducted by Reyes (2003) support the findings of other authors that fluid weathers schist to kalonite. Tweed et al. (2005) distinguished groundwater flow paths by sampling water from a fractured rock aquifer in the Dandenong Range in Australia, and found that less permeable pathways imparted a greater ionic concentration to groundwater than more permeable pathways. Event scale variations in solute chemistry were also used by Holloway and Dahlgren (2001) to distinguish relative contributions of groundwater and surface water to stream flow. The known weathering paths of schist, coupled with the capacity of chemical analyses to distinguish fast flow from more tortuous pathways, makes major ion geochemistry a potentially useful method for research of the kind discussed in this thesis.
Transfer of heat from rock to a circulating fluid means that spatial and temporal patterns in water temperature can be used to infer rates and patterns of groundwater movement (Healy, 2010). The redistribution of heat by structurally controlled groundwater movement (termed forced convection (Anderson, 2005)), plays a significant role in the distribution of heat in fault zones and the surrounding rock mass (López and Smith, 1995; Turcotte et al., 1980).

The temperature of infiltrating water is seasonally dependent and is approximately equal to air temperature at the time of infiltration (Anderson, 2005; Healy, 2010). Shallow rock masses with constant heat flux from below tend have temperature signatures approximately equal to mean annual air temperature (Rybach and Pfister, 1994). Therefore, infiltrating water may introduce heat to the rock mass in the warmer summer months and extract heat from the rock mass in the cool winter months. By defining the total energy of the water before and after infiltration, total heat exchange can be calculated. The total heat exchanged is proportional to the volume of fluid in the rock mass and the contact time between fluid and rock (Anderson, 2005; Blatt, 1992).

The heat capacity of water (4.18 J cm\(^{-3}\) K\(^{-1}\) at 25 °C), is high compared to the range of values measured in schist (which are typical of many metamorphic rocks) – 2.19 to 3.18 J cm\(^{-3}\) K\(^{-1}\) (Waples and Waples, 2004). Furthermore, the specific density of water (998.2 kg m\(^{-3}\) at 20°C), is less than half that of schist (reported by (Waples and Waples, 2004) at 2800 kg m\(^{-3}\) at 20 °C). As a result, infiltrating waters do not remove substantial heat from the rock mass but readily transport that heat by advection. The majority of studies conducted into heat mining by meteoric water were conducted in geothermal fields, but heat mining has been shown to operate at temperatures as low as 3 °C (Goldstein et al., 2001), and in the shallow circulation systems of cold, mountain environments (Rybach and Pfister, 1994; Rybach, 1995; Marechal and Perrochet, 2001). Rybach and Pfister (1994) and Rybach (1995) used temperature measurements in alpine tunnels and the region’s geothermal gradient to identify source area and temperature of infiltrating fluids. Stable isotope measurements confirmed that snowmelt was the source of tunnel waters, and further modelling allowed flow paths to be mapped with confidence.
2.10 Modelling Infiltration

Different forms of data from instrumented boreholes, tunnels and surface observations are often from measurements of different aspects of shallow fluid circulation. Models provide one of the most common ways to integrate structural, isotopic, chemical and flow data to enhance an understanding of complex patterns of infiltration and groundwater movement. Recent increases in computing power have allowed more sophisticated analytical and numerical models to be developed.

The most common type of groundwater model uses a numerical approximation of the groundwater flow equation to predict the distribution of hydraulic head (Zaidel et al., 2010). The MODFLOW package written by the United States Geological Survey (USGS) has been applied to a variety of infiltration studies (e.g. (Eisenlohr, 1997; Zaidel et al., 2010)). However, it was designed to simulate flow in a saturated medium, an assumption often violated by percolation of fluid through the unsaturated zone. In such cases more complex numerical and analytical models have been utilised to simulate the passage of water influenced by adhesion and capillary action (Henagen et al., 2001; Jamieson and Freeze, 1983). Assumptions of uniform rock mass permeability, spatially constant infiltration and the role of air in the unsaturated zone are often violated (Peters and Klavetter, 1988; Pruess, 1999; Pruess et al., 1999). In such cases, measurements that made use of the techniques outlined in section 2.9 mitigate the effects of these violations.

Regardless of the type of model used the most important factor is the set of assumptions for the model, known as its boundary conditions. Boundary conditions have been shown to be the most significant influence on the ability of a model to emulate real world observations (Sanford, 2002). Analytical and numerical models in this research are used to verify an underlying conceptual model. Because little is known about the rate and magnitude of infiltration in the Southern Alps, development of a conceptual model was a necessary first step in the present research.

Conceptual models are not restrained by strict boundary conditions and the nuances of numerical representations. In the domain of this research the purpose of a conceptual model is to infer the relative rate and magnitude of subsurface processes. Geological and isotopic data have been used to calibrate numerical models and to develop conceptual models of large scale fluid movement in the Southern Alps (Koons et al.,
Modelling mitigates the challenge of up-scaling point observations to large spatial and temporal scales by relating measurements to process. Furthermore, models can be used to transform different types of data into a comparable form, thereby allowing patterns to be identified. Models that make justifiable assumptions about real world processes can also be used to isolate system components (such as infiltration, percolation, groundwater flow, isotopic and chemical exchange) in order to better understand their effect. To develop a conceptual model of shallow fluid circulation in the Southern Alps, infiltration, groundwater movement, residence time and rock mass permeability must be quantified.

2.11 The Current Research

This research draws on the concepts and methods discussed in this chapter to address the research aims outlined in the Introduction. Firstly, by identifying the poorly understood system of shallow fluid circulation that lies within the larger regional scale fluid circulation beneath the Southern Alps (Figure 2.2). In reality the different elements of shallow fluid circulation are inter-connected, and feedback loops exist between them. Storm events, fluid sources, surface and rock mass controls on infiltration, fracture networks and the Alpine Fault were presented separately for ease of interpretation. Different elements of shallow fluid circulation can be isolated conceptually, but any research investigating them must recognise that such separation in methods may not be possible in practice and it was with this in mind that the research strategy outlined in the next chapter was developed. The research strategy distinguishes between aspects of shallow fluid circulation that are measured and those that are inferred.
Figure 2.2: Large scale fluid circulation beneath the Southern Alps and the measurements needed to infer that. The section labelled A identifies the research gap that this research will address.
Chapter 3: Research Strategy

The rainfall and snowmelt that enters the schist bedrock on the western flanks of the Southern Alps is the main input to convective fluid circulation beneath the mountains. The other significant input, although much smaller in volume, is metamorphic fluid released at depth, but the spatial and temporal timescales of these latter processes exclude them from the present study. The large annual rainfall results in rapid erosion of the Southern Alps and increases local exhumation rates. Numerical modelling has shown that a rapid exhumation rate reduces the strength of the upper crust and can significantly alter the mechanical behaviour of the plate boundary (Koons et al., 2003). While fluid affects the Alpine Fault through the coupling of climatic and deformation processes, infiltrating water can also directly affect the stability of the Alpine Fault. Observations of exposed portions of the Alpine Fault show the presence of clay minerals, the outcome of infiltration of meteoric water into the active fault zone.

While the infiltration of meteoric water exerts a strong control on the behaviour of the Alpine Fault, the proportion of rainfall that infiltrates the shallow crust is largely unknown. Identification of this knowledge gap is straightforward, but it is difficult to gather empirical data to address it. The study of subsurface flow that cannot be directly observed presents serious challenges which primarily concern assumptions of homogenous permeability. A research strategy that addresses this matter must recognise that although infiltration occurs in the upper crust, the processes that influence it — i.e. in the atmosphere and in the lower crust— operate over much larger spatial scales than shallow circulation. The thermal and stress states of the rock interact with water from precipitation to control shallow fluid circulation.

The scope of this research was geographically limited to a small part of the rock mass immediately adjacent to the Alpine Fault near the township of Franz Josef and for a period of nine months. Two main research themes were identified: the flow rate of infiltrating water, and the balance between dissolution and dilution processes in the rock mass surrounding a tunnel cut into the schist rock mass. The research interrogates inputs to shallow circulation through precipitation, as well as rates and patterns of groundwater flow once it enters the rock

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1 Data was collected from April 2012 to January 2013, due to the timeframe requirements for post-graduate students at the University of Otago.
mass. It then considers the interaction of infiltrating water and rock. The relative dominance of dissolution and dilution processes—assessed through chemical analyses and temperature monitoring—sheds light on the storage properties of the rock and the relative permeability of different portions of the rock mass.

The two themes are complementary and overlapping in that the storage of fluid in a rock mass exerts a strong control on flow dynamics. The over-arching concept for the field programme and methods for the analysis of data collected are described here, while the specifics of field and laboratory methods are outlined in Chapter 5:

### 3.1 Sampling Infiltration

Tatare Tunnel, located adjacent to the Franz Josef township, lies on the western flanks of the Southern Alps, and intercepts infiltrating waters as they percolate downward through the rock. All water that enters the tunnel comes from seepage through the rock mass, meaning that tunnel discharge is a proxy for groundwater recharge. While use of the Tatare Tunnel as form of natural lysimeter for the Southern Alps is tempting, there are two important differences between it and a standard lysimeter, and they are both a strength and a weakness of the field site:

1. A lysimeter is laterally confined in a column of soil. This has the advantage of isolating recharge by excluding lateral flows of groundwater. In contrast water that percolates the Tatare Tunnel may be sourced from directly above and from lateral flow of groundwater;

2. The catchment area of a standard lysimeter is known, and can be used to convert rainfall measurements to volumes of rainfall. The exact catchment area of the Tatare Tunnel is unknown, so the total volume of rainfall receipt cannot be calculated.

For these reasons Tatare Tunnel cannot be treated as a standard lysimeter, but while the latter samples infiltration through a well defined column of soil the Tatare Tunnel integrates infiltration along its 354 m length. This allows the investigator to monitor potentially large variations in infiltration in the rock mass at a single point (the tunnel outlet).

The second factor means that rainfall depth cannot be directly compared with discharge flux, but the concept can still be utilised to compare rainfall and recharge signals, hence allowing
inferences about the rock mass that separates the two. Three components of the two signals were identified:

1. The amplitude of the rainfall signal, represented by mean rainfall intensity in units of mm hr\(^{-1}\);

2. The amplitude of the discharge signal, assumed to be a proxy for the amplitude of the recharge signal, represented by peak tunnel discharge in units of l s\(^{-1}\);

3. The volume of recharge induced by rainfall, termed the ‘excess tunnel discharge’, in m\(^3\).

Once those signals were quantified, three comparisons were possible: (a) the amplitude of the rainfall signal could be compared with the amplitude of the discharge signal, (b) the amplitude of the rainfall signal could be compared with the transmission time of the recharge signal through the rock and, (c) the amplitude of the rainfall signal could be compared with the volume of recharge in the tunnel. By comparing these pairs of signals, inferences about the permeability of the rock mass, fluid flow paths, and hydraulic conductivity could be drawn. Figure 3.1 outlines this schematically.
Figure 3.1: Schematic showing how the amplitude of the rainfall signal was estimated, how the recharge signal was estimated and how the relationship between the two can be used to infer rock properties.

3.2 Precipitation

The Tatare Tunnel lies at an elevation of 380 m ASL and the nearest raingauge is approximately 3 km to the south-east. Several authors (Anderson et al., 2006; Woods et al., 2006) have estimated rainfall gradients in the south Westland region and their estimates suggest the gradient is steepest at elevations above 500 m (Anderson et al., 2006). It was therefore felt that precipitation measured at the automatic weather station in Franz Josef, at an elevation of 80 m ASL, could be used as a proxy for the amount of rain that fell immediately around and above the tunnel. Use of this precipitation data involves two key assumptions:

1. The amount and seasonal distribution of rainfall measured at Franz Josef represent the situation above the Tatare Tunnel.

2. The 15-minute resolution data adequately characterizes temporal changes in precipitation during storm events.
Both assumptions seem reasonable, given that the rainfall gradient is not expected to result in significantly more precipitation at elevations below 500 m and that temporal changes in rainfall smaller than the 15-minute detection limit at the Franz Josef site would likely be obscured by the effect of the overlying rock mass.

3.3 Spatially Integrated Infiltration

The Tatare Tunnel samples infiltration through at least 354 m of the hillside. Because the tunnel is expected to intersect a highly heterogeneous rock mass cross-cut by fractures and shears, seepage over the length of the tunnel can be treated as a suitable surrogate for infiltration at several sites along the tunnel. All water drains from the Tatare Tunnel via a small outlet half-pipe adjacent to the western entrance of the tunnel. By measuring discharge at the outlet, an integrated sample of seepage along the entire tunnel can be made. Before comparing the rainfall and discharge signals three key assumptions were made:

1. Tunnel discharge is potentially sourced from downward percolation of rainwater and lateral movement of groundwater within the hillside;

2. The catchment area of the tunnel, lying on the earth’s surface, does not vary;

3. Any water lost through the base of the tunnel before it reaches the outlet is minor compared with discharge measured at the tunnel outlet.

Both the time taken for infiltrating fluid to reach the tunnel (termed the transmission time) and the total volume of fluid that reaches the tunnel during and after a storm event are functions of rock mass saturation. The degree of saturation in a rock mass is a function of its storage capacity and the amount of available water. Precipitation input is matched with corresponding discharge measurements to calculate the proportion of rainfall infiltrated.

3.4 Residence Time

To estimate the residence time of fluid in the rock mass surrounding the Tatare Tunnel, as well as how that might change during the course of a storm event, two approaches were developed: chemical analyses, and temperature measurements. The rock surrounding the tunnel will impart a chemical or heat signature on percolating waters. Both can be used to infer the relative time fluid has been in contact with the rock mass. The observed signatures
are dependent on the ratio of fluid to rock, the speed at which fluid passes through the rock, and the total volume of fluid in the rock (‘rock mass saturation’).

3.5 Chemical Analyses

Water can dissolve part, or potentially all, of the rock it comes into contact with. The actual proportion of the rock that is dissolved is dependent on pH, temperature, the chemical concentration gradient between the water and the rock, and the duration of water-rock contact. It is reasonable to expect that the low temperature range of shallow rain-derived groundwater in non-hydrothermal systems, such as the Tatare Tunnel, means that the concentration of ions in solution will increase with rock-contact time. By sampling waters before they enter the rock mass (‘precipitation’) and after they seep into the Tatare Tunnel, differences in chemical concentration can be used to estimate the relative degree of water-rock contact. Increased water-rock contact time may indicate slower flow rates of infiltrated waters, a property related to rock structure and permeability. They may also indicate that the fluid has been stored within the rock for some time, and did not enter immediately after the most recent rainfall event (Ingebristen et al., 1992).

The rate at which different ions move into solution when rainwater comes into contact with rock is lithology-specific. A laboratory experiment was used to convert measurements of ionic concentration in solution into rock-contact times. The aim of the laboratory work was to quantify the rate at which individual ions were liberated from Alpine Schist and taken into solution. These relationships could then be applied to water samples from the Tatare and Amethyst Tunnels.

Because chemical signature is influenced by rock mass saturation, a property expected to change during a storm event, a more detailed sampling scheme was adopted for Discharge Event 4 on May 2012 (section 6.2) the purpose of which was to capture variations in water chemistry as the storm progressed. These samples could then be compared with measured discharge, a proxy for rock mass saturation.

The key assumptions behind the interpretation of chemical analyses to infer fluid residence time were:

1. The rock taken from the wall of the Tatare Tunnel for laboratory experiments was representative of the rock through which fluid flowed before seeping into the tunnel;
2. The chemical signature imparted on percolating waters was measurable and changed during a storm event;

3. The rates and conditions of chemical reactions in the laboratory were broadly representative of those in the field.

A chemical signature is not the only means of inferring contact time between fluid and rock. Heat has long been recognised as a useful groundwater tracer and was used as such in this study.

### 3.6 Temperature Analyses

With sufficient contact time water will heat/cool to the shallow rock temperature, and any difference in the temperature of water seeping into the Tatare Tunnel will likely result from either a change in temperature of the shallow rock mass that infiltrating waters are in contact with, or a water-rock contact insufficiently long for full thermal equilibration between rock and fluid to be reached.

The temperature of the rock and the fluid that flows through it are coupled, but the total amount of heat stored in the rock mass far outweighs that stored in the fluid. Given a sufficient temperature differential and ample fluid volume, infiltrating water has the potential to significantly alter the temperature of the rock mass, but a large increase in the volume of fluid flowing through the rock mass may mine enough heat from it to decrease its temperature.

Temperature measurements were used at the Tatare Tunnel field site to estimate the relative saturation of the rock mass, as well as how it changes during a storm event. These measurements complement chemical analyses and, in conjunction with flow measurements, shed light on interactions between infiltration, fluid storage and groundwater movement in the rock above the tunnel.
Chapter 4: Field Site

4.1 General Setting: Amethyst Tunnel

Section 2.5 outlined characteristics of the Southern Alps that control shallow fluid circulation. One of the most important of these is the structure of the rock mass adjacent to the Alpine Fault. Excavation of the Amethyst Tunnel (Figure 4.2), located under a slope beside the Wanganui River (Figure 4.1), yielded valuable information about the structure of the schist.

Information regarding the geology of the Amethyst Tunnel was compiled from Geotech Ltd and is presented here. Abundant shear zones within the rock mass (each up to 1.5 m thick) are conduits for fluid flow. Several shear zones, each filled with clay fault gouge, acted as aquitards and led to the formation of perched water tables. Figure 4.3 shows the spatial distribution of these features in relation to the tunnel, as well as the general nature of the overburden. When large shear zones were encountered during excavation, tunnel inflows temporarily exceeded 300 l s$^{-1}$. In time, many of the shear zones ran dry, suggesting that once the perched water table was drained, recharge was low. Several shear zones, noted in Figure 4.3, showed increased flow during rainfall events, indicating that large volumes of recharge can be transmitted several hundred meters along preferential flow paths (Wayne Merriman, Geotech Ltd, Pers. Comm.).

Importantly, further work at Amethyst tunnel has shown that controls on fluid movement within the highly deformed schist adjacent to the Alpine Fault are spatially variable, and can transmit large volumes of fluid to depths of several hundred meters or more. The setting and geology at the Amethyst Tunnel are directly comparable with that of the Tatare Tunnel.
Figure 4.1: Locations of the Tatare and Amethyst Tunnels, adjacent to the Alpine Fault, South Westland, New Zealand.

Figure 4.2: Location of the Amethyst Tunnel adjacent to the town of Hari Hari, 30 km north of Franz Josef.
Figure 4.3: Cross-section of the Amethyst Tunnel to show overburden, schistosity dip, location of boreholes and the frequency of shear zones encountered during drilling. Figure supplied by Geotech Ltd and used with their permission.
4.2 Tatare Tunnel Field Site

The Tatare Tunnel has several features that make it an ideal site and allow the proportion of rainfall that infiltrates the rock to be estimated. Situated 2 km east of the Franz Josef Township, the unlined 355 m long Tatare Tunnel was excavated through schist bedrock in the hanging wall of the Alpine Fault. It cuts through schist typical of the area and trends at near right angle to the Alpine Fault. The length and orientation of the tunnel mean that measurements taken along it sample a relatively thick section of rock mass near the earth’s surface (Figure 4.4). Furthermore, its position means that it may capture water that has infiltrated the bedrock and is flowing towards the Alpine Fault. The floor of the tunnel is approximately 25 m above the Tatare Stream, and all water caught in the tunnel has seeped through the bounding rock mass.

Figure 4.4: The location of the Tatare Tunnel adjacent to the surface trace of the Alpine Fault, 2 km east of Franz Josef township.
4.2.1 Tunnel Geology

Section 4.1 identified the broad structural controls on fluid movement in the Alpine schist adjacent to the Alpine Fault. This section now focuses on smaller scale features found in the rock surrounding the Tatare Tunnel, based on structural measurements made by Cox (2010).

The rock surrounding the Tatare tunnel is predominantly quartzofelspathic meta-pelitic to psammitic garnet-muscovite-biotite-plagioclase-quartz schist. It is concordantly interlayered with minor (cm-thick) bands of mafic amphibolite, metachert, and concordant to discordant veins of quartz (now deformed). Several mm- to cm- size extensional shear bands that deflect the older mylonitic foliation were observed near the western tunnel entrance. These ‘curly schists’ indicate that the rock surrounding the tunnel has been subject to several stages of deformation, at depth as well as in the shallow crust. The schist within the remainder of the tunnel is strongly laminated, with a relatively constant 60-70° degree southeast-dipping schistosity (mean dip direction/dip = 137° E/63°) (Figure 4.5) and a SW-pitching lineation.

While these structural features track the progressive ductile and brittle deformation of the schist, the orientation and prevalence of more recent fracturing controls fluid movement. The schist has been cross-cut by a series of brittle fractures that range in aperture from <1 mm to 10 cm. The orientation of the fractures was not uniform but Cox (2010) noted they tended towards either

1. Steeply northeast dipping and striking at a high angle to schistosity, or
2. Steeply southeast dipping, parallel or near-parallel to schistosity, or
3. Shallow-moderately northwest dipping oblique to schistosity

Fluid was seen seeping from some of the fractures when structural observations were made, and all observed fractures were recorded as ‘wet’ or ‘dry’ accordingly. Figure 4.5 shows the orientation and frequency of wet and dry fractures. While differences between the orientations of these two were subtle, seeping fractures tended to be at high angles to schistosity and oriented with a NW-SE strike (i.e. with poles trending SW).
Figure 4.5: Stereonet and rose diagrams to show the orientation of schistosity in all 142 fractures measured along the Tatare Tunnel. The fractures are divided into those that were 'wet' (seeping water) and those that were 'dry'. A subtle difference between wet and dry fracture orientation can be seen, with wet fractures at a high angle to schistosity and oriented with a NW-SE strike. All stereonets are equal area, lower hemisphere projections with planes shown as lines and poles to planes as points. Data supplied by Simon Cox, GNS Science.
1.1.1 Fracture Apertures

Measurements of aperture were made for 142 fractures along the length of the Tatare Tunnel. Aperture is defined as the distance between the parallel walls of the fracture and was measured in millimetres. Figure 4.6 shows the distribution of fracture apertures for the Tatare Tunnel, and can be described as log-normal with fractures having apertures less than 2 mm being most abundant.

Figure 4.6: The distribution of apertures for the 142 fractures measured in the Tatare Tunnel. Fractures with apertures less than 21 millimetres were the most abundant, while fractures with apertures of six to eight millimetres were least abundant.
Chapter 5: Field Methods

This chapter describes the methods used to obtain empirical measurements in primary field site, the Tatare Tunnel, and includes tunnel flow rate, water temperature and the groundwater sampling scheme. The analytical methods used to describe patterns and properties of the data obtained are outlined in Chapter 3. The purpose of the flow measurements was to estimate the magnitude and timing of groundwater infiltration and movement, while chemical analyses, coupled with laboratory based experiments as outlined in section 6.1, aimed to identify water residence time.

Section 5.2 describes the how flow data was collected from the Tatare tunnel and section 5.3 outlines how temperature measurements were made in the Tatare Tunnel. Section 6.1 then describes the laboratory experiment set up to quantify the rate that water dissolves the rock mass surrounding the tunnel. Finally, sections 6.2 and 6.3 describe the groundwater and isotope sampling schemes, respectively.

5.1 Observations at Tatare Tunnel

Three types of observations had components that required sampling schemes in the Tatare Tunnel between April 2012 and January 2013; discharge measurements, chemical measurements and temperature measurements. The transformation of the data obtained from the Tatare Tunnel into a more meaningful form, including the methods of interpretation, are outlined in Chapter 7. Each set of observations was expected to shed light on a particular aspect of shallow fluid flow, and it is the combination of these three that describes the overall behaviour of fluid in the rock mass. Chapter 2 described a large scale conceptual model of fluid circulation beneath the Southern Alps and the variety of observations taken in the Tatare Tunnel provides a means with which to develop a more specific conceptual model of fluid flow within the shallow rock mass.

5.2 Discharge Measurements

Continuous measurements of discharge were made using a flat-mounted ultrasonic doppler instrument installed on the bed of the tunnel outflow pipe (Figure 5.1). With a small pressure transducer to measure the depth of water above the instrument and a soundwave emitter for water velocity, the Starflow Ultrasonic Doppler Instrument (Starflow) provides readings of
average depth and velocity (Unidata, 2011). Recording was set at 15 minute resolution. The dimensions of the outlet pipe, mean water depth and velocity measurements were converted to discharge using the equation for flow in a half pipe that is less than half full. The equation takes the form:

\[ Q = \bar{V} \times A \]

Where \( Q \) is discharge in \( 1 \text{ s}^{-1} \), \( \bar{V} \) is average water velocity in \( \text{mm s}^{-1} \) (per 15-minute interval) and \( A \) is the cross sectional area of flow in the half-pipe, measured in \( \text{m}^{2} \). \( \bar{V} \) is measured directly by the Starflow instrument and \( A \) is calculated from the equation:

\[ A = \frac{r^2(\theta - \sin\theta)}{2} \]

Where \( A \) is the cross sectional area of flow in \( \text{m}^{2} \), \( r \) is the radius of the half-pipe in meters, and \( \theta \) is calculated from the equation:

\[ \theta = \cos^{-1}\left(\frac{r-h}{r}\right) \]

Where \( r \) is the radius of the half-pipe and \( h \) is depth of water in the half-pipe, both measured in meters. As in any channel, discharge of the outlet pipe varies as a function of water depth and velocity.

Tunnel discharge was measured continuously between April 2012 and January 2013 in order to capture storm events typical of the autumn and spring periods (March to May and September to November, respectively) the cool, drier winter months (June-August) and summer rainfall (December to January).
5.3 **Temperature**

Temperature measurements were made at three locations within the tunnel: (1) at the tunnel outflow, recorded at 15-minute intervals by the temperature sensor mounted in the ‘Starflow’ device; (2) at a large fissure, located 54m from the western tunnel entrance, at 15-minute intervals by a HOBO U12 Stainless Temperature Data Logger (U12-015); and (3) at a small opening, 285 m from the western entrance, air temperature was recorded at 15-minute intervals between April and August 2012, by a HOBO U12 Stainless Temperature Data Logger (U12-015). The purpose of measuring tunnel air temperature was two-fold: to correct fissure temperature measurements for air temperature fluctuations so that the air and water signals could be separated from fissure temperature records, and to assess any coupling/heat exchange between fluid moving through the tunnel and air in the tunnel.
Chapter 6: Water Samples for Chemical Analyses

6.1 Laboratory Experiment

Rock samples were taken from the walls of the Tatare Tunnel, 60m from its western entrance and from the floor of the tunnel at approximately 200m from the western entrance. Samples from the walls of the tunnel were taken to represent the rock that infiltrating water interacts with on its journey to the tunnel. The second sample was taken from unconsolidated sediment on the tunnel floor, likely deposited by the Tatare Stream when it flowed through the tunnel. The gravel on the tunnel floor is not identical to the rock mass surrounding the tunnel and water that enters the tunnel does interact with the gravels as it flows through tunnel. However, it does so for a relatively small period compared to its interaction with the rock mass surrounding the tunnel.

Schist taken from the tunnel wall was crushed to a coarse powder then placed in PVC sample vials with 1 L of distilled water. Four different water-rock ratios were set up for each rock type (tunnel and stream); 0.5g/100 ml, 1.0g/100 ml, 1.5g/100 ml and 2.0g/100 ml. Vials were monitored for EC, pH and dissolved anions/cations on a weekly basis between August-October 2012, no discernable change in EC or pH was observed after January 2013 so the experiment was concluded. This monitoring enabled estimation of the rate at which different chemical species are liberated from the rock into solution.

6.2 Tatare Tunnel Groundwater Samples

Groundwater samples were taken from: (1) the Tatare Tunnel outflow; (2) a fissure that regularly discharges large amounts of water, 54m from the tunnel entrance; (3) seeps located along the roof and walls of the tunnel and, (4) water ponding on the tunnel bed. Groundwater sampling details are displayed in Table 1.
Table 1: Date, number of samples and the corresponding discharge event for the five groups of samples taken in the Tatare Tunnel. NDR = no discharge recorded.

<table>
<thead>
<tr>
<th>Date Taken</th>
<th>Number of Samples Taken</th>
<th>Discharge Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>30/01/2012</td>
<td>10</td>
<td>NDR</td>
</tr>
<tr>
<td>27/05/2012</td>
<td>22</td>
<td>4</td>
</tr>
<tr>
<td>04/06/2012</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>28/10/2012</td>
<td>2</td>
<td>15</td>
</tr>
<tr>
<td>15/01/2013</td>
<td>1</td>
<td>NDR</td>
</tr>
</tbody>
</table>

Groundwater samples were stored in 250 ml PVC twist-top sampling bags and then stored in a refrigerated compartment for transport to the laboratory for analysis.

The sampling on 26-28 May 2012 during DE 4 was the most detailed of the five during the period from 2012-2013, and aimed to sample variations in tunnel water chemistry during a discharge event. Water samples were collected from the tunnel outflow, large fissures, roof seeps and the Tatare Stream three times during the storm, for a total of 22 water samples. Rainwater samples were also collected during the discharge event. Chapter 7 describes the patterns identified for Tatare Tunnel waters analysed for DE 4.
Figure 6.1: Graph showing Tatare Tunnel water samples were collected on the rising limb of the DE 4 discharge hydrograph. Rainwater samples were collected from outside the tunnel and are shown superimposed over the rainfall Franz Josef rainfall record.

6.3 Isotope Samples

In order to infer the input state of waters (either snow, rainwater or some mixture of the two) that recharge the rock surrounding the Tatare Tunnel 11 samples for isotopic analyses were taken during the August 2012 sampling period, two in October 2012, and five in November 2012. Water samples were collected from precipitation, several sites in the Tatare Tunnel, and from the nearby Tatare Stream. Water samples were stored in 30 ml vials, filled to the top to exclude air then sealed to avoid exchange between the water samples and the atmosphere.
Figure 6.2: Graph showing the timing of isotope samples super-imposed on tunnel discharge and rainfall. All sampling occurred in the winter and spring seasons.
Chapter 7: Data Analysis Methods

Having outlined the methods by which data was acquired at the Tatare Tunnel field site as well as the contribution of external data sources, this chapter will focus on methods for processing and analysing of the data. How the data set was modified, corrected and displayed dictated the manner in which it can be interpreted. A primary goal of this research was to enhance understanding of the effect of storm cycles on shallow fluid flow. Individual storm events are expressed in the tunnel as increased discharge and the section below outlines how these periods characterised.

7.1 Identification of Discharge Events

A discharge event (DE) was defined as any period in which a measurable input of precipitation induced an increase in tunnel discharge beyond the natural variability of the discharge measurements. Small amounts of precipitation (~2mm of precipitation < 60 minutes), were commonly seen in the precipitation records and, with few exceptions, were insufficient to induce a discernible increase in tunnel discharge. Such events were included in the total precipitation of the nearest preceding discharge event. The criteria for both a discernible rainfall pulse of over 10mm (termed a rainstorm) and an increase in tunnel discharge beyond the normal level of variation allowed for several discharge events to be identified, whilst avoiding the potential for an unrealistic number of such events.

There is potential uncertainty in measured discharges at the tunnel outlet, amount of rain that falls above the tunnel and the dimensions of the rock mass surrounding the tunnel. To place emphasis on small rainfall-pulses that trigger no detectable response in the tunnel would only create an additional source of uncertainty. Instead, Discharge Events were kept large so as not to enhance the influence of small events. Figure 7.1 and Figure 7.2 outline graphically the criteria for recognising a Discharge Event, as well as the terminology used in the analyses.

The duration of a Discharge Event (DE) is dictated by rainfall and moderated by tunnel discharge. The beginning of a Discharge Event is defined as the beginning of a distinct rainstorm, while the end is defined as the time at which tunnel discharge either falls to 0 or increases sharply as a new surge of water reaches the tunnel. The time delay between the start of a rainfall pulse, and the beginning of increased tunnel discharge, means that some
discharge events have little overlap. Section 7.2 outlines how tunnel flow was assigned to a discharge event and the potential for uncertainty in this approach.

![Diagram of a simple, well-defined discharge event](image)

**Figure 7.1:** Schematic of a simple, well-defined discharge event. The beginning of rainfall marks the beginning of the discharge event. The time interval between the beginning of rainfall and the initial increase in discharge is termed $T_1$ and the time interval between peak rainfall and peak tunnel discharge ($Q^*$) is termed $T_2$. Rain that falls during the receding limb is included in the total rainfall for the Discharge event. The end of the discharge event follows the receding limb until the arrival of a new wave of water causes the discharge hydrograph to rise again.

### 7.2 Precipitation-driven Tunnel Discharge

Inferences about the rock mass surrounding the Tatare Tunnel involve input (measured rainfall) and output (discharge of the Tatare Tunnel) measurements for a given Discharge Event. Cumulative discharge is a descriptive term for discharge from the tunnel beyond a specified level, and assumed to be have been induced by a given rainfall event. Quantifying the cumulative discharge of the tunnel allows patterns of infiltration to be better described. Differences in the cumulative volume of water that reaches the tunnel during Discharge
Events reflect differences in infiltration and the rate water moves through the rock surrounding the tunnel.

The purpose of this section is to assess patterns across Discharge Events, given certain (and minimal) assumptions. In order to represent rainfall as a volume, rainfall is assumed to be evenly distributed across the entire catchment for the duration of a Discharge Event.

To assess patterns between rainfall and tunnel discharge the cumulative discharge of the tunnel was partitioning among the different events. Partitioning discharge usually requires the use of tracers but such detailed sampling was not possible for all Discharge Events. Therefore, the discharge was partitioned empirically by defining reference values. This reference value takes several forms. When the reference discharge is 0 l s\(^{-1}\), the excess discharge is termed total flow. Total flow is the sum of all discharge values (where each value is a 15-minute average) and is the volume of water that passes through the tunnel during a given Discharge Event. This metric makes no assumptions about (and it need not) the source rainstorm of these waters. All other reference levels were determined by discharge at the end of the preceding Discharge Event.

Reference discharge may take the value of discharge immediately preceding the inflection of the discharge hydrograph at the beginning of a sequence of storms. In essence, if several discharge events occur in quick succession, each increasing discharge from the tunnel, then the value of discharge at the beginning of such a sequence becomes the reference value. This reference discharge is termed the 'pre-DE-sequence level'. A discharge sequence is defined as a series of Discharge Events in which the receding limb of one event is sharply interrupted by the start of the next. Such a situation is outlined in Figure 7.2.
Figure 7.2: Schematic illustrating a more complex Discharge Event than the one shown by Figure 7.1. The rainfall attributed to the current Discharge Event has multiple peaks, as does the discharge hydrograph. The Discharge Event identified above has an overlap between the receding limb of the current Discharge Event and the beginning of a new rainstorm.

On the timescale of an individual Discharge Event, reference discharge may take the value of discharge immediately prior to the inflection of the storm hydrograph: i.e. the value at the start of the rising limb (outlined in Figure 7.3). This reference level is termed the ‘pre-discharge event reference level’. Both the ‘pre-discharge event reference level’ and ‘pre-discharge event sequence level’ are constants throughout the entire period of discharge.

Reference discharges that vary with time are also used, and are a means of partitioning discharge between two consecutive events. By fitting an exponential decay curve to the receding limb of the preceding discharge event, and projecting values into the time domain of the current discharge event (DE), a ‘previous event-decay’ discharge is obtained. This method was restricted to discharge events in which the falling limb of the previous discharge hydrograph could have an exponential decay model fitted. Additionally, an average exponential decay model was derived from all DEs in which discharge decayed at the end of the event. In this case the coefficient of decay (denoted $\alpha$) was averaged for all suitable DEs,
and the intercept was set equal to the value predicted by the exponential decay model for that DE. This had the effect of mapping values of average decay of discharge onto DEs, whilst not drastically over-predicting discharge values by using an un-realistically high Y intercept. This method is outlined schematically in Figure 7.4.

While the assumptions for the fixed reference discharges and the exponential decay curves were applied to all DEs, it is likely that they simplify the true partitioning of discharge between consecutive events. The fate of different storm waters, especially in saturated systems with apparently random but frequent inputs, is poorly understood (Burns et al., 1998; Buttle, 1994). While isotope, chemical or temperature data are often used to partition waters according to their origins and to assign them to subsequent flow paths, such data were not available for all DEs in the present research. Therefore, the empirical method outlined here, was utilised.
7.3 Recession Analysis

Tatara Tunnel is fed exclusively by groundwater. Although it is artificial, it can be regarded as a natural spring and the techniques commonly used to analyse spring discharge through time can be applied to it. These well-developed techniques are useful in determining the magnitude and timing of groundwater response to rainfall events. They also shed light on controlling mechanisms.

Like any hydrograph, the discharge hydrograph from Tatara Tunnel discharge hydrograph shows changes in flow with time. Analysis of discharge hydrographs for rivers, springs and tunnels can yield valuable information about the physical mechanisms controlling discharge (such as the transmissivity and storage properties of an aquifer).
Between April 2012 and January 2013 the Tatare Tunnel discharge hydrograph could be readily separated into distinct discharge regimes. Several important components of the discharge hydrograph were identified for each DE: namely, rising limb, peak discharge ($Q^*$), receding limb, and termination of the discharge hydrograph. These components are outlined in Figure 7.5. This differs from the nomenclature used by Kresic (2010), in which a recession curve begins at the inflection point on the falling limb of the hydrograph. The period between peak discharge and inflection of the spring discharge hydrograph is termed quickflow, and is assumed to represent flow through a well-developed conduit network (Amit et al., 2002).

$^2$ Kresic (2010) used the term quickflow to describe the rapid decay of the discharge hydrograph immediately after its inflection point. This nomenclature is especially relevant for karst springs, but is applied to early stages of the receding limb here.
Figure 7.5: Schematic showing recognised portions of the discharge hydrograph used for recession analyses. The quickflow portion following peak discharge ($Q^*$) is not used in recession analysis in Karst systems or in streamflow recession analyses, but utilised in this study. See text for explanation.

The later stages of the falling limb represent drainage of the aquifer as a whole. Many analytical techniques based on the spring recession and the exponential decay equations used to describe them, were developed for use in karst landscapes, where caverns or well-developed conduit networks are the main controls on the rate of flow. Extensive conduit networks are unlikely to have formed in the metamorphosed schist at Tatare, in which the pervasive fracture network has a much lower aperture than conduits in karst. Therefore, retaining the ‘quickflow’ portion of the recession curve immediately following peak discharge is important. If the quickflow portion of the hydrograph can also be described using an exponential decay, then techniques usually reserved for the lower portions of the recession phase can be applied across the entire hydrograph.

The methods of Kresic (2010) were used to perform recession analysis on the receding limb of the discharge hydrograph for several Discharge Events. The notation and techniques were broadly adopted from Padilla et al. (1994), Bonacci (1993) and Amit et al. (2002), with additional calculations based on the techniques of Bonacci (1993).
7.3.1 Recession Curve Equations

Several authors have used mathematical decay functions to describe the receding limbs of hydrographs (Boussinesq, 1904; Maillet, 1905). Whether they be empirical models based on graphical analysis or solutions to analytical equations of reservoir drainage, recession curve equations are not only useful for comparing recession hydrographs but can often provide plausible physical explanations for a range of phenomena. While the techniques of recession curve analysis were originally developed for streams, they have been increasingly applied to other data sets, including spring discharge. The recession analysis presented here is solely involved with fitting analytical solutions to observed recessions, and not application of the more complicated multi-reservoir models. The aim of this research is to describe rates and patterns of groundwater flow. Recession curves are highly variable at the discharge event and seasonal levels, so to obtain characteristic curves or parameters can be difficult.

Spring recession curves have generally been shown to exhibit exponential decay in discharge with time, with many exhibiting power-law decay in their early stages. The recession curves of the Tatare Tunnel were considered analogous to a spring recession curve, and only exponential models were fit. While power-law behaviour is evident in stream hydrographs, it is far less pronounced in spring recessions (Tallaksen, 1995).
For this research the exponential model first proposed by Maillet (1905) was used. It took the form:

\[ Q_t = Q_0 e^{-\alpha t} \]

where \( Q_t \) is discharge at time \( t \), \( Q_0 \) is discharge at the start of the recession and \( \alpha \) is a recession coefficient related to characteristics of the aquifer.

The receding limbs of discharge hydrographs for different discharge events (outlined in section 7.1) were identified and named. Because a high degree of variation was expected between the exponential parameters of different discharge events, an 'average' curve was computed, with its coefficients the average of those for all other discharge events.

### 7.4 Modelling

#### 7.4.1 Rainfall, Recharge and the Soil Moisture Balance Model

The input to groundwater flow has thus far been termed precipitation, including rain and snow as well the other intermediary states of water, such as sleet or water-vapour. While meteoric water is the main input, an important distinction must be made here between rainfall and recharge. Recharge is the proportion of water that infiltrates the surface and percolates through the soil column/rock mass toward the water table. It is usually a time-dependent percentage of total rainfall and is notoriously difficult to measure. Given the difficulties in measuring recharge, modelling tools provide a way to obtain an estimate of recharge, given certain meteorological measurements.

The well-known Soil Moisture Balance Model (SMBM), from the family of water-budget models commonly used in hydrological and meteorological studies (e.g. Taylor & Howard, (2010); White et al. (2003) and Scott, (2004), was utilized in this research to transform measurements of total rainfall into estimates of groundwater recharge. A core principal of any water-balance model is the conservation of mass. A water-budget model partitions water to each component of the hydrological cycle so the net sum is 0. The general SMBM utilized here has proven reliable in other studies (Scott, 2004; White et al., 2003). The models used here estimate recharge, with an associated level of uncertainty, and are dependent on the values assigned to different model parameters. Caution must be exercised when evaluating
the recharge predicted by the model, as storage models such as the SMBM are not always suitable representations of the rate and magnitude of actual recharge processes.

For recharge to occur, incoming rainfall in a given time-period must exceed both the evaporation rate and the storage volume of the soil. In such cases, excess rainfall infiltrates downward toward the water table. The amount of water that enters the soil storage reservoir depends on evaporation and surface runoff. Evaporation is usually estimated by the Penman-Taylor method and is assigned a value of 0 when rainfall is actually occurring. The surface runoff component is usually defined as a percentage of total rainfall, its actual value reflecting soil permeability, slope and the balance between rainfall intensity and maximum soil infiltration capacity. To assign a single value to runoff may be unrealistic, as it is likely to vary with soil moisture and rainfall intensity, but the most common approach is to set a rainfall intensity threshold below which runoff is a fixed proportion and above which the percentage of runoff increases. This reflects actual runoff, particularly during intense storm events. The soil reservoir has an upper limit for the volume of water it can store, and this is known as soils field capacity. In situations where the total volume of water stored in the soil is less than field capacity, the soil water reservoir is said to be in deficit. The initiation of recharge requires that the soil moisture deficit (SMD) be 0, and for further rain to fall. Table 2 outlines the parameters of the SMBM used, their physical basis, and the part of the model they control.

Uncertainties in parameter values such as field capacity are very important in dry climates, where the soil is nearly always in deficit. However, in situations of extreme rainfall, commonly encountered in the Westland region, such uncertainties are less important as rainfall is a likely to exceed soil storage capacity.

Several parameters, such as direct recharge, the surface runoff coefficient and the root constant, exert a major control on recharge in the SMBM. In the case of the Tatare Tunnel, calibration of the SMBM was difficult because independent measurements of water-table height or runoff in the adjacent Tatare Stream were not available. Rainfall data at 15-minute resolution, temperature and Penman-Taylor PET was taken from the automatic weather station, located at 80m elevation, approximately 5km west of the Tatare Tunnel, for the entire study period. Because the tunnels elevation was approximately 240 m greater than the rain gauge at Franz Josef, and that both the tunnel and the rain gauge lie in the steepest portion of the rainfall gradient, a precipitation adjustment factor of 1.25 (a 25% increase in measured
precipitation) was applied to all rainfall data (Anderson et al., 2006; Henderson and Thompson, 1999; Woods et al., 2006). A sensitivity analysis was conducted in order to determine which component of the model exerted the greatest control on calculated recharge, and Table 6 shows the sensitivity of the model to variations in key parameters.

### 7.4.2 Modelling Infiltration

Numerical modelling was used to identify the patterns of tunnel discharge resulting from different rainfall events in the Tatare catchment. While factors such as the exact catchment area of the tunnel, the spatial distribution of rainfall, and antecedent moisture conditions of the soil are unknown, assigning reasonable numbers to these factors allowed the sensitivity of the model to be assessed.

A simple numerical model was used to model the proportion of total rainfall that infiltrated the soil column to become groundwater recharge, as well as the accompanying infiltration rate for each Discharge Event identified between April 2012 and January 2013. The aim of the simple model was not to provide precise estimations of infiltration rates and proportions but, rather, to constrain them within several orders of magnitude and compare patterns between Discharge Events.
Table 2 Components of the SMBM used in the Tatare catchment, the associated units, range of realistic values and the purpose of each model component. Blue text indicates a measured parameter and red text indicates an inferred parameter.

<table>
<thead>
<tr>
<th>SMBM parameter</th>
<th>Units</th>
<th>Range of Realistic Values</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measured</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall, R</td>
<td>mm</td>
<td>0-10</td>
<td>The volume of water input to the SMBM</td>
</tr>
<tr>
<td>Potential Evaporation, ET</td>
<td>mm.hr⁻¹</td>
<td>0-10</td>
<td>The rate at which the atmosphere extracts water from soil storage</td>
</tr>
<tr>
<td>Timestep, t</td>
<td>hours</td>
<td>0.25</td>
<td>The resolution of all data is 15-minutes</td>
</tr>
<tr>
<td>Temperature, T</td>
<td>°C</td>
<td>-10-30</td>
<td>Controls PET and whether precipitation falls as rain or snow</td>
</tr>
<tr>
<td><strong>Inferred or Computed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root Constant, C</td>
<td>mm</td>
<td>800-1500</td>
<td>The effective volume of water that can be stored in the soil reservoir</td>
</tr>
<tr>
<td>Permanent Wilting Depth, D</td>
<td>mm</td>
<td>801-1501</td>
<td>The lower limit that the volume of water in the soil reservoir may reach before plants die and evaporation becomes limited</td>
</tr>
<tr>
<td>Runoff Coefficient, RC</td>
<td>%</td>
<td>0-40</td>
<td>The percentage of rainfall that becomes runoff and does not enter the soil reservoir</td>
</tr>
<tr>
<td>Precipitation Adjustment factor, P_adj</td>
<td>%</td>
<td>10-25</td>
<td>The multiplier applied to correct rainfall for variations in altitude between the rain gauge and the Tatare Tunnel</td>
</tr>
<tr>
<td>Rain/snow Threshold, R/S</td>
<td>°C</td>
<td>0-0.9</td>
<td>The temperature below which precipitation will fall as snow</td>
</tr>
<tr>
<td>Degree Day Factor, DDF</td>
<td>mm.day⁻¹.°C⁻¹</td>
<td>1-5</td>
<td>The depth of snowmelt generated per day per unit increase in air temperature</td>
</tr>
<tr>
<td>Direct Recharge, R Directorate</td>
<td>%</td>
<td>0-25</td>
<td>The percentage of total rainfall in any timestep that bypasses soil storage and becomes recharge, regardless of the SMD</td>
</tr>
<tr>
<td>Starting SMD, SMD₀</td>
<td>mm</td>
<td>0-1000</td>
<td>The soil moisture deficit at the beginning of the model run.</td>
</tr>
</tbody>
</table>
For such a model to apply, several important assumptions about these parameters were required:

1. The rainfall total as well as 15-minute totals (mm) recorded at the Franz Josef Township, approximately 2km east of the Tatare Tunnel were assumed to apply across the catchment of the tunnel. This is distinct from the SMBM above in which a precipitation adjustment factor of 1.25 % was applied.

2. Rainfall recorded at 15 minute resolution was assumed to be evenly distributed throughout each binning interval, allowing for the duration of rainfall to be calculated for each storm event.

3. Discharge from the Tatare Tunnel, as defined in section 7.2, was assumed to be derived solely from infiltration during and after the corresponding rainfall event (see Figure 7.4).

4. Catchment area could be calculated from topographic boundaries and didn’t change between storm events.

The equation used to calculate the infiltration proportion was (as derived by the author):

$$I_P = \frac{Q_E}{V_R}$$

Where $I_P$ is the proportion of rainfall that infiltrates the rock mass to reach the Tatare Tunnel, $Q_E$ is the excess discharge of the tunnel during the DE in m$^3$; and $V_R$ is the total volume of rainfall for the designated catchment area, also in m$^3$. $Q_E$ was calculated using the equation:

$$Q_E = \sum_{t=1}^{t=n} Q_t - Q_{bt}$$

Where $Q_t$ is the tunnel discharge at time $t$ in m$^3$, $Q_{bt}$ is the baseflow discharge during the DE at time $t$, in m$^3$.
$V_R$ was calculated by:

$$V_R = A \times R_d$$

Where $A$ is catchment area (m$^2$) and $R_d$ is rainfall (m).

By varying catchment area and rainfall volume, the proportion of rainfall that infiltrated the rock mass, and the mean infiltration rate could be calculated for each Discharge Event.

### 7.5 Chemical Analyses

One common method used to estimate fluid residence time and flow paths involves chemical analyses of tunnel waters (Marechal and Etcheverry, 2003; Pastorelli, 2001; Shimojima et al., 1993; Shimojima et al., 2000).

As fluid passes through a rock, some minerals are dissolved more readily than others. Consequently fluid inherits a chemical signature that is determined by the rock mass it passes through. The exact chemical composition of this signature can be related to contact time between the fluid and the rock, and the type of rock the fluid came into contact with. The aims of chemical measurements made at the Tatare Tunnel field site were:

1. To characterize and describe the chemical signature acquired by rainwater as it passes through the schist rock mass surrounding the Tatare Tunnel;

2. To use solute chemistry to partition tunnel waters among the different flow paths;

3. To assess whether or not the chemical signature of tunnel waters changes as a storm progresses;

4. To determine whether or not dissolution and dilution processes dominate the chemical signature of waters that pass through the rock mass.

#### 7.5.1 Diffusion, Advection and Dilution

The chemical concentrations of groundwater taken from the Tatare Tunnel (section 6.2) are primarily the results of two processes; diffusion and advection. These two concepts
were used to interpret the chemistry of groundwater samples collected from the Tatare Tunnel and are outlined below.

7.5.2 Diffusion

Put simply diffusion is the movement of mass from an area of high concentration to one of low concentration. Diffusion occurs along gradients both within and between the three states of matter; solid, liquid and gas. Of primary interest here is the diffusion of mass from the schist rock mass surrounding the Tatare Tunnel to solution (the fluid that flows through fractures surrounding the tunnel), a process termed rock dissolution. The concentration of different ions in solution is controlled by the rate at which they are liberated from the rock to solution, and is also known as the dissolution rate. The rate at which dissolution occurs is controlled by (a) the concentration gradient between the two, and, (b) the rate at which an ionic species is liberated from the rock. The latter is lithology specific. The rainwater that infiltrates the rock mass surrounding the tunnel has comparatively low concentrations of almost all major ions present in the rock mass. It follows that ions diffuse out of the rock mass and into the infiltrating water. The process of diffusion and its relevance to flow through fractured mediums is illustrated in Figure 7.6. As the fluid within a fracture approaches saturation, the rate of diffusion decreases. Dissolution determines the rate at which ions are supplied to solution. However, unless the fluid is stored within the fracture network, the process of advection continuously replenishes saturated fluid with fresh rainwater.
Figure 7.6: The processes of diffusion and advection in fracture flow, where compound B is more soluble than compound A. Adapted from Sharifi Haddad (2012).

7.5.3 Advection

Advection is mass transport in the flow of water and is the main process that moves dissolved ions from one point to another (Schwartz and Zhang, 2003). As the volume and velocity of groundwater moving through a fracture increase, so too does the rate of advection. An increased rate of advection has the effect of diluting groundwater in two ways; (1) Increases in fluid velocity reduces the contact time between fluid and rock, limiting molecular diffusion between the rock mass and groundwater, (2) increased volumes of water increase the fluid: rock ratio. Rates of dissolution are controlled by size of the chemical gradient between rock and solution, temperature and surface area of rock that supplies compounds. Rates of advection are controlled by the volume and velocity of groundwater in the rock mass, i.e. by permeability and rock mass saturation. The affect of enhanced advection has on the chemical signature of groundwater is displayed schematically in Figure 7.7A.

Dissolution and dilution processes compete to control the chemical signature of groundwater that enters the Tatare Tunnel. When dissolution processes dominate, chemical concentration increases with time. In instances where advection/dilution processes dominate, chemical concentration decreases with time. During storm events,
when the volume of groundwater in a rock mass changes, a shift from dissolution-dominated signatures to dilution-dominated signatures may be observed. This ‘flushing’ behaviour, illustrated schematically in Figure 7.7B, has been observed to occur on a wide range of scales (Craw, 2000a; Davies et al., 2011).

![Diagram](image)

Figure 7.7: (A) the effect of an increase in fluid velocity, synonymous with a decrease in fluid-rock contact time, on the concentration-time relationship observed where groundwater is sampled, (B) a typical ‘flushing’ curve, as rock mass saturation and fluid velocity increase the chemical signature of groundwater shifts from dissolution dominated processes to dilution dominated processes.

A naming scheme was adopted to simplify the description of concentration patterns observed in groundwater samples taken from the Tatare Tunnel section 6.2. Figure 7.8 shows the four patterns identified and the symbols used to denote them.
Figure 7.8: The terms used to describe changes in chemical concentration with time for samples taken during storm 4 in May 2012. Four categories were identified: increase, decrease, spike/drop and drop/increase.

7.6 Isotope Analyses

Section 6.2 described the sampling scheme used to collect isotope samples at the Tatare Tunnel field site. This section outlines how the samples were analysed and interpreted.

The stable isotopes of oxygen ($^{18}$O and $^{16}$O) and hydrogen ($^2$H and $^1$H) allow determination of the source of groundwater (Sharp, 2007). The heavier of the two hydrogen isotopes, $^2$H, is commonly referred to as D, and this terminology will be used here. The ratio of the abundance of heavy to light isotopes is generally expressed relative to the ratio in a common standard. This internationally recognised standard is known as Vienna Standard Mean Ocean Water (VSMOW) and is the reference used for all samples in this study.

Evaporation of isotopically light molecules ($^{16}$O and $^1$H) and preferential condensation of isotopically heavy molecules ($^{18}$O and D) results in distinct differences between water in the solid and liquid phases (Sharp, 2007). Snow and ice are relatively enriched in ‘light’ isotopes compared to liquid water, while ice, snow and liquid water are all enriched in light isotopes compared to VSMOW.
Oxygen and hydrogen Isotope ratios are usually related to VSMOW and represented by a delta value (δ). Delta values have units of parts per thousand (per mil) and take the symbol ‰. Delta values are calculated by:

$$\delta = \left( \frac{R_x - R_{std}}{R_{std}} \right) \times 1000$$

Where $R$ is the ratio of heavy to light isotopes, $x$ denotes the sampled waters and std is an abbreviation for standard (in this case VSMOW). Negative δ values indicate ratios that are smaller than the standard, while positive values indicate ratios that are higher.

Ratios of $^{18}$O/$^{16}$O and D/ $^{1}$H were determined using a Picarro 2120 wavelength-scanned cavity ring-down spectrometer, in the Department of Chemistry, University of Otago. For each sample, eight aliquots were analysed and the raw results were filtered by removal of values more than 1 standard deviation from the average. The average was corrected to the international VSMOW-SLAP isotope scale using a three point calibration provided by three laboratory standards measured before and after every batch of 80 samples. Standards adopted by the University of Otago Chemistry Department Laboratory are ice, tap water from Dunedin and sea water. The δ values of the laboratory standards are listed in Table 3.
Table 3 Delta (δ) values for both $^{18}\text{O}$ and $^2\text{H}$ for the three laboratory standards used to calibrate samples from the Tatare field site.

<table>
<thead>
<tr>
<th></th>
<th>“ICE”</th>
<th>“TAP”</th>
<th>“SEA”</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta^{18}\text{O}_{\text{VSMOW}}$, ‰</td>
<td>-32.20 ± 0.09</td>
<td>-258.1 ± 0.5</td>
<td>-12.00 ± 0.09</td>
</tr>
<tr>
<td>$\delta^2\text{H}_{\text{VSMOW}}$, ‰</td>
<td>-79.92 ± 0.7</td>
<td>-0.27 ± 0.09</td>
<td>-1.94 ± 0.7</td>
</tr>
</tbody>
</table>
Chapter 8: Flow Results

This chapter is in seven sections, each corresponding to a particular aspect of shallow groundwater circulation. It begins by describing the depth and velocity of water as it exits the tunnel. Although this raw data is ultimately transformed to tunnel discharge, on which all other analyses were based, an assessment of the raw data provides quality control and allows suspect measurements to be identified before any importance is assigned to them.

The second section compares patterns of rainfall measured at Franz Josef with flow from the Tatare Tunnel during Discharge Events. Instances when tunnel discharge increased in the absence of significant rainfall were identified as Anomalous Discharge Events (ADE). While such instances were rare during the study period, they provide examples of behaviour that may otherwise be masked by large Discharge Events (DE) but form an important component of annual discharge. The time interval between the onset of rainfall and the onset of tunnel discharge as well as the time interval between peak rainfall and peak tunnel discharge are presented. These time intervals ($T_1$ and $T_2$, respectively) are then compared with other metrics, such as mean rainfall intensity and total rainfall.

Section 8.3 presents the results of recession analyses performed on the receding limb of the discharge hydrograph for identified Discharge Events. Individual DE recession curves are then examined in more detail.

Section 8.4 compares cumulative tunnel discharge— the total discharge of the tunnel assumed to be driven by rainfall— with two rainfall metrics from the corresponding event; mean rainfall intensity and total rainfall.

Chapter 9: presents the results of two models applied to the data: recharge predicted using a soil moisture balance model (SMBM), and infiltration rates and proportions predicted from a second model. The SMBM was used in an attempt to distinguish between rainfall and infiltration, an important distinction that has consequences for relationships identified in previous sections. The second infiltration model was used to identify patterns among Discharge Events.

8.1 Tunnel Discharge

Before the search for patterns of rainfall and discharge in the Tatare Tunnel could proceed, trends in the raw data that was used to calculate discharge had to be identified. The raw data
consists of two measurement sets: the velocity of the water flowing through the outlet pipe, and the pressure head exerted on the ‘Starflow’ instrument by the water in the outlet pipe (water depth). This section outlines measurements of water depth and velocity at the tunnel outlet. It then presents calculated tunnel discharge values for the entire measurement period.

Figure 8.1 shows depth and velocity values recorded by the ‘Starflow’ instrument from April 2012 to January 2013. Three trends can be identified in the data, based upon the extent to which depth and velocity are co-dependent. The April to June period is characterized by a decline in water depth, and has a range of 25mm. By contrast, the period from July to November has a range of 105mm and shows an increase in water depth. Finally, water depth declines again between November and January. Depth approached 20mm, the lower detection limit of the ‘Starflow’ instrument, several times between April and June. Depth readings in this region were expected to be less reliable, so discharge was not calculated for this timeframe. The range of velocity values is high throughout the entire study: 639 mm s\(^{-1}\) and 869 mm s\(^{-1}\) for periods April to June and July to January, respectively. The correlation between change in velocity per unit time and change in depth per unit time, termed the depth-velocity correlation, was consistently low (\(r= 0.057\) from April to June and \(r= 0.31\) from June to January). The two data sets are highly variable and the low values for the depth-velocity correlation are likely an artefact of this.

### 1.2 Rainfall

The average air temperature of Franz Josef was 11 °C in 2012, with 3110 mm of rainfall recorded over the measurement period (Tait et al., 2012). Figure 8.2 also shows that the spring and summer months have greater rainfall and tunnel discharge than the drier autumn and winter months, with the Franz Josef region experiencing a flood event with a return period of 10 years in January 2013 (Tait et al., 2012). The winter months of 2012 were unusually dry in Westland and soil moisture was correspondingly low, yet Franz Josef received its largest snowfall in 18 years (Mills, 2012).
Figure 8.1 Water depth at the tunnel outflow, and water velocity at the tunnel outflow, both logged at 15-minute resolution from April 2012 to January 2013. Three trends in water depth can be identified: general recession, a stepped recovery and another general recession. Water depth and velocity do not appear to be co-dependent during the first general recession, but do appear to be co-dependent during the stepped recover and second general recession.
Figure 8.2 Discharge of the Tatare Tunnel April 2012 to January 2013, plotted against rainfall received at Franz Josef for the same period. Data gaps are indicated where depth of flow dropped below the instruments minimum operating depth of 20 mm, hence unreliable results. A red box surrounds anomalous discharge events one and two, when tunnel discharge increased but no corresponding rainfall was observed. Boxed portions are illustrated in Figure 8.4 and discharge events are identified in Figure 8.3.
Figure 8.3: Tatare Tunnel discharge from April 2012 to January 2013; numbers indicate recognised Discharge Events (DE.) identified in the text.
8.2 Patterns of Rainfall and Discharge

Patterns of rainfall and discharge were compared in order to assess any relationships between the two. Relating rainfall to discharge allows inferences about the rock mass surrounding the tunnel to be made. This section compares rainfall metrics with fluid transmission time tunnel discharge. The section begins by outlining the two Anomalous Discharge Events observed and then moves on to transmission, finally it compares the transmission times to mean rainfall intensity.

For the measurement period April 2012 to January 2013, discharge from the Tatare Tunnel ranged between 0.091 l s$^{-1}$ to 40.0 l s$^{-1}$. April to August were characterized by episodic increases in tunnel discharge, after which discharge returned to baseflow levels. September to November was characterized by an overall increase in tunnel discharge and superposition of multiple discharge events. The month of December was characterized by low flows and came prior to the largest Discharge Event (in terms of both rainfall and peak tunnel discharge) in January 2013 (Figure 8.2).

While tunnel discharge responded to almost all identified rainfall events, the magnitude and style of response (shape of the discharge hydrograph) were not consistent across the period (Figure 8.2). The September-December period was characterized by discharge events in rapid succession, with a broad increase in tunnel discharge across the entire period. Tunnel discharge returned to levels approaching 0 l s$^{-1}$ at the end of November 2012, only to rise rapidly to its highest recorded value of 40 l s$^{-1}$ in January 2013 (Figure 8.2). Tunnel discharge responded rapidly to rainfall events, and the rising limb of the discharge hydrograph was often nearly vertical. An exceptions to this was Anomalous Discharge Event 2 (ADE 2) in which the rising limb was notably shallower compared to other events (Figure 8.2). A similar situation, albeit of shorter duration and less magnitude, was observed in early April 2012, and is labelled ADE 1 in Figure 8.2. Such anomalies were exceptions to the patterns observed for almost all other Discharge Events. Such unusual discharge behaviour may be indicative of multiple sources of water contributing to the discharge of the Tatare Tunnel.

8.2.1 Anomalous Discharge behaviour

Figure 8.4 shows these anomalous events in more detail. In both instances there was significant rainfall before and after the time of increased tunnel discharge, but little rain
fell during the period of maximum discharge. A phase of rapid fluctuation in discharge occurred in ADE 2. Raw data for this period shows that the signal was the result of rapid depth fluctuations, while the corresponding change in velocity was negligible. The cause of these rapid fluctuations is not immediately obvious. The fluctuations initially occurred once every four hours before changing to every 11 hours, 20 hours later, increasing from 45 to 70 mm in depth each time. Possible reasons for these rapid changes in depth include changes in battery output due to low temperatures or water damming in the outlet pipe behind ice or debris from the forest floor. Inspection of the battery and condition of the outlet channel shortly after Anomalous Discharge Event 2 suggested that these mechanisms are unlikely to be responsible for the depth fluctuations observed. In the absence of any other simple explanation, temporary equipment failure seems possible. The period of rapid depth fluctuation and stable velocity was not observed at any other time during the study period. Furthermore, increases in depth and velocity during normal discharge events were well beyond the range of average fluctuation and likely represent varying water inputs to the tunnel.

8.2.2 Peak-to-Peak Time Intervals

Three time differences were defined for the Discharge Events: T₁, T₂ and T₃. The first interval is between the onset of rainfall and the upward inflection of the discharge hydrograph. T₂ is the interval between peak rainfall and peak tunnel discharge, and T₃ is the interval between a second peak in rainfall and a second peak in tunnel discharge.

Time differences between the onset of rainfall and the upward inflection of the discharge hydrograph were variable between Discharge Events and included several negative values—when an increase in discharge occurred before rain began (DE 1, 4 and 9). Rather than being a proxy for the transmission time of water from the surface to the tunnel, negative T₁ and T₂ values indicate a mismatch between measured rainfall at Franz Josef and the timing of rainfall above the tunnel. It was not possible to quantify time intervals on any numerical basis, as discharge event hydrographs are unique, so they were assigned subjectively. Determination of T₁ was the least subjective of the three as onset of rainfall and increases in discharge were easily tracked.

Time differences between peak rainfall and peak discharge (T₂) exhibited greater ranges than T₁ values (T₂ range 37.75 hours) and in several instances, peak discharge occurred
before peak rainfall. At least part of the variability in $T_2$ values can be attributed to the
difficulty in identifying peak rainfall. While there can be less confidence in $T_2$ values, peak
rainfall could be identified for all Discharge Events. $T_1$ and $T_2$ are associated and show a
correlation coefficient of $r=0.59$, indicating a weak positive relationship. Discharge Events
with greater $T_1$ values tended to have larger $T_2$ values.

The identification of a second peak-to-peak time interval ($T_3$) was less common than the
calculated $T_2$ values because not all Discharge Events had multiple rainfall and discharge
peaks. For Discharge Events with multiple rainfall-discharge peaks, the correlation
coefficient for $T_2$ against $T_3$ was $r=0.68$. This indicates that the timing of rainfall and
discharge was similar for peaks one and two. Larger values for $T_1$ and $T_2$ were associated
with a larger range in $T_3$ values, which had a range of 47.75 hours. In several Discharge
Events the second peak in discharge occurred before the second peak in rainfall.
Figure 8.4: Two anomalous discharge events (A) ADE 1 in April 2012 and (B) ADE 2 in July 2012 respectively. 0 and 0.1 mm of rain was recorded during Discharge Anomaly one and two, respectively. The rapid discharge fluctuations attributed to rapid changes in depth are indicated for the July anomaly and have a near constant period 6 hours.
Figure 8.5: Time intervals, $T_1$ and $T_2$, for all 21 Discharge Events. DEs in April to August show markedly lower values (including several instances when discharge peaked before rainfall) than those in September to January.

Figure 8.5 illustrates the marked differences in $T_1$ and $T_2$ values between April and January. April to August shows much lower values of $T_1$ and $T_2$, including many negative values. Median $T_1$ values were 7.5 and 20.9 hours for the April to August and September to January periods, respectively, while $T_2$ values were 9.5 and 19.6 hours for April to August and September to January periods, respectively. $T_2$ values were generally larger than the corresponding $T_1$ values for all months, and September to January had $T_2$ values that are notably larger than the others (DE 10 and 17).

8.2.3 Mean Rainfall Intensity and Peak Timing

Rainfall intensity in mm hr$^{-1}$ was calculated at 15-minute intervals. Time intervals $T_1$, $T_2$ and $T_3$ are surrogates for the transmission time of a fluid (or a fluid pressure wave) from
the surface to the tunnel below. A degree of consistency between the three measurements might be expected. The travel time of fluid pressure waves decreases with increasing rock mass saturation, meaning $T_1 > T_2 > T_3$ would be the expected progression (Kresic, 2007; Kresic and Bonacci, 2010).

The difference in $T_1$ and $T_2$ values evident in Figure 8.5 suggests that the time taken for the rainfall signal to reach the tunnel is different between the April to August and September to January periods, the April to August transmission times being markedly lower than those in September to January (Figure 8.5). Due to the observed differences in transmission time, the relationship between the amplitude of rainfall signal (mean rainfall intensity) and transmission time was analysed for the April to August and September to January periods separately (Figure 8.6). They do not include the two Anomalous Discharge Events (ADE 1 and 2). With the exception of DE 1, the $T_1$ and $T_2$ values show a positive correlation with mean rainfall intensity in the months of April to August. However, in the September to January months, no relationship is apparent. While September to January $T_1$ and $T_2$ values are more variable than those for April to August, the spread of values decreases as mean rainfall intensity increases (Figure 8.6). From April to August, an increase in the amplitude of the rainfall signal correlated with a decrease in the fluid transmission time. In the September to January months an increase in the amplitude of the rainfall leads to a decrease in the variance of the $T_2$ transmission time. These patterns mirror the differences between the months of April to August and September to January seen in Figure 8.5.

The amplitude of the rainfall signal was then compared to the amplitude of the recharge signal (peak tunnel discharge). Figure 8.7 shows mean rainfall intensity vs. peak tunnel discharge for the April to August and September to January periods, respectively. With the exception of DE 6, the April to August months show an inverse relationship between mean rainfall intensity and peak tunnel discharge. With the possible exception of DE 9, the opposite is true in the months of September to January, where an increase in mean rainfall intensity correlates with an increase in peak tunnel discharge.

These results mean that the more intense the rainfall, the lower the tunnel discharge during the months of April to August. This counter-intuitive result is discussed in Chapter 12.
Figure 8.6: April – August mean Rainfall intensity vs. $T_1$ (A) and $T_2$ (B) time intervals and September – January mean rainfall intensity vs. $T_1$ (C) and $T_2$ (D) time intervals. Numbers refer to discharge events.
Figure 8.7: Mean rainfall intensity vs. peak tunnel discharge for (Top) April – August and (Bottom) September – January. Numbers refer to discharge events.
8.3 Recession Analysis

The purpose of the recession analyses was to quantify the rate that water drained from the rock mass surrounding the tunnel. Spatial variations in the permeability of the rock mass surrounding the tunnel lead to changes in the slope recession curves of the tunnel discharge hydrograph. Similarities or differences in the recession curves of different Discharge Events shed light on changes in the portion of the rock mass drained during each event. Consistent decay coefficients suggest that the rock structure is the primary control on the discharge signal and changing coefficients suggest structure is not the only control on fluid movement in the rock.

As outlined in section 7.3.1, exponential decay models were fitted to recession curves, to quantify change in discharge over time. Table 4 summarises the exponential model fit to each of these curves, the associated $R^2$ value, and the model coefficients. Many discharge events (DE) either did not show decaying discharge, or the fit for an exponential model was too poor to warrant inclusion (i.e. $R^2 < ~0.5$). With the exception of curve 18 (with $R^2 = 0.67$); $R^2$ values were generally large, indicating that exponential models were generally a good fit to the data (discharge events are numbered in Figure 8.3). Overall, the fitted exponential models showed a wide range of decay coefficients and an even greater range of Y-intercepts. The latter, which are influenced by, but not equal to, maximum discharge, were plotted against the relevant decay coefficients to assess whether the rate of discharge decay is a function of maximum discharge.

Figure 8.8 shows the range of Y-intercepts and decay coefficients for selected Discharge Events. Figure 8.8(B) shows an outlying group of DE curves characterized by low discharge and high decay coefficients. The DEs in the outlying group all occurred between April and August 2012 and the inflections in their discharge hydrographs occur at low values of discharges. Also shown is the inferred trend of Y-intercept vs. decay coefficients, when discharge events between April and August are excluded. Recession analysis assumes saturated flow conditions, an assumption that may be violated in the months of April to August 2012. Therefore, the greater decay coefficients for discharge events between April and August may represent un-saturated flow conditions, and not the permeability of the rock mass.
When these recession curves are excluded, increasing Y-intercepts are positively correlated with increasing decay coefficients. Y-intercepts are a reasonable proxy for peak discharge, so DEs that have greater peak discharge, tend to show decay more quickly.

Figure 8.8: (Top) The Y-intercept vs. the decay coefficient for all DE’s that had exponential models fit to them. (Bottom) The same as the top with an outlier group (circled) and possible trend identified.
Table 4: Exponential decay models fitted to recession curves with the actual exponential model, associated $R^2$ values, decay coefficients ($\alpha$) and the Y intercept of each model ($Q_0$).

<table>
<thead>
<tr>
<th>Recession Curve</th>
<th>Exponential Decay Model</th>
<th>Exponential Decay $R^2$</th>
<th>$\alpha$ Coefficient</th>
<th>$Q_0$ (Model Intercept)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>$Q = e^{-0.0115t} \times 2.9622$</td>
<td>0.93</td>
<td>-0.0115</td>
<td>2.96</td>
</tr>
<tr>
<td>6</td>
<td>$Q = e^{-0.0098t} \times 4.9024$</td>
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<td>-0.0098</td>
<td>4.90</td>
</tr>
<tr>
<td>9</td>
<td>$Q = e^{-0.0072t} \times 6.5715$</td>
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<td>-0.0072</td>
<td>6.57</td>
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<tr>
<td>10</td>
<td>$Q = e^{-0.0029t} \times 6.5849$</td>
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<td>-0.0029</td>
<td>6.58</td>
</tr>
<tr>
<td>12</td>
<td>$Q = e^{-0.0077t} \times 20.0962$</td>
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<td>-0.0077</td>
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<tr>
<td>13</td>
<td>$Q = e^{-0.0046t} \times 13.5804$</td>
<td>0.87</td>
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<tr>
<td>14</td>
<td>$Q = e^{-0.0045t} \times 13.2851$</td>
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<tr>
<td>15</td>
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<td>-0.0035</td>
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<tr>
<td>16</td>
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<tr>
<td>18</td>
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<tr>
<td>20</td>
<td>$Q = e^{-0.0131t} \times 24.2058$</td>
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<td>-0.0131</td>
<td>24.21</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>0.93</td>
<td>-0.0046</td>
<td>9.08</td>
</tr>
</tbody>
</table>
8.4 Rainfall-Driven Tunnel Discharge

This section outlines how rainfall-induced tunnel discharge was calculated and partitioned among Discharge Events. Four values for discharge were used to compute cumulative tunnel discharge, they were:

- No Flow, i.e. 0 l s\(^{-1}\), or ‘total flow’;
- Where Discharge Events occurred in rapid succession, discharge at the beginning of the sequence was used to calculate cumulative tunnel discharge. This reference was termed the ‘pre-sequence discharge’;
- The discharge at the start of an event was used as a conservative estimation of rainfall induced tunnel discharge. It was termed the ‘pre-discharge event level’;
- Where an exponential decay model could be fitted to the recession curves of Discharge Events, discharge predicted by the model was used as the reference for the following storm. This was termed the ‘previous discharge event exponential decay’ level. It was the only reference value that varied with time.

The next analysis was of relationships between cumulative discharge and other storm parameters: namely, mean rainfall intensity, total rainfall, and rainfall-discharge time intervals (T\(_1\), T\(_2\) and T\(_3\)). The purpose of comparing cumulative tunnel discharge to these parameters is to relate infiltration to inputs (rainfall receipts) and rock mass characteristics. The rainfall-discharge time intervals represent the time taken for fluid to infiltrate the surface and travel to the tunnel.

Section 7.2 outlines how cumulative discharge was calculated for each of the reference levels. Table 5 shows calculated cumulative discharge (discharge assumed to be induced by a rainfall event) for each of the four defined reference levels. These cumulative discharge values, calculated using the ‘total flow’ reference level, were the largest because all discharge at the time was attributed to the rainstorm occurring during that event. This assumption excluded the possibility that rainfall some time ago was influencing the current tunnel discharge. In cases where a DE event lies at the beginning of a discharge sequence, pre-sequence discharge and the pre-DE discharge are identical. Relative to one-another, values of cumulative discharge would be Total Flow > Pre-Sequence > Previous storm exponential decay > Pre-storm. The calculated cumulative discharge alone, regardless of the reference level, is of limited use. Such
calculations are most valuable when Discharge Events are compared to one-another and to other parameters. These comparisons are outlined in below.

8.4.1 Cumulative Discharge and Relevant Storm Parameters

By comparing cumulative tunnel discharge calculated with rainfall intensity metrics, potential controls on the volume of fluid moving through the surrounding rock mass could be identified. Parameters that have little or no direct influence on tunnel discharge will show little or no correlation with discharge. Mean rainfall intensity (the rate of fluid input to the system), total rainfall (the magnitude of the system input) and the time intervals defined in section 8.2.2 (a proxy for the transfer time between the surface and tunnel at the unknown depth) were plotted against cumulative tunnel discharge. Selection of an appropriate reference discharge is difficult given flow data alone. Therefore, the four reference discharges are compared here so patterns among DEs can be more accurately attributed to differences in flow process.
Table 5 Storm induced tunnel discharge (cumulative discharge) using four reference levels: pre-sequence inflection, pre-storm inflection, previous storm exponential decay and total flow. Storms in which the previous storm was not decaying upon discharge inflection (and hence not exponential decay curve was fit) are marked NC (Not Calculated). DEs 1 to 19 occurred in 2012 and DEs 20 to 21 in 2013.

<table>
<thead>
<tr>
<th>Event</th>
<th>Discharge Date</th>
<th>Pre-Sequence Inflection (m$^3$)</th>
<th>Pre-DE Inflection (m$^3$)</th>
<th>Previous DE Exponential decay (m$^3$)</th>
<th>Total Flow (m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7/4 – 14/4</td>
<td>582</td>
<td>582</td>
<td>NC</td>
<td>1435</td>
</tr>
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8.4.1.1 Total Rainfall

Figure 8.9 and Figure 8.10 show cumulative tunnel discharge when using 0.1 s\(^{-1}\) and the pre-sequence level as the reference discharge, respectively. These two reference levels attribute the majority of flow in the tunnel to the current rainstorm, partitioned flow in a simplistic manner and the events occurred in quick succession. Discharge Events (DE) with notably higher cumulative discharge (compared with total rainfall) occurred in the months from September 2012 to January 2013. Discharge greater than the pre-DE level is the most conservative partitioning of tunnel discharge and is likely to underestimate actual tunnel discharge initiated by rainfall events, especially when they occur in quick succession. Figure 8.11 shows a weakly positive relationship between total rainfall and cumulative discharge above the pre-DE level, suggesting that as total rainfall increases, so too does tunnel discharge for a given DE. Interestingly, the group of DEs that have a higher than expected calculated discharge all occurred in the months of September to January (Figure 8.11).

Finally, Figure 8.12 shows the calculated cumulative discharge when using ‘exponential decay of the previous DE’ as a reference discharge. This data set is smaller because a limited number of DEs could have exponential decay models fitted to their recession curves. All DEs displayed in Figure 8.12 occur in the months of September to January. The reference discharge used is not the most conservative of all reference discharges, but is physically the most likely. Dashed lines were drawn to indicate the envelope of calculated discharges and to emphasize a generally positive trend in the data. From September to January, an increase in total rainfall will lead to an increase in tunnel discharge. In all plots, DE 20 has the greater total rainfall and calculated tunnel discharge.
Figure 8.9: Total rainfall vs. cumulative tunnel discharge, using 0 as the reference discharge. Storm 20 has notably higher rainfall and cumulative discharge and the indicated group are all spring storms, their large discharges are a result of the reference discharge.

Figure 8.10: Total rainfall vs. calculated discharge using the ‘pre-DE sequence level’ as the reference discharge. Two groups have been identified, the lower group of DE’s occurred throughout the entire study period, while a second group of DE’s that show higher cumulative tunnel discharge for a given total rainfall occurred only in the months between September and January. Numbers refer to Discharge events (Figure 8.3).
Figure 8.11: Total rainfall vs. calculated discharge using the ‘pre-DE level’ as the reference discharge. A group of DEs with notably higher calculated discharges (given their respective rainfall totals) have been circled and occur between September and January. A slight positive correlation between total rainfall and cumulative tunnel discharge can also be seen. Numbers refer to Discharge Events (Figure 8.3).

Figure 8.12: Total rainfall vs. cumulative discharge using the ‘previous DE exponential decay’ as a reference level. The smaller data set is due to the fact that only certain DEs were able to have a decay curve assigned to them. Dashed lines show the envelope of values. Numbers refer to DEs and, again, DE 20 shows a notably higher total rainfall and calculated discharge.
These relationships between total rainfall and calculated tunnel discharge (based on the four reference discharges) point to three features:

1. When a conservative reference discharge is used, DEs between September and January showed strong correlation between tunnel discharge and total rainfall;

2. All DEs with a high calculated discharge, given their respective rainfall totals, were between September and January;

3. DE 20 had a markedly higher value of cumulative tunnel discharge than all other events.
Chapter 9: Modelling Results

The purpose of the modelling was threefold; (1) To provide broad estimates of the proportion of rain and snowmelt that infiltrates the rock mass, (2) to identify common patterns among Discharge Events analysed, and finally (3) to identify DEs that do not conform to the patterns observed in (2).

The preliminary modelling outlined in this section takes two forms. First, a soil moisture balance model (SMBM) was used to estimate groundwater recharge for given values of rainfall receipt, potential evaporation, temperature and other user-defined variables. Model structure and selected parameter values are outlined in section 7.4.1. Secondly, a basic infiltration model was used to calculate time-dependent infiltration rate and space-dependent proportion of rainfall infiltrated for comparison between Discharge Events.

1.3 Recharge Predicted From the SMBM

Sensitivity analysis was carried out on three key parameters of the SMBM: the root constant, the runoff coefficient, and the direct recharge parameter. This analysis determined which parameters exerted greatest control on calculated recharge. The root constant (C, or soil water storage in the model), the runoff coefficient (RC), and direct recharge \( R_{direct} \) were changed by fixed proportions while other model parameters were held constant, and the effect on calculated recharge was noted.

Total recharge— the total volume of precipitation the SMBM predicted would enter the rock mass, including both rain and snow— was most sensitive to changes in the direct recharge parameter. Direct recharge is rainfall that becomes recharge regardless of prevailing soil moisture conditions (Table 6).

Sensitivity analysis (Table 6) showed a 12-fold increase in total recharge for a unit increase in direct recharge. Total recharge was also sensitive to values of the runoff coefficient and the root constant. Total recharge calculated using the SMBM is especially sensitive to surface runoff and direct recharge, both of which increase during high-intensity rainfall events. Although the two processes offset each other, tunnel discharge significantly increased during intense rainstorms, indicating that direct recharge is the a more important determinant of total recharge.
Figure 9.1 (A) shows rainfall measured at Franz Josef between April 2012 and January 2013. This is input to the SMBM. Figure 9.1 (B) shows direct recharge and snowfall predicted by the SMBM. Whether or not snowfall melts and infiltrates the rock to become recharge is determined by temperature. Until air temperature rises, snowfall will remain on the surface. The model predicts a single snowfall event of ~1.8 mm in Late June 2012, this period corresponds with the time when snow fell to sea level in the Franz Josef area. Although the model under-predicts the total magnitude of snowfall, it does predict its timing with some accuracy. Figure 9.1 (C) is the total recharge predicted by the SMBM and is the sum of direct recharge, snowmelt infiltration and recharge initiated when soil storage is exceeded.

The effect of direct recharge (and therefore of high-intensity rainfall) can be seen in periods without discernable direct recharge, or when little or no total recharge is predicted by the model. The model shows very little recharge in early December, despite the rainfall total. Such a result is likely due to enhanced evaporation during the early summer months. While rainfall in any 15-minute time step was as much as 8mm, total recharge in any 15-minute time step never exceeded 1 mm.
Table 6: Sensitivity of calculated recharge to the root constant (C), runoff coefficient (RC) and direct recharge (R_{Direct}) for the SMBM applied to the Tatare catchment.

<table>
<thead>
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<th>Model Parameter</th>
<th>Sensitivity (unit change in recharge per unit change in parameter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
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</tr>
<tr>
<td>RC</td>
<td>-10</td>
</tr>
<tr>
<td>R_{Direct}</td>
<td>12</td>
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Figure 8.2 shows a high correlation between rainfall events and tunnel discharge, but the SMBM fails to adequately simulate the frequency of recharge suggested by the tunnel discharge records. This is a critical limitation of the model. Without independent measurements of runoff, evaluation of recharge predicted by the SMBM is limited to comparison with tunnel discharge.
Figure 9.1: (A) Rainfall at Franz Josef, used as the input to the SMBM, (B) predicted direct recharge (in light blue) and snowfall (indicated by arrow) from the SMBM and, (C) total recharge predicted using the SMBM, incorporating normal recharge, direct recharge and snowmelt. All data is from April 2012 to January 2013. Recharge predictions were made using the parameter values outlined in Table 2.
1.4 Infiltration Modelling

Figure 9.2(A) and (B) show the calculated infiltration rate and proportion of rainfall infiltrated when cumulative tunnel discharge was calculated using a reference level of 0 l s\(^{-1}\) and ‘pre-DE sequence level’ respectively. The calculated infiltration rate and the proportion of total rainfall that entered the groundwater system are influenced by assumptions about catchment area. Catchment area is unknown and so is the absolute value of each parameter. However the purpose was to evaluate patterns of infiltration rate and to calculate the proportion of rainfall that infiltrates the rock mass between discharge events, given certain assumptions. Figure 9.2 shows that as calculated infiltration rate increased so does the proportion of rainfall infiltrated. As total rainfall increased, the intensity of infiltration that would be needed to induce the tunnel discharge (given the duration of the DE) also increased. A similar pattern is seen in Figure 9.3, for the reference discharges defined in section 8.4.

Figure 9.2 and Figure 9.3 illustrate the increasing in the proportion of rainfall infiltrated for discharge events with greater predicted infiltration rates. Variation in the volume and duration of rainfall for different DEs meant that four values of cumulative discharge were calculated for each DE. Therefore, four possible values of the predicted infiltration rate and proportion were possible for each Discharge Event. For reference discharges that result in greatest calculated tunnel discharge (‘total flow’ and the ‘pre-DE sequence level’), DE 15 appears anomalously high. For the more conservative reference discharges of ‘pre-DE level’, DE 18 also appears to be anomalously high (Figure 9.3). Regardless of how cumulative tunnel discharge was calculated, DEs with higher calculated proportions of rainfall infiltrated and higher infiltration rates all occur in the months of September to January. It is possible that a greater amount does infiltrate into the rock mass, and at a faster rate, during these months. The larger calculated proportions and rates resulted from the greater volume of tunnel discharge during DEs in September to January. While the greater volume of water that entered the tunnel during these months may be the result of enhanced infiltration, it is also possible that a rising water table and associated lateral movement of groundwater, is responsible for delivering more groundwater to the tunnel during these Discharge Events. The possibility of, and evidence for, a rising water table is further examined in 12.2.4.
While the strong positive correlation between calculated infiltration rate and proportion of rainfall infiltrated may be an artefact of the model design, the two parameters are only related to cumulative discharge. The duration of rainfall is used to calculate the infiltration rate, which means that outlier storm events may have higher proportions of infiltrated rainfall than the duration of that rainfall would suggest. While cumulative discharge influences the calculated infiltration rate and the proportion of rainfall infiltrated, the duration of a storm event exerts a greater influence on infiltration rate. This implies that infiltration rate and the proportion of rainwater infiltrated are ‘semi-independent’.
Figure 9.2: The calculated infiltration rate and proportion of rainfall infiltrated using the infiltration model. Infiltration rates and proportions were calculated using (A) Cumulative tunnel discharge when 0 l s⁻¹ was the reference discharge and (B) Cumulative tunnel discharge when the pre-DE sequence level was the reference discharge. Numbers refer to DEs and the red line separates storms from the April to August and September to January periods.
Figure 9.3: The calculated infiltration rate and proportion of rainfall that infiltrates the rock mass using the infiltration model. Infiltration rates and proportions were calculated using (A) Cumulative tunnel discharge when the pre-DE level was the reference discharge and (B) Cumulative tunnel discharge when the exponential decay of the previous DE was the reference discharge. Numbers refer to DEs. The red line separates DE’s in April to January from those in September to January only.
9.1 Summary

The months between April and August 2012 were generally dry, and tunnel discharge frequently dropped to low levels while the months of September 2012 to January 2013 had considerably more rainfall, increased average tunnel discharge and Discharge Events occurred in rapid succession. Two discharge anomalies were identified in 2012, when there was an increase in discharge without a corresponding rainfall event. These anomalies suggest multiple water sources feed the Tatare Tunnel.

Overall, the response of tunnel discharge to rainfall events differed in timing and magnitude between the two periods. The time interval between the onset of rainfall and increases in tunnel discharge ($T_1$) and the time interval between peak rainfall and peak discharge ($T_2$) were different between the months of April to August and September to January, with the former having markedly lower $T_1$ and $T_2$ values. Relationships between rainfall metrics (mean rainfall intensity and total rainfall) and tunnel discharge metrics (peak tunnel discharge and cumulative tunnel discharge) took different forms between the periods and suggested a change in surface or subsurface processes between April to August and September to January.

Differences between the April to August and September to January periods were mirrored in the findings of the recession analyses. Discharge events that occurred in the months of September to January exhibited a positive exponential relationship between peak tunnel discharge and the rate of discharge decay. This suggests a common control on the volume of water that can enter and exit the rock mass surrounding the Tatare Tunnel.

Regardless of how cumulative tunnel discharge was calculated, discharge events that had high cumulative discharges for a given rainfall volume all occurred between September 2012 and January 2013 (Figure 8.9 and Figure 8.12).

Modelling identified several Discharge Events that had a greater proportion of total rainfall infiltrate at a greater rate than other storms. A positive relationship between infiltration rate and the proportion of rainfall infiltrated was also observed. All storms with high infiltration rates and high proportion of rainfall infiltration occur in the months of September to January. This supports the differences in patterns observed in sections 8.2, 8.3 and 8.4. It follows that there are fundamental differences in rock mass
saturation between the April to August and September to January periods and this is further explored in section 12.2.3.
Chapter 10: Results: Chemical Analyses

The aim of this chapter was to use chemical and temperature analyses to shed light on how water behaves once it enters the rock mass surrounding the Tatare Tunnel. Rock mass saturation is an important control on the rate and pattern of groundwater movement. Groundwater chemistry can be used in conjunction with discharge measurements at the tunnel outlet to infer rock mass saturation and how it varies in response to external factors such as rainfall and snowmelt infiltration.

Initially the relationship between fluid-rock contact time and the concentration of ion species in solution was quantified in controlled laboratory conditions (section 6.1). Secondly these relationships were used to interpret the chemical signature of groundwater entering the Tatare Tunnel during a single discharge event. Section 10.1 outlines the results of the laboratory experiment conducted, while section 10.2 characterizes waters sampled from the Tatare Tunnel Field site and the Amethyst Tunnel field site. Section 10.2 draws the two data sets together, allowing chemical-contact-time relationships to be mapped onto field samples. Finally, section 10.3 presents the result of the stable isotope analyses used to characterize the source of waters entering the Tatare Tunnel.

10.1 Empirical Estimates of Dissolution

Changes in the chemical concentrations of groundwater with time may reveal whether the rock mass is dominated by dissolution or dilution. The dissolution rate of different ions varies. Therefore at a given level of rock mass saturation, some species with higher dissolution rates may impart a dominantly dissolution signature on groundwater while less soluble species may impart a dilution style signature. In order to estimate the relative rate at which different ions are liberated from Alpine Schist, a simplified empirical experiment was undertaken. The experiment is a highly simplified representation of the rock mass conditions surrounding the Tatare Tunnel, the most simplification of which is that the volume of fluid that rock exchanges with is fixed and immobile. In real world conditions, new water enters the rock mass and flushes old water out. This has the effect of maintaining the concentration gradient between fluid and rock at any site within the rock mass. Furthermore, in the laboratory, fluid volume
far exceeded the volume of rock, whereas in the rock mass surrounding the Tatare Tunnel, the volume of the rock mass is far greater than the volume of circulating fluid.

Because the solution in the beakers was not replenished with new water, the concentration gradient between fluid and rock diminished more rapidly than would be expected in the real world. While experiment design meant the solution became saturated it did allow dissolution rates to be estimated.

Figure 10.1 illustrates the relationship between fluid-rock contact time, measured in days, and the concentrations of the Cl, SO₄, Na and K ions in solution. All four ions showed an increasing concentration with increasing rock contact time. The relationship between concentration and contact time can be described by a power-law relationship. R² values for these models ranged from 0.87 to 0.99 (Figure 10.1 and Figure 10.2). Cl was the only ion that showed a decrease in concentration with larger rock contact times, with its concentration at 176 days being lower than that at 66 days (0.019 and 0.020 mEq l⁻¹ respectively). The rate of dissolution of the sodium, potassium and chloride ions appeared to slow significantly after 36 days of rock contact, while sulphate concentrations continued to grow throughout the entire experiment.

Figure 10.2 illustrates the relationship between fluid-rock contact times and concentrations of Ca, Mg, Ca: Mg ratio as well as Electrical Conductivity. With the exception of the Ca²⁺:Mg²⁺ ratio, all relationships could be described by positive power-law models. R² values range from 0.68 to 0.97. Given that concentrations of Ca and Mg increased with increasing rock contact time, the decreasing values of the Ca: Mg ratio with time indicates that Ca dissolution from the rock occurs at a greater rate than Mg.

Figure 10.1 show that SO₄ has the greatest dissolution rate and Cl the lowest, with power-law exponents of 0.5025 and 0.1005 respectively. Figure 10.3 illustrates the relationship between fluid rock contact time and the Na/Cl ratio of the solution. As with most other chemical species this relationship is characterized by a power-law.

The power-law behaviour of chemical concentration over time suggests that the release rate of all chemical species is initially high and then slows. Chloride, potassium and to a lesser extent, magnesium concentrations, showed little to no increase in concentration in the later stages of the experiment, indicating dissolution slowed through the experiment. However dissolution rates of sulphate, sodium and calcium all appeared to maintain high levels throughout the entire experiment period. The power-law behaviour
also suggests that the waters used in the experiment approach saturation with respect to all ions within 80 days. The lack of advection processes distinguishes the laboratory experiment from the groundwater in the rock surrounding the Tatare Tunnel. While the experiment was limited in this respect, the relative dissolution rates of different ions were identified.

Figure 10.1: Concentrations of chloride, sulphate, sodium and potassium during the 176 day water-rock laboratory experiment. The relationship between water-rock contact time and chemical species concentration is described by a power-law model for all ions.
Figure 10.2: Concentrations of calcium and magnesium during the 176 day laboratory experiment. Also shown is electrical conductivity and the Ca: Mg ratio for the same period. Positive power-law models describe calcium, magnesium and electrical conductivity, while the Ca: Mg ratio is described by a negative power-law model.

Figure 10.4 is a Piper Diagram that shows the composition of water samples from the laboratory experiment and from groundwater in the Amethyst Tunnel. The two data sets were plotted together as an independent quantification of contact time was available for each. In the case of the Tatare samples this was known exactly, while in the case of the Amethyst samples, relative contact time was inferred from the known tunnel overburden. The axis shows the proportion of all ions in solution that a single species occupies. Laboratory water samples were initially grouped and plotted on the same axis as Amethyst groundwater samples to illustrate differences between the two. It is evident that laboratory samples have not perfectly emulated the chemical signature of real
world waters. Their positions on the diagram indicate that both sample sets have similar proportions of sulphate (SO₄), Magnesium (Mg) and total hardness (commonly represented as CaCO₃). Differences in both Calcium (Ca) and combined Sodium and Potassium (Na and K) are obvious, with no two water samples from either set overlapping. Both data sets show increasing concentrations of Ca and SO₄ with increasing rock-contact time and tunnel overburden. While there is significant overlap, laboratory samples show generally lower proportions of chloride than do the Amethyst Tunnel groundwater samples.

The decreasing Ca: Mg ratio of laboratory samples seen in Figure 10.2 is expressed as a rise in the mixing curve identified in Figure 10.4, a feature not observed for the Amethyst groundwater samples.

![Graph](image)

Figure 10.3: Na: Cl ratio vs. fluid-rock contact time for the laboratory experiment. The relationship between these two is characterized by a power-law.
10.2 Analysis of Groundwater Samples from the Tatare and Amethyst Tunnels

This section summarises the results of chemical analyses of groundwater samples from the Tatare and Amethyst Tunnels. Figure 10.5 shows the composition of the laboratory samples and the groundwater samples collected from the Tatare Tunnel. There are differences between rainfall samples, laboratory experiment samples and groundwater samples taken from the Tatare Tunnel for Ca, Cl, Na and K. Laboratory samples also have SO\textsubscript{4} concentrations that are greater than those for the rainwater and Tatare Tunnel groundwater samples. Total hardness is much higher for Tatare Tunnel samples than for rainwater and laboratory water samples, reflecting the purity of both the rainwater and the distilled water used in the laboratory.
Figure 10.6 is a ternary diagram illustrating differing chemical compositions (Figure 10.5) in relation to the composition of the rock mass bounding the Tatare Tunnel. Rainwater samples cluster to the right of the rock sample, while laboratory samples, Tatare and Amethyst Tunnel groundwater samples cluster to the left. The boxed portion of Figure 10.6 surrounds groundwater samples from the Tatare Tunnel and this is further illustrated schematically in Figure 10.7. Increasing concentration of Ca and decreasing concentrations of Na are associated with greater tunnel overburden. The Tatare Stream samples constitute the end of the mixing line, with high concentrations of Ca and the lowest concentrations of Mg and Na.

Figure 10.5: Piper diagram showing the chemical composition of the laboratory water, rainwater samples, tunnel outflow, tunnel seeps and a large tunnel fissure.
Figure 10.6: Ternary diagram to show the chemical composition of rainwater, shallow fissures in the Tatare Tunnel, the rock surrounding the Tatare Tunnel, The gravel that lines the floor of the Tatare Tunnel, laboratory water, Amethyst Tunnel Samples and water issuing from deeper seeps in the Tatare Tunnel. The boxed portion, is displayed schematically in Figure 10.7.

Figure 10.7: Chemical evolution of a water sample taken from the Tatare Tunnel field site, indicated by the boxed section in Figure 10.6. Here distance from the western tunnel entrance is a surrogate for tunnel overburden.
1.5 Tatare Tunnel Groundwater: Discharge Event 4

Variations in rock mass saturation (the fluid: rock ratio) and the dominance of diffusion over dilution processes may alter the chemical composition of Tatare Tunnel groundwater (section 6.2). The heterogeneous nature of the rock mass affects permeability, and different sampling locations within the tunnel exhibit different chemical signatures. In order to capture such variation, a more intensive sampling scheme was adopted for discharge event (DE) 4 in May 2012. Tunnel groundwater sampling sites were chosen to represent the variety of flow types, including seeps, fissures and the tunnel outflow. Groundwater samples were taken at each site at approximately 12-hour intervals, and the findings are presented here.

A small number of patterns in the concentration of ions were observed. In order to capture these behaviour patterns, and to group ions and sampling sites that follow similar patterns, a classification scheme was devised (section 7.5.1) and applied to each major ion examined for the five tunnel sampling sites. The patterns listed in Table 7 relate to the simple experiment conducted in the laboratory. Laboratory derived Ion dissolution rates (in descending order) were: SO$_4$ > Mg > Ca > Na > K > Cl.

Groundwater sampling sites in the Tatare Tunnel across all chemical species showed changes in concentration as DE 4 progressed. The concentration of different chemical species also varied within and between sampling sites. Because concentration may be discharge dependent, samples times were plotted against the discharge hydrograph for the tunnel (Figure 10.8). Table 7 displays the type of change for each of the ions analysed as well as Electrical Conductivity (EC) and two ion ratios.

Seeps at 140 m and from the fissure 54 m from the western entrance are both dominated by decreasing concentrations of all major ions, suggesting that continued dilution through increases in the fluid: rock ratio or enhanced mass advection through the fracture network is the dominant process in the portion of rock that feeds the two sites. Interestingly, Ca concentrations in groundwater from the fissure at 54 m appear to be increasing, while all other ions show decreases. Given that SO$_4$ and Mg, which show decreasing concentrations at the site, had greater values of dissolution in the laboratory, this findings is surprising. One possible reason for the continued diffusion of Ca under conditions of general dilution is the presence of a significant local source of calcium, such as calcite, unlike of the other major ions. Ca and Mg ions show similar
concentration patterns at the 5m fissure groundwater sampling site. Possible explanations for this are further explored in section 12.7.2.

Although only 100 m from the seep at 140 m, the groundwater that seeps from the tunnel roof at 257 m from the western entrance of the tunnel shows different characteristics. There, the seeps show increasing concentrations for almost all ions, indicating that either diffusion is still dominating over dilution or the groundwater sampled at this site was, in effect, stored water being actively ‘flushed’ from the rock mass. The ‘flushing’ of old, stored water from the rock mass would result in a distinctive diffusion signal in groundwater seeping in the tunnel, while a dilution-dominated system might occur deeper within the rock mass at the time. The latter ‘flushing’ explanation is favoured here. Given the greater overburden of the tunnels eastern section, a greater volume of water may be stored above a given length of tunnel. As a result, the ‘flushing’ of the rock mass takes longer in this section than in the western section.

The signal observed in the tunnel is a function of the total number of groundwater samples taken during the DE. The Cl and K ions are exceptions to the pattern observed at this site: initially increasing, and then decreasing in concentration. Interestingly the Cl and K ions had the lowest laboratory-determined dissolution rates, so they might be expected to show dilution effects.

The EC of all sites decreased as DE 4 progressed, suggesting that dilution was the dominant processes in the rock mass surrounding the Tatare Tunnel during DE 4. Differences in dilution and diffusion signatures between groundwater sampling sites, as well as possible complicating factors, are discussed in section 12.7.4.
Figure 10.8: Rainfall and tunnel discharge for DE 4, with the timing of samples indicated.
Table 7: Net change in ion concentration during DE 4. Patterns were classified as increase (↑), decrease (↓), rise-return (∧) or drop-return (Ѵ) according to the scheme outlined in section 7.5.1. N/A=not analysed.

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10.3 Stable Isotopes

Figure 10.9 presents the findings for stable isotope analyses on rainwater, groundwater and Tatare Stream samples collected in August, October and November 2012. The plot also includes an additional rainwater sample, taken in the Copland Valley - 30 km SW of the Tatare Tunnel, by Cox (2010). This rainwater sample shows the natural variability of δ¹⁸O and δ D values in New Zealand rainwater. The position of rainfall values on the New Zealand Meteoric Water Line (NZMWL) is variable and depends on both the temperature and altitude at which precipitation nucleates (Sharp, 2007).

Purdie et al. (2010) sampled the composition of snowfall on the Franz Josef Glacier at an elevation of 2300 MASL for 24 days in 2010 and the mid-point of the sample distribution was plotted on Figure 10.9. This value represents the snow end-member of the distribution of δ¹⁸O and δ D values that characterize precipitation falling on the Tatare Tunnel catchment.
Given sufficient temperature and contact time, any rainwater that infiltrates the crust may undergo isotopic exchange with the metamorphic host-rock. Such exchange is represented by a shift in the $\delta^{18}O$ values of the rainwater. Figure 10.9 includes a value for rock-exchanged fluid that has undergone a positive shift in $\delta^{18}O$ values. The value was obtained by analysing $\delta^{18}O$ and $\delta D$ values concentrations in calcite and quartz taken from fissure veins by (Jenkin and Fallick, 1994).

All groundwater samples taken in the Tatare Tunnel, as well as the Tatare Stream samples, lie along the NZMWL between the rain and snow end-members. No shift in $\delta^{18}O$ values is apparent, suggesting that the duration and temperature of contact between rainwater and schist in waters entering the Tatare Tunnel was insufficient to induce isotopic exchange with the rock mass.

While there was substantial overlap between groundwater samples taken in August and October 2012, groundwater samples taken in November 2012 were more depleted in lighter isotopes than their August and October counterparts. Displacement of samples along the NZMWL toward the depleted end-member requires either a decrease in the temperature at which precipitation began, or an increase in the proportion of snowmelt present in the sampled groundwater.

This suggest that either the November samples were derived from rainwater that formed at a much lower temperature, or that the groundwater seeping into the Tatare Tunnel in November had a greater proportion of snowmelt than that entering the tunnel in August and October. This second possibility is more likely, and is discussed in light of other results in section 12.3.1.1.
Figure 10.9: Trends in $\delta^{18}O$ vs. $\delta$ D for water samples from Tatare Tunnel groundwater, rainwater outside the tunnel and Tatare Stream Water. With the exception of the rainwater sample collected by Cox in 2010 all samples were collected in 2012. Also included is an additional rainwater values from Cox (2010), a rock-exchanged value from Jenkin et al., (1994) and Rainwater a value for snow on the Franz Josef Glacier from Purdie et al., (2010). The glacier snow and rainwater values form end-members of the distribution All samples lie on the NZMWL, indicating that no isotopic exchange with the rock mass has occurred.
10.4 Summary

All ions, Electrical conductivity and the Na: Cl ratio showed increasing concentrations with time while the Ca: Mg ratio decreased with time. The relationship between concentration and fluid-rock contact time was characterized by power-law models. The laboratory samples were chemically distinct from water samples collected at the Tatare and Amethyst tunnels, with laboratory samples having lower concentrations in all ions except Ca and Mg. The laboratory experiment established that concentrations of all ions increased with fluid-rock contact time, but that the volume of water used in laboratory experiments approached saturation after approximately 40 days.

Differences in the chemical signatures were found between the different sampling sites in the Tatare Tunnel and between the field and laboratory waters. Greater tunnel overburden at both the Tatare Tunnel and the Amethyst Tunnel (although not known with any precision for the Tatare site) correlated with an increasing concentration of most chemical species in solution (Figure 10.7).

The Tatare rock mass was diluting during the discharge event studied. While almost all groundwater sample sites showed decreasing ion concentrations during the event, the behaviour of Ca and Mg ions was counter-intuitive. These ions had some of the highest laboratory-determined dissolution rates, but showed decreasing concentrations at sites where diffusion was still dominating other ion species.

Both the fissure at 54 m sampling site and the seep at 140 m sampling site showed a decrease in all chemical species with time, while other sites had several ‘spike/drop’ classifications.

Finally section 10.3 showed that \( ^{18} \)O and D concentrations were lower in samples taken from the Tatare Tunnel relative to ocean water. All samples plotted on the NZMWL and showed no signs of having isotopically exchanged with the schist host rock. Groundwater samples collected in November were more depleted in light isotopes than their August and October counterparts, suggesting a greater proportion of snowmelt was present in November groundwater.
Chapter 11: Temperature Regime

11.1 Tunnel Temperature Measurements

Figure 11.1 shows runs of temperature readings for Tatare Tunnel during the study period. The temperature of water leaving the tunnel and from a fissure located 54m from the western end of the tunnel were recorded between April 2012 and January 2013, but data on tunnel air temperature was only obtained from April 2012 to August 2012 because equipment went missing from the tunnel (thought to be theft). The air temperature measurements show the greatest variation, followed by fissure temperatures, while the tunnel outflow water temperature remained relatively stable from April to January.

Figure 11.2 shows a strong correlation between air temperature and outflow water temperature between April and August 2012. The air mass: groundwater volume ratio for the tunnel is large, so once groundwater enters the tunnel and begins to flow towards the outlet, its temperature becomes influenced by air temperature in the tunnel. The high correlation between water temperature at the tunnel outflow and tunnel air temperature (Figure 11.2), means that this suite of water temperatures can be used to predict the tunnel air temperatures between August 2012 and January 2013. The interpolated air temperatures are displayed in Figure 11.1.

The fissure at 54 m has a variable flow rate and at times is completely dry. Therefore, the temperature probe located in the fissure records a mixture of tunnel air temperature (when the fissure runs dry) and, at tunnel discharges greater than ~3 l s⁻¹, the temperature of water flowing from the fissure. As a result of variable flow rates, the temperature of the fissure changed abruptly several times during the study period, rising when water flows over the probe and falling when the fissure runs dry. With the exception of April 2012, fissure temperature was always greater than tunnel air temperature by approximately 2 °C. The most striking feature of the fissure temperature record is the clear difference between the months of April to August and September to January.

At several times between April and August fissure temperatures showed a diurnal pattern in phase with changes in air temperature. The tunnel air temperature likely
controls fissure temperature during such times. Given that the focus here is on water-rock contact times and the thermal signature of groundwater, these times are of little interest and were not further considered. The abrupt increase in fissure temperature to approximately 10.4 °C that occurred during a Discharge Event was interpreted as the consequence of water flowing over the temperature probe. Because the rock mass: groundwater ratio is large, the temperature of infiltrating water quickly equilibrates with the un-saturated rock temperature of 10.4 °C. The temperature of the fissure water drops to tunnel air temperature when tunnel discharge falls below approximately 3 l s\(^{-1}\) (Figure 11.1). While the pattern of increased fissure temperature, followed by a drop in fissure temperature, characterizes almost all discharge events between April and August, a slightly different pattern was observed during Discharge Event 6 and the subsequent anomalous Discharge Event 2 (ADE 2) (boxed inset, Figure 11.3). During Discharge Event 6 and anomalous Discharge Event 2 fissure temperatures gradually cooled from an initial value of 10.4 °C to 9.8 °C. This was the only time throughout the entire period of observations (April 2012 to January 2013) that this was observed. The observed cooling curve is interpreted as the result of cooling of the rock mass surrounding the tunnel as the rock mass: groundwater ratio decreased. As the increased volume of infiltrating water cooled the rock mass, isotherms were pushed downwards and the temperature of groundwater entering the Tatare Tunnel decreased to 9.8 °C as it equilibrated with rock temperature.

While fissure temperature fluctuated with tunnel discharge between April and August, it increased to ~9.8 °C at the beginning of September 2012 and remained relatively stable until the end of November 2012. Following a brief drop in temperature in early December, coincident with tunnel discharge dropping below 3 l s\(^{-1}\) for the first time since September, the fissure temperature began to fluctuate and rose above 10.4 °C. This increase of fissure temperature above previously recorded levels is attributed to an increase in the predicted tunnel air temperature affecting the dry fissure temperature (Figure 11.1). Fluctuations in fissure temperature can be attributed to changes in fissure flow rate and are restricted to the April to August period. By contrast the September to January period is characterized by stable fissure temperature readings.

The distinction between April to August and September to January is mirrored in almost all flow results. The shift between an un-saturated rock mass in April to August to a saturated rock mass between September and January has a distinctive temperature
signal. Section 12.5 provides further explanation and comments on the significance of the cooling curves observed during DE 6 and ADE 2.
Figure 11.1: Tatare Tunnel discharge, temperature of the large fissure and tunnel outflow waters temperature for the period April 2012 to January 2013. Also included are the tunnel air temperature for the period April to August 2012 and the tunnel air temperature predicted by the relationship outlined Figure 11.2 between August 2012 and January 2013.
Figure 11.2: Tattle Tunnel air temperatures vs. tunnel outflow water temperatures. The data is sourced from the April to August period. These air temperature and outflow water temperature show a strong positive relationship that is quantified by the fitted line equation.

\[ T_{\text{Outflow}} = 0.113 \times T_{\text{Tunnel Air}} + 8.259 \]
Figure 11.3: Fissure temperature and tunnel discharge for the period April 2012 to January 2013. Abrupt changes in tunnel discharge coincided with abrupt changes in the fissure temperature between April and August, whereas fissure temperature remained relatively stable at 9.8 °C between August and January.
11.2 Chapter Summary

Differences in fissure temperature when tunnel discharge was markedly above or below 5 l s\(^{-1}\) indicate a functional link between tunnel discharge and the thermal state of groundwater in the Tatare Tunnel. Tunnel air temperature and tunnel outflow water temperatures exhibit a strong positive correlation. This suggests a coupling between the air mass of the tunnel and the fluid that flows into it. Such a coupling is important because it shows that both the surrounding rock mass and the tunnel air influence the thermal signature of circulating waters. A strong difference in fissure temperature patterns is seen between April to August and August to January. The difference is interpreted to be the result of a non-saturated rock mass between April and August and a saturated rock mass between August and January.
Chapter 12: Discussion

This chapter uses information collected in the field and the body of literature outlined in chapter two to addresses the specific aims of this research which were outlined in chapter one, and to use the results to develop a conceptual model that describes how fluid infiltrates and moves through the shallow rock mass above the Alpine Fault. The physical processes invoked to explain the findings in the three results chapters involve three critical interpretations, made in this chapter. The three interpretations link atmospheric, surface and sub-surface processes. The three interpretations were based on tunnel geology measurements, flow measurements and anecdotal evidence. They were:

1. The influence of snow cover on patterns of infiltration during rainfall events and at times when snowmelt is initiated.

2. How the geometry and abundance of fractures controls the permeability of the rock mass surrounding the Tatare Tunnel and fluid transit time.

3. How both water and snow influence patterns of infiltration, rock mass saturation and the elevation of the water table in the rock mass surrounding the Tatare Tunnel.

Positive feedback between infiltration, permeability and rock mass saturation mean that the three interpretations are not independent of each other. The three critical interpretations are presented in the form of a conceptual model that emphasizes the strong link between atmospheric, earth surface and sub-surface processes. The three interpretations are addressed in sections 12.2.1, 12.2.2 and 12.2.3, respectively.

Sections one draws on the findings of the discharge analysis (Chapter 8:) and modelling (Chapter 9:) to develop the conceptual model. It outlines the general characteristics of tunnel discharge and interprets possible causes of the Anomalous Discharge Events observed in April and July 2012. Section two relates the relationships defined in chapter three—mean rainfall intensity vs. transmission time of fluid, mean rainfall intensity vs. peak tunnel discharge, and total rainfall vs. cumulative tunnel discharge—to rock mass characteristics. This section details how comparison of rainfall and discharge signals was used to understand how water moved through the rock mass, the driver of the conceptual model. The abundance, aperture and orientation of fractures
control fluid movement in the rock mass. Section three interprets measurements made in the Tatare Tunnel to provide a physical basis for the conceptual model. Section four interprets the findings of the flow results chapter and in the process, identifies the main elements of the conceptual model. The anomalous transmission times noted in chapter five are counter-intuitive and at odds with the conceptual model. Possible processes that may lead to the observed behaviour are considered in section 12.2.5 before the conceptual model is summarized in section 12.3.

The purpose of the second part of the chapter is to evaluate the conceptual model, examine groundwater flow during the discharge events using thermal and chemical methods more suited to assessing rock mass saturation, and to place the study period in a long-term context. This is achieved by using the findings from the recession curve, chemical and temperature analyses.

Section 12.4 interprets temperature records from the Tatare Tunnel in light of the conceptual model and provides additional support for several of the conclusions reached in section 12.3. Section 12.6 uses methods suitable for individual recession curves of discharge events to characterize how water drains from the rock mass.

The task of section 12.7 was two-fold: to explain the differences in chemical signature observed in the groundwater samples taken along the Tatare Tunnel, and to use chemical analyses to provide a more detailed account of how fluid moves through the rock mass surrounding the tunnel. This is achieved by interpreting major ion concentrations of water seeping into the tunnel and showing how these concentrations change during Discharge Events.
Part One: Underpinning of the Conceptual Model

12.1.1 Characteristics of Tunnel Discharge

This section explains patterns of rainfall and discharge observed throughout the study period at the Tatare Tunnel field site. Both rainfall and discharge were greater from September 2012 to January 2013 than from April to August. The differences in rainfall and temperature, outlined in section 8.1, are typical of mid-to high-latitude climates. The Westland region’s seasonality is moderated by its proximity to the Tasman Ocean, so a dry period between April and August and a wet period between September and January were expected (Stuart, 2011).

In temperate, non-urbanised environments, recharge patterns tend to follow rainfall (Healy, 2010), a proposition supported by the strong correlation between rainfall and discharge in the Tatare Tunnel (section 8.2). However, there is a difference between rainfall measured at Franz Josef and rainfall received above the Tatare Tunnel. While the elevation difference between the rain gauge at Franz Josef and the Tatare tunnel is small, the catchment area of the tunnel may span a large surface area, meaning there may be differences in the timing of rainfall at Franz Josef, and the timing of rainfall above the tunnel.

Increases in the total volume of rainfall between September and January were matched by increases in the magnitude and frequency of discharge events in the Tatare Tunnel. The change in discharge behaviour is indicative of changes in the supply of water to the tunnel and changes in sub-surface processes, such as fluid flow and storage. Infiltration is intrinsically linked to antecedent moisture conditions in the rock (Gueguen, 2004), and while precipitation is the source of tunnel discharge, during a storm, rainfall may simply initiate discharge into the Tatare Tunnel by forcing water already stored in the rock mass to be expelled in the tunnel. Consequently the water that reaches the Tatare Tunnel will not necessarily be that which fell during the most recent rainstorm. The fact that increased rainfall led to increased tunnel discharge demonstrates the intrinsic link between atmospheric and sub-surface processes. Therefore, the role of atmospheric and surface processes is an important aspect of the conceptual model.
12.1.2 Anomalous Discharge

In Chapter 7: an anomalous discharge event was defined as an increase in tunnel discharge when no corresponding rainfall event was recorded. Two anomalous discharge events were identified in April and July 2012. These events suggest that rainfall may not be the sole source of Tatare Tunnel discharge. Two mechanisms that may explain their role are discussed here, as well as their implications for the conceptual model developed in section 12.2.

Figure 8.4 (section 8.2.1) illustrates the two anomalous discharge events — in April 2012 and July-August 2012 — when environmental conditions were relatively dry. Two sources of infiltrating water are possible: isolated rainfall recharge and snowmelt infiltration: either precipitation events at the site that are not recorded at Franz Josef, or the infiltration of snowmelt that could not be recorded at the Franz Josef rain gauge. Both recharge mechanisms and the supporting evidence for each are outlined below.

1.5.1 Isolated Rainfall Recharge

The steep rainfall gradients of the Southern Alps mean that while orographic rain may fall in the mountains none will fall at Franz Josef. The town (and the rain gauge) lie at an elevation of 80m ASL (Griffiths and McSaveney, 1983). Given that the rainfall gradient steepens significantly above 500m ASL, any spatially isolated rainfall event above this altitude could be in the tunnel’s catchment area. As de Vries and Simmers (2002) noted, depressions as well as minor variations in topography and bedrock slope exert major controls on recharge. It follows that rainfall events may not lead to a spatially constant recharge. The most striking difference between the discharge hydrograph of a typical recharge event and the hydrographs for anomalous discharge events, lasting for nine days or more was the slope of the rising and the falling limb. The abrupt, steeply rising limb observed after most storm events was absent, and peak discharge was more subdued relative to flow immediately before and after the event. Kresic (2010) showed how water from an isolated recharge event travelling through a rock mass would be expressed in a spring discharge hydrograph (Figure 12.1). Suppression of the peak, and an increased spread of discharge with time bear a strong similarity to records of anomalous discharge events in the Tatare Tunnel.
Figure 12.1: The formation and subsequent movement of a groundwater ‘wave’ caused by a localised recharge event, where $t$ is time and $C$ is wave velocity. Tatare Tunnel is analogous to the spring in this diagram. Water that recharges the Tatare Tunnel may be ‘old’ water discharged under the pressure of the recharge wave. Taken from Kresic (2010).

1.5.2 Snowmelt Infiltration

Anomalous Discharge Event 2 (ADE 2), in July-August 2012, followed a significant rain-on-snow event. While snowmelt is most sensitive to increases in atmospheric temperature, increases in latent heat flux associated with the melting of surface snow during a rainfall event can also induce substantially more melt (Anderson and Mackintosh, 2012b; Ishikawa et al., 1992; Marcus et al., 1985). In cases when rain falls on a snowpack, the release of liquid water, subsequent infiltration and groundwater flow are offset in time from the rainfall event.

On June 27 2012, snowfall occurred during a Discharge Event (DE 5). The rain gauge in Franz Josef was not specifically designed to register snowfall, so the recorded amount of 128 mm during DE 5 incorporated water from rain and snowmelt. The storm brought over 18 cm of snow to sea level in the Franz Josef region and anecdotal evidence indicates that much of it remained on the forest floor above Tatare Tunnel for at least 14 days (D. Waters, DoC, pers. comm.). As after other storms, tunnel discharge increased during DE 5. The DE 6 rainfall event on 12 July 2012 that followed the snowstorm was the second largest storm recorded during the study period, at 299 mm. Coincident with this anomalous discharge, and during the period in which snow had been observed to lie on the forest floor, was an increase in air temperature, measured at 500 m elevation in the Callery Valley (adjacent to the Tatare catchment) (T. Kerr, NIWA, pers. comm.). Both the intensity of rainfall for DE 6 and the increase in air
temperature recorded in the Callery Valley would have been sufficient to induce snowmelt and generate recharge. Cutler and Fitzharris (2005) measured temperature-induced snowmelt pulses of up to 78 mm d\(^{-1}\) that lasted between five and eight days, and calculated a degree-day factor of between 3.4 and 9.4 mm °C d\(^{-1}\). These values are consistent with increased air temperature driving rapid and substantial snowmelt.

A well-developed network of tributaries feed the Tatare Stream. Although it was not gauged, an increase in stream discharge coincident with ADE 2 would have indicated that large volumes of snowmelt soon flowed into the Tatare Stream. As the rate of meltwater generation exceeds the soil and rock infiltration capacity, surface runoff is initiated, inducing a storm-like response in the stream’s discharge signal. However, the nearby Waiho and the Whataroa rivers (3 km south and 30 km north of Tatare, respectively) showed no increase in discharge. While the signal for the Waiho River is dominated by the Franz Josef Glacier, and the Whataroa catchment is considerably larger than the Tatare, their lack of response suggests that the area affected by snowmelt was small and limited to the Tatare catchment, or occurred over too long a period to induce a discernible pulse in river discharge. The lack of a clear snowmelt signal in the two nearby rivers indicates that snowmelt was slow enough for melt-water to infiltrate the rock mass.

While snow is present at high altitudes throughout the year, it falls locally to lower altitudes only during the winter season (Anderson et al., 2006). Snowmelt infiltration is probably restricted to where snow falls or is sourced at altitude some distance from the tunnel. Snow was observed at the tunnel elevation of 280 m following DE 5 and persisted in greater amounts at higher elevations.

The combined impact of an uneven depth of snow and a spatially variable snowmelt go some way to explain the complexity of the discharge hydrograph for Tatare Tunnel. Indeed, a combination of these two may have influenced rates and patterns of infiltration during the entire measurement period. The seasonal component and representativeness of the 2012-2013 tunnel discharge record are examined further in section 12.3.1.1.
12.1.3 Rainfall-Recharge: Interpretation of the Signal

Patterns of rainfall and tunnel discharge (section 8.2) indicate that there are differences in the volume of fluid moving through the rock mass during the April to August and September to January periods. Anomalous Discharge Events described above also suggest that a source other than rainfall is influencing patterns of tunnel discharge. This section outlines how rainfall and discharge signals were compared and the factors that control them in order to understand the role of the rock mass between the surface and the tunnel. The comparisons between mean rainfall intensity and metrics such as peak tunnel discharge and the transmission time of fluid are outlined, and two broad requirements of the conceptual model, developed in section 12.2, are listed.

Patterns of infiltration are influenced by the interaction of permeability, saturation and thickness of the rock mass between the surface and the tunnel. Given that the forest canopy remained unchanged during the study period, the proportion of rainfall intercepted by the forest cover can be assumed to have remained constant between April 2012 and January 2013.

In arid environments, the role of the soil in controlling rates of infiltration is potentially large and variations in the depth and structure of the soil can profoundly influence groundwater recharge (Heppner et al., 2007; Olofsson, 1994). However, in the Tatare catchment, the soil layer is thin relative to the bedrock above the tunnel, and the soils have been shown to have a high rate of fluid transmission (Henagen et al., 2001). Therefore, no information on the depth-distribution or physical characteristics of the soil was collected during the study. Permeability via fractures in the schist likely dominates the transmission of fluid to the tunnel and the structure of the schist at shallow depths (within ~5m of the surface) has been shown to exert a strong influence on rates and patterns of infiltration ((Gillon, 1992; Macfarlane, 1992); Cox pers. comm. 2013). Therefore, relationships between rainfall and tunnel discharge were interpreted primarily in terms of rock features.

Fluid transmission time was less in the dry months of April to August than in the wet months of September to January. At first glance, this is counter-intuitive (Figure 8.5, section 8.2.2) and possible reasons for the unanticipated distribution of T1 and T2 values are explored in section 12.2.5. The present section defines the three relationships between rainfall and the discharge metrics used to inform the conceptual model:
1. The relationship between mean rainfall intensity and fluid transmission time (section 12.2.1);

2. The relationship between mean rainfall intensity and peak tunnel discharge (section 12.2.1);

3. The relationship between the total rainfall and the cumulative rainstorm-induced tunnel discharge.

Any explanation must be realistic, given the nature of the rock surrounding the Tatare Tunnel (section 12.1.4), and involve a shift in processes between the months of April to August 2012 and September 2012 to January 2013.

**12.1.4 Interpretation of Tatare Tunnel Rock Structure**

This section interprets the structure of the rock mass surrounding the Tatare Tunnel to provide the physical basis for the conceptual model. Measurements of the quantity, orientation and aperture of rock fractures in the Tatare Tunnel, presented in Figure 4.5 and Figure 4.6 (section 4.2), are then related to regional stress orientations.

The Tatare Tunnel lies at the transition between distal mylonites and the western folded zone described by Little et al. (2002b). The rock mass has been subject to ductile deformation at depth and, more recently, fracturing during rapid exhumation (Little et al., 2002b).

The statistical distribution of fracture orientations observed in the tunnel results from changes in stress conditions attributable to four key factors:

1. Relief of vertical stress as overlying rock is eroded during uplift (Miller and Dunne, 1996)

2. Tensile stress induced by collapse and rotation of the hillside towards the Tatare Stream valley (Miller and Dunne, 1996; NRC, 1996)

3. The maximum horizontal stress direction acting on the rock: estimated to be 115±10° (80% confidence level) in rocks adjacent to the central Alpine Fault (Boese et al., 2012)
4. Perturbation of stress orientations by excavation of the Tatare Tunnel (Loew et al., 2007; Zangerl et al., 2003).

Under all four of the above, fractures oriented NW to SE can be expected to be opening, while fractures oriented NE to SW can be expected to remain the same or to close under mechanical stress. This interpretation is supported by the observation that fractures orientated NW-SE had a weak tendency to be wet, whereas those orientated NE-SW, were generally dry (Cox, Pers. Comm. 2012). The lack of a sharp distinction between wet and dry fractures, according to orientation, suggests that components 1 and 2 (above) overprint the regional stress orientation, influencing the capacity of fractures to transmit water.

The NW-SE oriented fractures surrounding the Tatare Tunnel are the likely candidates for the large/open fractures outlined in section 12.2.1, while those oriented NE-SW are more likely to be small/tight fractures.

12.2 Two-Dimensional Conceptual Model

This section develops a conceptual model of shallow fluid circulation in the rock mass surrounding the tunnel. The model is based upon the findings of chapters x(flow) and x(model) which used data collected between April and January to quantify the relationships between rainfall and discharge. Together, these two data sets shed light on the link between surface processes, such as runoff and snowfall, and sub-surface processes, such as fluid percolation and the role of rock storage capacity. While each of these processes is described separately, positive feedback loops in the shallow circulation system mean they are intrinsically linked. This section is structured around the three rainfall-discharge relationships defined in section 12.1.3.

12.2.1 Amplitude and Transmission Time of the Rainfall Signal

The time interval between the onset of rainfall and initial increase in tunnel discharge ($T_1$) and the time interval between peak rainfall and peak tunnel discharge ($T_2$) were defined in order to quantify the time taken for infiltrating fluid to travel through the rock mass to the tunnel. Figure 8.6 in section 8.2.3 shows the relationship between mean rainfall intensity and the $T_1$ and $T_2$ time intervals. From April to August, an increase in rainfall intensity led to an increase in transmission time, but between
September and January increased rainfall intensity led to a decrease in transmission time and a narrower range of \( T_1 \) and \( T_2 \) values (Figure 8.6).

Figure 4.6 suggests that fractures with lower mean aperture, hereafter referred to as tight fracture sets (Moore, 1992), are more abundant than the larger, more open fracture sets. Because their greater abundance also dramatically increases the likelihood that fractures will intersect, the connectivity of tight fractures will also be high (NRC, 1996). Therefore, due to their abundance and connectivity, the tight fracture sets are the major storage reservoir in the rock mass surrounding the tunnel. An increase in mean rainfall intensity will then drive fluid into the rock at a greater rate, forcing more water into available storage sites and further decrease transmission time. Assuming that the rock mass is not saturated between the months of April to August (the storage reservoir is not full), then the flow of water into voids in the rock would slow the advance of a packet of water towards the tunnel.

This process is flow-path specific, in that the fluid must move through small sets of fractures that are likely to store water, as opposed to sets of large, open fractures that have relatively little long to medium-term storage capacity. Instead the open fracture sets rapidly transmit water through the rock. In brief, empty voids in the rock mass will be progressively ‘filled up’ by infiltrating water so that any delay in transmission time will be proportional to the extent of rock mass saturation.

If increases in rainfall intensity are to cause increases in transmission time between April and August, then a significant proportion of total flow must be through these fracture sets. If this is the case, then tight fracture sets will exert a strong influence on transmission times and volumes of discharge in relatively dry periods, when a greater proportion of total flow moves through these pathways. Flow through tight fracture sets during the dry months of April to August does not mean no flow at that time moves through open fractures. Open fractures have lower resistance to flow and may remain responsible for the rapid transmission of some fluid (Manga, 1999) \( (T_1, \text{ see section 12.2.5}) \). However, the open sets are rapidly drained so do not act as a storage reservoir in the rock. Consequently, during the dry months of April to August, tight fracture sets are the dominant control on flow through the rock mass. Further support for a difference in the dominant flow paths between the April and August and September to January periods is presented in sections 12.2.1 - 12.2.5.
Figure 12.2: Schematic to show how the flow of water into storage in the months of April to August lowers the amplitude of the discharge signal. The flow of water through a set of tight, saturated fractures leads to a decrease in transmission time as the fluid-pressure wave propagates. Red fractures are dry and blue fractures are saturated.

Figure 8.6 shows that during the months of September 2012 to January 2013 there was a negative relationship between mean rainfall intensity and $T_1$ values. A decrease in the range of $T_2$ values was also noted as mean rainfall intensity increased. Furthermore, the greatest mean rainfall intensities were associated with the lowest $T_2$ values. This suggests that while $T_2$ values were less sensitive to mean rainfall intensity from September to January, a negative relationship between the two may have been in operation. A large increase in mean rainfall intensity (the amplitude of the rainfall signal) led to a decrease in transmission time. A decrease in transmission time implies that either a greater proportion of the signal was transmitted by hydrostatic pressure waves (Rasmussen, 2000) or the velocity of fluid in the rock mass increased (Scesi and Gattinoni, 2009).

For the velocity of fluid in the rock mass to increase, water must move through open fracture sets with a high volume to surface area ratio. In such cases, fluid will move through the saturated tight fracture set and through the open fracture set. The decreased resistance to flow in the larger fracture sets means that as rainfall intensity increases, the signal will be transmitted more rapidly through the rock.

Following this logic, the relationship between mean rainfall intensity and transmission time, between September and January is the consequence of fluid flow through predominantly open fracture sets. The switch from tight fracture set dominated flow to flow through open fracture sets implies that the rock mass has reached its storage capacity and become saturated. In effect fracture geometry controls the impact of
rainfall amplitude on the speed at which water moves through the rock mass. This interpretation is supported by the widespread recognition that across many scales, fracture geometry is a major control on fluid flow (Caine, 2003; Peters and Klavetter, 1988; Streltsova, 1976).

While two groups of fractures have been identified — tight and open — various fracture apertures between the open and tight end-members are possible, and may accommodate fluid flow. This contention is supported by measurements of ‘wet’ fractures in the Tatare Tunnel made by Cox (2010) (Figure 4.5). Water never moves exclusively through one set or the other, but a greater proportion may flow through one of them. Although water flows through open and tight fractures during Discharge Events, either the open or tight set will transmit a greater proportion of the infiltrating water (Bloomfield, 1996; Finkbeiner et al., 1997). The two end-member model is analogous to dual-porosity in the rock mass, which is common in fractured basement rock (Caine, 2003; Moore, 1992).

Having outlined how the two types of fracture sets control the transmission time for infiltrating water, attention now turns to the relationship between the amplitude of rainfall and the amplitude of tunnel discharge.

### 12.2.2 Amplitude of Rainfall vs. Amplitude of Discharge

So far the conceptual model has focused on rock mass characteristics that control the rate of fluid movement between the surface and the tunnel, namely fracture apertures. Having accounted for travel of water through the rock mass, this section now examines how the rock mass influences the timing of the arrival of fluid in the tunnel, by relating mean rainfall intensity to peak tunnel discharge (relationship no. 2 in section 12.1.3).

In the previous section, the relationship between mean rainfall intensity and fluid transmission time (relationship no.1 in section 12.1.3, Figure 8.6) can be explained by two factors: the statistical distribution of fracture geometry, and the control exerted by un-saturated vs. saturated rock masses. The same mechanism is also a plausible explanation of differences in the relationships between the amplitude of the rainfall signal and the amplitude of the recharge signal observed in Figure 8.7. Between April and August 2012 an increase in mean rainfall intensity was correlated with a decrease in peak tunnel discharge. By contrast, between September 2012 and January 2013 an
increase in mean rainfall intensity was correlated with an increase in peak tunnel discharge.

Like transmission time, negative correlation between two signal amplitudes (Figure 8.7) can be explained by the geometry of fracture sets. The tight fracture sets reach saturation quickly, so they transmit less water to the tunnel than do the open fracture sets. While overall transmission times in tight fracture sets are low, due to fluid-pressure waves, the signal (volume of water) that is transmitted is limited by less permeable flow paths. Net transmission time through open and tight fracture sets between September and January is substantially slower than during the winter months (section 12.2.5), but it allows for the transmission of a far greater volume of fluid per unit time (NRC, 1996) (Figure 7 section 31.2). This signal is expressed as high peak discharge values when large volumes of fluid arrive at the tunnel in a short period of time.

While tight fracture sets limit the total volume of water that can move through the rock mass, surface processes are also capable of reducing infiltration enough to suppress peak tunnel discharge between April and August. The presence of snow or ice on the surface reduces infiltration (de Vries and Simmers, 2002), and the shallow zone of ‘toppled’ schist immediately below the soil horizon (Figure 12.2) provides spaces for rainwater to pool and freeze during times of low air temperature, further reducing infiltration. Snow usually insulates the surface, thereby stopping the ambient ground temperature from changing abruptly. When snow falls on earth with a temperature above 0 °C, surface temperature is too high for ice to persist below layers of snow (Dobinski, 2011; French and Binley, 2004). But if snow falls on frozen ground then it will inhibit the temperature from rising above 0 °C, thus preserving any subsurface ice. Reduction in infiltration is caused by the presence of snow or ice. Because air temperature seldom falls below 0 °C in the area surrounding the tunnel (Appendix A), the presence of permanent ice in the subsurface is unlikely, so a snow cover is most likely the cause of reduced infiltration. The combined influences of fracture geometry and snow cover illustrate the intrinsic link between surface and sub-surface processes.

Figure 8.7 suggests a temporal change in the abundance of snow between the April to August and September to January periods. However, the spatial distribution of snow cover and sub-surface ice is unknown. Snowline surveys of the Southern Alps
conducted by Chin in 1979 and 1995 suggest that snow is permanent above altitudes of 1860 m (± 63 m) (Chinn, 1995b). The snowline of the Franz Josef Region was calculated as 1830 m (±11 m), dropping to 1570 m (± 14 m) between April and August using a lapse rate of 0.5 °C 100 m⁻¹ (Anderson et al., 2006). If snow is assumed to fall when air temperature is below 1 °C (Barringer, 1989), then the same lapse-rate calculation suggest the Tatare Tunnel catchment area may spans a vertical distance of ~1500m above the tunnel. The persistent snow signal in the tunnel discharge hydrograph and the large altitude range that snow falls over mean the tunnel catchment area may be large. A large catchment area also implies that water flows along considerable lateral distances through the hillside before reaching the tunnel.

Reduced infiltration from the winter snow cover will be most pronounced in the April to August period, but its net effect will be determined by its ability to either reduce infiltration or induce infiltration by snowmelt. The net effect will likely also be present in the discharge hydrographs between September and January. In contrast to the April to August period, a more pronounced rainwater signal and a rising water table should mask the effects of snow and ice on the tunnel discharge hydrograph between September and January (section 12.2.3).

Figure 8.7 shows that during the months of September to January, an increase in rainfall intensity is associated with an increase in the amplitude of tunnel discharge, unlike the April to August period. Flow predominantly through open fracture sets between September and January also explains why peak tunnel discharge was greater than in the April to August period. Open fracture sets can transmit larger volumes of water per unit time than tight fracture sets. As a result, the period of the groundwater wave that moves through the rock mass will be small and tunnel discharge will peak at higher values. The arrival of a sharp pulse of groundwater at the tunnel within two hours of rainfall beginning is also consistent with near saturation of the rock mass surrounding the tunnel (Rasmussen, 2000; Schwartz and Zhang, 2003).

Figure 12.3 shows the conceptual model developed so far. Between the April and August (unsaturated) and the September to January (saturated) periods, the fracture sets that transmitted a greater proportion of water changed and the flow of infiltrating water into storage reduced the magnitude of peak discharge between April and August.
12.2.3 Cumulative Discharge: Modelling

Sections 12.2.1 and 12.2.2 focused on the physical factors that control fluid transmission time and the rate at which water arrives at the tunnel during a discharge event; i.e. how fast water travels through the rock and how much arrives at the tunnel at one time. Differences between the April to August and September to January periods were explained by a combination of surface processes and the geometry of fractures in the rock mass. This section builds on these concepts by analysing the cumulative volume of water that enters the Tatare Tunnel during a discharge event. The results of the infiltration model developed in Chapter 7 are used to elaborate on the conceptual model and, with additional tunnel observations from October 2012, lend further support to a shift in the dominant control of tunnel discharge between the April to August and September to January periods.

The most important finding of section 8.4 was that discharge events between September and January were associated with larger values of cumulative tunnel discharge (as defined in section 7.2) for a given amount of rainfall than were storms between April and August. The greater discharge associated with events between September and January (Figure 8.9 and Figure 8.12) meant that they had greater values for the

Figure 12.3: A conceptual model to explain differences in peak discharge between the April to August and September to January

- Flow through tight and open fractures
- Percolation
- Runoff
- Tunnel
- Flow predominantly through tight fracture set
- Percolation
- Runoff
- Tunnel
- Saturated
- Unsaturated
- Flow into storage reduces magnitude of peak discharge

Flow into storage reduces magnitude of peak discharge
infiltration rate and the proportion of rainfall infiltrated (Figure 9.2 and Figure 9.3). These values show that the cumulative discharge is not simply a facet of DE duration, which is influenced by how a discharge event is defined. Rather, more water enters the tunnel in a shorter time between September and January than between April and August.

Several discharge events that transmitted large volumes of water relative to total rainfall were identified. The cumulative discharge of DE 20, 21, 18 and 15 was greater than all other storms in the September to January period. Interestingly, these events not only led to greater volumes of water, but were associated with the highest peak discharge values of all discharge events. Discharge Event 20 suggests that the large, open fracture sets intersected by the tunnel are capable of transmitting fluid at rates of at least 40 l s⁻¹.

The conceptual model uses flow through either open or tight fracture sets to explain differences between tunnel discharge, rainfall metrics and fluid transmission time. However, fracture geometry alone does not explain why the cumulative discharge of events between September and January was higher than for those between April and August. The increased discharge induced between September and January may have resulted from water sourced from lateral, saturated flow in the hillside.

12.2.4 Evidence for a Rising Water Table

The water table is defined as the upper boundary of an unconfined body of groundwater between the saturated (phreatic) and unsaturated (vadose) zones (Schwartz and Zhang, 2003). The presence of air in voids in the rock, and the physical forces of adhesion and capillary action, impede the movement of water in the unsaturated zone. In the saturated zone, where all voids appear filled with groundwater and resistance to flow is markedly lower, flow is described by Darcy’s Law and is primarily a function of hydraulic head. The negative pressure head in the unsaturated zone may inhibit percolation of water into the Tatare Tunnel, whereas if the rock mass surrounding the tunnel is saturated, then the pressure head acting on the water column will drive water toward the tunnel. Therefore, the position of the water table relative to the Tatare Tunnel is an important control on the rate and volume of groundwater that seeps into the tunnel (Moon and Fernandez, 2010; Zaidel et al., 2010; Zhang and Franklin, 1993).
The change from an un-saturated (or variably saturated) rock mass surrounding the tunnel between April and August, to a saturated rock mass between September and January was associated with an increase in the total volume of water surrounding the tunnel, thus enhancing the pressure difference (pressure head) between the tunnel and surrounding rock mass. This increase in hydraulic gradient will drive water toward the tunnel. The pressure at any point below the water table is greater than atmospheric pressure, and tunnel air pressure is equal to atmospheric pressure, so water may flow into the tunnel from all directions, including from rocks below the tunnel floor. Movement of water through the tunnel floor is a strong indication that the water table in the rock mass lies above the elevation of the tunnel floor. This was observed in the Tatare Tunnel during October 2012 and is shown in Figure 12.4. An increase in the elevation of the water table between September and January may explain why cumulative tunnel discharge was greater during this period. Between September and January, rainfall not only entered the tunnel by percolation from above but also the lateral movement of water through the hillside.

Figure 12.4: A photograph taken in October 2012 showing one of several locations where water under pressure water was observed seeping through the tunnel floor. Photo: S. Cox, GNS Science.

Figure 12.5 summarises the conceptual model schematically. Snow was stored on the surface between April and August before melting and infiltrating the rock mass between September and January. The contribution of snowmelt is discussed in more detail in section 12.3.1.1, where the conceptual model is discussed in its seasonal.
context. Between April and August the water table was inferred to lie below the elevation of the tunnel and fluid flow was primarily through percolation, whereas between September and January, the elevation of the water table rose to intersect the tunnel. When the water table rises, saturated flow initiates the lateral movement of water in the hillside and increases the total volume of fluid that can enter the tunnel.

Figure 12.5: An increase in the elevation of the water table from September to January can result in increased tunnel discharge during a rainfall event. Water flowing laterally through the saturated zone can be intercepted by the Tatare Tunnel.

12.2.5 Unexpected Findings: Transmission Times

The conceptual model developed thus far has fulfilled the two criteria outlined in section 12.1.3, namely, the model is realistic and predicts a change in processes between the April to August and the September to January periods. The change in processes is reflected in the sub-surface; when water predominantly flows through either a tight or open fracture set and, on the surface; by the presence or absence of
snow. However, differences in $T_1$ and $T_2$ time intervals between the April to August and September to January periods cannot be explained by the mechanisms invoked in the conceptual model. Differences in $T_2$ values—the time interval between peak rainfall and peak tunnel discharge—between the two periods are explained below and possible reasons for discrepancies in $T_1$ values are discussed.

### 12.2.5.1 Discrepancies in $T_2$ Values

By necessity, peak rainfall occurs soon after the onset of rainfall. Therefore, $T_2$ values represent the movement of a rainfall signal through rock that already contains infiltrated water. Between April and August the lower $T_2$ values presumably resulted from the dominance of fluid-pressure waves (as opposed to the simple flow of water) through tight fracture sets. The movement of water into storage (see section 12.2.2) during the rising limb of the discharge hydrograph ultimately allowed a tight fracture set to saturate, and the force of infiltrating rainfall then expelled fluid stored within the rock mass into the Tatare Tunnel. Because fluid pressure waves travel up to 1000 times faster than the water percolating by gravity over the same distance (Rasmussen, 2000) low-volume, high-abundance tight fracture sets are capable of transmitting rainwater signals more rapidly than un-saturated open fracture sets.

It is likely that many of the $T_2$ values between September and January were controlled by a rising water table in the rock surrounding the tunnel. The rise of a water table relies on the actual flow and accumulation of water, so develops at a much slower rate than the transmission of a pressure-wave (Berkowitz, 2002; Rasmussen, 2000). The rapid transmission of the rainfall signal through the tight fracture sets that control $T_2$ during April to August also occurred later in the year, but was obscured by the rising limb of the discharge hydrograph between September and January. It is concluded that $T_2$ values are controlled by tight fracture sets and fluctuation of the water table, while $T_1$ values are controlled by the open fracture sets.

The greatest discrepancy between the April to August and September to January periods was in their respective $T_1$ values. Given that flow through low-resistance open fractures may control $T_1$ values, reasons for this discrepancy must involve a change in the role of open fractures.
12.2.5.2 Swelling Clays

The accumulation of swelling clays, due to the infiltration of meteoric water into schist, can modify the porosity and permeability of rocks in the brittle crust (Warr and Cox, 2001). By reducing the aperture of open fractures and sealing the intersections of fracture sets, swelling clays can inhibit the flow of water. Reyes (2003) studied the weathering of schist in eastern Otago and found that schist readily weathered to Kaolinite. This mineral was observed in shear zones in the Amethyst Tunnel, indicating that Alpine Schist follows a similar weathering path to schist in eastern Otago, and that the production of Kaolinite is likely to be occurring in the rock mass surrounding the Tatare Tunnel. The formation of clays in the rock mass surrounding the tunnel is ongoing but increases in rock mass saturation between September and January may accelerate weathering processes. Given that Kaolinite is not prone to swelling and shrinking (Warr and Cox, 2001), it follows that swelling clays are unlikely to be responsible for the discrepancy in $T_1$ values between the April to August and September to January periods.

12.2.5.3 Seismic Shaking

The passage of seismic waves can enhance rock mass permeability by initiating new fractures (Sibson, 1996), and may enhance permeability and fluid flow by dislodging precipitated minerals and weathering products from fractures (Sibson, 1992). If sufficient time has passed since the passage of seismic waves, then sufficient weathering products and precipitated minerals may accumulate to significantly reduce rock mass permeability (Manga and Wang, 2007). The central Southern Alps experienced a total of 10 earthquakes greater than $M_w$ 3.0 between April 2012 and January 2013 with an average depth of 5.6 ± 1.6 km (GeoNet, 2013).

However, increases in $T_1$ values between the two periods (Figure 5 section 3.1.2) were abrupt, which is not a characteristic of the gradual accumulation of weathering products. Furthermore, the tunnel shows none of the obvious responses to earthquakes that are typically observed in springs and groundwater systems (Manga, 2001), so the time elapsed since the passage of seismic waves is unlikely to explain the discrepancy in $T_1$ values.

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The above proposals fail to explain difference in $T_1$ values between the April to August and September to January periods, and this requires research beyond the scope of this inquiry. In particular, we require more detailed measurements of surface conditions and fracture apertures.

### 12.3 Model Summary and the Recharge Signal

Inferences from the conceptual model were based on the log-normal distribution of fracture apertures in the Tatare Tunnel (Figure 4.6). The inferred set of tight fractures may correspond to fractures with apertures of between 1 and 2 mm, while the open fracture set may correspond to those with apertures greater than 10 mm. Fractures with apertures between the two end-members also accommodate fluid flow during Discharge Events, but the transmission of fluid will be dominated by one end-member or the other. Additionally, the conceptual model outlined in section 12.2 identified several differences between the April to August and the September to January periods:

1. Between April and August, groundwater flow was predominantly through a pervasive network of tight fractures. The more abundant tight fracture sets became saturated when empty voids filled with water and were then unable to accommodate infiltrating rainfall, whereas during the months of September to January, flow was through networks of tight and open fractures.

2. The rock mass surrounding the Tatare Tunnel was un-saturated between April and August, and variably saturated between September and January;

3. The water table lay below the Tatare Tunnel from April to August but intersected the tunnel between September to January; and

4. During the period of cool weather from April to August snow on the surface and possibly ice in the shallow bedrock resulted in reduced infiltration.

The most important feature of the conceptual model is the difference in predicted flow patterns between the April to August and September to January periods. This difference resulted from changes in rock mass saturation, as well as surface processes that influenced infiltration. The relatively dry period from April to August, and the comparatively wet period from September to January, corresponds with the autumn and winter and spring and summer seasons, respectively. The April to August period spans
the latter half of autumn and the whole of winter, while the September to January period spans the whole of spring and the first half of summer. Groundwater recharge usually occurs during seasons with maximal rainfall and groundwater usually declines during seasons with rainfall minima (White et al., 2003). With respect to the rock mass surrounding the Tatare Tunnel, winter is characterized by dry weather, reduced infiltration, and movement of groundwater into storage, whereas summer is characterized by an increase in rock mass saturation and increased in infiltration.

12.3.1.1 Shifting Recharge Signal

The summary in the previous section placed the conceptual model in its seasonal context, and Figure 12.6 shows that peak recharge occurs in the summer. This interpretation indicates that patterns of recharge in the rock mass surrounding the Tatare Tunnel are influenced by both rainfall and snowmelt, whereas in lowland catchments, the effect of snowmelt is less pronounced (Healy, 2010; Scott, 2004; White et al., 2003).

Figure 12.6 shows monthly rainfall total at Franz Josef in 2012 compared with the mean monthly totals between 2002 and 2012. With the exception of April, October and December the monthly rainfall in 2012 was similar to the 2002-2012 monthly means. A clear spike in the rainfall record occurred in April and a clear spike in the discharge of the Tatare Tunnel occurred in October 2012. The conceptual model suggests that recharge of the rock mass surrounding the tunnel occurred in spring of 2012 (section 12.3.1.1). The approximately 6-month lag from peak rainfall in April to peak recharge in October supports that total rainfall is not the sole control on the timing and magnitude of groundwater recharge.

The timing of recharge at Tatare is attributed to snowmelt infiltration during the wet months of spring and summer. Infiltration was reduced between April and August 2012 when precipitation falling as snow reduced the supply of fluid to the rock in winter (French and Binley, 2004; Marechal and Etcheverry, 2003; White et al., 2003). The most compelling evidence in support of enhanced snowmelt infiltration during spring and summer is a shift in the $^{18}$O and D concentrations of groundwater seeping into the Tatare Tunnel (Figure 10.9). Groundwater samples drawn from the Tatare Tunnel in November 2012 were more depleted in both $^{18}$O and D than samples taken in August and October 2012. This shift along the New Zealand Meteoric Water Line (NZMWL),
toward the snow end-member, suggests that water entering the tunnel in November contained more snowmelt than did water that entered the tunnel in August and October (Marechal and Etcheverry, 2003; Sharp, 2007).

Snow is stored on the surface during winter, but melts and may infiltrate the rock mass during spring and summer. This was expressed as a broad peak in tunnel discharge (attributable to a rising water table) and a shift in $^{18}\text{O}$ and D values between September 2012 and January 2013. It follows that snow storage has a significant influence on the recharge patterns of water storage sites surrounding the Tatare Tunnel.

12.3.1.2 Representativeness of the Study Period

With respect to monthly rainfall totals, but with the exception of April, the 2012 study period appears representative of long-term recharge conditions. However, section 1.2 noted that a large snowfall affected the Franz Josef region in late June 2012. The October discharge peak observed in Figure 12.6 may therefore be due to enhanced snowmelt infiltration (or armouring) in 2012. Rainfall that entered the rock mass in April may have been stored until October, when a rising water table forced the fluid into the tunnel. Given the normally large April rainfall, groundwater levels can be expected to peak in October each year, assuming the influence of snowmelt in 2012 is representative of other years.
Figure 12.6: Mean monthly rainfall between 2002 and 2012 and monthly rainfall for 2012 at Franz Josef. Also included are the monthly discharge values for the Tatare Tunnel between April and December 2012.
Part Two: Model Evaluation

This section evaluates supporting evidence for the conceptual model described in Part One of this chapter. Reference to temperature, chemical and recession analyses, provides an increased level of detail for fluid flow in the rock mass surrounding the Tatare Tunnel. Section 12.4 uses measurements of tunnel air and outflow water temperatures, along with similar measurements for an intermittently flowing fissure to make inferences about changes in water content of the rock mass surrounding the tunnel. Section 12.6 contains more detailed analyses of flow patterns, and compares the hydrograph recession curves from different discharge events. Discharge decay coefficients are interpreted in terms of fracture geometry and area to provide a means to validating the conceptual model of Part 1. Section 12.7 uses chemical analyses to identify fluid flow paths in the rock mass and characterize patterns of flow during discharge events.

12.4 Heat Extraction and Patterns of Fluid Flow

Allis et al. (1979) and Allis and Shi (1995) used models to explain how the rapid uplift rate of the Southern Alps leads to a consistently large heat flux towards the surface. The temperature gradient was measured in shallow boreholes by Sutherland et al. (2012). Rock temperature at the surface is \(~10\) °C, which is comparable with a mean annual air temperature of \(9.8 \pm 0.52\) °C (Figure B1). The ability of flowing fluids to mine heat from rock has been observed at rock temperatures as low as \(3\) °C (Goldstein et al., 2001) so any rainwater that infiltrates the rock surrounding the tunnel can be expected to do the same.

Heat exchange between infiltrating water and the rock mass means that water can extract enough heat from the rock to decrease its temperature by a measurable amount. The initial temperature of infiltrating water, the temperature of the rock mass and the contact time between the fluid and rock are the most important controls on heat exchange.
12.5 Intermittent Fissure Flow

Figure 11.1 showed that the fissure flowed intermittently between April and August. When tunnel discharge exceeded of 3 l s$^{-1}$, the temperature of the fissure abruptly rose. This abrupt increase in temperature was attributed to the flow of warmer water over the probe. The relationship between tunnel discharge and fissure temperature is the result of exchange of heat between the rock mass and the infiltrating water. Rainfall temperature (assumed equal to air temperature at the time) was frequently below 10 °C between April and August. Pulses of infiltration led to pulses of heat extraction from the rock mass, recorded by the temperature of water flowing from the fissure.

Fissure temperatures observed during Discharge Event 6, and the subsequent Anomalous Discharge Event 2, showed a pronounced cooling trend (Figure 11.1). The initial rise in fissure temperature to ~ 10.4 °C implies water that the infiltrating water had equilibrated with the temperature of the rock at that time. The cooling of the fissure to 9.8 °C was interpreted as a decrease in the temperature of the rock mass surrounding the tunnel. A large proportion of this cooling curve occurred during Anomalous Discharge Event 2, which was interpreted as the result of either isolated recharge or snowmelt infiltration (section 12.1.2). The suppression of temperature in rock surrounding the tunnel was likely caused by the low temperature of infiltrating snowmelt. As snowmelt infiltrates, the enhanced temperature differential between fluid and rock means that more heat is transferred from the rock mass to the infiltrating water. The relatively high permeability of the rock mass means that extraction of heat from the rock by the infiltrating snowmelt (advection) occurs at a faster rate than the flow of heat from the rock mass below (conduction) (Goldstein et al., 2001; Healy, 2010). As a result, the cold infiltrating snowmelt lowers rock temperature.

Enhanced temperature differences may explain the cooling curve observed in Figure 11.2, but heat extraction may also result from a significant decrease in the water: rock ratio. A greater volume of water per unit volume of rock is available to extract heat in a saturated rock mass and, at the same time, an increase in hydraulic conductivity enhances the rate at which advection can remove heat from the rock mass. Therefore, an increase in the extent of rock mass saturation will increase the rate of heat mining from the rock, thereby decreasing its temperature.
The results depicted in Figure 11.1 show that in September 2012 the temperature of fissure water rose to approximately 9.8 °C and remained at this level until December 2012. The fact that fissure temperatures remained at the saturated rock mass temperature of 9.8 °C supports the conceptual model outlined in section 12.2; the Tatare Tunnel rock mass was saturated between September 2012 and January 2013. The stability of the temperature reading (9.8 °C) during this time suggests that fluid-rock thermal equilibrium was quickly reached and that the rate of heat extraction by infiltrating water approximately equalled the rate of heat conduction through the rock mass from below.

12.6 Discharge Decay

So far, discussion of discharge and temperature patterns has been restricted to the seasonal level. This section makes a closer examination of patterns of groundwater flow in the rock mass. It focuses on the recession curves of individual discharge events and relates discharge decay coefficients to fracture geometry and elements of the conceptual model (Figure 8.8). Two findings of Chapter 8 support the conceptual model of flow in rock surrounding the Tatare Tunnel:

1. Peak discharge was positively correlated with rate of discharge decay between September and January; and

2. The recession curves of discharge events between April and August showed rapid decay coefficients and variable behaviour. Given the un-saturated conditions that likely prevailing in the rock mass during this period, recession analyses techniques were not suitable. Therefore, these curves were not given further attention.

Maillet (1905) was the first to show that recession curves can be characterized by exponential decay. The value of the exponential decay coefficient (the ‘decay exponent’) embeds information on aquifer characteristics such as permeability and rock storage capacity (Amit et al., 2002). The rate at which discharge decays once rainfall has ceased is directly determined by the rate at which the rock mass is drained of water. For example, high decay exponents in karst aquifers were interpreted by Bonacci (1993) as the consequences of more direct flow paths, an observation supported by the results of similar studies by Amit et al. (2002) and Kresic and Bonacci (2010). The
authors then expanded their interpretation to fractured rock in general. The differences in decay exponents observed in Figure 8.8 are interpreted as the result of different permeabilities or, more specifically, increasing rates of flow through open fractures with greater mean aperture. Although the tight fracture sets are more abundant than the open fractures, their lower mean aperture means they transmit lower volumes of fluid. As infiltration continues, these low aperture fracture sets fill to capacity, forcing excess water begins to ‘spill’ and flow through the open fracture set. Therefore as the volume of infiltrating water exceeds the rocks storage reservoir, an increasing proportion of flow moves through open fracture sets.

Figure 8.8 shows a trend towards increasingly rapid drainage of water with increasing peak discharge for the months of September to January. This relationship is interpreted as the product of flow through a high-volume, open fracture set. The larger mean aperture of open fracture sets allows the passage of high volumes of water per unit time, but open fractures have low storativity and drain rapidly. During high intensity rainfall events, such as Discharge Event 20, the rock mass surrounding the Tatare Tunnel could transport large volumes of water, meaning little opportunity for water to move into storage.

The inflection in the receding limb of the discharge hydrograph occurred when quickflow ceased and the drainage of less permeable portions of the rock mass (the tight fracture set) dominated the discharge hydrograph (Amit et al., 2002; Manga, 2001; Padilla et al., 1994). The rapid sequence of Discharge Events and the continued influence of rainfall between September and January, meant that the discharge hydrograph rose abruptly to its inflection point. Therefore, drainage of the saturated, tight fracture set cannot be conclusively identified in the Tatare Tunnel discharge hydrograph.

12.7 Residence Time

Having used temperature and recession curve analyses to evaluate the conceptual model proposed in section 12.2, this section examines fluid flow in more detail by considering the residence time of fluid in the rock mass. Chemical analyses were also used to infer different fluid flow paths feeding the tunnel and to infer changes in rock mass saturation during discharge events. The interpretations of chemical analyses are then couched in terms of the conceptual model. The increased detail possible using chemical
analyses provides a means of (a) identifying whether or not there is evidence of variations in rock permeability along the length of the tunnel, (b) assessing whether or not changes in rock mass saturation control patterns of tunnel discharge during a discharge event and, (c) identifying the major products of chemical weathering in the rock mass surrounding the tunnel.

12.7.1 Flow Path Identification by Chemical Analyses

Figure 10.6 shows a clear distinction between the different sampling sites within the tunnel, with seep sites closer to the eastern end of the tunnel generally having greater concentrations of ions in solution. This is interpreted as the result of a greater tunnel overburden and correspondingly longer groundwater flow-paths. Increased length of flow path means that fluid is in contact with fracture walls for longer. As the relationships in section 10.1 show, any increase in fluid-rock contact time leads to an increase in ion concentrations.

Tweed et al. (2005) used such a pattern to distinguish different flow path lengths in the fractured rocks of the Dandenong Range in South Australia, and showed that major ion geochemistry is a practical alternative to the more expensive isotope methods (for example (Brantley, 1998; Clow, 1997)). Frape et al. (1984) used major ion concentrations to distinguish dilute, shallow groundwater, flowing through high permeability areas from deep, saline groundwater in the Canadian Shield. Increases in fluid-rock contact time may also arise from differences in the ratio of fluid volume to surface area for a flow path. Fluid that moves through fractures with a smaller aperture contacts a greater area of rock per unit volume of fluid, thus liberating more ions into solution. In such instances relative increase in reaction surfaces leads to diffusion dominating over dilution. Flow through less permeable, more tortuous fracture sets results in increased chemical concentrations compared to the situation in more permeable fracture pathways (Holloway and Dahlgren, 2001).

Shimojima et al. (1993) and Shimojima et al. (2000) used electrical conductivity, a strong indicator of ion concentrations, to distinguish between the slower, less permeable matrix flow paths and the faster, more permeable, fissure flow paths for a mountain tunnel in Japan. Although the carbonate rocks of this area imparted a stronger chemical signature than did those of metamorphic origin, different portions of the
Tatare Tunnel showed differences in chemical concentration. These differences are interpreted as the result of fluid flow pathways of differing length and permeability.

The explanation above suggests that the eastern section of the Tatare Tunnel, that shows more concentrated seeps, has a greater overburden and a less permeable network of fractures than does the western section.

12.7.2 The Chemical Signature of a Discharge Event

The chemical analyses suggests that the groundwater seeping into the eastern portion of the tunnel follows a longer pathway and may flow through less permeable rock. Examining change in concentration at sampling sites during a discharge event is a means of assessing this finding and a way to tell whether or not stored water is flushed from the rock by infiltrating rainwater.

To identify patterns in ion concentration raised difficulties given that repeated samples were taken from five sampling sites within the tunnel. In order to simplify the interpretation, the Ca\(^{2+}\) and Mg\(^{2+}\), Na\(^{+}\) and K\(^{+}\) and the SO\(_4\)\(^{-}\) ions were grouped together. The grouped ions had identical valences, so were expected to behave in similar ways. This allowed patterns to be identified at the different sampling sites.

At all sampling sites the ionic concentration of waters changed as Discharge Event 4 progressed. Additionally, the style of change differed between sampling sites (Figure 12.7). The decreasing concentration with time for almost all groups, together with an increasing dominance of dilution over diffusion, is consistent with either enhanced rates of advection or an increase in the fluid volume: rock surface ratio. Enhanced advection is caused by an increase in the velocity of water as the rock saturates, due to an increase in the hydraulic conductivity. Whereas an increase in the ratio of fluid volume to rock surface area results from an increase in the total volume of fluid in the rock diluting the ionic solution (Pacheco, 2012).

While evidence of dilution was found along the tunnel, seeps located 275 m from the western entrance exhibited different behaviour. Several ions at this site appeared to be either increasing in concentration, or first increasing then decreasing. This kind of behaviour, in which fluids rich in solutes are ‘flushed’ from the rock, has been observed at the aquifer and catchment scale (Burns et al., 1998; Craw, 2000b; Davies et al., 2011; kim, 1999). Interestingly, the Cl\(^{-}\) ion was the only one that did not follow the
trend of decreasing concentration during DE 4. The greater amounts of Cl\(^-\) in solution can be attributed to increasing input from rainwater. Cl\(^-\) is not noticeably diluted because, unlike ions liberated from the rock mass, its supply is effectively unlimited.

The increased fluid volume inferred for the first ~250 m of the tunnel is compatible with the observation that this portion of rock occupies a different part of the diffusion-dilution pathway. Saturation of the rock mass increased as DE 4 progressed, but the western portion of the rock mass became saturated faster than the eastern portion. The faster saturation at the western end of the tunnel suggests a more permeable rock mass. The greater overburden at the eastern tunnel portion means that the total volume of material available for flushing, and the time for this to occur, are greater than at the western end. While major ion geochemistry has been used to distinguish flow paths in other studies (e.g. (Craw, 2000b; Shimojima et al., 2000; Tweed et al., 2005)), the analyses presented here have achieved this in greater detail. Figure 12.7 summarises concentration patterns across the different sampling sites in the Tatare Tunnel.

Figure 12.7: The behaviour of ions during DE 4 in May 2012. Two sections of the tunnel were identified, net dilution was observed at the western end and the flushing cycle was observed at the eastern end of the tunnel. Large blue arrows indicate the relative flow rates of seeps and fissures. The tunnel outflow behaviour is not directly comparable with other sites as it is influenced by gravel on the tunnel bed.
12.7.3 Chemical Weathering

The dissolution of individual ion species has been described but so far with little consideration of chemical weathering. Section 10.1 showed that increasing water-rock contact time leads to increasing proportions of Ca\(^{2+}\) and total hardness as well as decreasing proportions of Na\(^+\), K\(^+\) and Cl\(^-\). The Amethyst Tunnel samples showed significantly higher proportions of SO\(_4\)\(^-\), which increased with greater tunnel overburden. Rainwater samples were relatively pure and contained the highest proportions of Cl\(^-\). The increasing dominance of Ca\(^{2+}\) appears to be at the expense of Na\(^+\) and K\(^+\).

Calcite, which is often found as a secondary precipitated mineral in fluid flow paths, has dissolution rates up to 30 times faster than those of other minerals, so it tends to dominate the cation signal observed in waters that interact with it (Craw, 2000a). The trend to increasing proportions of calcite can be explained by the greater dissolution rate of Ca\(^{2+}\). The laboratory experiments conducted in this research, however, contradict the findings of Craw (2000b) and Litchfield (2002) and showed dissolution rates of Mg\(^{2+}\) are higher than those for Ca\(^{2+}\). The samples used in the laboratory experiments were representative of the rock mass surrounding the tunnel, and calcite veins were absent. The decreased rate of Ca\(^{2+}\) dissolution is therefore attributed to its limited abundance in the sample. Figure (results rock sample) shows that Mg\(^{2+}\) proportions were slightly higher in the sample rock and thus were more readily available to be dissolved. It follows that proportions of Ca\(^{2+}\) do not provide particularly useful insights into water residence time because water quickly saturates in Ca\(^{2+}\). Given that fractures, and therefore fluid flow, are mostly along existing rock discontinuities, it is likely that infiltrating fluid will contact the precipitated calcite.

Craw (2000b) and Rosen (1998) found that fully-equilibrated waters in schist had Na:Cl ratios of 2:1. Na:Cl ratios in experimental waters steadily increased from 0.3 to 1.54, indicating that for the volume of fluid used, equilibration was not possible in 174 days. Tunnel waters showed a steady increase in Na:Cl ratios with greater distance from the western tunnel entrance. This association is consistent with a greater inferred rock-contact time. The steady increase in Na\(^+\), relative to Cl\(^-\), is attributed to the dissolution of Albite (Rosen, 1998).
Given the dominance of the calcite signal, and its likely presence in the rock mass surrounding the tunnel, cation concentrations on their own are not good indicators of water-rock contact time. The Na:Cl ratio is the next best candidate for tracking the development of water-rock equilibrium. However, this relationship was established in systems where influx of rainwater occurred on timescales that did not drastically alter Cl\(^-\) concentrations. The fluid system in the rock around Tatare Tunnel has persistent flux during Discharge Events, and dilution and additional inputs of Cl\(^-\) meant that chemical signature of tunnel water can not accurately reflect rock contact time.

12.7.4 Chemical Analyses and the Tatare Rock Mass

While major ions were not especially good tracers of water-rock contact time in the shallow setting of the Tatare Tunnel, they did shed light on the relative saturation of the rock mass during Discharge Events. The observation that rock at the western end of the Tatare Tunnel became saturated more rapidly than did that at the eastern end can be used to draw two spatial inferences about the rock surrounding the tunnel. (1) fluid flow-paths are longer in the eastern portion of the rock mass and (2) the western portion of the rock mass saturates more readily. The preferential saturation of the rock mass at its western end could be true for two reasons: a thinner overburden or, increased volume of stored water. An increase in the volume of fluid stored would mean less infiltration is required to fill all voids with water, thereby rapidly saturating the rock mass.

The chemical analyses provided insight into the spatial distribution of open and tight fracture sets discussed in section 12.1.4, as outlined in the conceptual model. Preferential saturation of the western portion of the rock suggests that the fracture network is more pervasive in this section of the rock mass and that tight fracture sets are more common there than open fracture sets.

While addressed separately, the findings of the physical (fracture geometry), flow, thermal and chemical analyses are all mutually supportive. By analysing the rock mass with different methods and at different scales a more comprehensive understanding of shallow fluid circulation has been attained.
Chapter 13: Conclusions and Research Prospects

13.1 Conclusions

While rainstorm events are the main driver of increases in tunnel discharge, the anomalous discharge events observed in this research suggest that an additional source of tunnel discharge, either recharge at altitude or snowmelt infiltration (neither of which was recorded at Franz Josef), initiated increases in tunnel discharge. The anomalous discharge events show that rainfall over a small surface area can be responsible for significant recharge, and that snowmelt infiltration is capable of inducing increases in tunnel discharge comparable to significant rainfall events.

In several instances increases in tunnel discharge preceded the onset of rainfall taken from the rain gauge at Franz Josef, suggesting that the start of rainfall at the township may occur after rainfall begins above the Tatare Tunnel. \( T_1 \) and \( T_2 \) values were greater during the September to January period than in the April to August period. Although several explanations for this were proposed in section 12.2.5, the reason for this difference remains unknown.

Changes in surface processes between the April to August and September to January periods resulted in changes in the relationships between transmission time, tunnel discharge and rainfall. Between April and August snow on the surface and ice in the underlying zone of toppled schist, reduced the proportion of rainfall that infiltrated the rock mass. Therefore, infiltration rates are seasonally dependent, with the proportion of rainfall infiltrating the crust being less in winter.

A greater volume of tunnel discharge was induced by rainfall events between September and January than from April to August. This was attributed to increased infiltration and a reduced capacity of the rock mass to ‘buffer’ infiltration through storage. Infiltrating water was evidently forced into storage between April and August, reducing the total volume of water able to reach the Tatare Tunnel. Between September and January, however, the propagation of hydrostatic pressure waves expelled stored water into the tunnel.
The log-normal distribution of fracture apertures in the rock mass surrounding the Tatare Tunnel has two end-members: tight fractures with small apertures, and open fractures with larger apertures. While tight fractures are more abundant in the rock mass, open fractures are capable of sustaining flows of up to 40 l s\(^{-1}\). These two types of fracture explain variations in the rate and volume of groundwater movement between April 2012 and January 2013. Chemical analyses indicated that different parts of the rock mass surrounding the tunnel became saturated at different rates. The rock above the western portion of the tunnel is more permeable, and as a result this area saturated more quickly during rainstorms than did the eastern portion of rock. Furthermore, fluid likely flowed through more tortuous pathways in the rock above the eastern portion of the tunnel.

Between April and August 2012, groundwater flow was predominantly through the tight fracture set, whereas between August 2012 and January 2013 groundwater flowed through the tight and the open fracture sets. As water seeps through tight fractures an unknown proportion flows into empty voids, where it will lead to gradual saturation of the rock mass. As the storage capacity fills, a greater proportion of water will flow through open fracture sets. Because more water apparently flows through open fracture sets during high-intensity rainfall events, less water is moved into storage at such times. The change in behaviour between the two periods is the result of the rock mass becoming saturated.

The flow of water into empty voids between April and August may explain why the rock mass was un-saturated at that time, and that flow was primarily by percolation. When the rock mass was saturated between September and January, however, the water table increased in elevation and intersected the tunnel. As a result, a significant proportion of the flow that entered the tunnel was by lateral movement of groundwater.

Anomalous discharge events showed that snowmelt infiltration can be an important source of groundwater in the rock mass surrounding the tunnel. The increased elevation of the water table between September and January may be in part due to the infiltration of snowmelt that melts during spring. The presence of snow on the surface can shift the recharge signal from winter to spring, so snow may constitute an important control on rates and patterns of infiltration.
This over-arching aim of this thesis was to gain a first-order understanding of shallow fluid circulation in the rock mass above the Alpine Fault. Despite difficulties associated with a lack of empirical data the thesis used the Tare Tunnel to provide insight into rates and patterns of infiltration and groundwater movement. A conceptual model was built that allowed the important links and feedbacks between atmospheric, surface and sub-surface processes to be identified and evaluated, especially the influence of snow cover and rock mass saturation.

13.2 Research Prospects

13.2.1 Snowmelt Infiltration

The total volume of snow that falls in mountain areas is often unknown or inaccurately estimated. Given that snowmelt infiltration is an important control on the total volume of fluid available to percolate through the crust, a better understanding of this process is needed. The first step in quantifying rates and patterns of snowmelt infiltration will be to measure the proportion of precipitation that falls as snow. A practicable approach will involve a combination of modelling and surface measurements. Specialised gauges to measure snowfall have recently been employed in the Southern Alps (e.g. Kerr, 2012) and used to establish relationships between meteorological variables and amounts of snowfall. These same gauges could be used in conjunction with sub-surface measurements of infiltration to establish relationships between it and total snowfall.

Ablation stakes used on glaciers provide a cheap and effective method that can be widely deployed to measure cumulative snowfall after a storm event or at the end of winter. Coupled with good rainfall measurements, reliable estimates of the total volume of snowfall would allow water budget modelling to better account for the proportion of groundwater (or runoff) that is sourced from snow.

A better understanding of the amount of snowmelt initiated by increases in temperature, in the absence of large glaciers, would allow for the more accurate predication of snowmelt events. The volume of snow stored on the surface above the Alpine Fault is potentially large, scarcely accounted for, source of water for infiltration. Seasonal pulses in snowmelt may reach the Alpine Fault and affect its behaviour. Therefore, quantification of snow and controls on melting are important aspects of the shallow fluid circulation process that require further research.
13.2.2 Storage Properties of Schist

Fluctuation of the water table within the schist rock mass adjacent to the Alpine Fault is largely controlled by the storage and drainage of water. A better understanding of the rate at which water moves into and out of storage (storativity) in the schist is required. The volume of water stored in a rock mass determines effective stress levels in shear zones and other planes of weakness. Therefore, effective stress levels in the rock mass may follow a similar pattern to seasonal or event scale fluctuations in the elevation of the water table. Many slopes in the Southern Alps have been steepened by glacial erosion and are prone to sudden failure (Barth, 2013; Cox et al., 2012b; Korup et al., 2005). Coupling between the water content of the schist and the probability of slope failure means that a better understanding of the storage capacity of Alpine Schist is likely to lead to more reliable landslide hazard assessment.

13.2.3 Fracture Distribution

The storage capacity of schist determines the saturation of the rock on a seasonal timescale. The orientation and apertures of fractures within the shallow crust are primary determinants of rock mass saturation during a storm event. A log-normal distribution of fracture apertures was proposed for the Tatare hillside and suggests how large volumes of water can be transported through the rock in a short period. Aperture size, abundance and orientation of fractures at greater depth control the transmission of water toward the Alpine Fault and the saturation of the Alpine interior. Investigations into whether or not fracture patterns in the shallow crust are representative of conditions at greater depth would allow the probability of deep-seated landslide failure to be better estimated. A better understand of how forcing in the shallow crust—such as hydrostatic pressure waves and pulses of snowmelt infiltration—affects earthquake nucleation and friction during seismic events is required.

Investigations into structural characteristics of the rock mass at greater depth would best be achieved by instrumented boreholes and tests that determine hydraulic conductivity and storage. The 2 km deep borehole proposed by the Deep Fault Drilling Programme is an excellent candidate. Water table monitoring at greater depths could be used with continued discharge measurements at the Tatare Tunnel, along with water level and temperature measurements from the 150 m deep DFDP 1B borehole, to
compare the recharge signal near the surface, in the shallow crust and on the Alpine Fault.

Future research should focus on better quantifying the infiltration of meteoric water into the shallow crust, and estimating the proportion of infiltrated water that is transferred to greater depths. An enhanced understanding of both would enable greater understanding of the dynamics of the Alpine Fault, landslide hazards and the behaviour of the landscape during earthquakes.
## Appendix A: Descriptive Statistics for Discharge Events

Table 8: Basic storm characteristics for both rainfall and tunnel discharge for all 21 Discharge Events. Negative timing values occur where an increase in tunnel discharge precedes the onset of rainfall at Franz Josef.

<table>
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<th>Storm No</th>
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<th>Rainfall</th>
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<th>T&lt;sub&gt;2&lt;/sub&gt; (Hours)</th>
<th>T&lt;sub&gt;3&lt;/sub&gt; (Hours)</th>
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Appendix B: Franz Josef Air Temperature

Figure B1: Franz Josef air temperature 2003 – 2013. Mean annual air temperature (9.8 °C) is indicated by the red line.
References


Unidata 2011. Starflow Ultrasonic Doppler Instrument With MicroLogger - Model 6526. 3.4 ed. Unidata Pty Ltd 40 Ladner St, O'Connor Western Australia 6163.: Unidata Pty Ltd.


