Effects of scale and spatial variability on streamflows in NZ Alpine catchments

By

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Abstract

Mountain catchments have high spatial variability, but these catchments are the freshwater resources of the world and will be affected by potential future climate change. In this study the TopNet hydrological model is used with soil, landcover and elevation, with climate information from Virtual Climate Station network (VCSN) to calibrate present flows and estimate future flows in the Hakataramea, Ahuriri and Pukaki catchments and sub-catchments. The spatial variability is strongly influenced by the Main Divide of the Southern Alps, which creates a rain shadow effect with significantly higher precipitation near the divide and lesser further away from the divide. This variability is more distinct in sub-catchment scale compared to catchment scale. There is not much difference between present and future flows in the Hakataramea catchment, but the Ahuriri and Pukaki catchment future flows are significantly higher than present flows. The increase in future temperatures will cause more snowmelt and reduce the possibility of snow, while the possibility of rain increases: sub-catchments also showed similar results. The changes in timing and seasonality in future flow will have negative impacts on domestic, agricultural, commercial and industrial water users and detrimental effects to some endangered birds and other aquatic and plant species from the loss of habitat. Hydroelectric stations will enjoy positive impacts but may also suffer from an increase in flood and erosion frequency. The information of future flows can be analysed and planned for beforehand to minimise the negative effect on people, animals and plants. The precipitation is estimated using VCSN in 5 km x 5 km: this increases the accuracy of modelling, because there are sparse rain gauges in mountains. Similar studies can be done in other mountainous areas or even plain areas with similar precipitation to confirm these findings.

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Chapter 1. Introduction

Climate change is expected to change future temperatures and precipitation around the globe. This will lead to extreme weather events and related natural disaster if the problem of climate change is not addressed now. The earth's surface has been successively getting warmer since the last millennia and records from satellites and remote sensing, available since 1950, show unprecedented warming (IPCC 2013). The research shows high confidence that the temperature increase during the 1983-2012 period was the warmest 30-year increase in the past 800 years' history of the Northern Hemisphere. The increase in global mean temperature is projected to increase between 0.3 to 4.8°C. However, the increase and decrease depend on location. The global surface temperature will change between -0.5 to 9°C with higher increases inland and away from the sea. Future precipitation increases in some area and decreases in some other areas. Precipitation in the high latitudes and equatorial Pacific Ocean will increase up to 50% (IPCC 2013). These increases and decreases are for the 20-year period between 2081-2100, compared to a baseline period of 1986-2005.

Mountainous catchments are highly variable spatially, therefore any future change in temperature and precipitation will affect flows in these catchments in different ways. The increase in future temperature will increase snowmelt (Gawith et al. 2012). Changes in future temperature and precipitation will affect seasonality and the magnitude of streamflow from mountain catchments. Mountain catchments are sources of most of the freshwater resources in the world (Viviroli et al. 2011), therefore streamflow from these catchments support a large proportion of the 7.2 billion people currently living on this earth.

Water from these mountainous catchments provides water supplies for agriculture, industry and drinking purposes. These catchments also provide water for wildlife cycles, including spawning, migration, and reproduction of species, with these activities linked to particular seasons and flow regimes. Changes in flow availability can range from significantly lower flows than required to significantly higher flows causing flooding. Any significant change in timing and magnitude of flow can have negative impact on water uses and can be detrimental to aquatic species. To better understand the effects on streamflow from the mountainous catchments, it is essential to study the drivers of spatial variability in these types of catchments.

1.1 Spatial variability in mountain catchments

Mountainous catchments are heterogeneous in nature because of the high spatial variability created by soil type, vegetation, bedrock, slope, aspect, wind patterns and elevation. The physiographic complexity of mountains can create a hierarchy of environments at the local scale and dominant climatic patterns on the regional scale (Shafer et al. 2005). Grant et al. (2004) suggested the source of variability may be because of static properties (e.g., soil type) or dynamic properties (e.g., precipitation). Grant et al. (2004) studied the spatial variability in Reynolds Creek Experimental Watershed, Idaho, USA, and their findings showed higher spatial variability and lower temporal variability in the catchment. They attributed this to catchment heterogeneity and similarity in soil type respectively. In a study of 181 catchments of Europe, Donnelley et al. (2016) reported strong relationships between long-term flow and upstream area, agricultural soil, elevation, mean temperature and mean precipitation.

Pan et al. (2012) found that the soil properties, geology and landscape are more important than precipitation in small rural catchments because these properties determine the portion of precipitation that is converted into streamflow. This study does not show which physiographical property is more important for runoff generation. Geris et al. (2015) emphasised that soil type has a dominant effect in runoff generation, compared to the vegetation in headwater catchments on both plot and catchment scale. However, their study catchments do not consider seasonality in precipitation. When the natural forest of the Comet river catchment in Australia was cleared, a 78% increase in streamflow was reported, compared to the pre-clearing period (Siriwardena et al. 2006).

Most studies are paired catchment studies where two nearby catchments, having similar climate, soil, elevation and slope, are compared for water yield in each landcover type. Also, comparisons are usually performed for 100% area conversion: this lacks spatial distribution, as there may be many landcover types in a catchment. Fahey and Payne (2017) found that annual water yield is reduced by 33% between tussock and *Pinus radiata* catchments. Most research in landcover is done using paired catchments, where one catchment is used as a control; however, these paired catchment studies consider only one type of landcover, while most catchments have several types of landcover within a single catchment. Most studies are based on catchment-scale changes, which lack higher resolution or sub-catchment change because the landcover is spatially variable, even within a small area, and, catchment-wise, the studies cannot be representative.

Birsan et al. (2005) studied streamflow trends in 48 catchments of Switzerland. They found that streamflow was positively correlated with mean elevation, glacier area and rock and negatively correlated with catchment average-soil depth. However, all their study catchments were Swiss alpine catchments, which lacked spatial variability such as dry vs wet and regulated vs unregulated (natural) catchment. Furthermore, if the mountain has a dominant effect on orographic precipitation, then elevations on the leeward and windward sides may have different precipitation and flow regimes. Staudinger et al. (2017) investigated the role of elevation in catchment water storage. They reported an increase in elevation resulted in the largest dynamic and mobile water storage. The streamflow in lower elevations of the Colorado River Basin (USA) depends on the proportion of rain vs snow, while in higher elevations it depends on the timing, recharge, magnitude and storage capabilities of sub-surface water. While earlier researchers have reported on the role of elevation in streamflow generation, these studies are based on catchment scale or large river basins: these are not comparable to the mountain catchment of New Zealand, with its remarkably high spatial variability, which needs a smaller or sub-catchment scale study.

Berghuijs et al. (2014) suggested that the influence of temperature on flow depends on whether the catchment is snow dominated or rainfall dominated. They found that snow-dominated catchment produced more streamflow compared to the rainfall-dominated catchment for the same temperature in coterminous United States. Simoni et al. (2011) researched the spatial variability of streamflow generation in an alpine catchment of the Swiss Alps. They found that the near-surface air temperatures responsible for snow accumulation and streamflow in the catchment were influenced by topographic variability such as slope, aspect and elevation. The spatial variability in snow-water equivalent (SWE) results from different hierarchical processes occurring either at hillslope or catchment scale (Clark et al. 2011). They further highlighted that the SWE at the hillslope scale is governed by snowdrift, non-uniform distribution of snow in forest canopies and snow trapped by shrubs, while spatial variability at the catchment scale is governed by elevation and temperature gradients. Clark et al. (2011) studied the spatial variability of snow data collected from the Jollie catchment of New Zealand. Their findings showed that hill-slope spatial variability was most pronounced at a spatial scale of less than 100m, and, after this was averaged out, a strong correlation was found between the snow depth and elevation. Spatial variability of snow accumulation on the windward (Franz Joseph Glacier) versus leeward studied (Tasman Glacier) sides of the Southern Alps by Purdie et al. (2010). Wind, temperature, and topographic interaction was found highly significant for Franz Joseph Glacier; however, interaction between wind and topography was only able to explain some of the variability in snow accumulation,

Topographical variability leads to a contrasting rainfall regime in the Yellowstone region of the northern Rocky Mountains (USA) when it interacts with large-scale atmospheric circulation (Shafer et al. 2005): northern and eastern parts of Yellowstone receive the major proportion of their annual precipitation in summer while southern and western parts receive the major proportion of their annual precipitation in winter. The summer-wet areas receive moisture from the Gulf of Mexico and summer-dry areas receive winter moisture from the Pacific Ocean (Whitlock and Bartlein 1993). In New Zealand, the Southern Alps, which are 700 km long and 2500 m high, act as a barrier to a dominant westerly circulation, creating different precipitation regimes (Purdie et al. 2010). The western part of the Southern Alps, which is on a windward side, annually receives as much as 12,000mm precipitation. However, the eastern part (leeward side) receives only 600mm (McCauley and Sturman et al. 1999). Research has been done previously to find out the orographic effect of mountains. The effects of windward and leeward side precipitation distribution in mountains have been studied globally and in New Zealand. However, these previous studies focussed on catchment scale and large area. Because of the large spatial variability in New Zealand mountain catchments, the orographic or rain shadow effect of the mountain needs to be investigated in different catchments, as well as different sub-catchments of the same catchment.

1.2 Climate change in mountain catchments

The study of climate is the study of weather events over an extended period. Climate change refers to change in the long-term average weather (>20 years) (Reisinger 2009). The Intergovernmental Panel on Climate Change (IPCC 2007) defines climate change as change in the state of the climate, which can be found (e.g., using statistical tests) by changes in the mean, and change that persists for an extended period: typically decades or longer (IPCC 2007). Earth’s climate is changing, and it will continue to do so despite mitigation efforts (Trenberth 2006). The IPCC states that warming of the climate is unequivocal, as is now clear from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea levels (IPCC 2007).

Anthropogenic climate change refers to changes caused by human activities that are responsible for increasing the concentration of water vapour, carbon dioxide, methane, halocarbons, methane, ozone and nitrous oxide (Garbrecht et al. 2006). Solomon et al. (2009) reported it will take 1000 years to complete the reversal of human-induced Carbon Dioxide (CO_2) after emissions are stopped. Direct measures of climate are ascertained by measuring the average surface temperature of the Earth. Measurements are also taken from the sea, by ship, because oceans cover almost 70 per cent of our planet. Brohan et al. (2006) analysed 150 years (1850–2005) of historical surface-temperature data. They reported that there was some uncertainty until the mid-20th century. However, the temperature increase over the 20th century is significantly greater than that of previous centuries, even taking uncertainty into account. Average Arctic temperatures increased at twice the global average rate in the past 100 years (IPCC 2007).

While the global land surface temperature increased by 1.12°C between the period 1905-2015 (Hansen et al. 2010).

1.3 Impact of climate change on temperature

IPCC (2013) reported a 0.85°C rise in global average temperatures in the past 100 years, causing an increase in temperature-related extremes. Hot days, hot nights and heat waves are more frequent in the later years in comparison with earlier periods. Hamlet and Lettenmaier (1999) analysed the change in average temperature in the Colorado River Basin (USA) using two General Circulation Models (GCMs). They projected average temperature increases of 1.8°C–2.1°C for 2025, and 2.3°C–2.9°C for 2045. Kerkhoven and Gan (2010) showed an average 4°C rise in temperature in the Fraser River Basin of Canada. Temperature plays a crucial role in the timing of snowmelt. Regions having a large portion of runoff driven by snowmelt would be especially susceptible to changes in temperature because temperature determines the fraction of precipitation that falls as snow and the timing of snowmelt (Vicuna et al. 2007). Since 1950, average temperatures have increased over most of Australia by 0.9°C, although with significant regional variations (CSIRO and BoM 2007).

The Ministry for the Environment (MfE 2008) summarised that future climate change in New Zealand, in general, will be an increase in mean temperatures, fewer frosts, sea-level rise and more rainfall on the west side of country than on the east side. The mean temperature increase for New Zealand is projected to be between 0.7°C and 3.7°C in 2040, 2090 and 2110 with the largest warming at higher elevations, considering different emission pathways and the IPCC 5th assessment (MfE 2016). Previous studies indicated that future temperature increase will be sensitive to snowmelt and runoff generation in the Clutha catchment of New Zealand (Poyck et al. 2011; Gawith et al.

2012) and in Upper Waitaki catchments (Caruso et al. 2017b). The international consensus is to reduce emissions to limit the global temperature rise to below 2°C by next century. The viability of this is questionable (Meinshausen et al. 2009). Anderson (2011) cautioned that if the temperature rise by the end of this century is more than 2°C, the implications will change from dangerous to extremely dangerous. The current emission trend has not declined, and it is slightly lower than the highest SRES marker scenario (A1F1). This study attempts to address this trend using the A2 SRES emission scenario for climate downscaling, one that is higher than a middle-of-the-road or average A1B scenario. In a what-if scenario report, Ministry for Primary Industries (MpI, 2013) illustrated the overall climate change impact on New Zealand if global temperature rise is 4°C by the end of this century. It simulated a 3.1°C to 4.4°C temperature rise in New Zealand based on the A2 SRES scenario and two different GCMs. However, there is not enough study to research the effects of the temperature increase in the mountainous catchment of New Zealand.

1.4 Impact of climate change on precipitation/streamflow

Several researchers have studied the effect of climate change on snowmelt, water resources and floods in different parts of the world (Zierel and Burgman 2005; Horton et al. 2006; Christensen and Lettenmaier 2007; Kerkhoven and Gan 2010). Zierl and Bugmann (2005) showed that the overall effect of different GCMs under SRESs will be substantial in shifting the runoff pattern across the European Alps. Their study findings showed increased winter runoff, reduced summer runoff, and a shift of snowmelt-induced peak flows to earlier dates. Horton et al. (2006) suggested the specific mean annual discharge in mountainous areas is generally higher than in catchments located at lower altitudes in the same climatic region. Higher precipitation amounts are induced by orographic effects and evapotranspiration rates are low, largely because of relatively low mean temperatures. They also found that the hydrological pattern of such environments is strongly influenced by water accumulation in the form of snow and ice and the corresponding melt processes that result in a pronounced annual cycle. Christensen and Lettenmaier (2007) studied the effect of climate change in snowpack and precipitation patterns of the Colorado River using different GCMs and SRES scenarios. Their findings showed a modest (−2% to +1%) change in precipitation and a significant decline in Snow Water Equivalent (SWE), which is the depth of water that the snowpack would produce if melted. SWE declined up to 38%, primarily because of higher winter temperatures, resulting in a decrease in the ratio of precipitation falling as snow versus rain. They also modelled the sensitivity of runoff with a 10% increase in precipitation. Their result showed winter runoff increased by 38%; however, summer runoff increased only by 23% in the studied catchment. The study by Kerkhoven and Gan (2010) suggested a large decline in annual runoff in the Athabasca River Basin of Canada by the end of this century. They showed −21%, −4.4%, and −41% average changes in annual runoff, mean maximum annual flow and mean minimum annual flow respectively, using different combinations of GCMs and SREs.

Climate change impacts on snowmelt, precipitation, streamflow and floods have been studied in New Zealand (Mpelasoka et al. 2001; Lill 2003; Sansom and Renwick 2007; MfE 2008; Hashmi et al. 2009; McMillan et al. 2010; Poyck et al 2011). Lill (2003) studied the effect of climate change on four alpine catchment discharges from the eastern Southern Alps of Canterbury (Jollie, Hooker, Rangitata and Rakaia). The model (HBV3-ETH9) predicted a higher volume of discharge in all seasons for all scenarios for the year 2080. The MfE (2008) report projected a change in rainfall between about –5 to +5% from 1990 to the 2030s, and about –10 to +15% from 1990 to the 2080s (the sign and amount varies around the country). The annual average rainfall is predicted to increase in the west (up to 5% by 2040 and 10% by 2090) and decrease in the east and north (exceeding 5% in places by 2090). Poyck et al. (2011) studied the weekly average flows of the Clutha river at Balclutha under climate change for the periods of 2030–2049 and 2080–2099. Their results showed a significant increase in streamflow: winter streamflow increased up to 40% in some places, and annual streamflow increased by 6% for the 2040 scenario and 10% for the 2090 scenario. The inter- and intra-catchment variability of the precipitation and runoff in the mountain catchments of New Zealand is poorly understood.

Globally, climate change in mountainous areas has been noted as having a significant impact on water supply, agriculture and hydropower generation. Mountains and higher altitude areas compose 25% of the Earth’s total land area and handle 32% of surface runoff (Meybeck et al. 2001). Viviroli et al. (2003, 2007) illustrated that upstream mountainous areas have a large contribution to total river-basin flow downstream. However, these areas are highly vulnerable because of increasing temperature and precipitation because of climate change (Beniston 2003). The increase in temperature causes increased snowmelt that has a much higher impact on downstream lowland regions: these regions depend heavily on mountain water resources (Kundzewicz et al. 2007). There have been many studies of climate change impact on water resources in high mountains. Viviroli et al. (2011) emphasised the importance of mountain catchments as a major source of global freshwater resources. They also cautioned this role might be significantly altered by climate change. Tenant et al. (2015) suggested a potential 3°C increase in the Salmon River catchment in Idaho, USA, will result in a 40% decrease in winter snow cover and an increase of snowline from 1980m (present) to 2440m.

Horton et al. (2006) showed that all climate change scenarios in their study of the Swiss Alps catchments resulted in shifts in hydrological regimes because of earlier snowmelt. They found catchments located at the lower altitudes were more strongly affected than the higher altitude catchments. A climate change study of the Andes (Bradley et al. 2006) predicted that cities and villages situated in mountains will be affected because they are heavily dependent on mountain water resources to meet their demands for water supply, hydropower generation and agriculture. A study of future climate change impact in the European Alps (Vanham et al. 2008) predicted a decline in future snow that will affect recreational snow activities in the Austrian Alps. Barnett et al. (2005) suggested some increase in water availability over next few decades in the Hindu Kush-Himalayan region. However, they cautioned there would be a sharp drop in water availability due to loss of ice sheets after some time. The change in future water availability suggests that water users will be forced into a trade-off between several water users.

Christensen and Lettenmaier (2007) studied future climate change impacts on the hydrology and water resources in the Colorado River Basin in the Rocky Mountains, USA. Their study showed significant impacts on storage reservoirs and hydropower because of a decrease in summer precipitation, increase in winter precipitation, decline in snowpack and seasonal shift in precipitation. Barnett et al. (2005) reported that less winter snowfall and earlier melting will force residents into a trade-off between summer-autumn hydroelectric power and spring-summer releases for the salmon runs in the Columbia River in the USA by 2050. Vicuna et al. (2007) reported that climate change will result in smaller streamflows, lower reservoir storage, decreased water supply deliveries and a decline in water supply reliability in the San Francisco Bay Delta, draining the Sierra Nevada mountains, USA. Ragettli et al. (2016) compared future climate change impacts on two catchments of the Andean and Himalayan mountains and illustrated contrasting results. They projected a decrease in future runoff in the Central Andes catchment but an increase in the Himalayan catchment.

In New Zealand, there has been a 0.5°C warming since 1950, with less frost, changes in rainfall and an increased intensity of droughts (Fitzharris 2007). Observed warming over several decades has been linked to changes in the large-scale hydrological cycle: shifts in the amplitude and timing of runoff in glacier and snowmelt-fed rivers and lakes have been observed (IPCC 2007). Researchers have cautioned that there are already alarm signals about the impact of climate change on water resources in New Zealand. McKerchar et al. (2010) reported a decline in streamflow on the east coast of the South Island when they studied data from eight catchments for the period 1958–2007. The Ministry for the Environment (MfE 2016) projected a decrease in annual precipitation in the north and east of the North Island and an increase in the South Island of the New Zealand.

Climate change shifts the seasonality of streamflow because of the change in proportion between snow and rainfall (Poyck et al. 2011). Change in streamflow affects energy generation of hydropower plants since power generation is dependent on discharge and available head. Any fluctuation in water availability because of climate change can impact power generation. Vicuna et al. (2007) studied climate change impacts for the State Water Project and Central Valley Project of California, USA. These projects investigate 13 hydropower stations and 21 reservoirs. Their findings suggest a decline of water availability results in a decrease in water delivery reliability, which is the per cent of total water demand in a region that is satisfied by surface water deliveries to that region. The water supply reliability of the system dropped from 75% to 53% when the impact of climate change was considered. VanRheenen et al. (2004) also predicted the future effect of climate change on the State Water Project and the Central Valley Project. They reported hydropower production (a function of reservoir storage) for the Central Valley may decline from 6 to 12%, considering three different scenarios.

Hydropower is a significant contribution to the economic development of New Zealand: 59% of the total electricity generated between 2013-2017 was from hydropower (Electricity Authority, 2017). Hydropower stations' future electricity generating capacity depends on available streamflow and they, in turn, are dependent on snowmelt. Future streamflow may be different because of climate change impacts, so evaluating effects of climate change on hydropower is essential. Better understanding of future precipitation, snowmelt and streamflow patterns is required to achieve these goals. It is questionable whether these goals can be achieved in the timeline allocated. Although there has been a decline in snowpack and an increase in streamflow in alpine catchments of New Zealand (Hoelzle et al. 2007), there is little information about how future climate change may impact water resources and hydropower generation in heterogeneous mountain catchments in New Zealand.

In a study of hydropower inflows from three headwater lakes of the upper Waitaki River, Caruso et al. (2016) reported an overall increase in future flows (2040s and 2090s), especially an increase in winter-early spring and a decrease in summer-autumn. Previous researchers studied climate change impact on the Clutha catchment (Poyck et al. 2011, Gawith et al. 2012). This research highlighted climate change impact on the Clutha catchment and two sub-catchments of the Clutha River. Previous research shed light on climate change impact on high-elevation catchments, but little attention has been devoted to determining climate change impacts on hydrologically different catchments. It is not well understood whether future climate change impacts on hydrologically modified catchments, natural unregulated catchments and catchments used for pastoral agricultural purposes will be similar or completely different. A good understanding of climate change impacts on different catchments of the whole river basin is essential to make an informed decision on future water resource management. Understanding spatial variability of climate change impacts on different smaller sub-catchments within the same catchment is an intriguing research that has been less explored.

1.5 Conclusion

In this chapter, the factors influencing the spatial variability of mountain catchments and sub-catchments flows are analysed. The role of elevation, soil type, landcover, precipitation and temperature on spatial variability is discussed. The importance of the sub-catchment scale study is emphasized. The mountain catchments also show temporal variability in present and future flows because of the future climate change. The precipitation distribution in mountain catchments can be highly variable based on the proximity of the divide which separates windward side with the leeward side of the mountain. These mountain divide can significantly influence the precipitation distribution from the rain shadow effect. The high elevation catchments and sub-catchments are sensitive to the temperature as temperature can decide whether the precipitation will fall as rain or snow, these are dependent on temperature for time and quantity of snowmelt. The temperature effects precipitation and precipitation including other physiographic factors determine the spatial and temporal variation of present and future streamflow.

Chapter 2. TopNet Model

The previous chapter discusses physiographic and climatic factors that influence the intra-catchments’ and inter-catchments’ spatial variability. The aims and objectives of the research are briefly presented in this chapter. In this chapter, types of hydrological models and model input data and simulation processes are discussed. The existing physiographic and climatic conditions of the study catchments are illustrated, and TopNet input data is explained, including Virtual Climate Station Network. Finally, TopNet model designs, limitations and uncertainties associated with the TopNet input data and the TopNet model are discussed briefly.

2.1 Problem description and Aims

Runoff in a mountain catchment with high spatial variability depends on many physiographic factors, such as elevation, slope, soil type, landcover and climatic factors such as temperature and precipitation. These factors influence the runoff generation processes when precipitation falls in the catchment, therefore their spatial and temporal resolution influence the ability of any hydrological models to correctly represent runoff generation processes.

The effect of physiographic factors in sub-catchment scale spatial variability is poorly understood because of limited research in this topic. These physiographical factors are complex because they are interlinked, and it is challenging to mathematically replicate the exact natural physical processes. The other challenge is to spatially represent the climatic features such as precipitation and use them in a hydrological model to estimate flow, which is a location parameter, not spread like precipitation. Since these physiographical and climatic factors are interrelated, the only way to discover how the individual parameter is affecting the streamflow is to investigate each of these separately. Also, a well-calibrated model with spatially variable fine-scale input (such as sub-catchment or grid) and output (in sub-catchment scale) is useful to reduce the errors of spatial variability.

The other challenge is to spatially represent climatic features such as precipitation. The spatial variability of precipitation is affected by the orographic effect of a mountain that creates a precipitation gradient between windward and leeward side of mountain, as well as the density of the precipitation network over the catchment.

Since physiographical and climatic factors are interrelated, a way to understand their relative influence on runoff generation is to use a hydrological model that enables users to analyse their impacts separately or as a combined set.

Climate is long-term average weather (Reisinger 2009): for example, decadal change in temperature and precipitation. Climate change and its impact on climate and physiographic processes is an important factor to consider in this study, as it will impact runoff generation processes (timing and spatial variability) (Barnet et al. 2005, Horton et al. 2006, Stewart 2009, Poyck et al. 2011, Hendrikx et al. 2012a). Globally, mountainous areas have been noted as having a significant impact on water supply, agriculture and hydropower generation. Mountains and higher altitude areas compose 25% of the earth’s total area and are responsible for 32% of surface runoff (Maybeck et al. 2001). Viviroli et al. (2003, 2007) claim that mountain discharge can represent a maximum of 95% of the total river basin flow. Snowmelt contribution from the Southern Alps is important source of water for the New Zealand rivers in the South Island. Kerr (2013) demonstrated the importance of snowmelt contribution in water resources of New Zealand, showing that snowmelt contributes the 17% of the mean annual flow of the Waitaki River. The temperature and precipitation determine the amount of snow stored in the catchment; this stored snow is called the Snow Water Equivalent (SWE). The change in future temperature and precipitation distribution affects change in the magnitude and seasonality of the flow. The change in temperature in alpine areas are crucial because this is the major factor that determines whether precipitation will fall as a rainfall or a snowfall. Hendrikx et al. (2012) investigated the change in future SWE due to potential climate change in New Zealand and reported the decrease in snow duration, the percentage of precipitation that would fall as snow and peak snow accumulation. In another study, Hendrikx and Hreinsson (2012) evaluated the climate change impact on future snow production. They reported a reduction in the number of snow days in the future in all locations and for all climate change scenarios and suggested the need for adaptation to compensate for the reduced snowmaking opportunities until the comprehensive assessment is available.

The climate change impacts on catchments with different land use, soil type, elevation, precipitation, and flow regime are poorly understood (Middelkoop et al. 2001; Jones et al. 2002; Arnell et al. 2015; Oafoku 2015; and Arheimer et al. 2017). Estimation of future streamflow generation from catchments is a fundamental requirement for sustainable water resource management. These can be different in different sub-catchments of the same catchment. Therefore, information of climate change impact on the catchment and sub-catchment scale are essential for any future agricultural, recreational, tourism, domestic and industrial water uses.

The aim of this is to understand the controlling factors for runoff generation mechanisms and to study the effect of spatial variability on streamflow in mountain catchments from the perspective of water resources. This study also aims to evaluate climate change impacts on heterogeneous study catchments that vary over space and spatial scale.

2.2 Objectives

The objectives of this study are the following:

1) Development of a hydrological model that simulates catchment/sub-catchments flows based on physiographic (elevation, soil, landcover) and climatic (temperature, precipitation) parameters.

2) Determine the importance of sub-catchment variability on streamflow in physiographic complex mountain catchments.

3) Determine climate change effect on sub-catchment streamflow in mountain catchmes with complex physiographic mountain catchments.

4) Determine the potential effect of climate change on discharge, with significantly different precipitation and how runoff affects the management of water resources.

2.3 Hydrological Models

All hydrological models rely on approximation because of the complex representation of processes such as surface water, ground water and climate change (Beven 2016). The hydrological models based on their ability to run spatial processes are briefly explained here.

2.3.1 Lumped Hydrological Models

Lumped models consider catchments as a single homogeneous unit with inputs (rainfall, soil, vegetation) averaged for the entire catchment. Many modelling systems use lumped models because they need fewer input parameters for calibration (Butts et al., 2004). Examples of lumped models are Unit Hydrograph (Sherman 1932), SCS Curve number method, HEC-1 (Perrone et al. 1998), and Stanford Watershed Model (Linsley, 1967). Lumped hydrological models are used for quality control, extension of historical records, synthetic data generation, water resource assessment and real-time forecasting (Blackie and Eeles, 1985). However, a major limitation of the lumped models is that the parameters are not related to the physical characteristics of the catchment (Reed et al. 2004; and Paudel 2010).

2.3.2 Distributed Hydrological Models

Distributed models divide the catchment into grid cells and use physical equations to solve the water balance (Paudel 2010). A distributed hydrological model can represent spatial variability within the basin and can simulate flows at interior points without needing a specific calibration at each point (Reed et al. 2004). An example of a distributed model is MIKE-SHE (Danish Hydraulic Institute, 1998). Distributed models are used to study the effect of land-use change, effect of spatially varied input and output, movement of pollutants, movement of sediments and simulation in an ungauged basin (Blackie and Eeles 1985). The major limitations of distributed models are the need for high-quality and extensive data, larger computing power requirements, longer processing time and higher levels of understanding.

2.3.3 Semi-distributed Hydrological Models

In semi-distributed hydrological models, a catchment is divided into smaller sub-catchments and each sub-catchment is computed separately. Sub-catchments are not gridded; however, a water balance is solved for each sub-catchment or each hydrologic response unit and flow routed to the river network. The lumped models are simple to calibrate but lack physical basis and spatial variability, and distributed models have physical basis, but they need large computational resources and a longer processing time.

Semi-distributed models have advantages of both lumped and distributed models. These models account for spatial variability like distributed models but solve the water balance within a sub-catchment-like lumped model. Precipitation Runoff Modelling System (PRMS) of United States Geological Survey, (Markstorm et al. 2015), HEC-HMS (US Army corps of Engineers, 1992) and TopNet (Bandaragoda 2004) are semi-distributed hydrological models.

2.4 TopNet Model

TopNet is a physically-based, semi-distributed hydrological model based on the TOPMODEL concept (Beven and Kirkby 1979) that uses the parametrisation of soil moisture deficit using a topographical index model. The catchment is modelled as the combination of sub-basins are linked to river networks and routed with kinematic wave river routing (Beven 1979; Goring 1995, Clark et al. 2008; Poyck et al. 2011; Gawith et al. 2012; and Singh et al. 2016). The TopNet model is capable of running diverse spatial and temporal scales in large catchments while using smaller catchments or sub basins as the model units (Bandaragoda et al. 2004; and Clark et al. 2008). The TopNet model includes precipitation, evaporation, minimum temperature, maximum temperature and, if other weather parameters are available, the weather information is also added.

The TopNet model is chosen for this study because even the distributed model would not give higher accuracy than input data, such as rainfall stations, and would be resource intensive: for example, cost and simulation time. TopNet is chosen for this study because 1) it has been extensively used in New Zealand for hydrological modelling, including climate change studies and 2) two study catchments (Ahuriri and Pukaki) have already been calibrated by NIWA. TopNet has been used in New Zealand for climate change studies (Poyck et al. 2011; and Gawith et al. 2012), Ministry of Environment New Zealand climate change guidelines (MfE2008; and MfE 2016), long-term streamflow prediction (Singh et al. 2016), validation as a national hydrological model for the whole of New Zealand (McMillan et al. 2016), hydrology of ungauged catchment (Booker and Woods 2014) and flood forecasting (Cattoen-Gilbert et al. 2016).

Table 2.1 presents the data used to develop the TopNet model for this study.

Table 2.1: Catchment characteristics input data required to run the TopNet model.

Data Type	**Data source in TopNet**	**Parameters**	**Description/ Spatial Characteristics**
Land Cover	Land Cover Database version 2 (LCDB2) (Newsome et al. 2000)	Land Cover	Shapefiles with classified land cover over NZ
Land Use	Land Resource Inventory (LRI)	Land Cover	Shapefiles with classified land information over NZ
Soil Properties	Fundamental Soil layers (FSL) from LRI (Newsome et al. 2000)	Soil attributes	Shapefiles consisting of GIS layers with a range of soil data over NZ
River Network	River Environment Classification version 1 (REC1) (Snelder and Biggs 2002)	River Network (identifier)	River reach lines, watershed polygon

DEM	New Zealand Digital Elevation Model (NZDEM)	Elevation, Slope	Elevation gridded data generated from Land Information NZ (LINZ) topographic map

The detailed description of TopNet basin processes and routing is found in Clark et al. (2008). A summary of the TopNet process description is included in Figure 2.1, which shows the basic principle that TopNet uses to calculate water stored in the catchment. TopNet estimates the water stored in the catchment as a combination of canopy storage, snowpack storage, soil root zone storage, aquifer storage and surface storage. The canopy storage is estimated based on the precipitation, throughfall and evapotranspiration from the canopy. The snow water equivalent (SWE) is calculated from the throughfall and snow melt rate. The soil storage is estimated based on the infiltration, evaporation and drainage from the soil to the aquifer. Each catchment is divided into three zones in the TopNet model based on the depth of the water table at three points: uninfluenced, influenced and saturated. If the water table is below the soil layer than it is called uninfluenced; if water table is between the top and bottom of the soil layer, it is called influenced; and if water table is at or above the soil layer, it is known as a saturated zone. The baseflow or aquifer discharge is calculated from the water table depth and drainable water content. The surface runoff is estimated from infiltration excess runoff, saturation excess runoff, sub-surface discharge and basin outflow. Finally, sub-catchment runoff from each sub-catchment is estimated and total flow is routed through the stream network to the basin outlet.

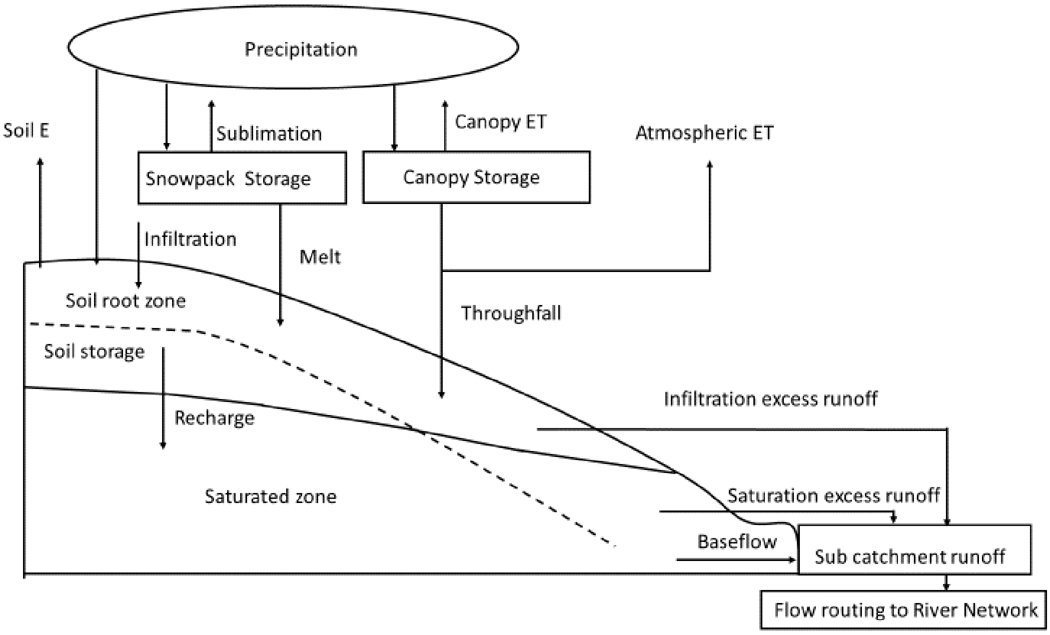


Figure 2.1: Systematic representation of TopNet model structure (Modified from Bandaragoda et al. 2004; and Singh et al. 2016).

2.5 TopNet Model Design

2.5.1 Study Catchments

The main objectives of this research are to model how potential climate change impacts on streamflows vary over space and spatial scales in a heterogeneous mountain river basin (Upper Waitaki) and compare streamflows of unimpaired catchments (Ahuriri), glacier-fed catchments that are regulated and used for hydropower with reservoirs (Pukaki) and drier catchments in the Lower Waitaki (Hakataramea). The Waitaki River basin is a good example of a large, spatially varied, heterogeneous mountain catchment in New Zealand's South Island. It consists of glacial lake catchments used to generate hydropower (Tekapo, Pukaki and Ohau), slightly drier unregulated catchments in the upper basin (Ahuriri and Jollie) and very dry lower catchments (Hakataramea and Otekaieke). The Ahuriri is a natural, unregulated catchment; the Pukaki catchment is a glacial catchment that is highly regulated for hydropower generation; and the

Hakataramea is a very dry catchment in the lower basin. The Hakataramea is a foothill river, draining into the lower Waitaki: the stock water and irrigation are the main water uses, therefore, Hakataramea River and its catchments are completely allocated (ECan 2012). Hakataramea catchment has been used for sheep and beef farming: a Land Resources Inventory stock survey by Howden (2012) reported 85% sheep farming and 11% beef farming. These activities match well with the LCDB2, as 86% of the Hakataramea catchment has been reported as grassland. The stream network inside the study catchments, Hakataramea, Ahuriri and Pukaki, are shown in Figure 2.2

This study focusses on understanding the controlling factor of runoff generation and evaluating climate-change impacts on water resources in three different catchments that exhibit spatial variability in runoff. The elevation of the study catchments are: Hakataramea (204-1886 m), Ahuriri (608-2454 m) and Pukaki (381-3680 m).

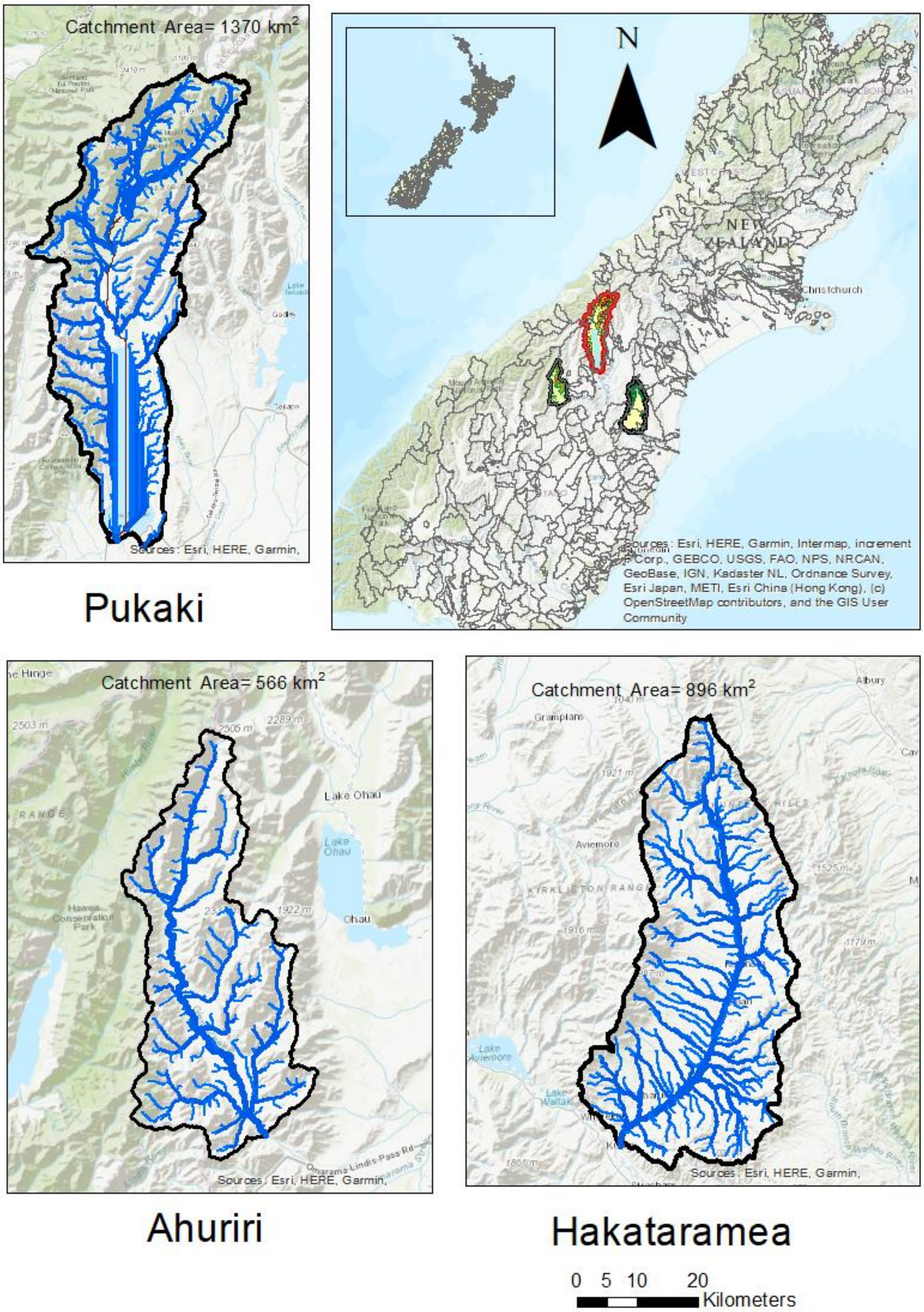


Figure 2.2: Stream network in the study catchments

2.5.2 Landcover

Grassland is the most prevailing landcover in the study catchments (Figure 2.3). The LCDB2 (Newsome et al. 2000) shows that it covers 86%, 64% and 34% of the total area of the Hakataramea, Ahuriri and Pukaki catchments, respectively, while the Ahuriri and Pukaki catchments contain 22% and 26% of lightly vegetated surface.

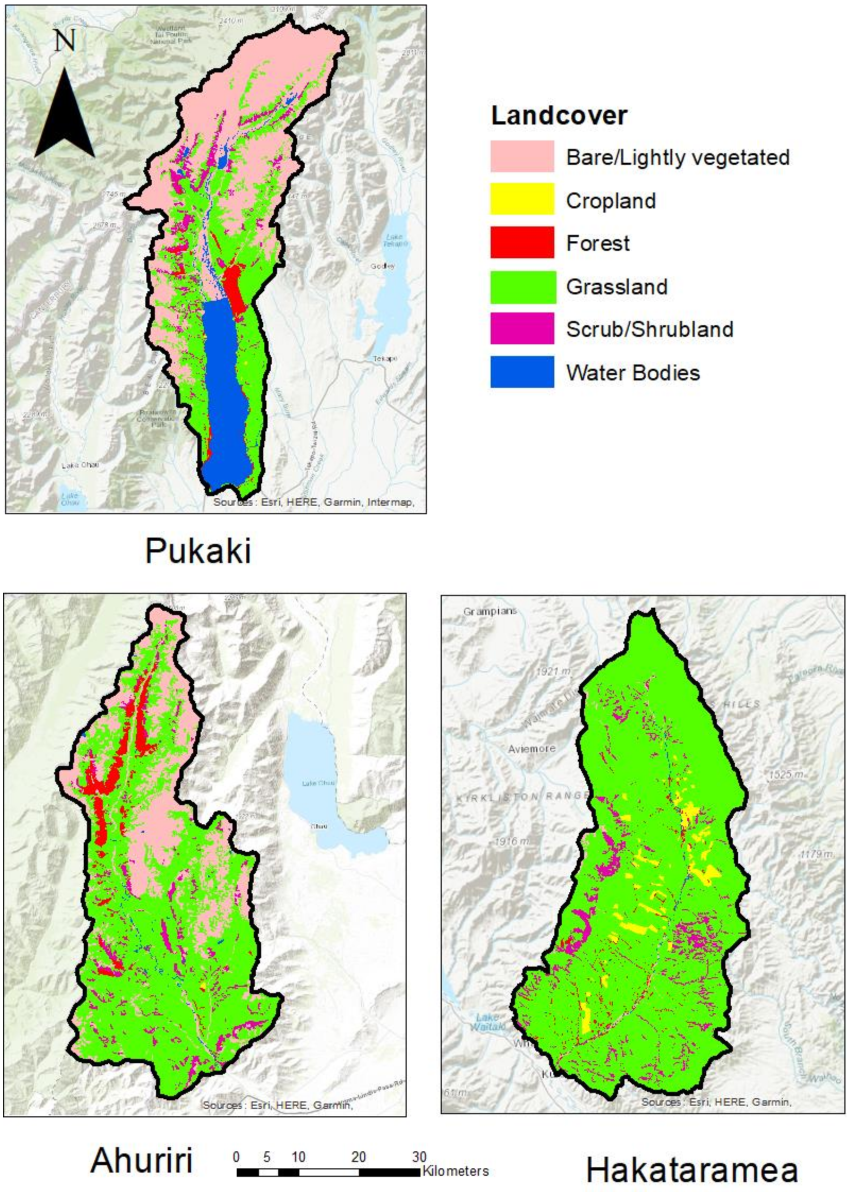


Figure 2.3: Landcover (LCDB2) of the study catchments Hakataramea, Ahuriri and Pukaki catchments

2.5.3 Soil

Diverse soils, landcover and elevation dominate the study catchments. The FSL layer (Newsome et al. 2000) has the information about the soil types in the study catchments

(Figure 2.4). The yellow-grey earth is the dominant soil type in Hakataramea, and more than half of the area of the Hakataramea catchment. The other major soils that are available are yellow-brown shallow stony soil and yellow-brown earth. The High-Country yellow-brown soil, upper-yellow brown soil and recent soil form most of the soils in the Ahuriri catchment. The major soils in the high elevation Pukaki catchments catchment area are upper-yellow brown soil, bare rock and High Country yellow-brown soil.

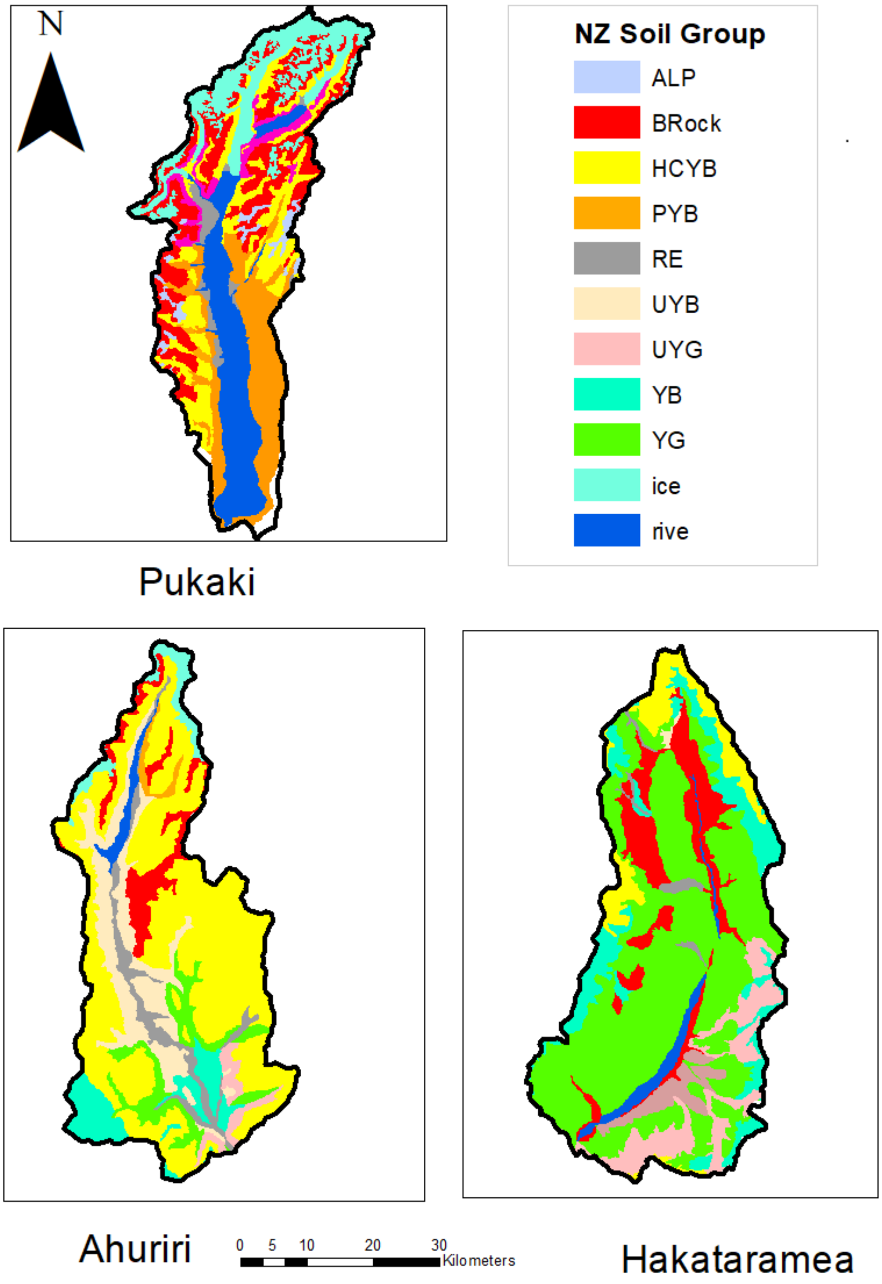


Figure 2.4: Soils in the Hakataramea, Ahuriri and Pukaki catchments

2.5.4 Climate

2.5.4.a) Climate Stations

Precipitation (P) and temperature (T) are required inputs for the model. The existing temperature and precipitation stations in the study catchments are summarised in Table 2.2. Wide variations in rainfall and flow exist between subcatchments of the

Waitaki River Basin (Waugh et al. 2003). There are several rainfall and temperature stations in the study catchments that are managed by different public, private and commercial entities.

Table 2.2: Rainfall/Temperature stations in the Hakataramea, Ahuriri and Pukaki catchments (ECan = Environmental Canterbury, PFSF = Public Good Science Fund, Meridian = Meridian Energy)

Hakataramea

Station Name	Tideda ID	Funding Agency	Elevation (masl)	Period of Record
Hakataramea at McRaes Gorge rainfall	403601	ECan	620	1985-Present
Hakataramea at Mt Florence rainfall	405610	ECan	385	1995-Present

Ahuriri

Station Name	Tideda ID	Funding Agency	Elevation (masl)	Period of Record
Ahuriri at Cassinia Moraine	491610	Meridian,PGSF	1043	1970-Present
Ahuriri at Base Hut	492610	ECan	760	1991-1992
Ahuriri at Plains	494611	PGSF	760	1968-1994
Ahuriri at Sth Diadem rainfall	494711	PGSF	694	1992-Present

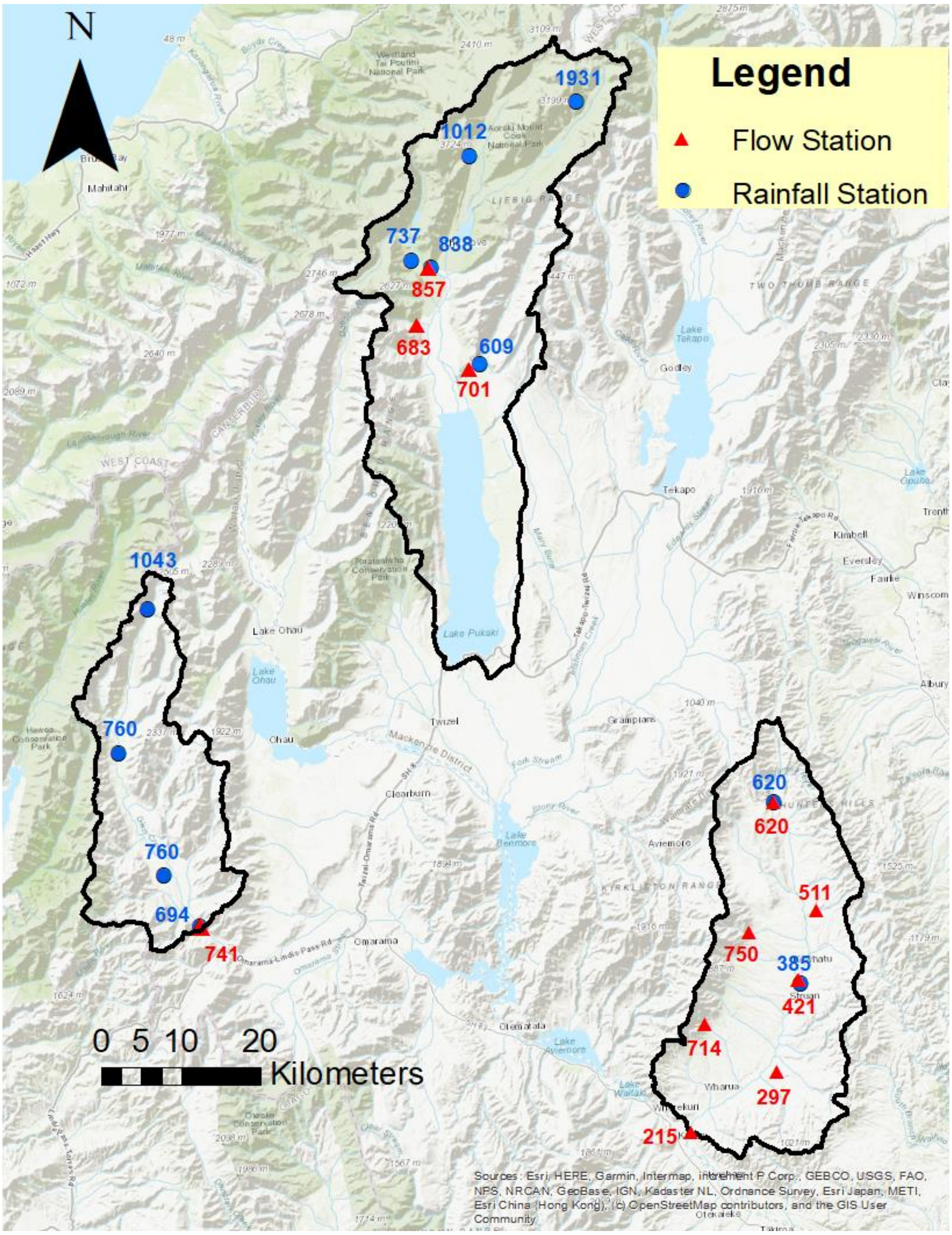
Pukaki

Station Name	Tideda ID	Funding Agency	Elevation (masl)	Period of Record
Murchison at Rose Ridge	305310	Meridian,	1931	2005-Present
Tasman at Ball Hut	306210	PGSF	1012	1972-1979
Hooker at Mt Cook (The Hermitage)	307001	ECan	737	1989-Present
Hooker at Ball Hut Rd rainfall	307110	Meridian	838	1993-Present
Jollie at Jollie Hut	308217	Meridian	609	1965-1999

The Waitaki Basin receives remarkably high rainfall close to the Main Divide, where the upper catchments of lakes Tekapo, Pukaki and Ohau receive more than 4000 mm of rainfall. This decreases sharply to Braemar Station (1914-2001) with 892mm on the eastern side of Lake Pukaki over 70 km, and, from the Hermitage to Grays Hills station, annual rainfall decreases from 4195 mm to 456 mm. The Duntroon station (1914-2000) in the lower Waitaki Valley receives only 549 mm of rainfall per annum.

However, Kerr et al. (2011) claim that the precipitation distribution in the upper Pukaki catchment is equivalent to the highest precipitation observations made anywhere in New Zealand. They note that a significant undercatch exists in present data and when the undercatch is included in the annual rainfall, some areas of catchment will be as high as 15000 mm. They demonstrated that the high orographic precipitation is created by spill over from the west of the Southern Alps.

The rainfall stations in the study catchments have long-term records for temperature and rainfall (Table 2.2). In addition, the gauging stations undergo quality control and testing before being available for analysis or publishing the data (Christian Zammit, personal communication). Table 2.2 shows that there are two (2) stations in the Hakataramea catchment, four (4) stations in Ahuriri catchment and five (5) stations in the Pukaki catchment. The Pukaki catchment has the larger rainfall variability: the higher elevation side of the Pukaki catchment receives one of the highest rainfalls in New Zealand, which sharply decreases in lower elevations near Lake Pukaki (Kerr et al. 2011). The Pukaki and the Ahuriri catchments have moderate numbers of rainfall stations, compared to the Hakataramea catchment. The spatial distribution of rainfall stations in the study catchments is displayed in Figure 2.5. In the Ahuriri and Pukaki catchments, the rainfall stations are spread over the catchments, but in the Hakataramea catchments there are only two rainfall stations: one in the central portion of the catchment and one on the side of the catchment. The elevation of the rainfall stations are displayed next to the rainfall station, Out of eleven (11) rainfall stations, only four (4) stations are located above 800 masl (metre above mean sea level) and only one station is located above 1500m. There are fewer rainfall stations in the higher elevation because only one station in Pukaki is located above 1500masl, only one station is located above 1000masl in the Ahuriri and none of the stations are located above 700masl in Hakataramea despite the elevation ranges in the study catchments - Hakataramea (204–1886 m), Ahuriri (608–2454 m) and Pukaki (381–3680 m).



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), (c) OpenStreetMap contributors, and the GIS User Community

Figure 2.5: Rainfall stations (circles) and flow-measuring stations (triangles) in the study catchments. The height, in metres above sea level, are displayed next to stations.

2.5.4. b) Virtual Climate Station Network (VCSN)

The rainfall stations are spread across the study catchments and this study uses the spatial scale of third-order Strahler ($\approx$ 7 km^2) and Virtual Climate Station Network (VCSN) is used to estimate the precipitation and rainfall data required to run the TopNet model. These data are estimated from the spatial interpolation of daily 9am climate observations that are available through NIWA’s National Climate Database. The VCSN data estimation is based on a thin plate spline spatial interpolation model, where two location variables (latitude and longitude) and a pattern variable are used to interpolate climate data from observed stations (Tait et al. 2006; Tait et al. 2012). The VCSN information consists of daily rainfall, potential evapotranspiration, maximum and minimum temperature, relative humidity, mean sea level pressure, solar radiation (shortwave) and wind velocity, interpolated on a 0.05 degrees latitude and longitude scale (approximately 5km spatial resolution) grid that covers the whole of New Zealand. The VCSN rainfall data has an advantage of providing data for filling gaps in actual gauges. Although VCSN might have some errors, because of the interpolation effect, it is a useful tool for the higher-elevation New Zealand catchments because of the limited number of rain-gauge stations in these catchments (Tait et al. 2012).

Figure 2.6 shows the VCSN grid, rainfall station, actual gauges and flow measuring stations in the Waitaki River Basin.

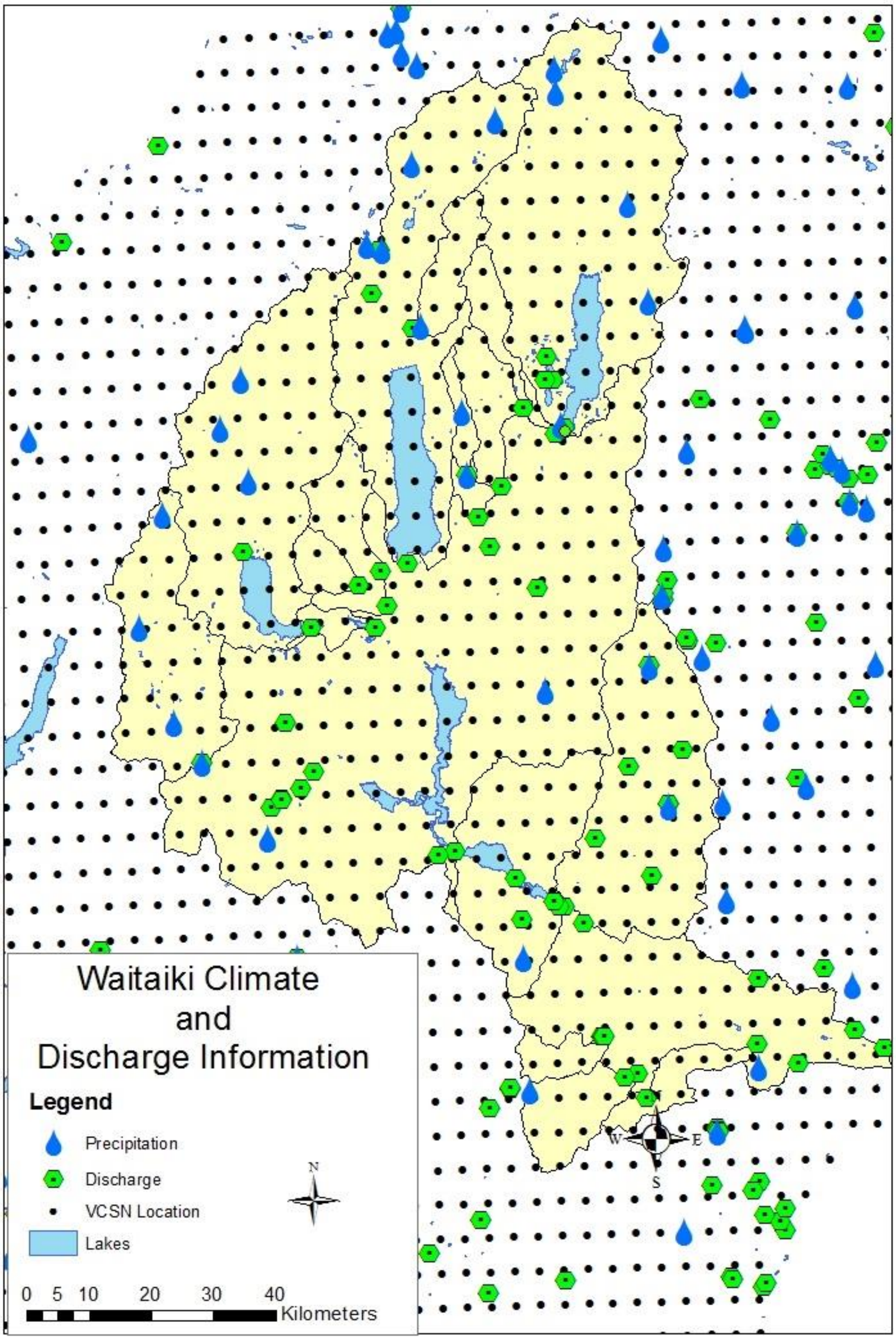


Figure 2.6: VCSN grids, precipitation stations and flow measuring stations in Waitaki River Basin from New Zealand Institute of Water and Atmospheric Research (NIWA) TopNet version 11.0.

2.5.4 c) VCSN and Station data

VCSN has been estimating daily rainfall over the whole New Zealand in an approximately 5km X 5km grid since 1972. Tait et al. (2006) estimated rainfall in a 0.05° latitude and longitude scale covering New Zealand, validated with average annual river flows and potential evapotranspiration. They reported a 7% bias and 15% RMSE using 1951-1980 rainfall surface and spline interpolation. The VCSN rainfall estimate is validated against the drainage and evapotranspiration (Cichota et al. 2008). They showed that VCSN has promising use in the agricultural sector in New Zealand and reported a substantial reduction in interpolation error when rainfall is analysed on a weekly or monthly basis.

Comparisons of the rainfall station and corresponding VCSN grid data for the Hakataramea, Ahuriri and Pukaki catchments are shown in Figures 2.7, 2.8 and 2.9. Figure 2.8 shows the data for Ahuriri at Cassinia Moraine. Figure 2.7 shows the precipitation distribution in the Hakataramea catchment. The Hakataramea at Mt. Florence is almost in the middle of the catchment. The Hakataramea catchment receives less rainfall and the variation is also lower compared with the Ahuriri and Pukaki catchments. The VCSN data shows a small error for the low elevation Hakataramea catchment (Figure 8 and 9). However, the percentage difference showed that the VCSN underestimated the precipitation, especially from October to January, and a small overestimation in February, March and August.

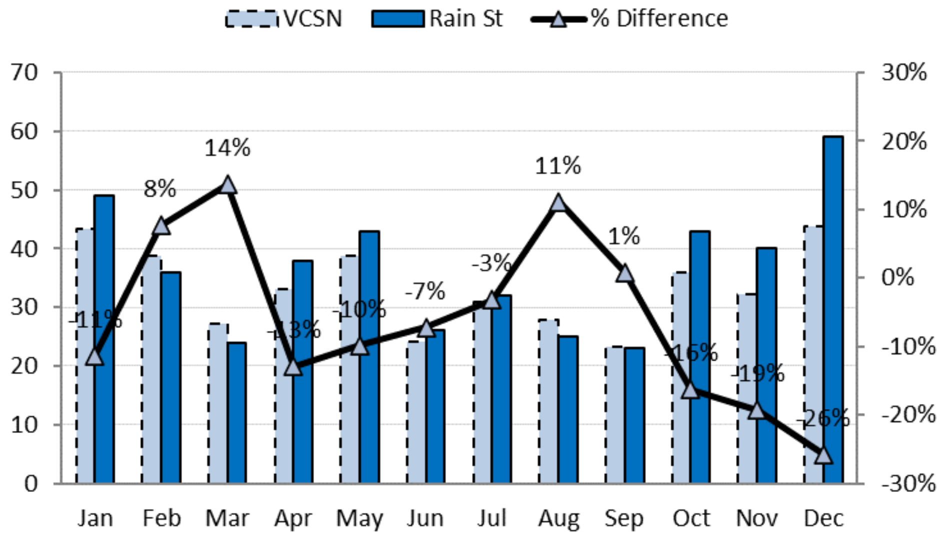


Figure 2.7: VCSN and station rainfall data for Hakataramea at Mount Florence (1995-2011) Station (385 masl)

The following figure (Figure 2.8) displays the VCSN rainfall, station rainfall data and the percentage difference for the Ahuriri catchment at the Cassinia Moraine station. The VCSN underestimated the rainfall in November, but overestimated in all other months with severe overestimation in February and July.

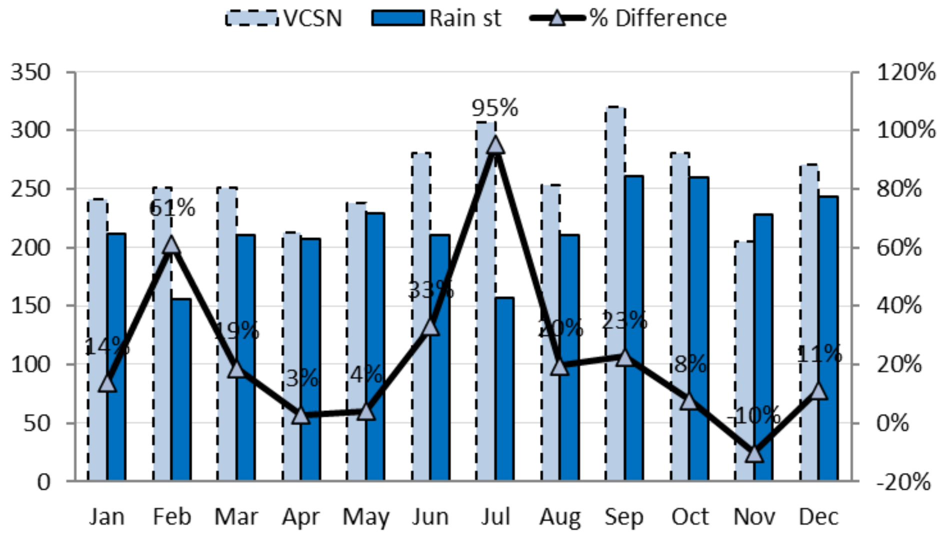


Figure 2.8: VCSN and rainfall data for Ahuriri at the Cassinia Moraine (1972-2011) Station (1043 masl)

Figure 2.9 shows the comparison between VCSN data, rain gauge and percentage differences in the Pukaki catchment at Jollie Hut. The precipitation was severely underestimated in October, November, and December and overestimated in February.

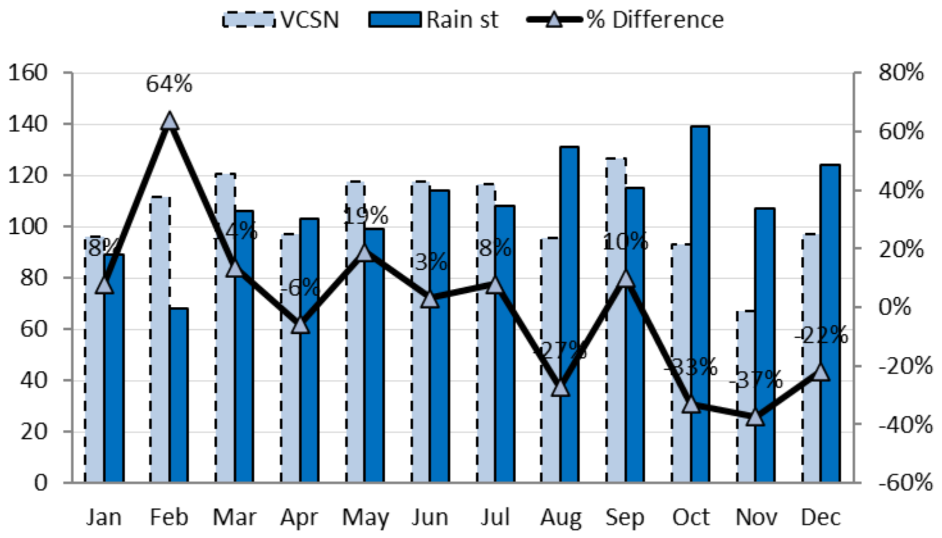


Figure 2.9: VCSN and rainfall data for Pukaki catchment at Jollie Hut (1972-1999) (609 masl)

Tait et al. (2012) validated VCSN daily rainfall estimates by comparing the VCSN estimates with observed rainfall data from 700 regional council weather stations in New Zealand. They reported mean absolute error (MAE) of 2-4mm for elevations less than 500m and 5-15mm for the areas higher than 500 m, when rainfall greater than 1 mm is considered. The MAE increases to 8-12mm for low-elevation areas and 10-40mm for high-elevation areas for heavy rainfall (>40 mm). The best way to achieve the good quality data is to have a network of good quality rain gauges for a sufficient period of time; however, in the absence of sufficient length of data or rain gauges, VCSN offers better quality data than data from rainfall stations that are far from catchments or data from different climatic zones (Tait et al. 2012). The VCSN data has been proven a useful tool for evaluating different water resources and climate change studies in New Zealand

and the following section provides examples of studies that have successfully used VCSN to answer different research questions.

Precipitation (P), temperature (T), digital elevation model (DEM), River Environmental Classification (REC), landcover and soil type are the input data for the TopNet and shown in Table 2.1 and Table 2.3. Precipitation and temperature data are the major input data for TopNet and provided from VCSN; however, there is also a provision to input directly from precipitation and temperature measuring stations.

Table 2.3: Minimal climate input data required to run the TopNet model.

Data Type	Data source in TopNet	Parameters	Description/ Spatial Characteristics
Precipitation	Virtual Climate Station Network (VCSN)	Precipitation	Daily (mm) 0.05 deg Lat/Long over NZ
Temperature	Virtual Climate Station Network (VCSN)	Temperature	Daily Min/Max (K) 0.05 deg Lat/Long over NZ

2.5.5 a)TopNet Model Design- Climate

Table 2.4: Flow stations in the Hakataramea, Ahuriri and Pukaki catchments (ECAN = Environmental Canterbury, PFSF = Public Good Science Fund, Meridian = Meridian Energy

Hakataramea

Station Number	Station Name	Start Date	End Date	Latitude	Longitude	Funders
71103	Hakataramea at above MHBr	26/11/1963		-44.72	170.49	ECan, PGSF
71154	Homestead Ck at Haughs Gorge	1/10/1985	7/04/1988	-44.66	170.63	ECan
71156	Kirkliston Stream at above water supply	21/02/2006		-44.60	170.52	ECan
71143	Hakataramea at Mt Florence	11/12/1995	26/04/2007	-44.56	170.67	ECan
71155	Hakataramea at above Mt Florence	16/04/2004		-44.56	170.67	ECan
71139	Cattle Ck at Invercroy	28/08/1985	12/04/1988	-44.50	170.59	ECan
71138	Peter Stm at Cloverbank	28/08/1985	12/04/1988	-44.48	170.70	ECan

71188	Hakataramea at McRaes Gorge	17/10/1985	31/03/1993	-44.35	170.64	ECan

Ahuriri

Station Number	Station Name	Start Date	End Date	Latitude	Longitude	Funders
71116	Ahuriri at Sth Diadem	18/09/1963		-44.47	169.73	Meridian, PGSF

Pukaki

Station Number	Station Name	Start Date	End Date	Latitude	Longitude	Funders
71124	Devils Elbow	1/01/1962	10/09/1967	-43.80	170.10	PGSF
71125	Hooker at Ball Hut Rd Br	20/09/1960	4/07/1979	-43.74	170.12	Meridian, PGSF
71125	Hooker at Ball Hut Rd Br	6/07/1994		-43.74	170.12	Meridian
71135	Jollie at Mt Cook Stn	7/12/1964		-43.86	170.18	Meridian, PGSF
71123	Lake Pukaki at Canal Inlet gate	20/09/1963		-44.18	170.14	Meridian, PGSF

2.5.5.b)TopNet Model Design – Water Consenting

Among the three catchments, Pukaki has been used for hydroelectric power generation, the Hakataramea catchment has been used for sheep and beef farming and the Ahuriri catchment is in natural reserve and protected. The majority of the Ahuriri catchments are protected by Water Conservation Order 1990. Figure 2.5 displays non-hydro water allocation consents in the Hakataramea, Ahuriri and Pukaki catchments from Booker and Henderson (2019). The values show the upstream total maximum rate (litres/second) of any abstraction that may take place. The maximum total upstream flow rate is 1247 l/s in the Hakataramea catchment. The TopNet does not consider abstraction, therefore if a large portion of flow is extracted in Hakataramea, it may affect the modelling results. The maximum abstraction rate in the Pukaki catchment is only 247 l/s. But, the Pukaki catchment is completely utilized for Hydroelectric Power Generation below the lake and the resource consent (ECan CRC905325.2) states that a maximum of 560 m^3/s of water is allocated for the Hydroelectric Power Generation. There was no information related to the water abstraction in the Ahuriri. Figure 2.10 shows the total annual maximum consent limits for each map created from the Canterbury map viewer (ECan, August 2020a) to investigate surface water uptake consents and groundwater uptake consents.

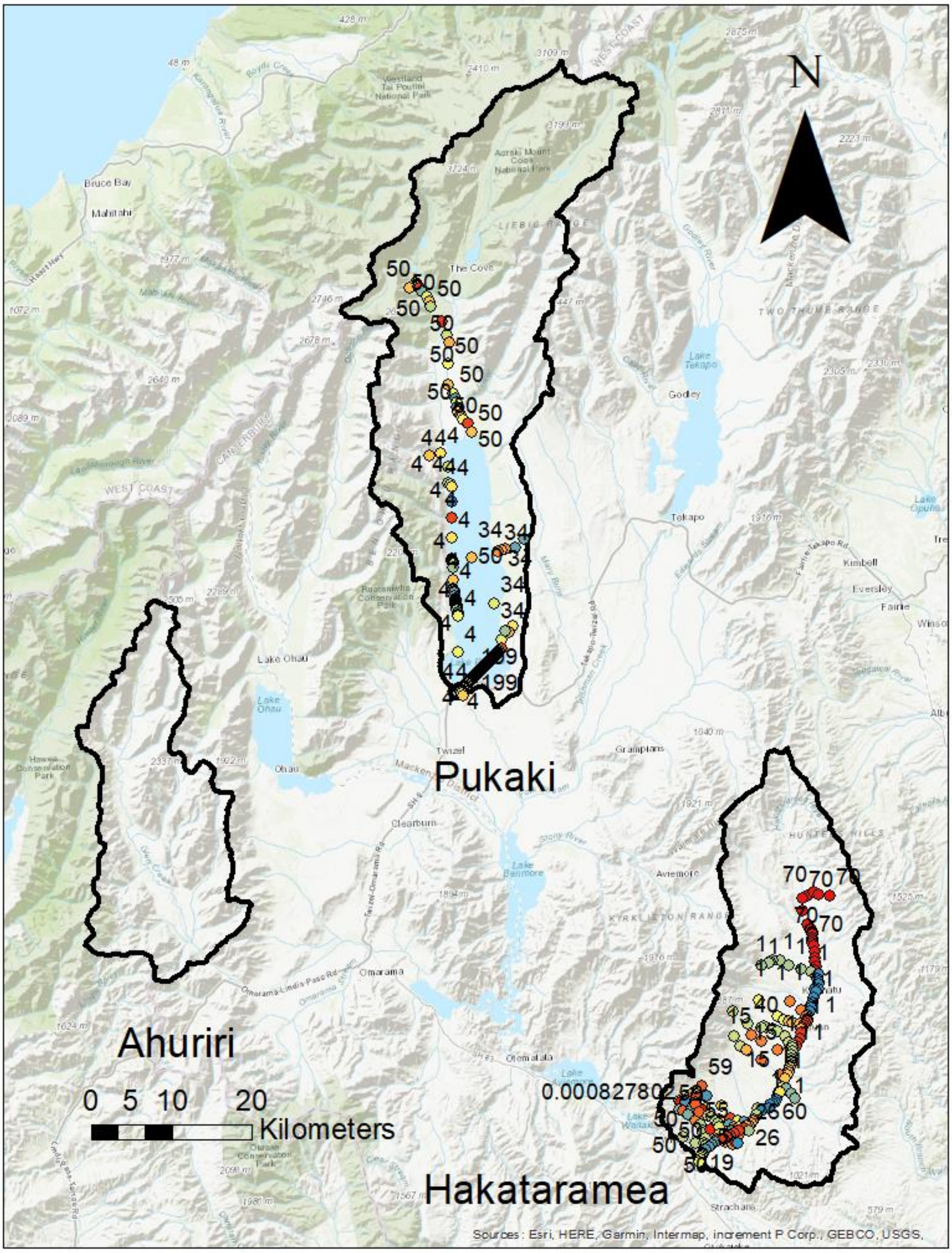


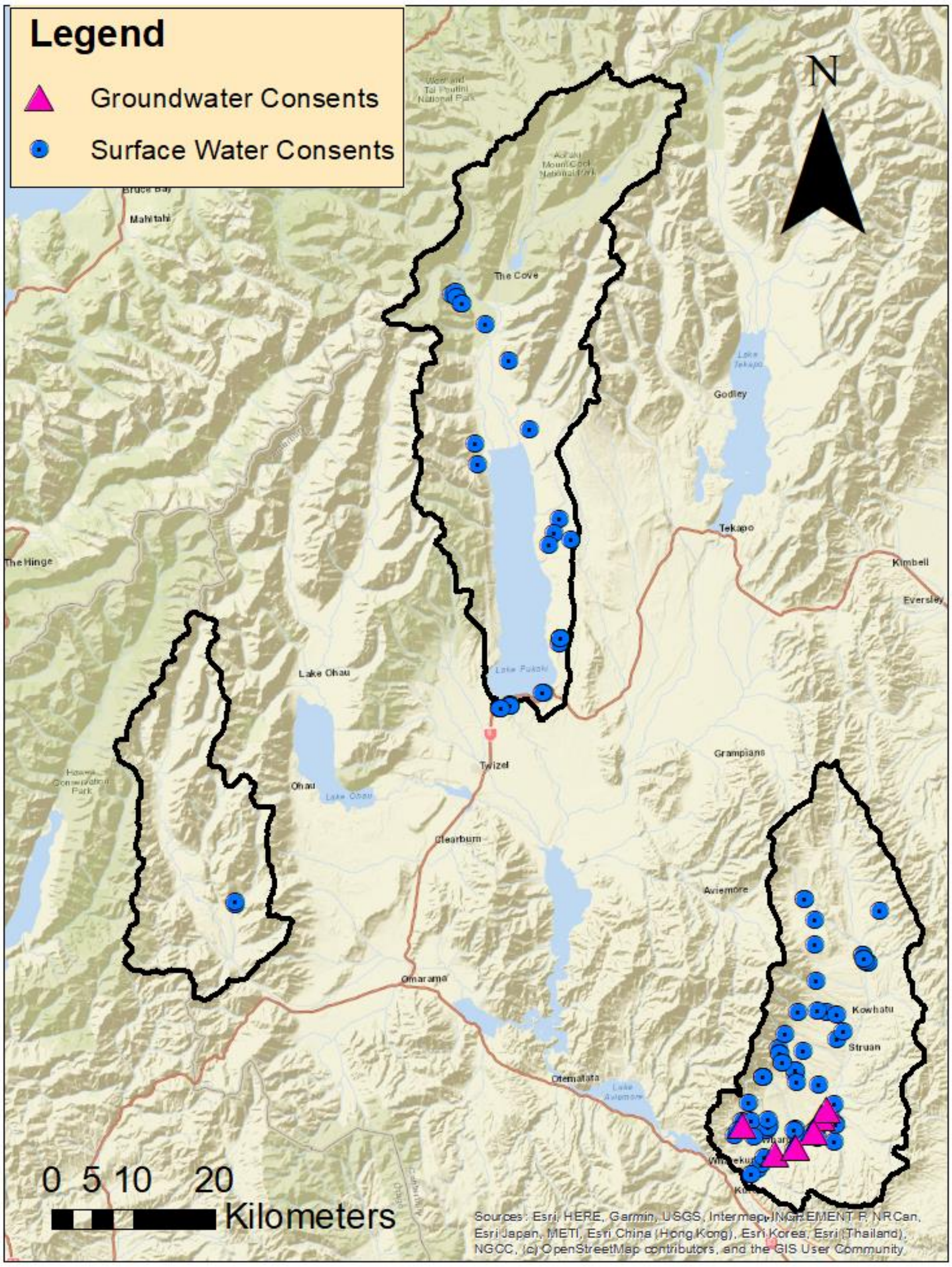
Figure 2.10: Surface water and groundwater uptake consents in the Hakataramea, Ahuriri and Pukaki catchments (ECan, accessed August 2020)

2.5.5.c) TopNet Model Design – Groundwater

The groundwater in the Waitaki River Basin is not at risk and only a fraction of the sustainable yield has been extracted (Heller and Williamson 2004). The groundwater in

Canterbury flows from the foothills to the Canterbury Plains and it follows the terrain from northwest to southeast (Westerhoff et al. 2019). They suggested that most of the streams in Canterbury Plains gain the flow due to the groundwater contribution. The model used for this study does not have two-way interaction between the surface water and groundwater. There are few groundwater basins in the nearby study catchments: Tekapo basin, Twizel basin, Omarama basin and Hakataramea basin (SKM 2004). The Tekapo and Twizel basins are large groundwater basins (>2500Mm^3) but these are in Lake Tekapo catchment and downstream of Lake Pukaki respectively. The Omarama basin (Ahuriri plus Omarama River catchment) has storage capacity of 235Mm^3 and 907Mm^3.

Figure 2.11 displays the total annual maximum consent limits for each map created from the Canterbury map viewer (ECan, August 2020b) to investigate surface water uptake consents and groundwater uptake consents. There are no active groundwater consents in the Ahuriri and Pukaki catchments. The water resources in the Hakataramea catchments are considered fully allocated for it has the lowest flows. The Lower Waitaki Zone coastal Canterbury zone implementation programme (ECan 2012) stated that this catchment's water resources are fully allocated for irrigation and stock water to the extent that any further allocation will have negative impact on river health during a low summer flow period.



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, (c) OpenStreetMap contributors, and the GIS User Community

Figure 2.11: Surface water and groundwater uptake consents in the Hakataramea, Ahuriri and Pukaki catchments (ECan, accessed August 2020)

2.5.6 VCSN, TopNet and Climate change case studies in New Zealand

The VCSN has been used in several study areas, such as agriculture, weather forecasting, streamflow modelling and climate change studies. Table 2.5 displays a few studies that used VCSN to solve a diverse range of problems in water resources, climate change and agricultural sectors. The VCSN has been used to study model land-use management (Cichota et al. 2008), pasture growth (Romera et al. 2010), assessment of *Campylobacter* in surface water (Elliot and Harper 2011) and *Pinus radiata* production (Kirschbaum and Watt 2011). Another use of VCSN is forecasting precipitation and energy availability. Ummenhofer et al. (2009) studied the relationship between 20th-century precipitation and large-scale changes in the Southern Hemisphere using 1979-2006 VCSN data. The VCSN has also been used for 15-day weather forecasts (Renwick 2011), seasonal snow simulations (Clark et al 2009), drought monitoring (Mol et al. 2017), and the infilling of missing precipitation data to prepare the New Zealand rainfall intensity indices (MfE 2017).

Further use of the VCSN has included forecasting lake levels, lake inflows and electricity generation for modelling work for the Electricity Authority and New Zealand Stock Exchange (NZX 2020). NZX and NIWA have also developed a paid subscription for hydrological data downloads based on the inflows calculated by using VCSN. Extensive use of VCSN data for streamflow and hydrological modelling studies in New Zealand demonstrates its reliability; for example, determining mean flow of New Zealand rivers (Woods et al. 2006), updating streamflow status in hydrological models (Clark et al. 2008), forecasting operational flow (McMillan et al. 2013), the National Water Accounts of New Zealand (MfE 2015) and the Validation of the National Hydrological Model for New Zealand (Mc Millan et al. 2016), weather modelling for flood forecasting (Cattoën et al. 2016) and validation of a national hydrological model (McMillan et al. 2016).

VCSN data is interpolated and stored daily (between 9am to 9am next day) for following variables: rainfall, potential evapotranspiration, air and vapor pressure, maximum and minimum air temperature, soil temperature, relative humidity, solar radiation, wind speed and soil moisture (Tait et al. 2006, 2012). These values are stored in NIWA's national climate database (CLIDB), covering 11,491 grid-points, with each grid point 5 km apart.

The VCSN is the primary dataset used in climate change impact studies (Tait et al. 2012) and is used for empirical statistical downscaling of the global climate models (GCMs) for New Zealand (MfE 2008). Other climate change studies where VCSN has been used include impacts on weather and climate variability (McKerchar,et al. 2010), impacts on the Waimakariri river (Zammit and Woods 2011), the Lindis and Matukituki catchments (Gawith et al. 2012), effects and impacts manual (MfE 2016) and Climate Change Projections for New Zealand (MfE 2018). These examples demonstrate that VCSN is an established tool that has been used by various researchers for climate change and water resources studies.

Table 2.5: Studies using VCSN data.

Agriculture/ Water Quality	Precipitation/ Weather Forecasting	Streamflow/ Hydrological Modelling	Climate Change Studies/ Guidelines
Farm land use management (Cichota et al. 2008)	Causes of 20th century trends in New Zealand precipitation (Ummenhofer et al. 2009)	Mean flows of New Zealand rivers (Woods et al. 2006)	Climate change effects and impacts assessment (MfE 2008)
Pasture growth model for dairy farm management (Romera et al. (2010)	15 day weather forecast of New Zealand (Renwick et al. 2009)	Streamflow updates in distributed hydrological model (Topnet) (Clark et al. 2008)	Tools for climate change impact on flooding (MfE 2010)
Assessment of *Campylobacter*			

in surface water (Elliott et al. 2011)	Simulation of seasonal snow for South Island (Clark et al. 2009)	Effect of climate change and sea level rise on future flooding (McMillan et al. 2012)	Kidson’s synoptic weather pattern and climate variability (Renwick 2011)
Model to evaluate *Pinus radiata* production (Kirschbaum and Watt 2011)	Automatic drought monitoring system (Mol et al. 2017)	Flood modelling and predicting effects of land use change (Beran 2013)	Climate projections and river flows in Waimakariri River (Zammit and Woods 2011)
	Infilling missing rainfall data (MfE 2017)	National Water Account of New Zealand (MfE 2015)	Climate change in Lindis and Matukituki catchments Gawith et al. (2012)
		Operational flood forecasting (Cattoën et al. 2016)	Climate change impacts on hydropower (Caruso et al. 2017b)
		Validation of national hydrological Model (McMillan et al. 2016)	Climate change projections for New Zealand (MfE 2018)

2.5.7 Limitations and Uncertainty

There are a few limitations and uncertainty that are related to input data . The rainfall data used in VCSN is interpolated from nearby rainfall stations therefore it depends on how close or sparse the rainfall stations located in the catchment. To correct the rainfall data from VCSN, a bias correction (Woods et al. 2006) is applied in TopNet model. the bias correction is estimated for the model runoff cells covering whole New Zealand. The gauge undercatch is one source of uncertainty in rainfall data and it was estimated as high as 18% in the Pukaki catchment (Kerr et al. 2011). The TopNet model has an ability to adjust this gauge undercatch during calibration process and reduce this uncertainty in rainfall estimation that otherwise effect modelling results. The bias correction algorithm estimates runoff from model cells covering New Zealand and averages cells runoff upstream of each flow recording site. The latest TopNet version uses the 2011 Landcover data but the TopNet version utilized in this study uses 2001 Landcover data (LCDB2). The LCDB2 Land Cover type is used for this research because this data (LCDB2) is created from the satellite imagery captured from the 1996-1997 and 2001-2002 period that closely matches with the baseline study period (1980-1999) used in this study. There may be slight changes in the hydrology because of the different Landcover. The Landcover is assumed constant to investigate only the climate change impact on the future streamflows, to outline the direct link between change in climate and change in hydrological regimes and associated runoff generation processes. Moreover, there may not be a major change in the Landcover of the study catchments because it is far from urbanised area and many areas are either inside the national park or located in culturally important locations. The closest town Kurow is 40 km from the centre of the Hakataramea Valley and an Urban Centre Timaru is further 110km from Kurow (Howden 2012) therefore there is less probability of Urban Sprawl. The Ahuriri River is protected by Ahuriri River National Water Conservation Order 1990 so Land Cover in the Ahuriri is less likely to change. A large portion of the catchment areas are covered by Lake Pukaki, Ahuriri Conservation Park, Kirkliston Range Conservation Area, Gamack Conservation Area and Aoraki Mount Cook National Park. “The Waitaki Catchment Water Allocation Regional Plan” emphasizes the cultural significance of Waitaki River and mentions that it is a taonga and it is a duty to maintain the natural resources of Waitaki River now and for future generation. It is unlikely to not have an adverse effect on water quality if the Landuse is changed rapidly by Land intensification.

The limited number of climate stations in the mountainous catchments is a major challenge. In the 897 km^2 area of the Hakataramea catchment, there are only two rainfall stations and six gauging stations. Having a larger number of climate stations is good for capturing many observation points; however, it is not practical due to the excessive cost. The VCSN precipitation data is estimated on 5 x 5 km grid based on the measured rainfall from the rainfall stations. The accuracy improves if the estimated precipitation on the catchment area has a denser climate station network.

The Landcover and Soil use are homogenised due to the assumptions in the TopNet model. The Strahler third order (approximately 7km^2) catchments are used in this study to run the simulations in a reasonable amount of time because finer spatial resolution would take longer time and more computing resources. Because of the difference in different soil and Landcover, the physical properties will be spatially averaged. The model solves water balance for each Strahler 3 catchments, therefore the flux (such as runoff) estimated inside each Strahler 3 catchment will be unique and does not vary on different location and associated with centroid. The VCSN precipitation data is stored as a daily precipitation total and disaggregated as TopNet model runs of hourly water balance. The daily rainfall data is temporally disaggregated using station rainfall data and that may cause slight inaccuracy in timing and magnitude of peak flow.

In addition, there are approximations in the different hydrological processes, e.g., interactions between soil and water are complex and cannot be represented 100% by mathematical formula. The model cannot calculate 100% accurately basin processes, such as canopy storage, snowpack storage, soil root zone storage or unsaturated zone storage. The hydrological processes are complex and any hydrological model is not expected to be perfectly capture these processes, so the uncertainty discussion is required

(Beven 2006, Montanari 2007, Sivapalan 2009, Clark et al. 2012, Nearing et al. 2016). The main message is that the model should not be rejected because it has errors but discussion of the uncertainty is important not only to understand caveats of the particular model but it is also important to improve other models in future.

The TopNet model version used in this study (2011) does not have capability to generate the effect of water abstraction for irrigation or the water loss or gain between catchments. The Environmental Canterbury has set up different conditions in the consents so the allowable water quantity will be reduced during low flow and if the flow is minimal, the water abstraction has to be completely stopped. This version of TopNet model does not consider water abstraction from the catchment or addition of water from another basin. If there is significant water abstraction from the Hakataramea catchment. The model used in this study does not estimate the water gain or loss from groundwater or aquifer water balances. It may not produce good results if there is a lot interaction between surface water and groundwater, for example the Selwyn River in Canterbury Plains.

2.6 TopNet Modelling System

For many applications of TopNet, the estimation of model parameter values currently requires calibration, usually using measured streamflow. The parameters requiring this type of estimation are generally associated with soil hydraulic properties (hydraulic conductivity and water holding capacity of soils). However, careful review of data quality (e.g., precipitation, temperature and streamflow) is a necessary first step, before calibration.

2.6.1 Observed Streamflow

Review of the measured streamflow in the Hakataramea, Ahuriri and Pukaki (Figure 2.2, fand Table 2.4) indicates that suitable discharge measurements (based on length of record) are available at one locations in the Ahuriri three in the Pukaki and six in the Hakataramera. These locations are listed in Table 2.6 and mapped in Figure 2.5 with their corresponding draining catchments.

Table 2.6: Suitable flow stations in Study catchments

Station Number	Station Name	Start Date	Latitude	Longitude	Catchment Area (km^2)	Funders
71103	Hakataramea at above MHBr	26/11/1963	-44.72	170.49	896	ECan, PGSF
71116	Ahuriri at South Diadem	8/09/1963	-44.47	169.73	566	Meridian, PGSF
71125	Hooker at Ball Hut Rd Br	20/09/1960	-43.74	170.12	107	Meridian
71135	Jollie at Mt Cook Station	7/12/1964	-43.86	170.18	140	Meridian, PGSF

The Pukaki catchment also has the three-hour timestep of lake levels and the monitored outflows managed by Meridian Energy (Lake Pukaki, site 8770). The TopNet hydrological model was built for three surface water catchments based on Strahler-three order. The number of Strahler-three catchments are 128 in the Hakataramea, 61 in the Ahuriri and 150 in the Pukaki catchments.

2.6.2 Precipitation

The VCSN precipitation input is used for this study. The daily precipitation obtained from the VCSN is spatially and temporally disaggregated. The disaggregation is done following the rainfall record of the two stations. The inverse distance weighted method was used for the spatial disaggregation. The bias correction is applied to correct the precipitation data. Any bias in the precipitation data is corrected using the method described by Woods et al. (2006): this method utilises the water balance approach and uses mean annual flow as a component of water balance.

It was decided to use the VCSN information as a driver of the hydrological model as this coverage encompasses all precipitation information available. For this project application, daily precipitation was stochastically and temporally disaggregated to hourly time steps, in order to better represent mid to low range of flow generation mechanisms in each of the gauged catchments.

2.6.3 TopNet Parameterisation

There are 31 parameters in the TopNet that are related to the physical characteristics of the catchment: landcover, soil properties, topography and channel properties are associated with these parameters. It is assumed that these physical properties do not vary temporarily.

The parameters of the basin model component of TopNet are nationally available and described in detail by Clark et al. (2009). Most of these parameters are associated and derived from LCDB, LRI, REC and some parameters have been kept constant nationwide. These are surface hydraulic conductivity, which is set up 0.01 m/s and overland flow velocity of 0.1m/s. In addition to these parameters, two parameters related to soil properties, Green-Ampt wetting front suction and Clapp-Hornberger c exponent, are set as 0.3 and 0.1, respectively.

The basin model parameters of TopNet are described in next chapter. The hydraulic conductivity and depth of hydraulically active soil are important parameters in The TopNet model. The surface hydraulic conductivity influences subsurface flow and groundwater recharge and depth of hydraulically active soil influences the hydrograph recession. Therefore, these parameters are calibrated from the streamflow.

The derivation of the catchment scale TopNet parameters from nationally available datasets is described in detail in Clark et al. (2008). These catchment scale parameters represent the default parameter values used in the subsequent sections. However, due to the paucity of some spatial information at national scales, the following parameters in TopNet are set to a single default value across New Zealand:

- Surface hydraulic conductivity is set to 0.01 m/s.
- Soil water characteristics (i.e., Clapp and Hornberger c exponent and Green-Ampt wetting front suction) are constant across the Oreti FMU and set to 1.0 and 0.3 respectively.
- Overland flow velocity is set to 0.1 m/s.

The depth of hydraulically active soil and the surface hydraulic conductivity are two of the most sensitive and critical parameters in TopNet. The depth of hydraulically active soil is associated with the characterisation of the hydrograph recession, while the surface hydraulic conductivity is associated with recharge to the groundwater and subsurface flow characterisation. As a result, those parameters are generally calibrated based on streamflow information.

The drainable water, plant available water, canopy storage and canopy evaporation is taken from the a-priori soil and vegetation related parameters in TopNet (estimated from nationally available datasets). The default calibration ranges are presented in Table 2.7

to illustrate the spatial variability of the TopNet parameters across each of the catchment of interest.

Table 2.7: Default calibration range of parameters in TopNet

Parameter name (internal name)	Parameter description	Calibrated range
Hydrological parameters		
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	[0.01-2] * default
Drainable soil water (swater1)	Range between saturation and field capacity	[0.05-10] * default
Plant available soil water (swater2)	Range between field capacity and wilting point	[0.05-10] * default
Hydraulic conductivity at saturation (hydcond0)		[0.1-10000]*default
Ch_exp	Clapp-Hornberger c exponent	[0.05-10] * default
Ga-psif	Green-Ampt wetting front suction	[0.05-10] * default
Canscap	Canopy storage capacity	[0.05-10] * default
Canenh	Canopy evaporation enhancement factor	[0.05-10] * default
Overland flow velocity (overvel)		[0.1-10]*default
Manning n	Characterises the roughness of each reach	[0.1-10] *default
Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	[0.7-1.5] * default
Gauge undercatch (gucatch)	Adjustment for non-representative precipitation	[0.5-1.5] * default
Snow parameters		
Threshold for snow accumulation (th_accm)	Temperature threshold for snow accumulation	270.15-275.15 [K]
Threshold for snow melt (th_melt)	Temperature threshold for snow melt	269.15-274.15 [K]
Snowddf	Degree-day factor for snow melt	1-10 [mm K^{-1} day^{-1}]
Minddf	Calendar day of the minimum degree-day factor	1-366 [days]
Maxddf	Calendar day of the maximum degree-day factor	1-366 [days]

Parameter name (internal name)	Parameter description	Calibrated range
Snowamp	Seasonal amplitude of degree-day factor for snow melt	0-5 mm K^{-1} day^{-1}]
Snowros	Addition in melt factor caused by rain-on-snow events	0-5 mm K^{-1} day^{-1}]
Decmelt	Decrease in melt due to higher albedo after fresh snow	0-5 mm K^{-1} day^{-1}]
Albdecy	Time decay of snow albedo	1-5 days
cv_snow	Subgrid variability representing the distribution of the snow pack across the catchment	0-2 [-]

2.7 Conclusion

This chapter illustrated the research problem and discussed briefly aims and objectives of this study. The advantages and disadvantages of different types of hydrological models are described and the suitable hydrological model (TopNet) is selected for this study. The basin processes of the TopNet model is discussed with a schematic diagram. The model design described the climate, soil, groundwater, landcover and how these parameters are linked for the TopNet model development. TopNet model theory, the model design and spatial input data requirement for the model is discussed and the basic principle of the TopNet modelling system is described. GCSMs are another input data that is required to run the TopNet model for future periods. Reasons for selecting the SRES scenario for this studied are explained. The limitation and uncertainty of the TopNet model is discussed. Finally, the streamflow observation for the potential calibration sites, precipitation data and parametrisation of the TopNet model is discussed.

Chapter 3. Calibration of TopNet model in the study Catchments

The Hakataramea, Ahuriri and Pukaki are part of the Waitaki River Basin (Table 3.1). The Waitaki Basin is quite variable in terms of elevation, land cover, precipitation, snow and glaciers.

The Pukaki and Ahuriri catchments have already been calibrated by NIWA, therefore this calibration was used to run the simulations for this study. The Pukaki calibration is also used for modelling climate change impact on headwater lakes and hydroelectric power generation (Caruso et al. 2017a, 2017b). The TopNet model is calibrated and validated for the Hakataramea catchment in this study. A brief description on the uncertainty, minimisation of calibration and simulation error is discussed, followed by the conclusion of this chapter.

Table 3.1: Main hydrological characteristics of catchments chosen for this study (Waugh et al. 2003)

Parameter	**Ahuriri at South Diadem**	**Lake Pukaki Outlet**	**Hakataramea Catchment Outlet**
Catchment Area (km^2)	557	1360	900
Mean Discharge (m^3/s)	23.9	129	6
Lowest Flow recorded (m^3/s)	6.6	2	0.71
Highest Flow recorded (m^3/s)	570	4095	1352

3.1 Variables of interest

The purpose of this study is to evaluate climate change impact on water resources. As such, our analysis focusses mainly on the mid-flow range to low-flow ranges. High-flow analysis is used only as indicative throughout this chapter as New Zealand catchments have generally a concentration time of less than 12 hrs (Griffiths (2007); Collins and Henderson 2018), which is a higher resolution than the climate and climate change temporal resolution. As a result, the following hydrological characteristics are the focus of this study.

The range between low to mid-range of flows are variables of interests in this study. One variable of interest is the flow thresholds in the Hakataramea catchment and water availability for the energy production in the Pukaki catchment. Ahuriri river flows in the Ahuriri catchment are important because Ahuriri catchment flow provides suitable habitat for many species. Currently, water resources are limited because they are fully allocated in the Hakataramea catchment, the Pukaki catchment downstream of Pukaki Dam is completely used for Hydroelectric Power Generation and Ahuriri Catchment provides unrestricted flow because of the River Protection Order 1990. Another aspect is looking as seasonality of these water resources and how the future climate change will impact these above concerns by different seasonality of flow and runoff. The calibration is done considering the following factors.

1) The calibration of a hydrological model is primarily based on two main factors: how well the modelled fluxes match with observed ones and a statistical quantification of the differences between observed and modelled flows, such as NS or root-mean-square error (RMSE). The strength of calibration in this study is checked by evaluating the relationship between observed and modelled flows.

This is checked by Nash-Sutcliffe efficiency coefficient (NS), logarithm of Nash Sutcliffe efficiency (NS log) coefficient. The NS efficiency coefficient (Nash and Sutcliffe, 1970) is a tool to assess the accuracy of predictive capacity of hydrological models. The NS coefficient 1 shows that the modelled flows exactly matches with the observed flows and negative NS coefficient (NS<0) shows the average of the observed values are better predictor of the model, compared to the model values.

2) The observed and predicted flow duration curve will be compared to find out whether there is any differences in the statistical distribution of flow.
3) The cumulative observed and predicted flow will be plotted to find out whether there is any bias in calibration process or not.
4) Total water balance is required to test whether the calibration is good over the simulation period. The annual average precipitation, evaporation and discharge will be evaluated for the total water balance at the gauging station.
5) The observed and predicted flows will be plotted to test whether the model has worked well to simulate the flows that can impact on future streamflows. The snow component is not important for the Hakataramea catchment, therefore the national parametrization is used in Hakataramea. The snow component for the catchments such as Pukaki and Ahuriri was calibrated by comparing remotes sensing snow cover information and utilizing Shuffled Complex Algorithm (SCE-A) (Duan et al. 1993).

3.2 TopNet Model Calibration

A detailed description of TopNet and its calibration process is provided in Bandaragoda et al. (2004); Clark et al. (2008); Clark et al. (2009); Poyck et al. (2011);,Gawith et al.

(2012); McMillan et al. (2016); and Singh (2016). The spatial distribution of catchment parameters are a priori in the TopNet and parameter multiplier values are set to 1 before calibration. A spatially constant set of parameter multipliers retains the topographical characteristic of the catchment and reduces the dimensionality. The calibration is done by adjusting the parameter multipliers. Seven hydrological parameters and ten parameter multipliers needed to be calibrated. Table 3.2 shows the range of parameter multipliers for Hydrological and Snow Parameters.

Table 3.2: TopNet model of hydrological and snow parameters ranges

Hydrological Parameters

Name (parameter name)	Description	Calibrated Range
Saturated Store Sensitivity(topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	[0.01-2] *default
Drainable soil water (swater1)	Range between saturation and field capacity	[0.05-10]*default
Hydraulic conductivity at saturation (hydcon0)		[0.11000]*default
Ch_exp	Clapp_Hornberger c component	[0.05-10]*default
Ga_psif	Green-Ampt wetting front section	[0.05-10]*default
Canscap	Canopy storage capacity	[0.05-10]*default
Canenh	Canopy evaporation enhancement factor	[0.05-10]*default
Overland flow velocity (overvel)		[0.1-10]*default
Manning’s n	Characterises the roughness of each reach	[0.1-10]*default
Atmospheric lapse rate (atmlaps)	Changes in temperature with elevation, used to adjust temperature from climate data sites to basin centroid	[0.7-1.5]*default
Gauge undercatch	Adjustment for non-representative precipitation	[0.5-1.5]*default

Snow Parameters

Name (parameter name)	Parameter Description	Calibration Range
	Temperature threshold for snow accumulation	270.15-275.15 [K]
Threshold for snow accumulation (th_accm)	Describes exponential decrease of soil hydraulic conductivity with depth	269.15-274.15 [K]
Snowddf	Degree-day factor for snowmelt	1-10 [$mmK^{-1}day^{-1}$]
Minddf	Calendar day of the minimum degree-day factor day	1-366[days]
Maxddf	Calendar day of the maximum degree-day factor day	1-366[days]
Snowamp	Seasonal amplitude for degree-day factor for snowmelt	0-5 [$mmK^{-1}day^{-1}$]
Snowros	Addition in melt factor caused by rain_on_snow events	0-5 [$mmK^{-1}day^{-1}$]
Decmelt	Decrease in melt due to higher albedo after fresh snow	0-5 [$mmK^{-1}day^{-1}$]
Albdecy	Time decay of snow albedo	1-5 days
cv_snow	Subgrid variability representing the distribution of the snowpack across the catchment	0-2[-]

3.3 TopNet Model Calibration for Hakataramea

The Hakataramea catchment drains an area of 897km^2 with elevation ranging from 204 to 1889 amsl stream networks, elevation, rainfall stations and flow measuring (gauging) stations. This is shown in Figure 3.1.

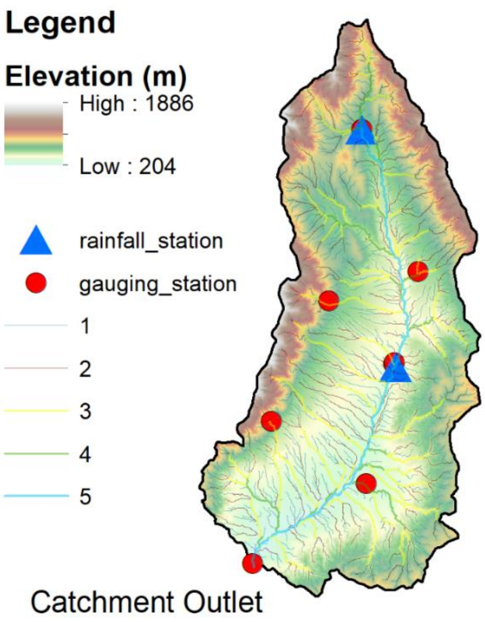
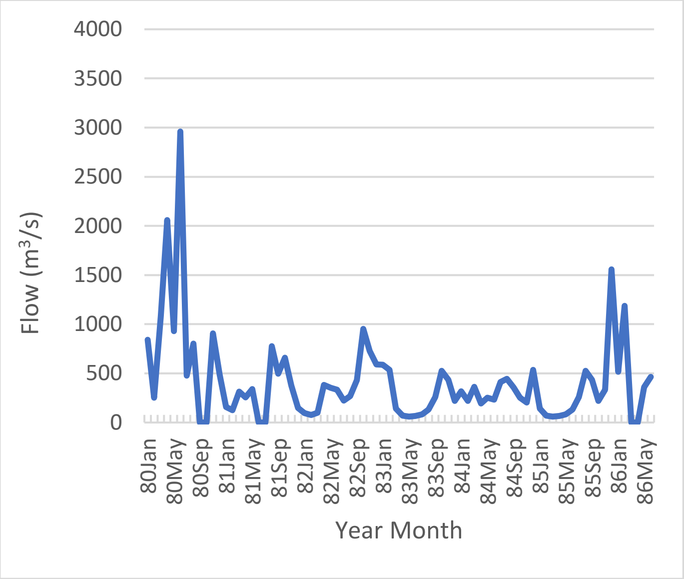
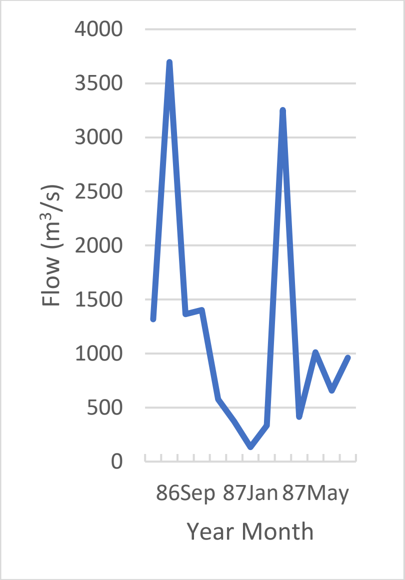


Figure 3.1 Hakataramea catchment gauges, elevations and stream networks

Previous chapters displayed that there are several (7) flow gauging stations in the Hakataramea catchment (Table 2.4).The TopNet model in Hakataramea is calibrated using the hourly discharge data of the Hakataramea River at the Main Highway Bridge (Hakataramea at MHBR) gauging station. This flow gauge is chosen because it has the longest available flow record in the Hakataramea catchment.

The TopNet model is calibrated for the Hakataramea catchment using the eight years' period between 1993-1999. This period was considered for calibration based of the analysis of flow. For this purpose, the calibration period should include low flows, because it will impact on applications for water consenting and agricultural uses and it should also have average flows, as that impacts on the overall water availability. However, the calibration period should not have only low flows or high flows for the entire period of calibration, because it would not be the representative scenario for the water resources perspective, and the calibration period from 1993 to 1999 is chosen because it is not dominated by only high or low flows. The monthly flows from the Hakataramea outlet (from Hakataramea State Highway Bridge gauge) between 1980 to 2000 are plotted in Figure 3.2. This shows extended periods of low flows dominated between 1980 to 1986, followed by high flows in 1986 and 1987, then a low flow between 1987-1990 and a high flow between 1990-1993. Therefore, this period is not dominated by a prolonged duration of higher flows or lower flows.





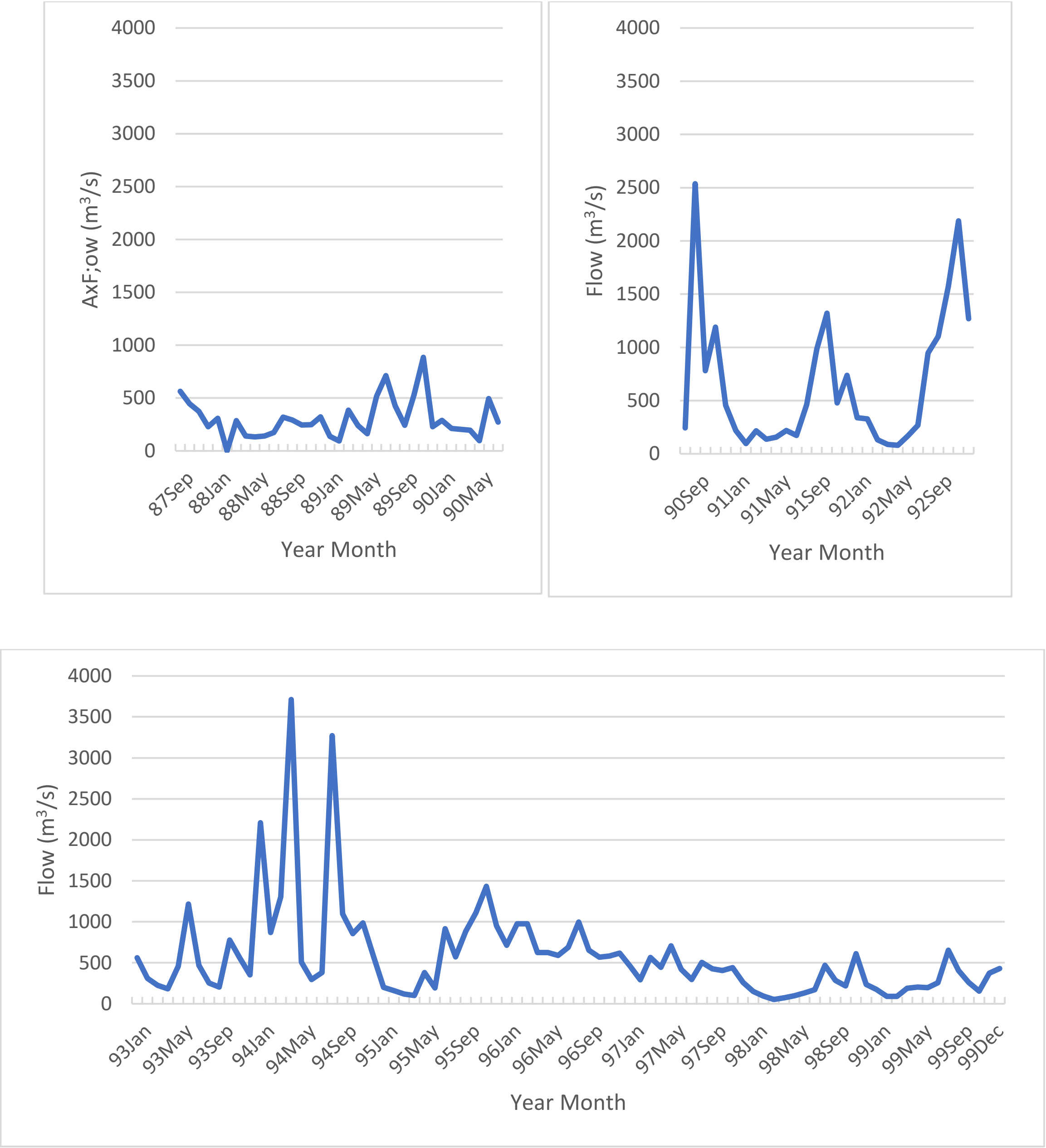


Figure 3.2 Hakataramea monthly river flow at Hakataramea State Highway Bridge for the periods between (a) 1980-1986, (b) 1986-1987, (c) 1987-1990, (d) 1990-1992 and (e) 1993-1999

The average monthly flow for the 1980-1999 period at the Hakataramea State Highway Bridge is plotted in Figure 3.3. The long-term monthly average shows that the flow is higher during late winter and early spring and lower in summer. This is due to the fact that most of the precipitation falls as rainfall and there is no permanent snow site in the catchment.

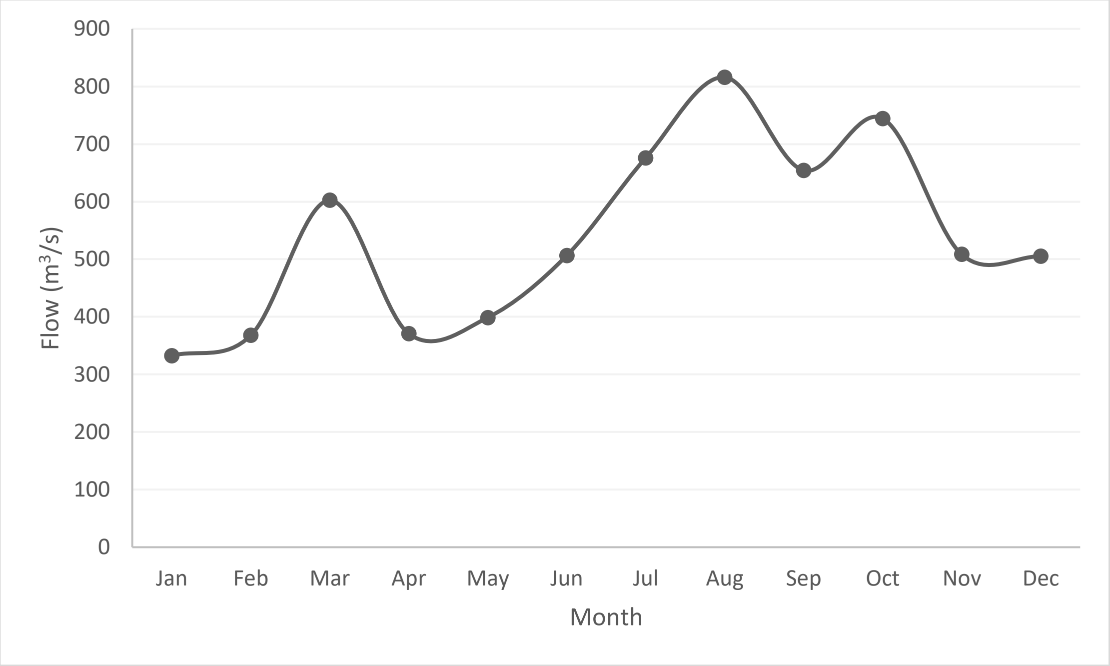


Figure 3.3 Hakataramea monthly average river flow at Hakataramea State Highway Bridge for the 1980-1999 period

A unique calibration technique, named Robust Parameter Estimation (ROPE), developed by Bradossy and Singh (2008), was used to get the optimal parameter set. The ROPE algorithm generates an ensemble of parameter sets and uses a geometrical approach based on Tukey's half space. The calibration process is susceptible to measurement errors, hence the calibration would not be accurate if the measurement errors are present. The manual calibration is cumbersome and also time consuming, because many parameters are related and a change in one parameter may affect other parameters and make it difficult to calibrate. Bradossy and Singh (2008) and Singh et al. (2012) describe the ROPE algorithm method of obtaining the best parameter set. The random number of parameter sets are generated from a uniform distribution from a parameter space. After this, the model is run for all parameters and N% of parameter sets are selected. The parameters outside the convex hull are removed and another set of higher depth of parameters inside the convex hull is obtained. Again, the performance is calculated and a N% of parameters are obtained. This cycle will continue until a) the number of iterations reaches predetermined values, or b) there is only a small difference between one set and subsequent set of parameters. The best parameter set that represents the catchment is the one that has best fit between observed and modelled values and can match the water fluxes. There is a difference between a ROPE algorithm and other parameter estimation methods. This algorithm does not select the best parameter, but it gives a set of predetermined parameter sets. The best parameter can be chosen from the parameter sets. In the Hakataramea calibration, the parameter sets obtained from the ROPE algorithm were run individually to get the best parameter set. ROPE was used to generate an ensemble of optimal mathematical TopNet parameter set for the objective function chosen. The calibrated parameters for the Hakataramea catchment with description and values are shown in Table 3.3.

Table 3.3: Calibrated parameters for the Hakataramea catchment TopNet model.

Parameter	**Description**	**Calibrated Parameters**
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.583*default
Drainable soil water (swater1)	Range between saturation and field capacity	0.646*default
Hydraulic conductivity at saturation (hydcon0)		1.953*default
Ch_exp	Clapp-Hornberger c component	2.086*default
Ga_psif	Green-Ampt wetting front section	2.048*default
canscap	Canopy storage capacity	2.425*default

canenh	Canopy evaporation enhancement factor	2.329*default
Overland flow velocity (overvel)		2.103*default
Manning’s n	Characterises the roughness of each reach	0.537*default
gucatch	Gauge under-catch for snowfall	0.907* default
th_accm	Threshold for snow accumulation	272.16 [K]
th_melt	Threshold for snowmelt	271.16 [K]
snowddf	Mean degree-day factor for snowmelt (mm $K^{-1}day^{-1}$ = kg m^{-2} $K^{-1}day^{-1}$)	7 [mm $K^{-1}day^{-1}$]
minddfd	Minimum degree-day factor day (Julian day: 1 to 366)	200 [days]
maxddfd	Maximum degree-day factor day (Julian day: 1 to 366)	356 [days]
snowamp	Seasonal amplitude of degree-day factor for snowmelt (mm $K^{-1}day^{-1}$ = kg $m^{-2}K^{-1}day^{-1}$)	5 [mm $K^{-1}day^{-1}$]
snowros	Rain on snowmelt factor (mm $K^{-1}day^{-1}$ = kg m-2$K^{-1}day^{-1}$)	0 [mm $K^{-1}day^{-1}$]
decmelt	Decrease in melt with fresh snow (mm $K^{-1}day^{-1}$ = kg $m^{-2}K^{-1}day^{-1}$)	2.5 [mm $K^{-1}day^{-1}$]
albdecy	Time scale for the reduction in snow albedo (days)	5 [days]
cv_snow	Coefficient of variation in sub-grid SWE	1 [-]

watflow	Transmissibility of water through the snowpack (m s^{-1})	0.01
fsnoalb	Fresh snow albedo	0.85

3.4 Model Calibration and Validation Results and Discussions

The calibration and validation of a hydrological model is primarily based on two main factors: how well the modelled fluxes match with observed ones and a statistical quantification of the differences between observed and modelled flows, such as Nash-Sutcliffe efficiency coefficient. The calibration and validation statistics is presented in Table 3.4.

Table 3.4 Objective function value in Calibration and Validation

Calibration/Validation Statistics	Calibration		Validation	
	NS	Log NS	NS	Log NS
Hakataramea at above MHBR	0.63	0.66	0.65	0.67

The validation of TopNet model in the Hakataramea catchment was done for the remaining baseline period, i.e., 1980-1992, a different period than the calibration period. The purpose of the validation is to check whether the model produces comparable results when tested outside the calibration period. When it was calibrated, the model produced comparable results in the simulation run outside the calibration period.

Figure 3.4 demonstrates the cumulative observed and predicted flows for the calibration period and Figure 3.5 displays the same for validation period. The cumulative modelled flow was slightly underestimated in the beginning of calibration but after a while it closely matched with observed flows, suggesting a good calibration. The modelled flow underestimated in a flood event during 1986 and matched with observed flow for other events.

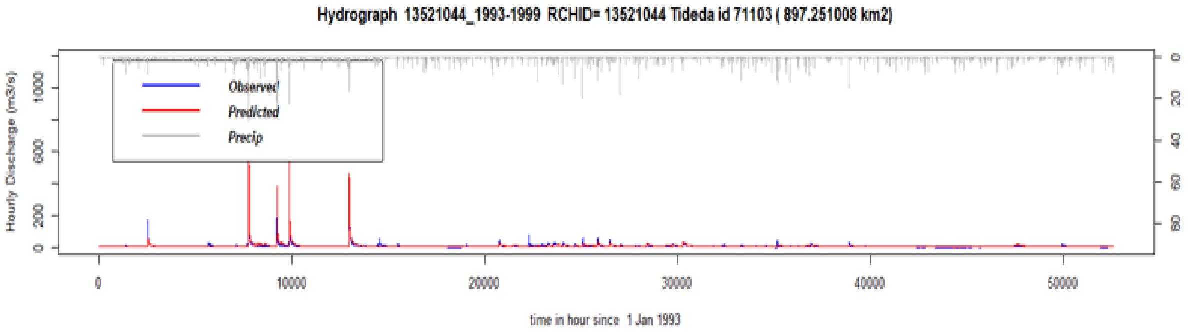


Figure 3.4: Observed and predicted flows for the calibration period.1993–1999

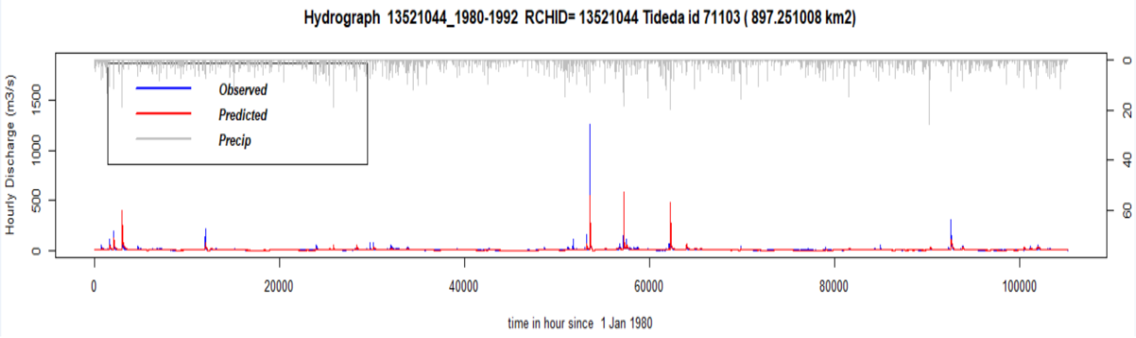


Figure 3.5: Observed and predicted flows for the validation period.1980–1992

Figure 3.6 and Figure 3.7 demonstrate the cumulative observed and predicted flows for the calibration and validation period. The cumulative modelled flow was slightly underestimated in both calibration and validation.

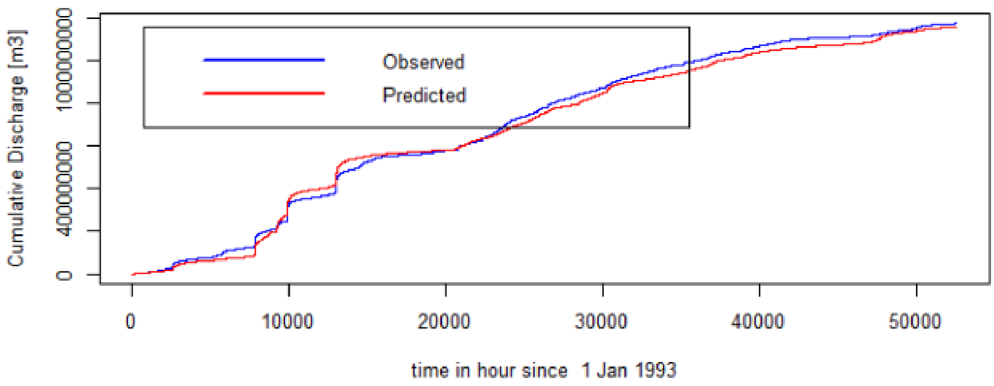


Figure 3.6: Cumulative observed and predicted flows for the calibration period. (1993–1999)

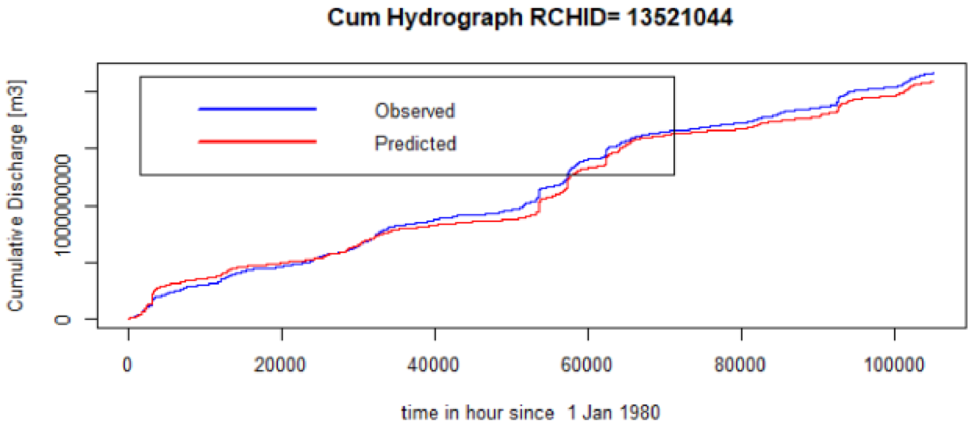


Figure 3.7: Cumulative accumulation and melt for the validation period (1980-1992).

The percentages of exceedance or probability of exceedance of the observed and modelled flows are shown in Figures 3.8 and 3.9 for the calibration and validation period. The vertical axis displays catchment flow at the outlet of the catchment and the horizontal axis displays probability of exceedance. The 100% percentage of exceedance means that the flow in the catchment outlet is always higher than that flow or that this is the minimum flow. The 0% means no flow is higher than that 0% flow, or probability of any flows higher than this value is 0%. The predicted flows are overestimated for smaller flows and closely matched for average medium or high flows. The simulated (predicted) flow is slightly overestimated in the beginning and closely matched with the observed flow for the rest of the flows higher than minimum flow. The minimum flow may not be accurate, due to the model deciding whether the precipitation is snow or rain based on temperature, which may be wrong. The flow duration curve for both calibration and validation show that the majority of flows in the Hakataramea catchment are low flows and average flows with a small percentage of flood (high flow). The flow duration curve displays that most of the time the water availability will be limited, therefore this catchment needs more attention to manage water resources efficiently.

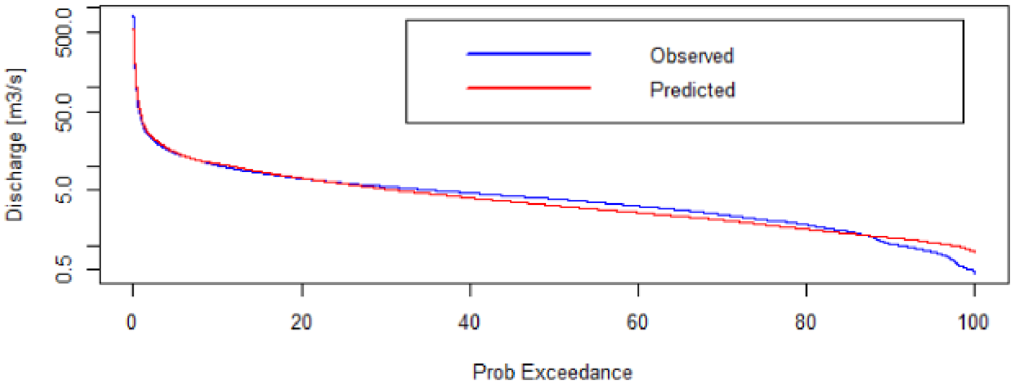


Figure 3.8: Observed and predicted annual flows for the calibration period (1993-1999).

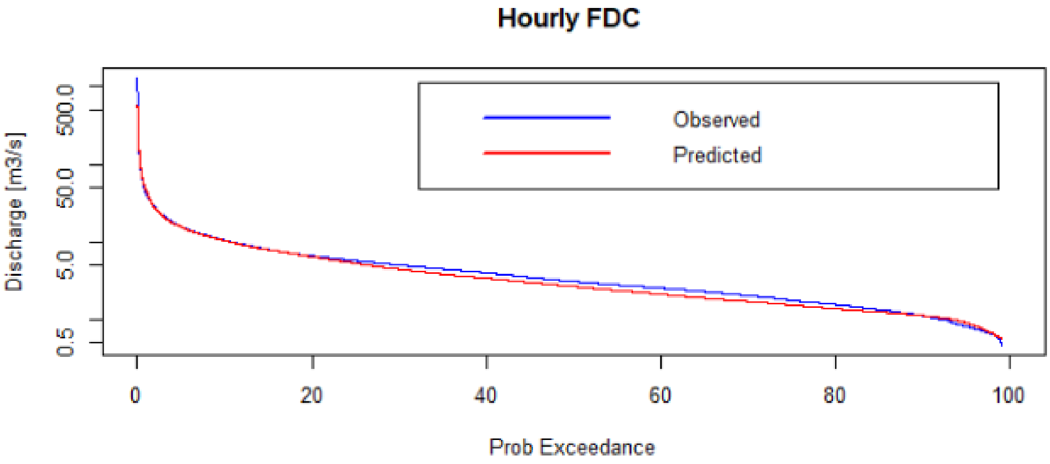


Figure 3.9: Observed and predicted annual flows for the validation period (1980-1992).

The water balance at the outlet is plotted in Figure 3.10 and Figure 3.11. The vertical axis displays cumulative flux in metres and the horizontal axis shows the time in hours.

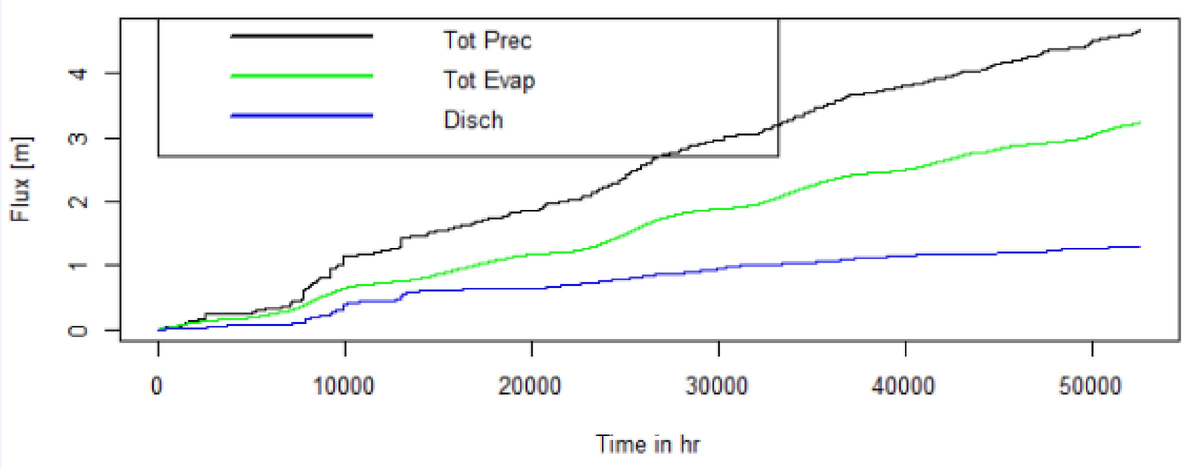


Figure 3.10: Cumulative precipitation, evapotranspiration and discharge for the calibration period (1993-1999)

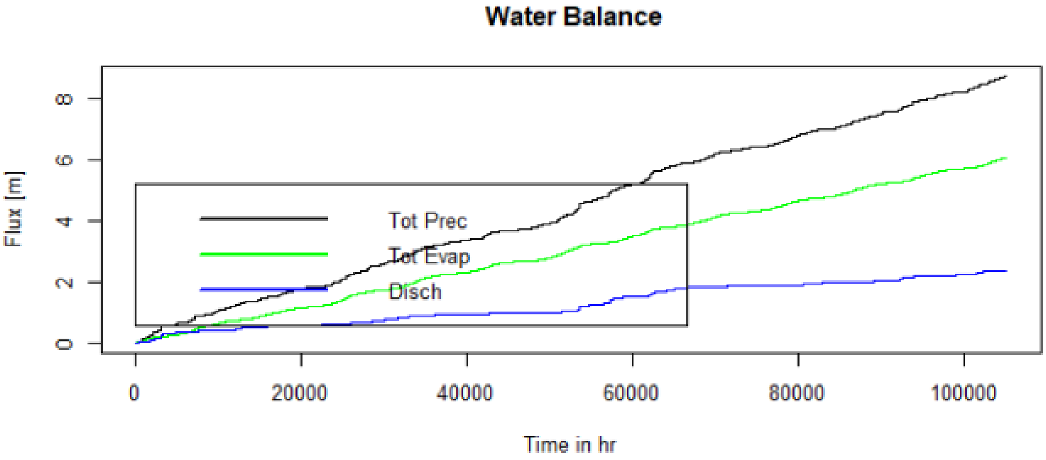


Figure 3.11: Cumulative accumulation and melt for the validation period (1980-1992)

The cumulative accumulation and melt for the calibration period in the Hakataramea catchment are shown in Figure 3.12 and 3.13. The vertical axis displays snow flux in millimetres and the horizontal axis shows calibration period in hours. This plot shows that there are only a few small periods of time when snow accumulates and quickly melts, coinciding with cumulative snow fluxes, suggesting the snow does not accumulate longer. Snow accumulation and melt are calculated using the temperature index model inside the snow model. These plots suggest that this catchment is rainfall driven and snow does not exert much influence here.

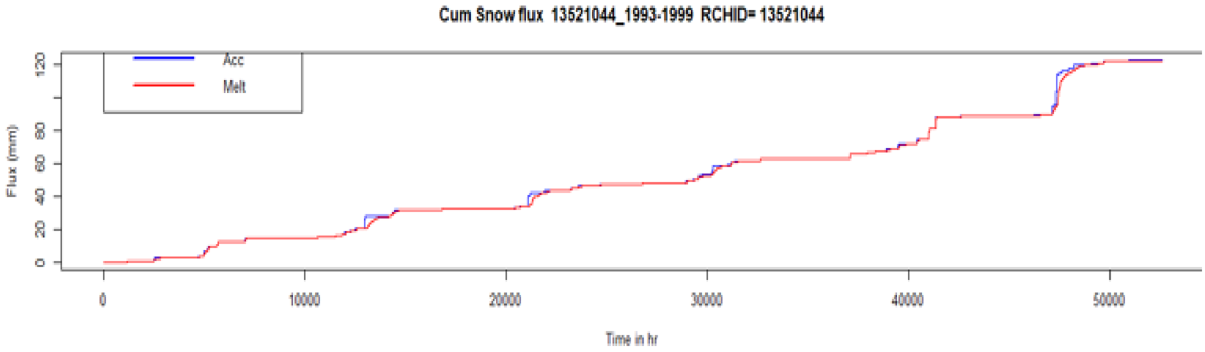


Figure 3.12: Cumulative accumulation and melt for the calibration period (1993-1999)

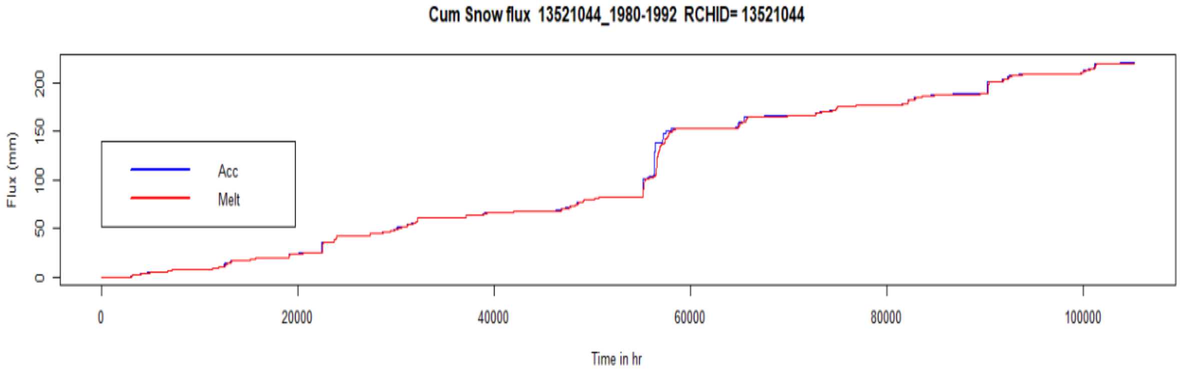


Figure 3.13: Cumulative accumulation and melt for the validation period (1980-1992)

3.5 Pukaki and Ahuriri Calibrations

The calibration of the Pukaki catchment was done on flow records of the Hooker and Jollie rivers and from the Pukaki lake inflow. The 1980-1990 period was selected as a calibration and the 1990-2000 period was chosen as validation. The calibration period was chosen to demonstrate different water resources condition, such as higher runoff as well as lower than mean annual flow. The model is validated for the 1980-1990 period. The accuracy of the model is evaluated using NS coefficient on discharge and log of discharge. The NS and NS log for calibration period are 0.527 and 0.502, while for validation it is 0.408 and 0.205, respectively. The calibration in the Pukaki catchment was not perfect, because of the overestimation of daily VCSN precipitation, caused by the lack of hourly precipitation data. The Pukaki catchment has been already calibrated by NIWA. The same calibration has also been used in another climate change study (Caruso et al. 2017a,2017b). Caruso et al. 2017b used the Pukaki calibration to evaluate climate change impact on hydropower lake inflows in the Waitaki catchment. The calibrated parameters are showed in Table 3.5.

Table 3.5: Calibrated parameters for the Pukaki catchment TopNet model.

Parameter name (internal name)	Parameter description	Calibrated value
Hydrological parameters		
Saturated store sensitivity (topmodf)	Describes exponential decrease of soil hydraulic conductivity with depth	0.513 * default
Drainable soil water (swater1)	Range between saturation and field capacity	1.621 * default
Plant-available soil water (swater2)	Range between field capacity and wilting point	0.861 * default
dthetat	Soil water content	1.644 * default
ch_exp		1.024 * default
ga-psif		1.075 * default
canscap		0804 * default
canenh		0.624 * default
Hydraulic Conductivity at saturation (hydcond0)		1.177 * default
Overland flow velocity (overvel)		0.480 * default
Manning n	Characterises the roughness of each reach	1.438 * default

Atmospheric lapse rate (atmlaps)	Change in temperature with elevation, used to adjust temperatures from climate data sites to basin centroid	0.400 * default
Gauge Undercatch (gucatch)	Adjustment for non-representative precipitation	0.720 * default
Snow parameters		
Th_acc	Temperature threshold for snow accumulation	275.71 [K]
Th melt	Temperature threshold for snow melt	274.88 [K]
snowddf	degree-day factor for snow melt	2.214 [mm K-1 day-1]
Min ddf	minimum degree-day-factor day	236 [day]
maxddf	maximum degree-day-factor day	36 [day]
snowamp	seasonal amplitude of degree-day factor for snow melt	4.469 [mm K-1 day-1]

The calibration of the Ahuriri catchment was done on flow records of the Ahuriri at the South Diadem gauging station. kaki lake inflow. This station has long term record since 1963. The calibration was performed on river inflow available at the only one gauging station. The calibration was poor with only 0.17 and 0.41 for NS and log of NS coefficient respectively The model overestimated the flows most of the time of flow duration curve One of the reason for lower accuracy may be there is no opportunity to compare the flow in one of the other internal gauge sites inside the catchment. All rainfall stations inside this catchment are located at higher elevation (>500 masl) and a portion of the area receive decent snowfall every year. The TopNet model version (2011) used in this study have limited capacity to interact with groundwater and there is a groundwater basin in Ahuriri Basin.

3.6 Uncertainty and Limitations

The purpose of the calibration and validation of the hydrological model is to tailor the model so that it fits the requirement or fulfils the intended objective. In a perfect world, the models should represent the real-world scenario. Beven (2006) showed that even though the Representative Elementary Watershed (REW) concepts provide the scale-independent framework for the representation of hydrological processes, the internal state variables and boundary fluxes of the REW are nonlinear and hysteretic. Hence, the simple averaging of the local flux may not be sufficient to solve the REW flux balance and this is, in fact, scale dependent. Montanari (2007) emphasizes the importance of coherent terminology and a systematic approach to address the uncertainty in hydrological models. The author emphasised that the uncertainty can be in design variables/processes or in forecasts. To provide the confidence to end users, Montanari further suggested that the uncertainty should be addressed by approximate analytical methods, statistical analysis of the model, sensitivity analysis and non-probabilistic methods. However, uncertainty estimation in hydrological modelling is paramount, because models need approximations: the input data are subjected to non-stationary errors and the product obtained from the processing of the erroneous data will be complex and non-stationary (Beven 2008). Sivapalan (2009) emphasised two important questions that hydrological science needs to ask: firstly, hydrological model users, such as policy makers and managers, should understand the prediction confidence of the model they are using so that they can make decisions accordingly. Secondly, hydrologists who develop models should recognise any uncertainty in the model and the sources of uncertainties, such as model structure, process description and parameter uncertainty. Instead of creating a complex model to fit the data perfectly, the author suggests the goal should be to utilise techniques, such as pooling the data of pan-evapotranspiration and using new-generation models – such as the model that uses mass, energy and momentum balance in catchments. Koutsoyiannis (2010) described that natural processes have unpredictability (randomness or stochastic) and predictability (deterministic), which are not mutually exclusive but co-exist in the natural world that is modelled by hydrological models. The author further suggested that the question of predictability depends on the time horizon: the longer the time horizon, the greater the randomness or uncertainty. Hydrological data are affected by measurement difficulties, such as rainfall or snow water equivalence; actual evapotranspiration cannot be measured accurately over catchments; and even rating curves might be developed from extrapolation of the data rather than direct measurement (Beven and Westerberg 2011). They characterised these inaccuracies as disinformation in the model and suggested avoiding this disinformation by identifying the disinformation periods in the data and avoiding using those periods of data in calibration and validation. The disinformation in the Hakataramea calibration is excluded by choosing a calibration period when the data was continuous. The calibration was chosen as 1993-2000 period, because there are four instances when data was not continuous between 1980-1990, due to an error in instruments and the maximum recorded flow was 1126m^3/s in March 1986.

Clark et al. (2012) emphasised the importance of utilising advancements in data collection, mathematical modelling and environmental physics in hydrological models. They encouraged comparison and suggested the discussion of model performances based on different statistical techniques and assumption will help to develop better models in the future. Beven (2016) cautioned that hydrologists may be focussing more on fitting the curve to calculate probability in such a way that it focusses on overfitting during calibration and validation. He further emphasized the focus should be on the investigation of the uncertainties that can arise due to the model structure or parametrization. Nearing et al. (2016) described the current uncertainty analysis as lacking a coherent approach and focusses on probability, when, instead, the focus should be on epistemological knowledge or how to use the available information more efficiently: flawed logic cannot provide any meaningful reasoning for modelling errors. Nearing et al. (2016) also emphasised asking questions, so meaningful discussion about uncertainty can lead the development of better future models. They argued that if there is an error in flow measurement, and calibration is done using this erroneous data, then the model results cannot be better, regardless of how much of a better fit is achieved during calibration. The Hakataramea calibration uses gauge “Hakataramea River at Hakataramea Main Highway Bridge”. The flow data that is obtained from this station undergoes quality control and is tested before it is available for analysis or goes public (Christian Zammit, personal communication). The possibility of data error is minimised in the calibration and validation because the data that is used in the study period of this research has been undergone a quality control process.

The accuracy of TopNet calibration depends on the accuracy of the input data: any error in measured and estimated data (precipitation, temperature, flows) can lead to errors in calibration. The *New Zealand Rainfall Intensity Indices* (MfE 2017) describes how the climate data is collected and stored in NIWA’s National Climate Database (CLIDB) and what type of quality control is performed to ascertain the quality of the data. First, any data that appears extremely larger or smaller is flagged for the verification process. Second, the data is stored frequently, such as hourly or six hourly, so that any potential error can be flagged at an early stage. Third, the daily cumulative estimation also logs any errors or warnings as “ERRLOG” and “WARNLOG” every midnight. After these tests, the data is either unchanged or corrected based on the data quality and some portions may even be deleted from CLIDB if it’s not possible to correct them.

The flow stations in the study areas are owned and operated by regional councils, energy companies and NIWA. All the flow gauges are calibrated and necessary steps are taken, like the climate data. The data, as well as flow equipment, is checked and tested, whether they meet the quality requirements or not. All the runoff data is quality controlled and has a quality rating of 1 or 2 (good) before its released (Christian Zammit, personal communication).

TopNet calibration depends on the accuracy of the input data: any error in measured and estimated data (precipitation, temperature, flows) can lead to errors in the model result.

The VCSN is used to reduce the error in precipitation and temperature estimation. The VCSN rainfall is accumulated in a daily basis; therefore, even though it’s disaggregated hourly, the timing and magnitude of peak is slightly different. However, this does not have a large effect on the overall water balance. Good calibration depends on high quality input data, which is available from measured data. The limited number of climate stations in the mountainous catchments is a major challenge. In the 897 km^2 area of the Hakataramea catchment, there are only two rainfall stations and six gauging stations. Having a larger number of climate stations is good for capturing many observation points; however, this is not practical due to the excessive cost. The VCSN precipitation data is estimated on 5 x 5km grid based on the measured rainfall from the rainfall stations. The accuracy could be improved if the estimated precipitation on the catchment area had a denser climate station network.

In addition, there are approximations in the different hydrological processes, e.g., interactions between soil and water are complex and cannot be represented 100% by mathematical formulae. The model cannot accurately calculate all basin processes, such as canopy storage, snowpack storage, soil-root zone storage or unsaturated zone storage. The snowmelt contribution to mean annual flow for the Ahuriri River, Lake Pukaki, and Waitaki River are 15%, 23% and 17% respectively (Kerr.2013). New Zealand does not have systematic historical snow observation therefore the interannual variability and future projection is generated using simulation model (Hendrikx et al. 2012). The temperature index snow model is used in this study. But it is a fact that the actual measured long-term snow data is better compared to the snow estimate using any simulated snow model. The hydrological processes are complex and no hydrological model is expected to perfectly capture these processes, so the uncertainty discussion is required (Beven 2006; Montanari 2007; Sivapalan et al. 2009; Clark et al. 2012; Nearing et al. 2016). The main message is that the model should not be rejected because it has errors, but discussion of the uncertainty is important, not only to understand caveats of the particular model, but to also improve other models in the future. The rainfall data used in VCSN is interpolated from nearby rainfall stations, therefore it depends on how close or sparse the rainfall stations are located in the catchment. To correct the rainfall data from VCSN, a bias correction (Woods et al. 2006) was applied in TopNet model. The bias correction algorithm estimates runoff from model cells covering New Zealand and averages cells runoff upstream of each flow recording site. The gauge undercatch is one source of uncertainty in rainfall data and it was estimated as high as 18% in the Pukaki catchment (Kerr 2011). The TopNet model has an ability to adjust this gauge undercatch during calibration and reduce this uncertainty in rainfall estimation that otherwise affects modelling results.

Strahler third-order catchment (10 km^2) is used in this research. TopNet considers modelled runoff and other fluxes are uniform across the spatial scale of Strahler three catchment in this study. It would be better to use a finer spatial scale, such as Strahler one, but this is computationally very demanding. Also, this would not achieve a significant benefit, unless all input data such as precipitation, temperature, soil, DEM and land use also have the finer resolutions. The TopNet 11 used in this study had a limitation: there was no interaction between surface water and groundwater. However, the latest TopNet version has an ability to interact between groundwater and surface water – that may be useful when there is a large interaction between groundwater and surface water or stream.

3.7 Conclusion

This chapter discussed how to calibrate and validate the TopNet model to determine present, as well as future, flows. The input data required to run the model and the basin model parameters that are obtained from soil, landcover and digital elevation data is discussed. This chapter described calibration strategy and calibration process. Model performance, and hence calibration, is evaluated based on modelled, observed and cumulative flows, probability or percentage of flow exceedance and the Nash-Sutcliffe efficiency values. The calibrations are good because the observed and modelled flows are in agreement with a good Nash-Sutcliffe efficiency, as well as other hydrological signatures, such as flow duration curve, cumulative runoff and water balance. The effect of uncertainty in calibration from input data and other factors are discussed. The simulation process to determine present and future flows is explained and the limitations are also discussed.

Chapter 4. Climate Change

The previous chapter discusses physiographic and climatic factors that influence the intra-catchments' and inter-catchments' spatial variability and calibration of the TopNet model. This chapter discusses climate change scenarios from the Special Report on Emission Scenarios (Nakicenovic and Swart 2000) and the scenario used in this study are discussed with the Global Circulation Model (GCMs). The process of downscaling from GCMs to local catchment is also mentioned and input data uncertainties are discussed at the end.

4.1 Global Circulation Models and Special Report on Emission Scenarios

Most climate change studies are based on Global Circulation Models or General Circulation Models (GCMs): A GCM models the change in climatic conditions (e.g., greenhouse gas concentration) and simulates the change in climate. It is a mathematical model of the planetary atmosphere based on complex computer programs and simulates the atmosphere, ocean and earth. These GCMs can simulate ocean currents and upwelling as well as atmospheric conditions, and simulate the exchanges of heat, momentum, and moisture between the atmosphere and ocean (MfE 2008).

Pittock and Salinger's (1982) work was one of the early studies about climate change in the Southern Hemisphere. They used four different scenario-generation methods, namely, numerical methods to predict the warming caused by an increase in carbon dioxide. Previous GCMs were unable to predict precipitation changes in the southern hemisphere (Renwick et al. 1999). Nonetheless, recent developments in these GCMs produce the expected changes in temperature and precipitation based on the Special Report on Emission Scenarios or SRES (Nakicenovic and Swart 2000). Four different types of SRES scenarios were developed with each storyline representing different demographic, economic, technological and environmental conditions. The A2 scenario is chosen for this study as it represents the current trend of temperature increase. This scenario assumes a differentiated world with regional orientation, continuously increasing population, and slow technological development. The B2 scenario assumes a lower rate of population growth than A2; however, it assumes more rapid technological development with an increase in local and regional solutions to environmental protection and social equity. The AR4 (IPCC 2007) report is based on SRES scenario but AR5 (2013) report is based on Representative Concentration Pathway (RCP). This study is based on A2 scenario. Since the recent AR5 report is based on RCPs, the relationship between RCPs and SRES is described by Van Vuuren and Carter (2014). Based on their comparison, the A2 scenario is between RCP6 and RCP8.5 (Figure 4.1).

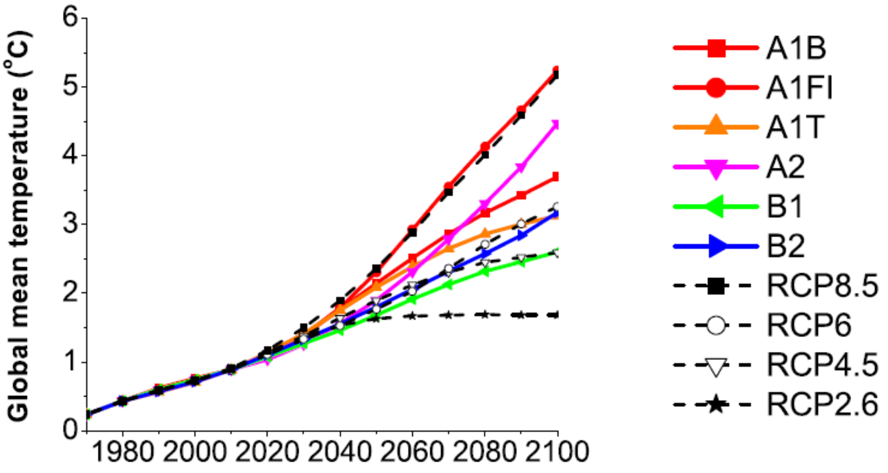


Figure 4.1: Comparison of different SRES scenarios with RCPS (Van Vuuren and Carter 2014).

Different countries have their own preferential GCMs: Australia’s is CSIROMk2b, USA’s is NCARPCM, Canada’s is CGCM2, UK’s is HadCM3 and Japan’s is CCSRNIES. These GCMs cover large spatial scales; hence, results of these GCMs do not reflect local changes directly. Only 12 GCMs are capable of downscaling

New Zealand temperature and precipitation (MfE 2008). The 12 GCMs capable of simulating climate change impact for New Zealand with their countries of origin are shown in Table 4.1.

Table 4.1 The 12 GCMs used in this study (Mullan et al. 2009)

GCM	Country of Origin
cccma_cgcm3	Canada
cnrm_cm3	France
csiro_mk3.0	Australia
gfdl_cm2.0	USA
gfdl_cm2.1	USA
miroc3.2_hires	Japan
miub_echog	Germany/Korea
mpi_echam5	Germany
mri_cgcm2.3.2	Japan
ncar_ccsm3	USA
ukmo_hadcm3	UK
ukmo_hadgem1	UK

4.2 Downscaling

Global circulation models (GCMs) have coarse spatial resolution, with cell sizes comprising hundreds of kilometres (100-500 km) and this results in each cell size having an area of hundreds of square kilometres, with each grid cell being homogeneous (Daniels et al. 2012). However, catchment hydrological models and processes of topographical features influencing catchment runoff are much smaller than these cell sizes. The scale of GCMs cannot incorporate runoff influences such as land cover, soil, topography and water bodies. Therefore, downscaling GCMs is essential to bridge the gap between coarse scale GCMs and finer scale catchment features. Downscaling establishes a relationship between the catchment properties and GCM output for the emission scenario, so that catchment properties can be obtained based on the relationship.

The local climate of a place depends upon various factors: elevation, air pressure, and precipitation. There are two types of downscaling: statistical downscaling and dynamical downscaling. Statistical downscaling has a 100-500 km scale (Trzaska and Schnarr 2014) and local climate characteristics are statistically derived from large scale atmospheric characteristics. Statistical downscaling is a two-step process. First, a statistical relationship is developed between local climate variables (ex-precipitation and air temperature) and large-scale predictors (ex-pressure fields). Second, these relationships are applied to GCM output to simulate local climates in future. The statistical downscaling method suggested by Mullan (2001) is used in this study. Wetterhall et al. (2005) explained statistical downscaling as statistical relationships between one or several large-scale variables (predictors) with local values (predictands). Statistical downscaling is popular, computationally inexpensive, and can therefore be used relatively easily for ensemble simulations. Mullan et al. (2001), MfE (2008), Hashmi et al. (2009); and McMillan et al. (2010); describe details about the statistical downscaling method for New Zealand. But, statistical downscaling assumes that its empirical relationship of the physical processes controlling the temperature and rainfall hold true in future (Boe et al. 2007).

Dynamical downscale runs a high-resolution climate model in a regional domain or boundary condition. In dynamical downscaling, the regional climate model (RCM), also known as limited-area models (LAMs), uses large-scale and lateral boundary conditions to resolve at grid and can parameterize physical atmospheric process (Fowler et al. 2007). In dynamical downscaling an RCM), running at a higher resolution, is forced at the boundaries with GCM predictions. The Regional Climate Model (RCM) uses dynamical downscaling, which has a higher spatial resolution (20-80 km). Dynamical downscaling using RCM has been used to study future climate in New Zealand (Renwick et al. 1998; Drost et al. 2007; , McMillan et al. 2010, Ackerley et al. 2012; MfE 2018a). However, these RCMs need comprehensive input data, high computational resources, more expertise for validation and may need further downscaling and bias corrections (Fowler et al 2007; Daniels et al. 2012).

Therefore, the main requirement for downscaling is to have good data for the observed period and from the climate model data sets (Mullan et al., 2001). New Zealand's location in mid latitude, and significant topography, creates contrasting regional climates resulting in strong statistical relationships, thus statistical downscaling is a promising option. Statistical downscaling is used in this study because it has been successfully used to study climate change study in New Zealand by many researchers (Renwick et al.1999;; Mpelakosa et al. 2001; Poyck et al. 2011; Gawith et al 2012; Caruso et al. 2017b) and the New Zealand government (MfE 2008; 2016; MfE 2018).

Statistical downscaling can be used for a delta change approach, weather classification or weather generator. Delta change or linear methods establish the relationship between predictor and predictand by some proportion. This proportion can be simple delta change or regression methods. In weather classification, local variables are predicted based on large-scale synoptic weather patterns and the weather generator is used in temporal downscaling, such as daily precipitation.

This study uses the same downscaling method suggested by Climate Change Effects and Impact Assessments: A Guidance Manual for Local Government in New Zealand (MfE 2008). In the statistical downscaling, a relationship is established from the observed data and the same relationship is applied to projected GCM change to obtain the future climate. The detail methodology for statistical downscaling for New Zealand can be found in Mullan et al. (2001) and the Climate Change Effects and Impacts Assessment (MfE 2010). The statistical downscaling method is summarized here. Grid space of the 12-downscaling model used in this study is 1.12 to 3.75 (123 km to 413 km) longitude and 0.56 to 2.5 (62 km to 275 km) degrees latitude (MfE 2010). Because of the coarse scale of the GCM grid, the downscaling was necessary to investigate the effect of climate change on Strahler 3 catchments (10 km^2) used in this study. The statistical downscaling is done for each VCSN grid point. The predictors are the large-scale zonally averaged anomalies above 160-190°E, Trenberth Z1 indices, Trenberth M1 indices, regional precipitation and regional temperature (Trenberth 1976). Z1 and M1 are pressure differences: Z1 (Auckland-Christchurch) and M1 (Hobart-Chatham Island). The downscaling procedure uses monthly anomalies over the period of 1972-2003. Regression equations developed for precipitation and temperature is:

$$S - L = a + bZ1 + cM1$$

Where, S is the station anomaly, L is the longitudinal average over 160E-170W at the latitude of the VCSN grid point, Z1 is the (anomalous) Trenberth Zonal index and M1 is the meridional index (Trenberth 1976). The three coefficients, a, b, and c are fitted by least squares. The underlying patterns were as expected: more rain in the west, under positive Z1 anomaly (more westerly), and lower temperature under positive M1 anomaly (more southerly). The regression analysis is formed in such a way that the departure of the local anomaly from the circulation anomaly is calculated from the anomalies in the wind indices; if there are low explained variances in the regression at a VCSN grid location, the climate change at that point will be the same as the latitude average evaluated at model grid scale (MfE 2010). An example of the regression equation for future climate is :

$$S' - L' = a + bZ1' + cM1'$$

The prime indicates projected GCM changes in future climate. When the regression equation is applied to future projections, the changes in circulation – Z1, M1 indices derived from the MSLP (mean sea level pressure field) model and latitude-average climate (from model precipitation or temperature fields), relative to the base period of 1980–1999 – replace the observed monthly anomalies.

4.3 Present and future flow simulation after model calibration

A schematic diagram of the main steps for this research is shown in Figure 4.2. In this study, a reference climate (baseline) is needed to compare the observed climate with future climate. The 20-year period of 1980 to 1999 was chosen as the baseline period, similar to IPCC (2007). Some climate change studies have used different baseline periods, such as 1951–1980 (Smith and Pitts 1997) and 1960–1990 (Kittel et al. 1995). However, IPCC's fourth assessment report specified a 20-year period as the baseline period, centred on 1990, and New Zealand's Ministry for the Environment (MfE 2008) has recommended 1980–1999 as the baseline period in the report *Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand* (MfE, 2008). Climate change impacts on future flows are studied relative to this baseline: 2040s (2030–2049) and 2090s (2080–2099) are future climate change periods relative to the baseline climate. This study aims to assess the climate change after 50 and 100 years compared to the present climate. For this study, baseline climate (1980–1999) data for temperature and precipitation is acquired from the VCSN. The procedure used to run TopNet is as follows.

Figure 4.2 shows the model should be run with all input data for calibration before it is used to estimate present or future flows. After calibration, TopNet was run to estimate present flows. To run the future flows in TopNet, the calibrated and validated model was used, but with different precipitation and temperature indexes obtained from VCSN with an average of 12 GCMs with A2 emission scenario forcing (Chapter 2). The statistically downscaled temperature (T) and precipitation (P) of future periods, the 2040s (2030–2049) and 2090s (2080–2099), input into the VCSN grid, as recommended by the Ministry for the Environment (2008). The 2040s flows and 2090s flows were estimated by running the model twice with VCSN downscaled precipitation and temperature for the 2040s and 2090s, respectively.

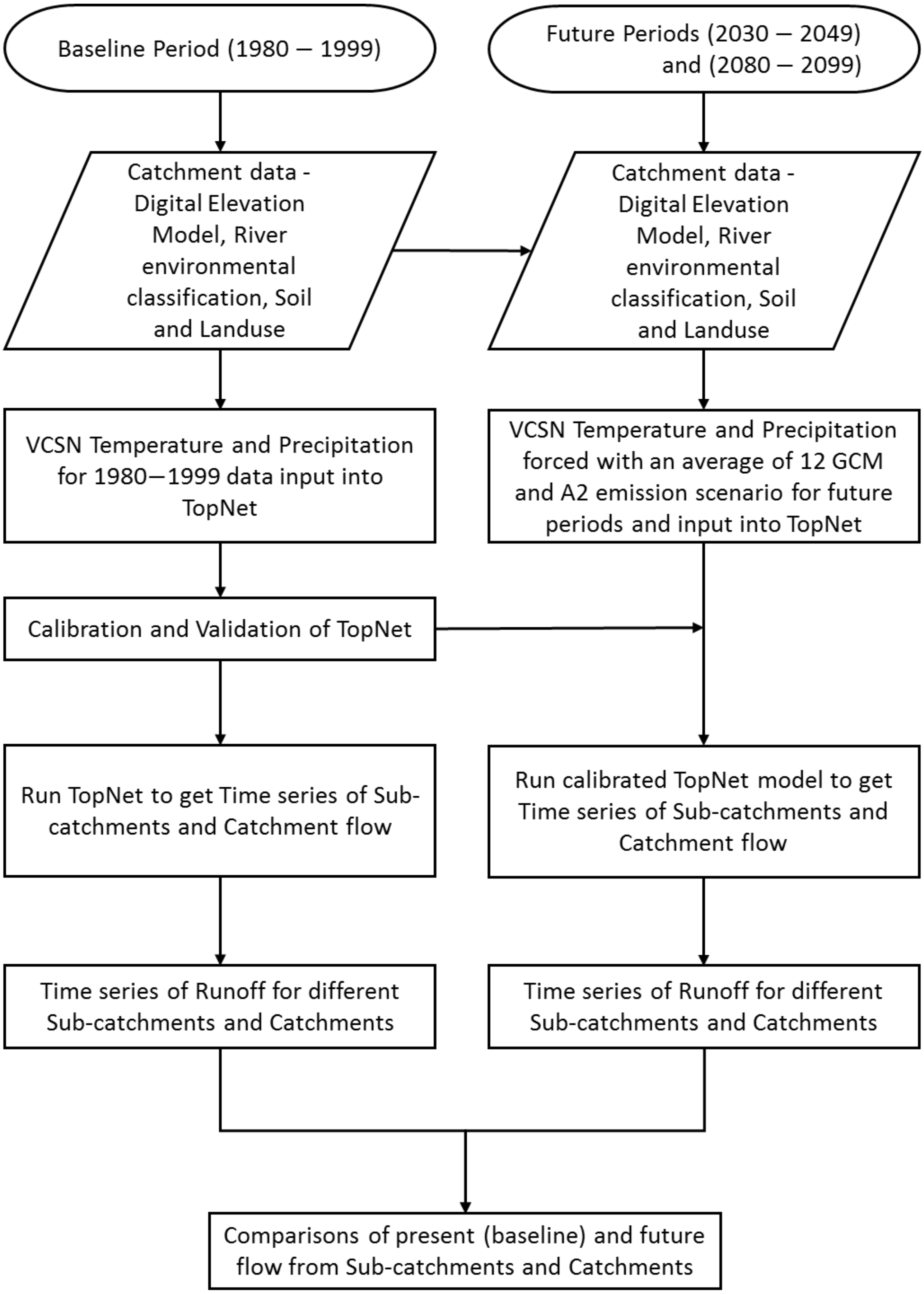


Figure 4.2: Schematic diagram of steps for this research.

4.4 Uncertainty and Limitations

The VCSN precipitation data is estimated on 5 x 5km grid based on the measured rainfall from the rainfall stations. The accuracy improves if the estimated precipitation on the catchment area has a denser climate station network. The precipitation and temperature are downscaled in the existing VCSN network to run the model. Therefore, future precipitation and temperature will follow the same bias correction (Woods et al. 2006) in TopNet model.

The error from the GCM downscaling is reduced by using the combination of GCMs recommended by Mullan and Dean (2009). They tested the model uncertainty of the 17 GCMs that were capable of statistical downscaling New Zealand’s climate. After investigating and mapping error, they showed that the combination of 12 GCMs (Table 4.1) produced minimum error compared to the average of 17 GCMs or individual GCM therefore they recommended using the average of the 12 GCMs for New Zealand..

The statistical downscaling used in this study was recommended by the Ministry for the Environment climate change documents (MfE 2008, 2010). Mullan et al. (2009) downscaled several GCMs and scrutinised whether those downscaled GCMs were successful or unsuccessful to capture New Zealand climate trend. This study cannot differentiate the range of errors from the individual GCMs. However, the model uncertainty is reduced by using Mullan et al. (2009) model because they already eliminated worst performing individual models by selecting best performing models and ensemble of these models for least error. Also, only one SRES emission is considered in this study. Future research should focus on more scenarios and more scenarios to evaluate the variability.

4.5 Conclusion

This chapter illustrated the climate change scenarios and discussed briefly about statistical downscaling and dynamical downscaling. The advantages and disadvantages of different types of downscaling models are described and the suitable downscaling method (Statistical) is selected for this study. The input data requirement to run the future flows is discussed and the basic principle of the TopNet modelling system to generate future flow is described. The present and future flows generation steps are demonstrated with a schematic diagram and uncertainty and limitation of the climate downscaling is explained.

Chapter 5 Strahler 3 catchments

This chapter investigates the cause of spatial variability of Strahler 3 catchments' runoff in the Hakataramea, Ahuriri and Pukaki catchments. The Strahler 3 catchments' runoff obtained from the TopNet model for the period of 1980-1999 is used to evaluate spatial variability. There are many factors that can influence catchments and Strahler 3 catchments' runoff. The relationship of Strahler 3 catchments' runoff with elevation, temperature, soil type, land cover and precipitation are analysed to better understand spatial variability. The Pearson correlation estimated is used to study the relationship between variables which is denoted by letters ρ or r.for the population and sample respectively. Pearson correlation decides the strength of the relationship between two variables and it varies between -1 to +1. The Pearson correlation coefficient or Pearson's r values further away from 0 i.e., (-1 or +1), shows the stronger relationship between two variables. Previous research has documented the relationship between runoff with topographical and climatic parameters, such as elevation, land use, soil type, temperature and precipitation. Pearson correlation of streamflow with land use (Gebremicael et al. 2019); correlation of streamflow with temperature (Ficklin et al. 2014); and correlation of SWE with elevation (Fassnacht et al. 2018). The relationship between runoff (continuous variable) and land use (landcover) or soil type (categorical variable) is also checked using Kruskal-Wallis test. The other factors affecting spatial variability, such as Strahler 3 catchments' proximity from the Southern Alps and precipitation distribution, is also discussed in this chapter.

5.1 Elevation

Elevation is a key factor that decides precipitation distribution in mountain catchments. Figure 5.1 shows the Pearson correlation between the baseline Strahler 3 catchment runoff and elevation for Hakataramea, Ahuriri and Pukaki catchments. Annual runoff from Strahler 3 catchments are plotted in the log scale on the x-axis and median elevation is plotted in y-axis. The linear trendlines and Pearson correlation coefficient are shown in Figure 5.1. The Hakataramea Strahler 3 catchment runoff has medium correlation (r_h = - 0.59) with Strahler 3 catchment elevation, where Ahuriri and Pukaki have a weak (r_a = 0.44) and moderate (r_p = 0.66) correlation. The negative correlation in the Hakataramea suggests that runoff decreases in the higher elevation; however, runoff increases with elevation for both Ahuriri and Pukaki Strahler 3 catchments. Figure 5.1 shows the non-unique relationship of runoff and elevation. There is a large variability in Strahler 3 catchments' runoff for the same elevation. For example, for the 800m elevation, values for the multiple sub-catchment's runoff varies and can be anywhere between 15-5400mm and it can be a Strahler 3 catchment of either the Hakataramea, Ahuriri or Pukaki catchments.

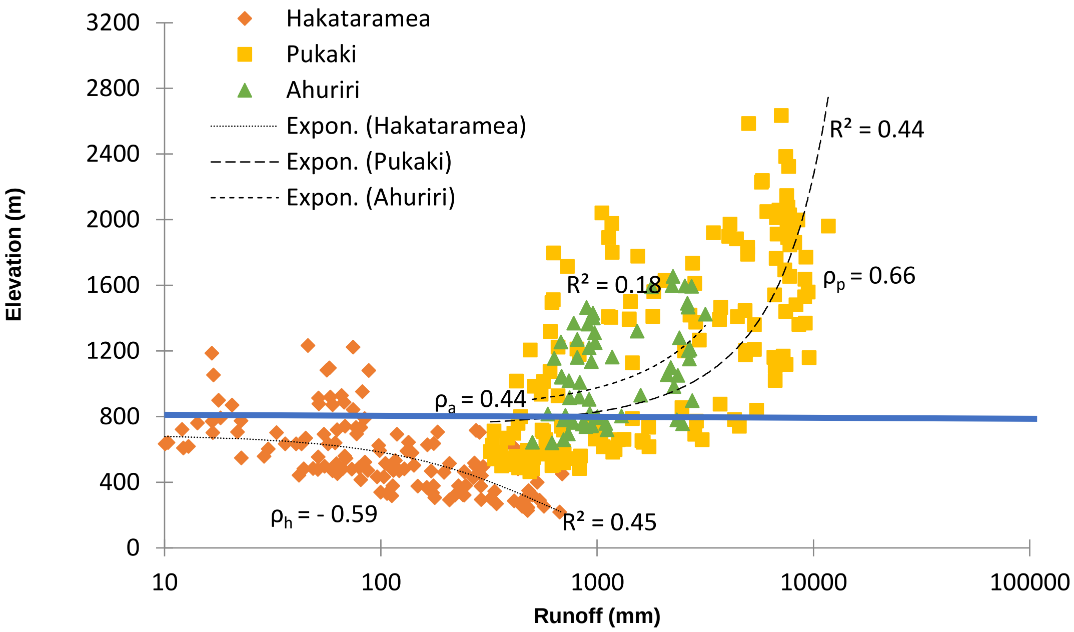


Figure 5.1: Pearson correlation of the Hakataramea, Ahuriri and Pukaki Strahler 3 catchments median annual runoff with median elevation.

There are other main factors that can explain why the correlation is not strong and not unique in study catchments: other factors such as temperature, soil type, land use and precipitation may be more important for the runoff generation compared to the elevation.

The accuracy of elevation as well as runoff data also affects the correlation. Each Strahler 3 catchment is in Strahler third order, with each Strahler 3 catchment having an area of approximately 7 km^2 catchment area.

Because there is one flow for each Strahler 3 catchment, the median elevation of the Strahler 3 catchment is used for the Pearson correlation, but the median elevation used in the correlation cannot be representative for the whole Strahler 3 catchment. This is a limitation because precipitation and runoff can be highly variable within this large area, especially for the Strahler 3 catchments closer to the Southern Alps. The TopNet model uses Virtual Climate Station Network (VCSN) to estimate precipitation and temperature and its spatial resolution is 5km x 5km. This is a large area, so there is already some averaging effect present in the precipitation and temperature estimation that TopNet uses for runoff calculation. If multiple weather stations are set up in various locations of the catchment and data is analysed based on the exact elevation and runoff from each site, not from the Strahler 3 catchment average, then the results might be different than estimated in this chapter. That will reduce the spatial averaging effect of VCSN, TopNet Strahler 3 catchment runoff and median elevation. This will take significant resources and time but may be an area for further research.

5.2 Temperature

The relationship between each Strahler 3 catchment's runoff and average maximum daily temperature is studied using Pearson correlation for Hakataramea, Ahuriri and Pukaki Strahler 3 catchments (Figure 5.2). A decrease in average daily maximum temperature is associated with an increase in runoff in Pukaki and Ahuriri catchments. On the contrary, an increase in temperature is related to an increase in runoff for the Hakataramea Strahler 3 catchments. The Strahler 3 catchments' runoff is plotted on the log scale on the x-axis and maximum temperature (T_{max}) is plotted in the y-axis. Strahler 3 catchments' runoff in the Pukaki and Ahuriri catchments are moderately and weakly correlated with temperature (r_p = - 0.73 and r_a = 0.78). Hakataramea has moderate positive correlation (r_h = 0.56) with temperature. Figure 5.2 shows that Strahler 3 catchments' runoff does not have a unique relationship with Strahler 3 catchment temperature. The Strahler 3 catchments' runoff is highly variable even for Strahler 3 catchments with the same daily temperature. For example, the average maximum daily temperature of 13°C (blue line) is associated with Strahler 3 catchments having wide ranges of runoff variability (17-4540 mm) in the Strahler 3 catchments of the Hakataramea, Ahuriri and Pukaki catchments.

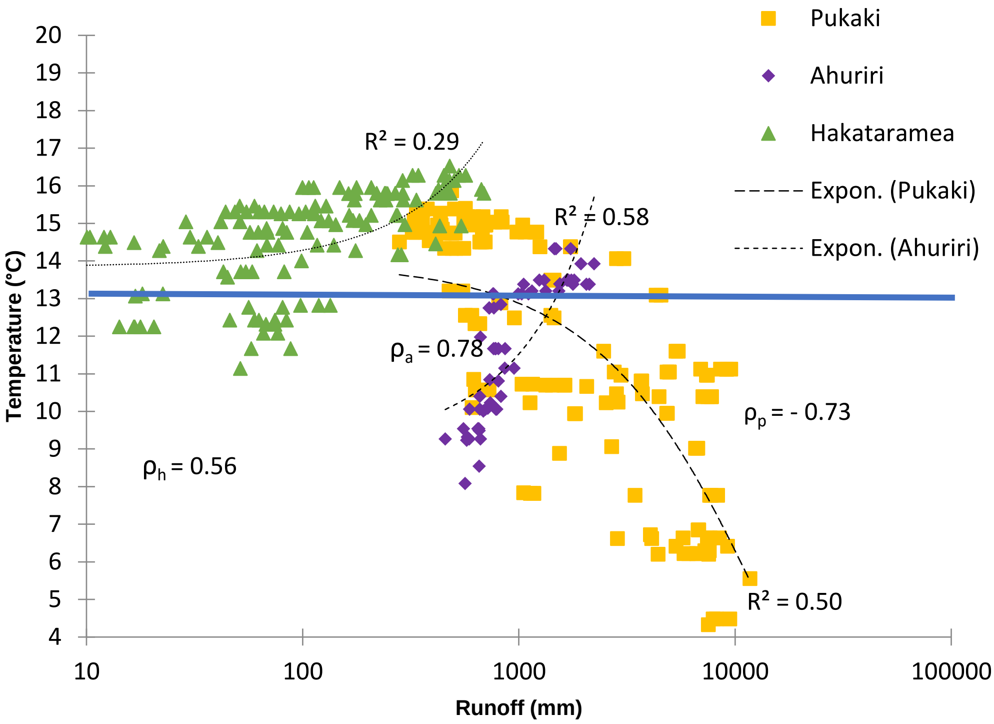


Figure 5.2: Relationship between median annual runoff (mm) and maximum average daily temperature (°C) for Strahler 3 catchments of the Pukaki, Ahuriri and the Hakataramea catchments.

Figure 5.2 illustrates the large amount of precipitation in the Pukaki and Ahuriri catchments compared to the Hakataramea. The high elevation catchments have lower atmospheric pressure therefore generally have lower temperature unless governed by the local variation in weather. The Hakataramea catchment is in lower elevation (204-2889 m), compared to the Ahuriri (608-2454 m), and Pukaki (381-3680 m). Therefore, Strahler 3 catchments of the Hakataramea catchment have a higher temperature range (11-17°C), compared to the Ahuriri (8-14°C) and Pukaki (4-11°C) Strahler 3 catchments. Figures 5.1 and 5.2, show elevation and temperature have a different relationship with runoff. Ahuriri and Pukaki Strahler 3 catchments' runoff is positively correlated with elevation, but negatively correlated with temperature. The Strahler 3 catchments' runoff in the Hakataramea is negatively correlated with elevation, but positively correlated with temperature. The Strahler 3 catchments' temperature used in this study is obtained from the VCSN. The VCSN estimates temperature using two position variables (0.05° latitude/longitude) with elevation as a dependent third variable. The temperature in VCSN is adjusted to mean sea level using 5°C/km lapse rate (Tait et al. 2012) with elevation. Therefore, temperature estimation is also influenced by the elevation because elevation is a dependent variable in temperature estimation along with the latitudes and longitudes.

5.3 Soil Type

The relationship between the Strahler 3 catchment runoff and corresponding soil type is not unique and consistent in the Pukaki, Ahuriri or Hakataramea catchments. The soil type data is obtained from soil FSL layer which is part of New Zealand Land Resource Inventory (Newsome et al. 2008). A small relationship exists between the Strahler 3 catchments' runoff and soil type, but soil types do not have a unique relationship with Strahler 3 catchment. Table 5.1 shows the Pearson correlation between Strahler 3 catchments' runoff and soil types for the Hakataramea, Ahuriri and Pukaki catchments respectively.

The Hakataramea Strahler 3 catchment runoff is positively correlated with some soil types and negatively correlated for some other soils. The Hakataramea Strahler 3 catchment runoff has a weak correlation (r = 0.430) with river (rive) and a weak correlation (r = -0.234) with High Country Yellow Brown Soil (HCYB). The positive correlation with rive suggests that when part of the rive area increases in a Strahler 3 catchment, the runoff increases because of river soil. The negative correlation with HCYB shows that an increase in area of HCYB decreases Strahler 3 catchment runoff. However, in the Ahuriri and the Pukaki Strahler 3 catchments, correlation is very weak and positive. This can be due to the higher precipitation in the high elevation Strahler 3 catchments of the Ahuriri and Pukaki catchments.

The Ahuriri Strahler 3 catchment runoff has a strong positive correlation with BRock (*r* = 0.539) and a moderate negative correlation with Yellow Gravel (*r* = -0.392). The strong positive correlation with bedrock (Brock) shows that Strahler 3 catchment runoff increases with the increase in bedrock. The Yellow Brown soil family have a unique property of draining water with no waterlogging in winter and no drought in summer (Landcare Research, 2018), which suggests these soils keep water for long time and replenish summer moisture from extra water in winter. Hence, Strahler 3 catchments' runoff decreases when there is an increase in Yellow Brown Earth.

The Pukaki Strahler 3 catchment runoff is strongly correlated to soil types, compared to the Hakataramea and Ahuriri catchments. Strahler 3 catchment runoff is strongly correlated (*r* = 0.811) with ice and moderately correlated with Upper Yellow Brown (UYB) Soil (*r* = - 0.537). Runoff from Strahler 3 catchment decreases in Pukaki when the proportion of UYB soil increases. The similar negative correlation was also obtained in the Hakataramea, but, in the Ahuriri Strahler 3 catchment, it increased, suggesting non-unique relationship.

Table 5.1: Correlation of Strahler 3 catchment runoff with soil types for the Hakataramea, Ahuriri and Pukaki catchments ($p < 0.05$).

Soil Type	Pearson correlation with runoff in		
	Hakataramea	Ahuriri	Pukaki
HCYB	**-0.234**	0.074	-0.015
YB	**-0.222**	**-0.301**	-
YBST	-0.155	-	-
YG	-0.100	**-0.392**	-

UYB	-0.073	-0.003	**-0.537**
RE	-0.172	**-0.283**	**-0.206**
rive	**0.430**	**0.481**	**-0.368**
UYG	**0.186**	**-0.275**	-
BG	**0.266**	-	-
ice	-	**0.414**	**0.811**
BRock	-	**0.539**	**0.200**
ALP	-	0.194	**-0.188**
PYB	-	**0.420**	-0.106
HCPYB	**-**	**-**	0.133

The relationship between the runoff and soil types were tested using the Kruskal-Wallis test. The null hypothesis assumed that there is no statistically significant difference in the medians between samples (Runoff and Soil Types) or they have the same distribution. The alternative hypothesis is that sample medians are significantly different. The level of significance used for the test is 5% (p = 0.05). The results of the tests for the Strahler 3 catchments of the Hakataramea, Ahuriri and Pukaki catchments are shown in Table 5.2 (a), (b) and (c) below. Results showed that p value of the test (<0.0001) for Strahler 3 catchments of above three catchments are lower than the level of significance used in this test (0.05). Therefore the null hypothesis is rejected, at 5% level of significance. Hence, there is a significant difference between medians of the runoff and soil types in the Strahler 3 catchments of Hakataramea, Ahuriri and Pukaki catchments.

Table 5.2: Kruskal-Wallis test of Strahler 3 catchment runoff with soil types for the Hakataramea, Ahuriri and Pukaki catchments ($p < 0.05$) respectively.

K (Observed value)	759.793
K (Critical value)	16.919

K (Observed value)	390.262
K (Critical value)	19.675

K (Observed value)	668.865
K (Critical value)	16.919

DF	9	DF	11	DF	9
p-value (one-tailed)	< 0.0001	p-value (one-tailed)	< 0.0001	p-value (one-tailed)	< 0.0001
alpha	0.05	alpha	0.05	alpha	0.05

One of the limitations of TopNet is that it uses VCSN precipitation and temperature to estimate runoff. The VCSN precipitation and temperature data are obtained from one value for each VCSN 5km X 5km grid, but the Strahler 3 catchments have an approximate area of 7 km^2. This mismatch in spatial scale can cause some inaccuracy. The NZLRI has polygon layers across New Zealand in 1:50,000 spatial scale. There is a possibility that they cannot capture the actual variability because soil can be highly variable within a couple of hundred metres and this can lead to some approximation in runoff estimation by TopNet. Lack of a dominant soil type or many soil types present within a Strahler 3 catchment can cause errors in Pearson correlation, because these multiple soil types having a zero or small area that has negligible influence on the Strahler 3 catchment runoff.

5.4 Landcover

Table 5.3 shows the Pearson correlation between the Strahler 3 catchments' runoff and land cover for the Hakataramea, Ahuriri and Pukaki catchments. Forest has a weak positive correlation (r = 0.142), moderate correlation (r = 0.597) and weak negative correlation (r = -0.235) with the Strahler 3 catchments of the Hakataramea, Ahuriri and Pukaki, respectively. Forests have high organic matter content, which enhances infiltration and reduces surface runoff, therefore it should be negatively correlated. This non-unique and opposite relationship may result from the fact that the Strahler 3 catchments do not have a dominant landcover type. Most of the Strahler 3 catchments have multiple landcover types that cannot be representative when correlated with an increase or decrease in runoff. Pearson correlation shows grassland has very weak (*r* = - 0.060), moderate (*r* = - 0.670) and moderate (*r* = - 0.559) correlations with the Hakataramea, Ahuriri and Pukaki Strahler 3 catchments, respectively. These values show that the runoff decreases in all study Strahler 3 catchments when the grass cover in the Strahler 3 catchment increases and increases when the grass cover decreases. The grass is useful to conserve water and enhances infiltration, therefore it is negatively correlated with runoff. The Pukaki Strahler 3 catchments are strongly correlated with permanent snow and ice. This type of landcover does not exist in the two other study catchments; the Hakataramea and Ahuriri Strahler 3 catchments show an absence of permanent snow and ice. The snow and ice are forms of precipitation, hence an increase in snow and ice in the Strahler 3 catchment increases Strahler 3 catchment runoff and a decrease in snow and ice decreases the Strahler 3 catchments' runoff.

Table 5.3 Correlation of Strahler 3 catchments' runoff with landcover types for the Hakataramea, Ahuriri and Pukaki catchments ($p < 0.05$).

Landcover	Pearson correlation with runoff in		
	Hakataramea	Ahuriri	Pukaki
Grassland	-0.060	**-0.670**	**-0.559**
Bare/Lightly vegetated	**0.310**	**0.515**	**0.284**
Scrub/Shrubland	-0.077	-0.150	**-0.144**
Forest	0.142	**0.597**	**-0.235**
Water Bodies	-0.018	-0.087	**-0.363**
Cropland	-0.114	-0.231	**-0.133**
Artificial surface	-	-0.164	**-0.105**
Permanent Snow and Ice	-	-	**0.816**

The association between the runoff and land use types was investigated using the Kruskal-Wallis test. The null hypothesis assumed that there is no statistically significant difference in medians between samples (runoff and land use) or they have the same distribution. The alternative hypothesis was that medians of the samples are significantly different. The level of significance used for the test is 5% (p = 0.05). The results of the tests for the Strahler 3 catchments of the Hakataramea, Ahuriri and Pukaki catchments are shown in Table 5.4 (a), (b) and (c). Results showed that p value of the test (<0.0001) for Strahler 3 catchments of above three catchments are lower than the level of significance used in this test (0.05).Therefore the null hypothesis is rejected at 5% level of significance. Hence, there is a significant difference between median of the runoff and soil types in the Strahler 3 catchments of Hakataramea, Ahuriri and Pukaki catchments.

Table 5.4: (a), (b) and (c) Kruskal Wallis test of Strahler 3 catchment runoff with land use types for the Hakataramea, Ahuriri and Pukaki catchments ($p < 0.05$) respectively.

K (Observed value)	627.715	K (Observed value)	390.262	K (Observed value)	775.947
K (Critical value)	12.592	K (Critical value)	19.675	K (Critical value)	15.507
DF	6	DF	11	DF	8
p-value (one-tailed)	< 0.0001	p-value (one-tailed)	< 0.0001	p-value (one-tailed)	< 0.0001
alpha	0.05	alpha	0.05	alpha	0.05

There are some limitations in the data due to the approximation needed, because of the 5km X 5km spatial extent of VCSN precipitation and temperature data used to calculate Strahler 3 catchment runoff. TopNet is used to estimate Strahler 3 catchment runoff. The landcover database second version (LCDB2) was used in this study. This LCDB2 is a digital map in which similar soil types were grouped together and these layers can be found in the satellite images (LCDB data is created from analysing the satellite data). Better results can be obtained from the field verification and using exact landcover rather than using landcover from LCDB2. However, this can be resource intensive and time consuming. The LCDB2 was used in the TopNet version of this study. If a similar study is to be completed in the future, it is recommended that the latest version of LCDB is used and that the landcover in the field is verified.

5.5 Precipitation

The relationship between Strahler 3 catchments' runoff and precipitation in the Hakataramea, Ahuriri and Pukaki show a very strong positive correlation. Strahler 3 catchments' runoff and precipitation are correlated with the Pearson correlation method. The Strahler 3 catchments' runoff and precipitation correlate very strongly in all catchments, confirming the variation in Strahler 3 catchment runoff explained by the variation in precipitation (Figure 5.3).

Figure 5.3 shows correlation between precipitation and Strahler 3 catchments' runoff for the Hakataramea, Ahuriri and Pukaki catchments. The Strahler 3 catchments of the Hakataramea have strong correlation (r_h = 0.881) where Ahuriri and Pukaki Strahler 3 catchments have very strong correlations (r_a = 0.988) and (r_p = 0.982,) respectively.

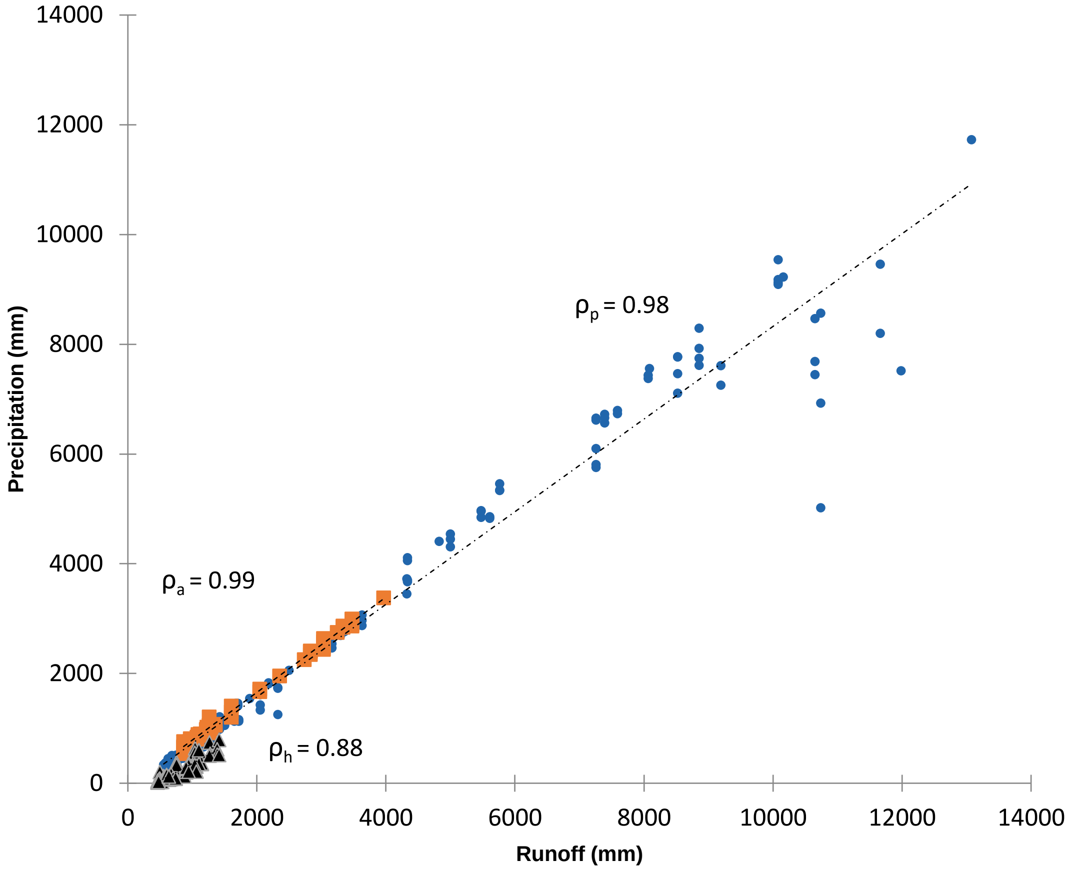


Figure 5.3: Correlation of Annual Runoff (mm) and Annual Precipitation for Pukaki, Hakataramea and Ahuriri Strahler 3 catchments respectively ($p<0.05$).

Variation in the Strahler 3 catchment runoff is well explained by the precipitation distribution, because strong correlations of 0.982, 0.884 and 0.998 are calculated between runoff and precipitation in the Pukaki, Hakataramea and Ahuriri Strahler 3 catchments.

5.5.1 Location of the Southern Alps and precipitation pattern

The location of the Southern Alps and prevalent weather system play a crucial role in deciding the amount of precipitation that falls in the study catchments. Figure 5.4 shows the location of Pukaki, Hakataramea and Ahuriri Strahler 3 catchments and main divide of the Southern Alps. The red line shows the approximate location of the main divide of the Southern Alps. Blue in the map denotes lower elevation while yellow and purple shows higher elevation and white colour stands for highest elevation. Strahler 3 catchment boundaries of the study catchments are black in colour and catchment boundaries are shown in purple. The Main Divide is very close to the Pukaki Strahler 3 catchments, slightly further for Ahuriri Strahler 3 catchments and the Hakataramea Strahler 3 catchments are farthest from main divide. All the Strahler 3 catchments are in the eastern side of the main divide of the Southern Alps.

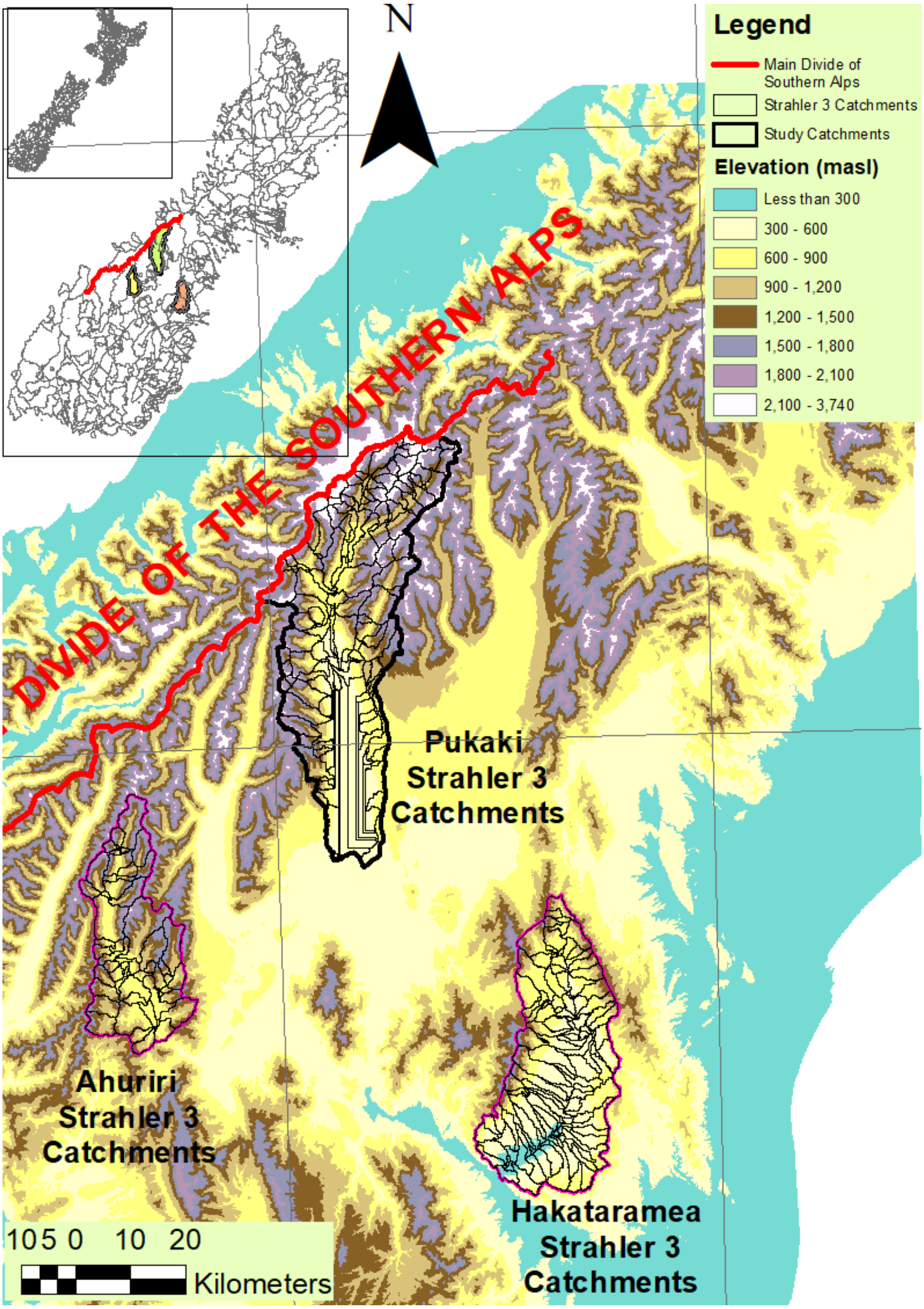


Figure 5.4: Approximate location of the Main Divide of the Southern Alps (red line) and Strahler 3 catchments of the Hakataramea, Ahuriri and Pukaki catchments .

Figure 5.5 displays the plot between the baseline Strahler 3 catchments' runoff and distance of the Strahler 3 catchment centroids of the Hakataramea, Ahuriri and Pukaki catchments from the Main Divide of the Southern Alps. The regression analysis shows the plotted data are in good fit with coefficient of determination (R^2) of 0.51, 0.95 and 0.80 respectively for Hakataramea, Ahuriri and Pukaki catchments. Distance from the Main Divide to Strahler 3 catchment centroids are plotted on the x-axis and annual runoff is plotted on the y-axis. The trendlines and Pearson correlation coefficients are shown in Figure 5.1. The Hakataramea Strahler 3 catchment runoff has medium correlation (r_h = 0.65) with Strahler 3 catchment elevation, while Ahuriri and Pukaki have a very strong (r_a = - 0.96 and r_p = 0.66) correlation. The negative correlation in the Ahuriri and Pukaki shows runoff decreases as the distance from the Main Divide increases or the highest runoff is generated in the Strahler 3 catchments near the main divide. However, runoff decreases with distance from the Main Divide increases for the Hakataramea Strahler 3 catchments. This change in correlation from negative to positive demonstrates that the rain shadow effect is dominant, or strong, for certain distances and does not have much effect far from the mountain.

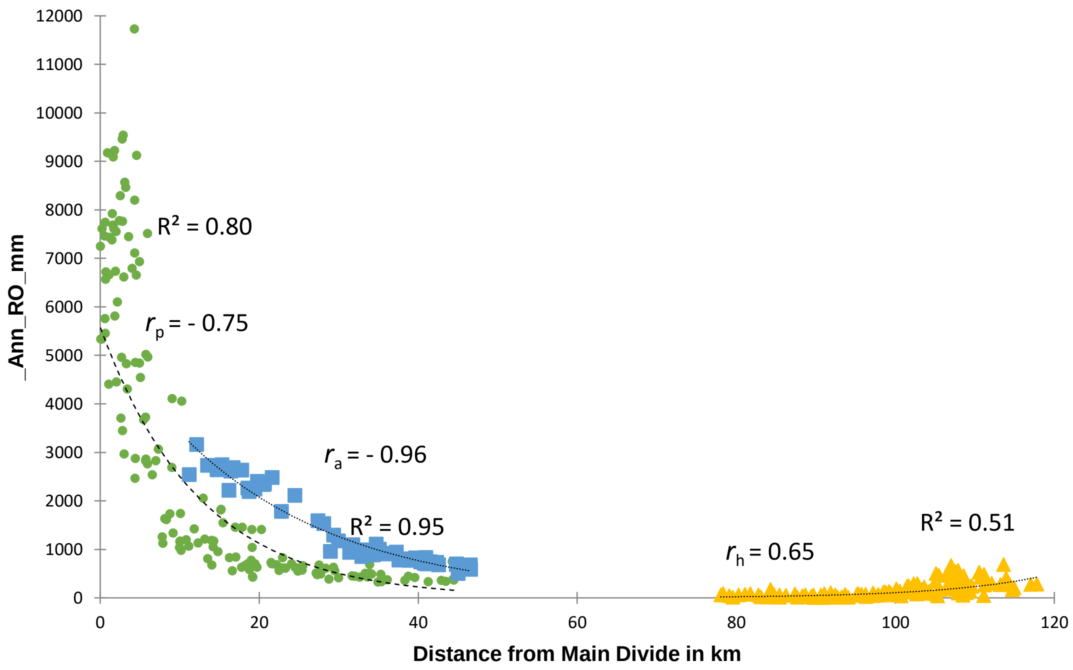


Figure 5.5: Correlation of Annual Runoff of Strahler 3 catchments of Hakataramea, Ahuriri and Pukaki with distance from the main divide of the Southern Alps ($p<0.05$).

Figure 5.6 shows the precipitation distribution for the Hakataramea, Ahuriri and Pukaki Strahler 3 catchments. The Hakataramea Strahler 3 catchment precipitation is in the range of 429-1290 mm, Ahuriri Strahler 3 catchments have 865-3963 mm and the Pukaki Strahler 3 catchments have the highest precipitation range from 555-13077 mm. The Southern Alps of New Zealand extends from south-west to north-east. It creates a precipitation divide with higher precipitation on the western side and near the Main Divide. The Strahler 3 catchments are in the rain shadow for the weather system coming from the Tasman Sea (western side). It is observed in New Zealand that the winter precipitation is determined by the large-scale weather systems, but summer precipitation is localised and is of convective origin (MfE 2008).

The large-scale weather system is responsible for the Southern Hemisphere circulation and precipitation variation, which is explained by Trenberth (1976) and also the Ministry for the Environment guideline (MfE 2008). According to Trenberth and MfE

(2008), the positive sign in large-scale anomaly field Z1 means more rainfall in the west and less rainfall in the eastern part of New Zealand. Pressure difference between Auckland and Christchurch is the Z1 anomaly of Trenberth. The air coming from the Tasman sea also creates an orographic lift for the low frontal system holding moist air coming from the Tasman sea and is consistent with the earlier findings (Sturman and Wanner 2001; John Stuart 2011). The correlation results from this study demonstrate that the runoff generation decreased with distance from the Main Divide for Ahuriri and Pukaki and decreased in Hakataramea. This is consistent with previous findings that combined the effect of distance from the Main Divide of the Southern Alps and the westerly weather system coming from the Tasman sea. The correlation in the Strahler 3 catchments runoff and precipitation is high because the amounts of precipitation and runoff are higher. Runoff for the Hakataramea, Ahuriri and Pukaki Strahler 3 catchments are in the range of 10-689 mm, 539-3378 mm, and 280-11727 mm.

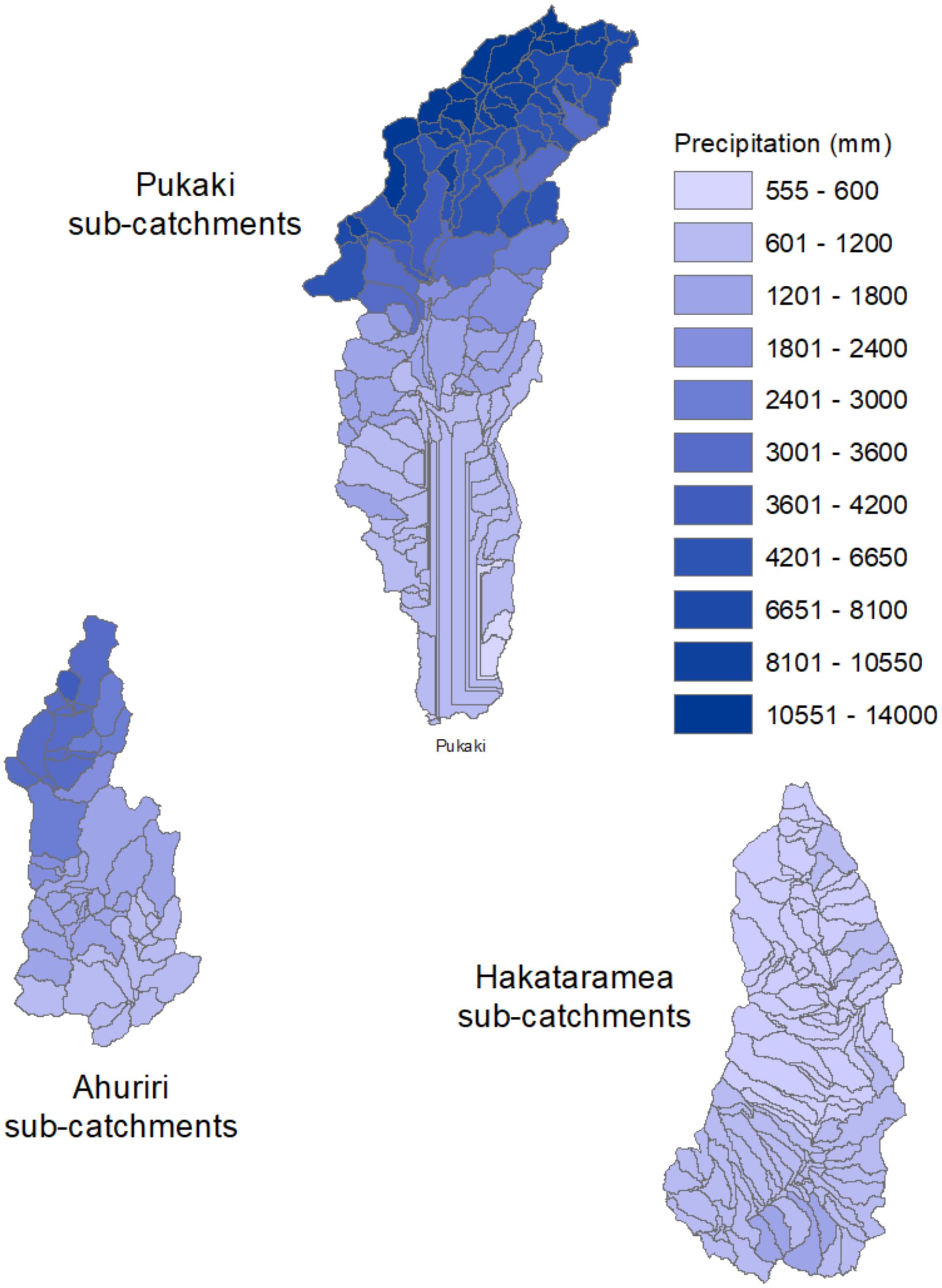


Figure 5.6: Existing precipitation distribution (1980-1999) in the Hakataramea (429-1290mm), Ahuriri (865-3963mm) and Pukaki (555-13077mm) Strahler 3 catchments.

Area west of the main divide particularly Franz-Joseph neve of the Southern Alps receives the highest precipitation in New Zealand but the highest precipitation straddles around the main divide (Kerr et al. 2011). Cropp Basin (Griffiths and McSaveney, 1983) and Milford Sound (Henderson and Thompson, 1999) are other two areas that also gets higher precipitation. Kerr et al. (2011) estimated that annual precipitation for the north western side of the Pukaki catchment close to15000 mm and reported steep precipitation gradient with annual precipitation near lake Pukaki outlet is only 652 mm. McSaveney et al.,1978 found the similar gradient for the precipitation distribution near Southern Alps in Hokkitika-Rakaia transect. In “The Southern Alps Experiment” (SALPEX), Wrat et al. (1996) investigated precipitation distribution in the Arthurs Pass, Hokitika, Franz Josef, Haast, and Milford transects in the Southern Alps. Kerr et al. (2011) estimated high precipitation gradient (1000 mm/km) in the Pukaki catchment. While this is a high rainfall gradient, Griffiths and McSaveney (1983) reported even higher (1200mm/km) rainfall gradient for Cropp Basin. A comparatively small precipitation gradient is reported for the Olympic Peninsula of USA (Daly and Taylor, 2000). Kerr et al (2011) noted the differences in mean precipitation between their study and study by Anderson (2004)and suggested that the precipitation distribution in the Southern Alps may be bimodal with one peak in windward and another peak in Leeward side of the main divide. The long term mean annual rainfall map of Canterbury region (https://niwa.co.nz/climate/national-and-regional-climate-maps/canterbury) shows that the precipitation is higher near the main divide of the Southern Alps in the Ahuriri and Pukaki catchment but starts to increase in the Hakataramea catchment across the Hakataramea River. These findings agree with correlation of flow with the distance from main divide where Ahuriri and Pukaki catchments show negative correlation and Hakataramea shows negative correlation

VCSN data is used to estimate runoff in TopNet model. Precipitation and temperature can be highly variable in mountain catchments, but VCSN has only one value for a 25km^2 area (5 km x 5 km grid). This can lead to imprecise Strahler 3 catchment runoff estimation. The main reason for this low resolution is partly due to the lower climate-station density in higher elevation catchments. Installation of a network of telemetered rain gauges would ensure robust and superior quality data. But it is not always practical in mountain catchments due to cost. In addition, excellent quality data needs to have a reasonable length of records. VCSN is the best alternative for this study because of the low density of telemetered gauge networks. There may be some error due to Strahler 3 catchment runoff estimation: the calibration is done at the outlet of the study catchment, but some calibration parameters, scaled by parameter multipliers, are used in Strahler 3 catchment runoff estimations. This approximation is acceptable because it is not possible to calibrate and validate all Strahler 3 catchments separately. Also, the annual precipitation and runoff was used in this study for correlation because of the substantial number of Strahler 3 catchments. If monthly values had been used, the correlation could be different.

5.6 Conclusion

In this chapter, the drivers of the Strahler 3 catchment runoff and its variability are analysed. The possible drivers of Strahler 3 catchments' variability, such as elevation, temperature, soil type, land cover and precipitation, are correlated with Strahler 3 catchment runoffs. It is shown that Strahler 3 catchments' runoff cannot be explained by the variations in Strahler 3 catchments' elevation, temperature, soil type and landcover. Although relationships exist between Strahler 3 catchments' runoff with different soil types, land covers, temperature, and elevation, they are not strong and not consistent for different catchments; however, this is not entirely correct in the case of smaller Strahler 3 catchments.

This suggests that there must be another factor that decides the runoff variability in the Strahler 3 catchments. The variability in runoff is explained by the variability in precipitation, because a strong relationship between Strahler 3 catchments' runoff and precipitation is found in this study. The variation in Strahler 3 catchments' runoff is in good agreement with the distance away from the Main Divide of the Southern Alps. The prevailing large-scale weather system, coming as westerly from the Tasman Sea, dumps a large amount of precipitation in the western side of the main divide and lesser precipitation towards the eastern side of the main divide. The precipitation, and hence runoff, is highest in the Pukaki Strahler 3 catchments, which are closest to the Main Divide. Ahuriri Strahler 3 catchments are slightly farther and the Hakataramea farthest, with the least precipitation and rainfall. It can be concluded that precipitation distribution is the most crucial factor that needs to be considered when analysing spatial variability in the mountain catchments.

To summarise the main implication of this chapter, the precipitation distribution due to the rain shadow effect is the most crucial factor for the runoff variability in the mountain catchments that are close to the Main Divide. The mountains, with rain shadow effect, create runoff variability, while other factors play only a minor role. The rain shadow effect creates more runoff generation with more precipitation near the main divide: this rain shadow effect diminishes with distance. There may be some relationship in the drivers of catchment flows, and elevation, temperature, soil type and land cover may show some relationship. However, it is different in finer spatial scale. This study also emphasized the importance and need to analyse the runoff variability in finer spatial scale (Strahler 3 catchment scale) to get better understanding of the drivers of the variability.

Chapter 6. Catchment and sub-catchment flows under climate change

6.1 Introduction

In the previous chapter, runoff variations in the Hakataramea, Ahuriri and Pukaki catchments were discussed. The catchment runoff variability was found to be in good agreement with the precipitation distribution and proximity to the Southern Alps. This chapter discusses present and future runoff in study catchments and sub-catchments. Present runoff is compared with climate change affected future runoff to find the difference. The causes of runoff variability are investigated and the runoff generation mechanism is analysed. This chapter also examines what causes this runoff variability at a sub-catchment scale. The effects of change in catchments and sub-catchments' future runoff are shown and the consequences of the change in runoff is discussed. Finally, conclusion will be discussed followed by a few limitations.

6.2 Hakataramea catchment flows

The catchment flows in the Hakataramea, Ahuriri and Pukaki show different trends based on their runoff generation mechanisms. Figure 6.1 shows the median monthly flows at the outlet of the Hakataramea catchment for the baseline, 2040s and 2090s periods. The median value is chosen to analyse because the median is more robust than the mean and is not affected significantly by extreme outliers. The data shows an increase in 2040s flows compared to the baseline from January to November. The 2040s' flow is not significantly different to the 2090s. The highest flow is in July for each baseline, 2040s and 2090s period. The 2040s and 2090s' July flows (8.6 m^3/s) are increased by 16% compared to the baseline (6.2 m^3/s). The highest present and future flows in July, plus the lack of increase in the future spring and summer flows, suggest that this is a rainfall dominated catchment without any significant snow storage. Figure 6.2 shows the rainfall to precipitation ratio (R/P ratio) of the Hakataramea catchment for baseline, 2040s and 2090s. This shows a slight increase in the R/P in July-the R/P ratios are 71%, 81% and 86% respectively for baseline, 2040s and 2090s periods. Figure 6.2 shows that the R/P ratio is highest in April for the baseline period and 2040s and 2090s periods have lower R/P ratios until July, when the baseline R/P ratio starts to increase. This shift in July shows that a small amount of precipitation that may fall as snow in July will fall as rainfall in future. A small part of the Hakataramea catchment receives some winter snow that lasts for only a few days; it does not have any permanent snow.

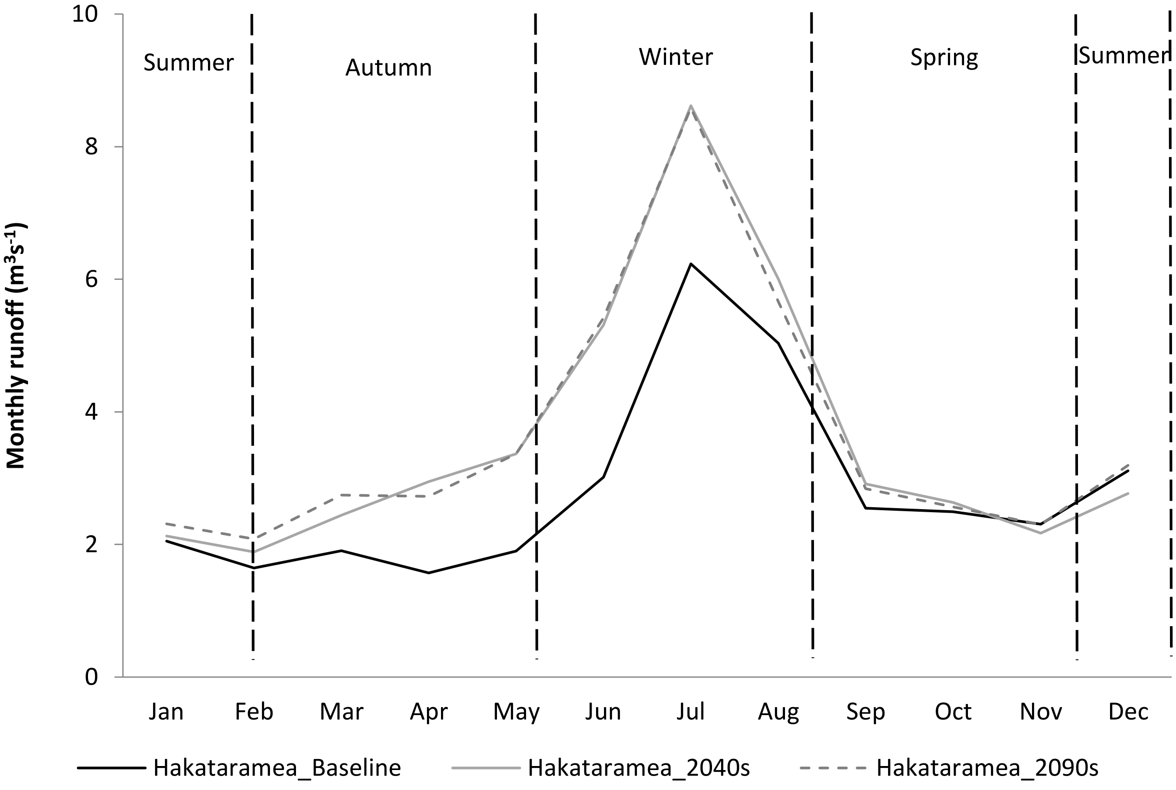


Figure 6.1: Baseline, 2040s and 2090s flows in the Hakataramea catchment.

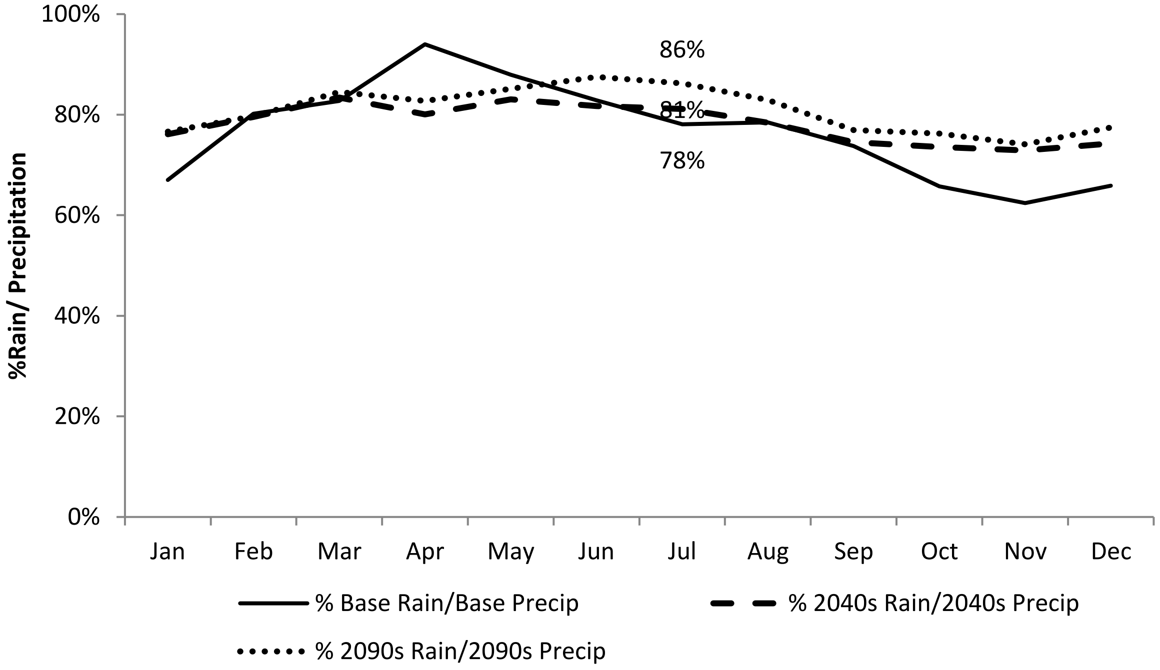


Figure 6.2: Percentage of baseline rain/baseline precipitation, 2040s rain/2040s precipitation, 2090s rain/2090s precipitation at the outlet of the Hakataramea catchment.

Another reason for the increase in future flows is due to an increase in future temperatures. Table 6.1 shows the range of temperatures in the Hakataramea catchment: the range of temperature is found as 11-17, 12-17 and 13-19 degrees for the baseline, 2040s and 2090s periods respectively. Ministry for Environment climate change guideline (MfE 2008) suggests that the future precipitation will increase with an increase in temperature since warmer air can hold more moisture compared to cooler air. Because of higher temperature, an increase in R/P ratio and lack of snow storage, present and future flows in the Hakataramea catchments are highest in winter.

Because the Hakataramea catchment does not have any snow storage, an increase in future autumn and winter flows will have a positive impact on water resources of the Hakataramea catchment. The lack of increase in future spring and summer flows will have a negative effect on the Hakataramea catchment because its water resources are considered fully allocated for irrigation and stock water (ECAN 2012). Also, the lower summer flows at present deteriorate water quality in the Hakataramea river (MfE 2018). This affects salmon spawning, and this will not improve in the future because future summer and spring flows in the Hakataramea catchment do not increase significantly.

6.3 Ahuriri catchment flows

Baseline, 2040s and 2090s flows at the outlet of the Ahuriri catchment are shown in Figure 6.3. The Ahuriri catchment flows are highest in October for the baseline and 2040s periods, but the 2090s flow is highest in August. The lowest flow is observed in July for the baseline and 2040s period; however, the flow is least in February during the 2090s. The future catchment flows in 2040s and 2090s are higher than the baseline since future temperatures in these study periods will be higher than baseline temperatures (Table 6.1). Since a significant proportion of precipitation falls in the Ahuriri catchment as snow, the higher temperatures cause more snowmelt and, as warmer atmosphere holds more moisture, the R/P ratio will increase in the future. Figure 6.4 shows the R/P ratio for the Ahuriri catchment for the study periods (Baseline, 2040s and 2090s), expressed as a percentage of rainfall to total precipitation. The lowest ratios for baseline, 2040s and 2090s are 26%, 29% and 51% respectively.

An increase in the R/P ratio for Ahuriri is seen for all months in the study period. The R/P ratio for the Ahuriri is lower in winter and higher in spring and summer. The reason for the low ratio is less winter precipitation falling as rainfall and more precipitation falling as snow in the Ahuriri catchment.

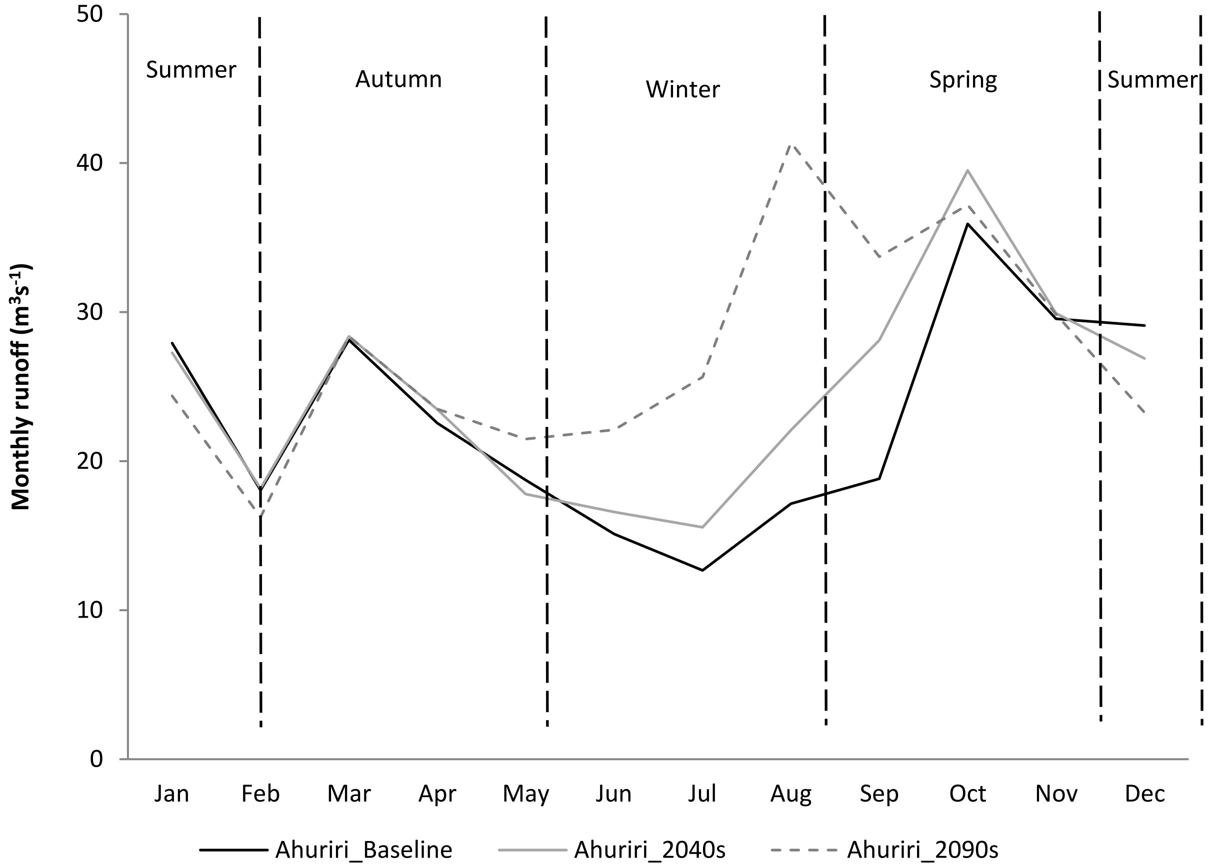


Figure 6.3: Baseline, 2040s and 2090s flow in the Ahuriri catchment.

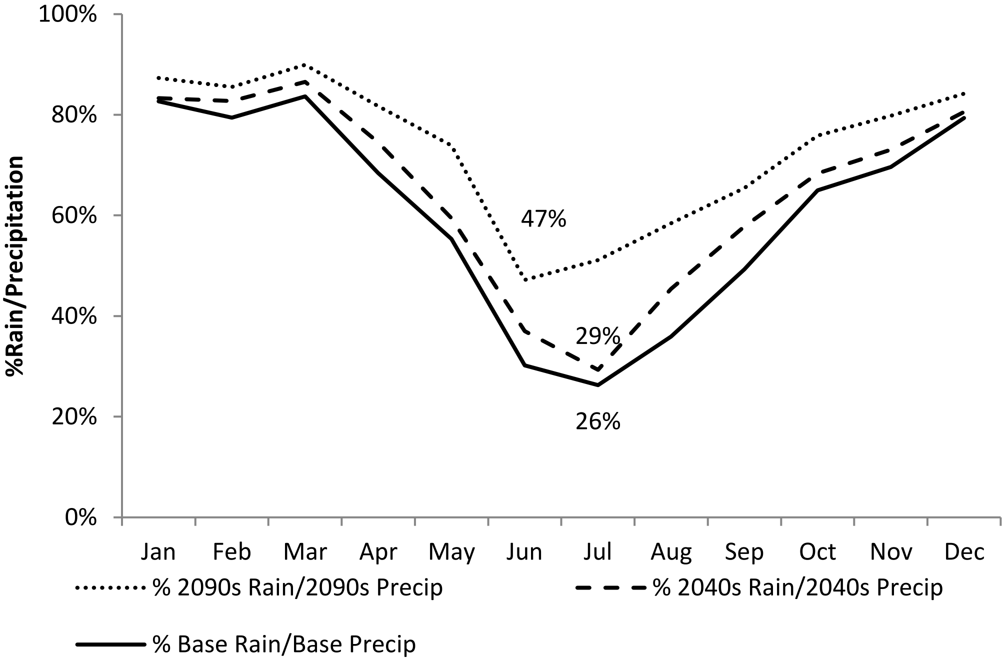


Figure 6.4: R/P ratio for the baseline, 2040s and 2090s period in the Ahuriri catchment.

This consistent increasing trend in R/P ratio shows more precipitation will fall as rainfall in future because of climate change. The R/P ratio is lowest in July for the baseline and 2040s but will shift to June in the 2090s. This shift shows the precipitation pattern in the GCM changes so much, that the R/P ratio in July is no longer the lowest R/P ratio in the 2090s and the R/P ratio in June becomes smallest R/P ratio for the 2090s. These precipitation changes are driven by the change in circulation pattern by the A2 scenario inside the GCMs.

The increase in winter flows in the 2090s and spring flows in the 2040s will have a positive impact on the hydroelectric power generation but may have negative impacts on braided river ecosystems. Therefore, water resources need to be managed to reduce the negative impacts on tourism, conservation of endangered species and social, cultural and economic impacts. More water will be available due to the increase in volume of water between April to September; however, if this extra water is not managed properly it could have a detrimental effect on river ecosystems.

6.4 Pukaki catchment flows

The Pukaki catchment has its lowest flows in the winter months and highest flows in the spring and summer months for the baseline, 2040s and 2090s periods (Figure 6.5). This shows that a lot of precipitation falls as snow in winter rather than rainfall. The 2040s and 2090s flows are larger than baseline flows and the 2090s flow, especially, is significantly higher than baseline flow. The Pukaki catchment flow is lowest in winter (July) and starts increasing in summer and autumn because of snowmelt and an increase in R/P ratio. The highest flow is in February 2040s, but the February 2090s flow is lower than the 2040s because the higher temperature causes earlier snowmelts in summer and autumn. The result of this study is in good agreement with another climate change impact study in Pukaki hydropower generation (Caruso et al. 2017a). They studied climate change impacts on hydropower using the A1B scenario, unlike the A2 scenario used in this study. They showed an increase in future winter and spring flows and a decrease in summer flows, which is similar to the results of this study.

Figure 6.6 shows the R/P ratio of the Pukaki catchment for the baseline, 2040s and 2090s period. The R/P ratio is the least in July for the baseline, 2040s and 2090s periods. Also, the R/P ratio in the 2090s increased, compared to the 2040s, and the 2040s R/P ratio increased compared to the baseline. This increase in future flow is due to an increase in R/P ratio because of the temperature increase. The higher future temperature will trigger more snowmelt and a warmer atmosphere holds more moisture, which increases rainfall rather than snowfall. The 2040s flow is similar to the baseline but there is a significant increase in flow between April to November for 2090s flows. Caruso et al. (2017a) showed that the R/P ratio for the Pukaki catchment is 0.49 for July, which is similar to the 0.52 R/P ratio obtained in this study. The R/P ratio of this study is slightly higher because of the higher emission scenario A2 used in this study compared to the A1B scenario. Since Pukaki is the major source of water availability for the series of hydroelectric dams downstream, an increase in future flows will have significant positive impact for the hydroelectric power generation in winter when the demand is highest in New Zealand. The Pukaki flow is crucial for the hydroelectric dams, not only for the economic point of view but also it is one of the hydroelectric power houses that enhance energy security of the South Island of New Zealand. The possibility of flooding/erosion with high intensity rainfall in future will be one of the negative impacts, since higher temperatures can create more intense storms.

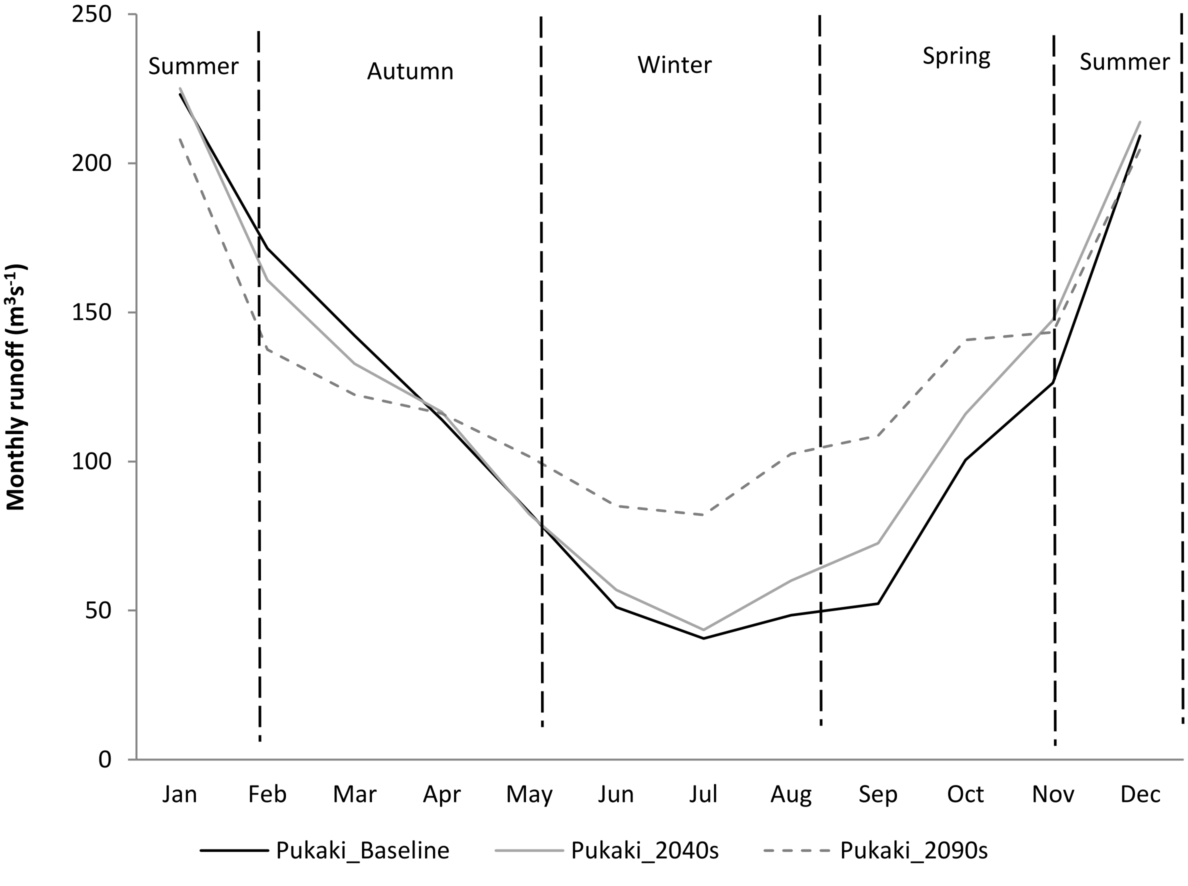


Figure 6.5: Baseline, 2040s and 2090s flows in the Pukaki catchment.

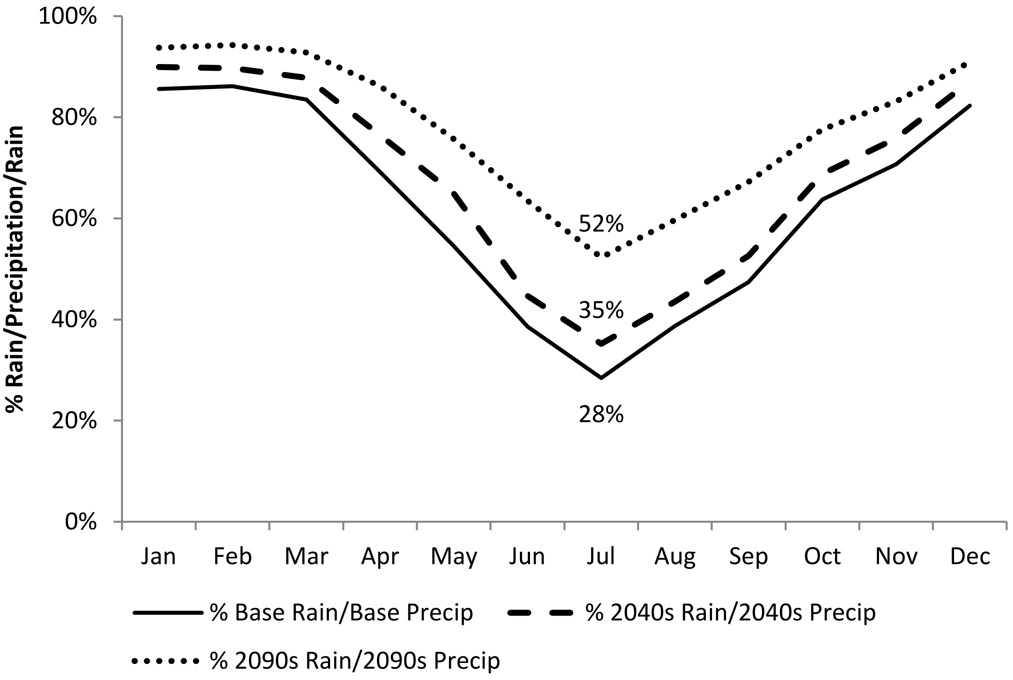


Figure 6.6: Percentage of baseline rain/baseline precipitation, 2040s rain/2040s precipitation and 2090s rain/2090s precipitation at the outlet of the Pukaki catchment.

6.5 Temperature for the study periods Baseline, 2040s and 2090s

Temperature is the main factor determining whether the precipitation falls as rainfall or snow. Table 6.1 shows the baseline, 2040s and 2090s sub-catchment' average of maximum daily temperatures in the catchments Hakataramea, Ahuriri and Pukaki. The sub-catchments of the Hakataramea catchment have the highest temperatures (11-19 °C), while the Ahuriri sub-catchments are the second highest and the Pukaki sub-catchments have the lowest temperatures (4-18 °C) for the baseline, 2040s and 2090s periods. The table shows an increase in temperature in the 2040s and 2090s compared to the baseline in all study catchments.

The role of snow and temperature in future streamflow in mountain catchments have been reported in different part of the world (Kerkhoven and Gan 2010; Simoni et al. 2011; Christensen and Lettenmaier 2007). An increase in future streamflow is reported in snow-dominated catchments because of the change in timing and amount of snow accumulation, snowmelt and rainfall in New Zealand (Zammit and Woods 2011; Poyck et al. 2011; Gawith et al. 2012; Caruso et al. 2017a). This role of snow is crucial in the South Island of New Zealand, where snowmelt from the Southern Alps contributes a large portion of mean annual flow of the rivers. (Kerr 2013)

Table 6.1: Baseline, 2040s and 2090s temperatures (℃) in the study sub-catchments.

Sub-catchments	Baseline	2040s	2090s
Hakataramea	11 - 17	12 - 17	13 - 19
Ahuriri	8 - 14	9 - 15	11 - 17
Pukaki	4 - 16	5 - 17	6 - 18

The baseline temperatures in VCSN are obtained from past data. The 2040s and 2090s temperatures are obtained from the Global Circulation Models, the 2040s and 2090s temperatures are obtained from VCSN, which is calculated by downscaling GCM to VCSN using Trenberth’s westerly and southerly anomaly patterns. Temperature increase can have a positive or negative impact. A negative effect could be felt by tourism as ski fields could suffer with rising temperature. The positive impact of more water for hydroelectric stations could be offset with frequent and intense storms, causing flooding and/or erosion problems. The impacts of temperature on aquatic and terrestrial endangered species can be devastating. However, while a few species may not survive, other species may thrive in new environments.

6.6 Baseline, 2040s and 2090s sub-catchments variability

The change in future temperature causes a shift in Snow Water Equivalent (SWE). SWE is the snowpack measurement showing the equivalent amount of water that is contained in the snowpack. The change in SWE is the main cause for the change in runoff in snow-dominated catchments or mixed rainfall and snow dominated catchments. SWE is the amount of water available in the sub-catchment snowpack: equivalent to the uniform depth of water (mm) in the same sub-catchment. When precipitation falls as snow in winter, SWE is the amount of snow that is stored in the catchment.

6.6.1 Hakataramea sub-catchments

There is no permanent snow cover in the Hakataramea catchment, hence SWE for the baseline, 2040s and 2090s periods for all Hakataramea sub-catchments is zero, Future sub-catchment runoff is entirely due to the change in the future precipitation and temperature. The GCM forced data from VCSN (Table 6.1) shows an increase in temperature for the study catchments. The increase in temperature and runoff in the future is due to the change in future weather patterns, obtained from the GCM.

Figure 6.7 shows that the Hakataramea sub-catchments' annual runoff is between 10-689 mm, 15-772 mm and 15-789 mm for the baseline, 2040s and 2090s respectively.

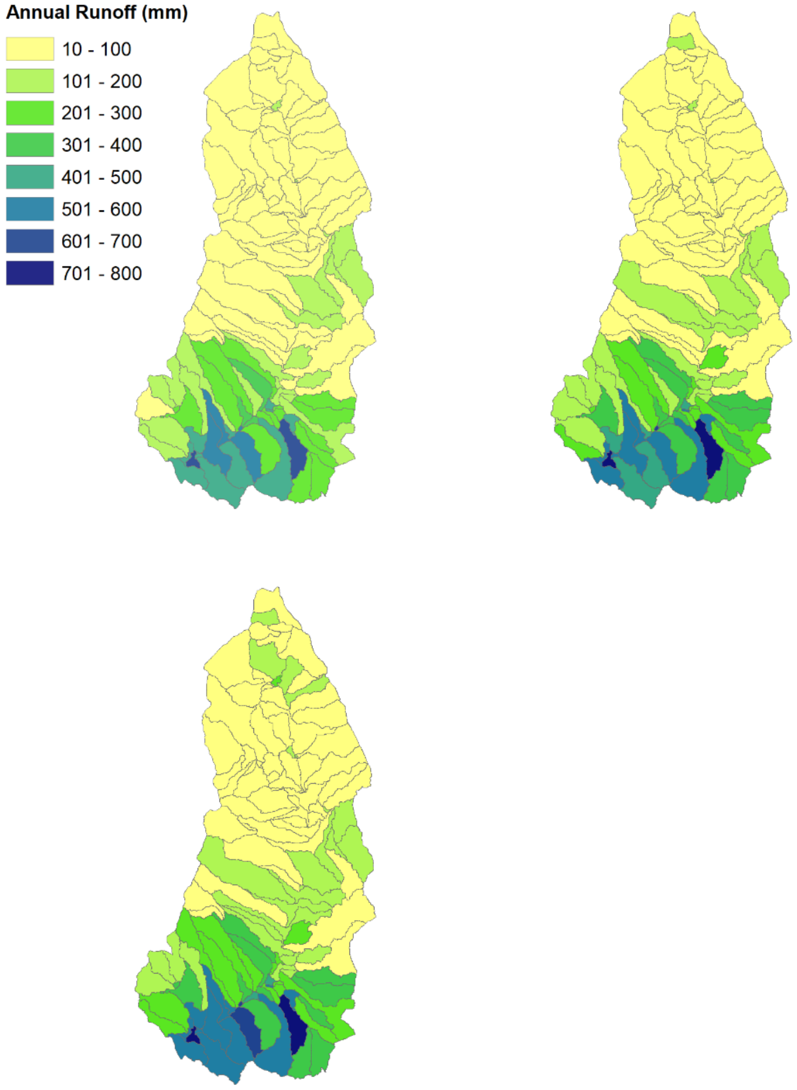


Figure 6.7: Baseline (10 - 689 mm), 2040s (15 - 772 mm) and 2090s (15 - 789 mm). Median annual sub-catchments runoff from the Hakataramea catchment (n = 128).

6.6.2 Ahuriri sub-catchments

Figure 6.8 shows that the Ahuriri sub-catchments have an annual average SWE of 89 mm (2-508 mm), 65 mm (1-377 mm) and 35mm (0-288 mm) for the baseline, 2040s and 2090s respectively The sub-catchments' runoff in the Ahuriri catchment, will increase in the 2040s and 2090s, compared to the baseline. The SWE will decrease in the 2040s and even further in the 2090s, compared to the baseline. The decrease in SWE means the volume of snow is reduced. This decrease in SWE is attributable to increased runoff in the 2040s and 2090s (Figure 6.9). In summary, temperature change affects SWE and the runoff in the study sub-catchments.

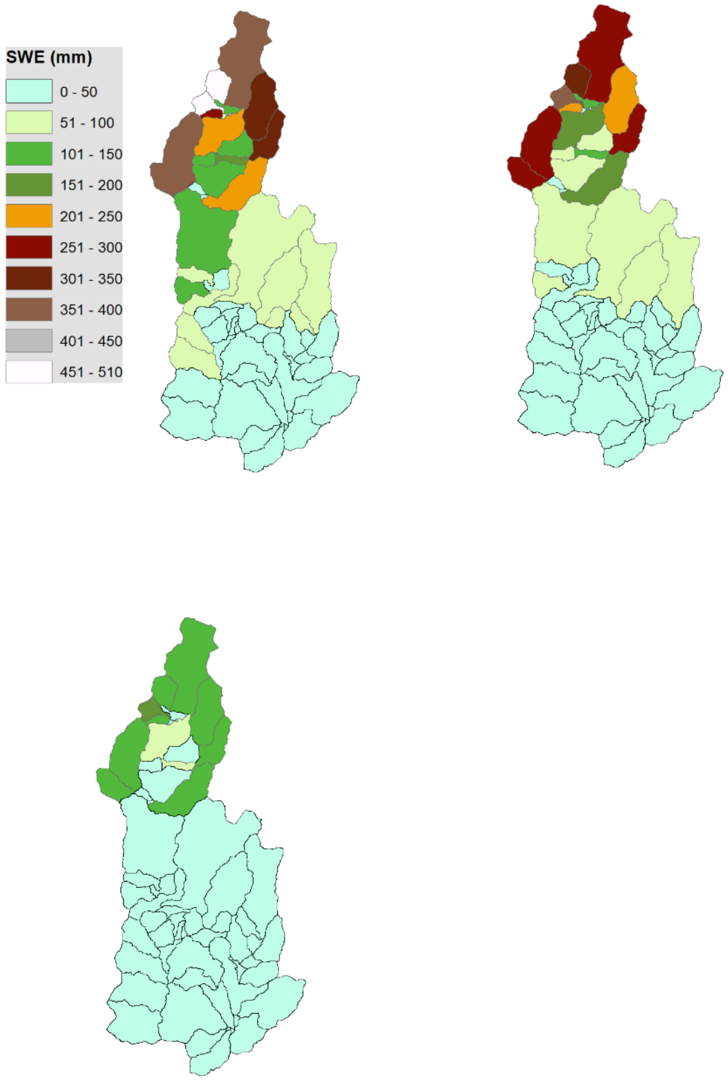


Figure 6.8: Average SWE 89 mm (2-508 mm) for baseline, 65 mm (1-377 mm) for 2040s and 35 mm (0-288 mm) for 2090s in the Ahuriri sub-catchments.

Figure 6.9 shows the SWE for the baseline, 2040s and 2090s for the Ahuriri sub-catchments. This decrease in SWE in the sub-catchments agree with an increase in the 2040s and 2090s runoff compared to baseline. Figure 6.2 shows that the catchment runoff is largest in spring for baseline and 2040s but for 2090s, this shifts to earlier in winter.

This shift in the Ahuriri runoff is due to the decrease in SWE, because a moderate amount of the snow will melt by the 2040s, and data shows it will melt further in 2090s. This causes a significant decrease in SWE and increase in runoff.

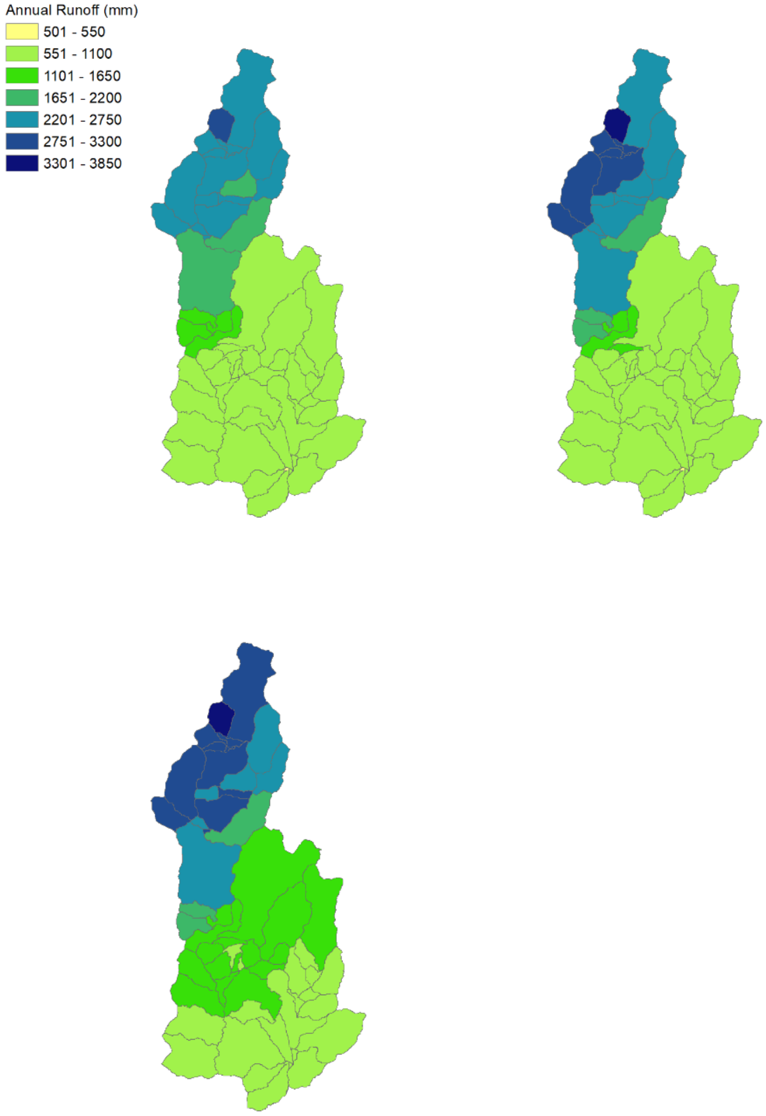


Figure 6.9: Baseline (502 - 3161 mm), 2040s (539 - 3378 mm) and 2090s (587 - 3619 mm). Median annual sub-catchments runoff from the Ahuriri catchment (n = 61).

The Ahuriri catchment is inside a national park where a water conservation order has been in force since 1990. Therefore, any changes in Ahuriri River flows have a significant impact on the natural ecosystem, tourism, recreational activities, cultural practices and hydroelectric power generation. There is not much difference in peak flows between the baseline and 2040s; however, there is a stark difference in the 2090s flow, which is double that of the baseline. This will have significant impacts on the braided river system of Ahuriri River. Because of its high importance for conservation, the Ministry for the Environment suggests practices in the "*waitaki catchment allocation regional plan"* are followed. The north-western side of the Ahuriri catchment receives remarkably high rainfall, while the lower Ahuriri, where it meets the Waitaki River, has a very dry climate. Any increase or decrease in the Ahuriri River flow can influence the Waitaki River system because the Ahuriri contributes a 9% natural and unregulated flow to the Waitaki.

There are many types of endangered fish species found in the Ahuriri River and one of them, the longjawed galaxias (*Galaxias prognathus*), is nationally critical. Braided rivers, like the Ahuriri, have 80 bird species: the black stilt/kakī (*Himantopus novaezelandiae*) is one of the rarest birds that are found in the Ahuriri and its total number declined to 23 in 1980s but due to the conservation efforts its population is now 132 in New Zealand (DoC 2020a). This area is also home for the black-fronted tern/tarapirohe (*Chlidonias albostriatus*), (DoC 2020a) and wrybill/ngutu pare (*Anarhynchus frontalis*) (DoC 2020b) are also endangered birds found here. The conservation status of black-fronted tern and wrybill are nationally endangered and vulnerable. Cruz et al. (2013) investigated the minimum and maximum flow range required for black stilts (kaki) and wrybill chicks to survive. They showed that kaki survival rate increases when the flow is larger than 10m^3/s, but wrybill chicks' survival rate decreases when flow is higher than 10m^3/s. In their investigation, Cruz et al. (2013) found that flood was the main reason for the nest failure: (7%) for the wrybill. The Department of Conservation claims that any change in river flows or alterations of braided patterns and wetlands will be a major threat to this species.

Figure 6.2. shows that August 2090s flows for the Ahuriri catchment will increase to 41 m^3/s, compared to the baseline flow of 17 m^3/s. In addition to this increase of 2.4 times the peak flow, there will also be a large volume of water (Figure 6.3) from April to October, compared to the baseline period. These effects will be detrimental and critical to black stilts and other animals that depend on the braided river and wetland ecosystems in the Ahuriri River. In addition to black stilts, there are 250 native plant species, 27 mosses, 35 lichens and many terrestrial and aquatic invertebrates, lizards and freshwater fish. River and wetland birds have habitats on the braided river systems in the Upper Waitaki including the Ahuriri River. Because Ahuriri is the only catchment that is natural and unregulated, any notable change in flows affects directly on the conservation efforts of these species. Therefore, a proper planning must offset the detrimental effects of change in future flows.

Water use from the Ahuriri river includes dryland grazing, irrigation and for water supply into Omarama. In the case of substantial change in future flows, such as the doubling of the peak flow in 2090, there will be a significant impact in the Ahuriri catchment because of its high landscape, aesthetic and recreational value. Although, high winter or spring 2040s or 2090s flow will have a positive impact on hydroelectric power generation downstream of the Ahuriri catchment, it will also worsen erosion and flooding problems in wet weather, especially in winter.

Ahuriri and whole Waitaki area has a cultural significance and cultural practices such as collecting fish is important for local people. Many people are dependent on tourism and it’s important to preserve all natural birds, fish and landscapes because more than 250,000 tourists visit Waitaki area for recreation purposes and its natural beauty and unique plant and animal species. Many animal and plant species live in different areas of braided river: for example, gravel islands, wetlands, slow moving river portions and river terraces. These species depend on the braided pattern, depth, width and how much sediment and gravel are carried downstream. Any notable change in river flow, depth or volume will significantly affect the survival of these species. The increase in runoff will have a positive impact on the hydropower generation but it will be critical for the braided river ecosystem such as plants, insects, and animals' habitats.

6.6.3 Pukaki sub-catchments

Figure 6.10 shows the SWE for the baseline, 2040s and 2090s periods in the Pukaki sub-catchments. The SWE for the sub-catchments of the Pukaki catchment are 7-57892mm, 4-49474 mm, and 1-31267 mm for the baseline, 2040s and 2090s respectively. The high SWE values show that sub-catchments of Pukaki have large amount of snow. A significant reduction in 2040s and 2090s' SWE, compared to the baseline, suggests the 2040s' runoff and 2090s' runoff are higher compared to the baseline, and sub-catchments runoff in 2040 and 2090s' runoff are 12% and 28% higher than the baseline period. The north-western sub-catchments, which are parallel to the Southern Alps, receive higher precipitation, compared to Southern sub-catchments. One of the reasons for this is the existing precipitation gradient created by the Southern Alps and prevalent wind direction (Chapter 4).

Sub-catchments' runoff is decided by the precipitation, temperature and SWE in those sub-catchments. In sub-catchments like Pukaki, where snow plays a vital role, SWE is an important factor on determining runoff. The 2040s and 2090s sub-catchments' temperatures are higher than the baseline period (Table 1). Temperature affects sub-catchment runoff variability when based on whether most of the precipitation falls as rainfall or snow. Figure 6.10 shows the SWE for the baseline, 2040s and 2090s and shows the amount of snow that is stored in the sub-catchments. SWE is very high at the top left-hand corner of the Pukaki catchment, closer to the Southern Alps (Chapter 4). SWE is very low towards the southern-side sub-catchments, as that is farthest from the Southern Alps. The runoff distribution is in good agreement with SWE (Figures 6.10 and 6.11). Runoff in the subcatchment is high where SWE is high and low where SWE is low. However, the 2090s and 2040s sub-catchments' runoff will be higher because SWE is decreased that means more snowmelt and higher proportion of rainfall compared to earlier periods.

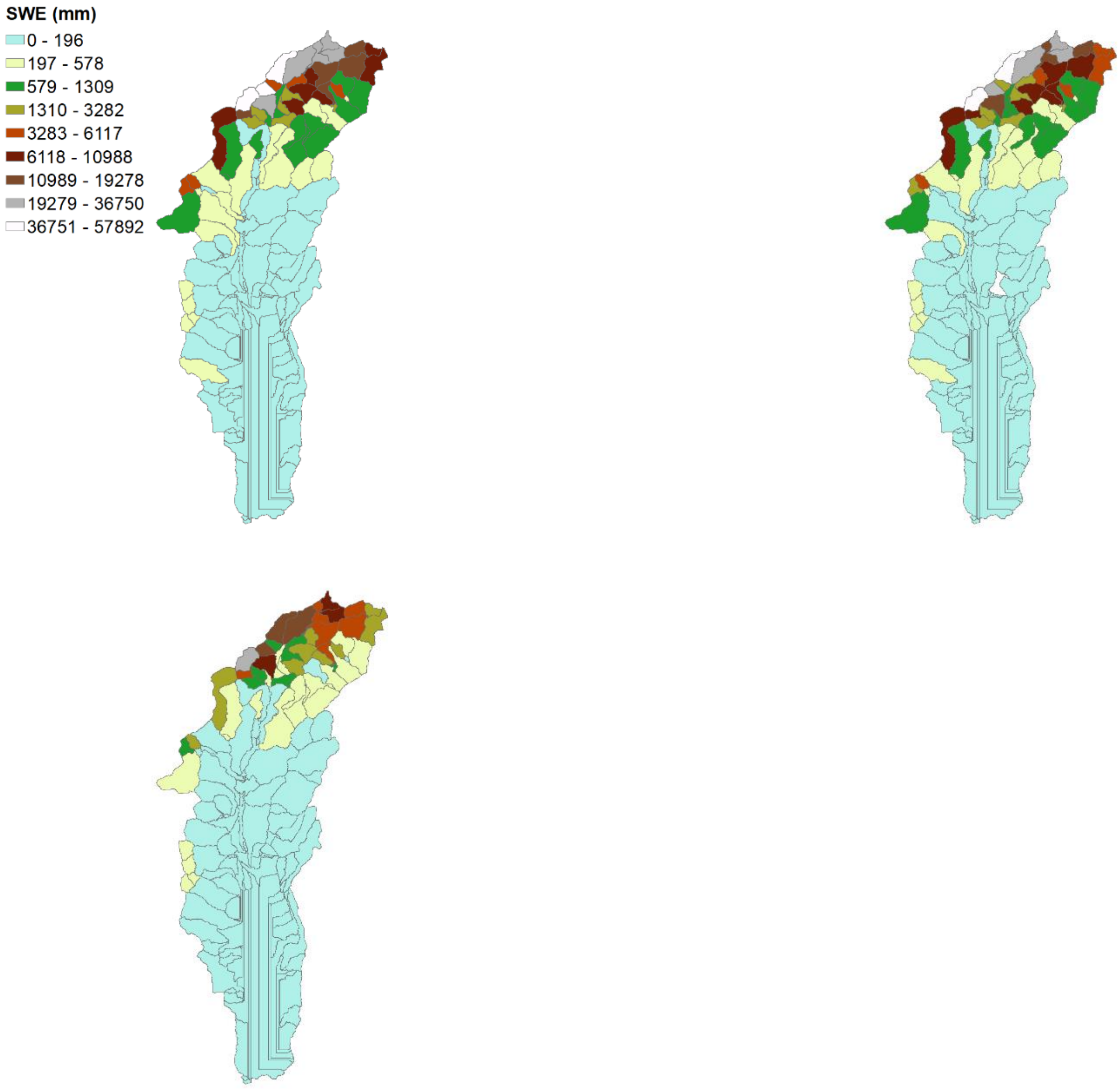


Figure 6.10 Average SWE 3417 mm (7-57892 mm) for baseline, 2415 mm (4-49474 mm) for 2040s and 1617 mm (1-31267 mm) for 2090s in the Pukaki sub-catchments.

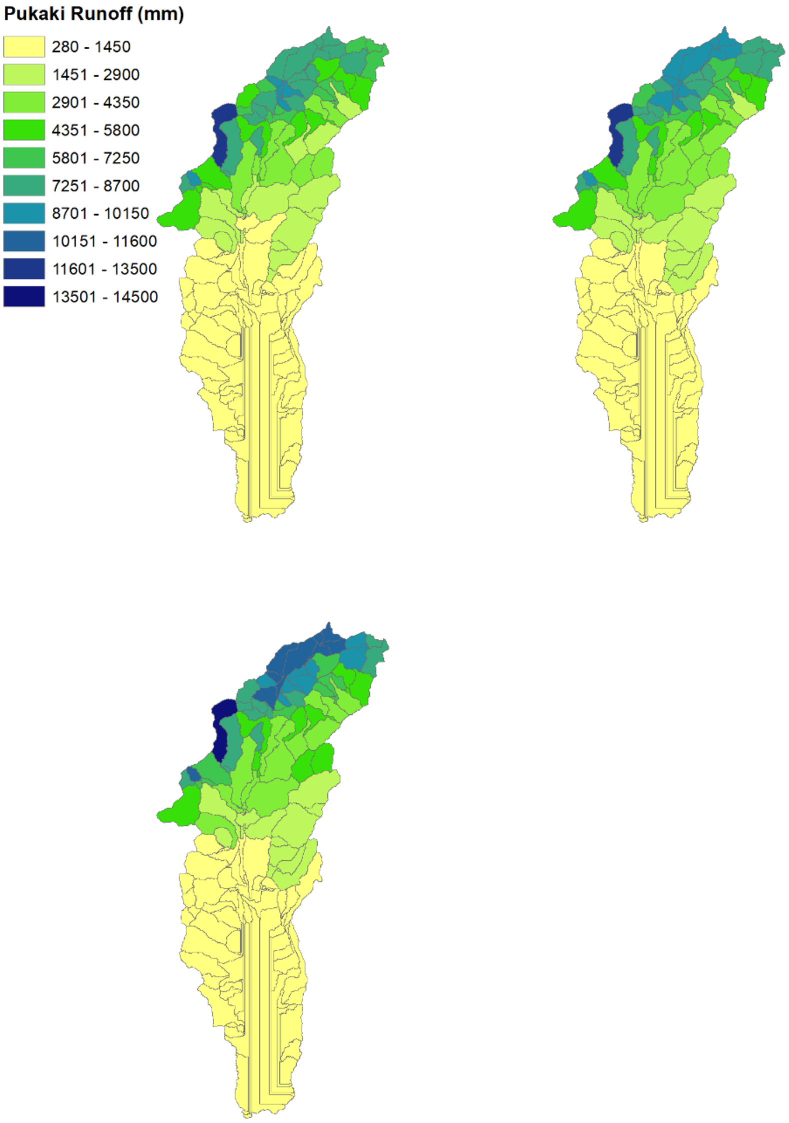


Figure 6.11: Baseline 3070 mm (280 - 11727 mm), 2040s runoff 3337 mm (322 - 12485 mm) and 2090s runoff 3611 mm (357 - 13525 mm). Median annual sub-catchments runoff from the Pukaki catchment (n = 153).

The effects from this increased sub-catchment runoff include a positive impact for the hydroelectric power generation in future. Since, hydroelectric power from Lake Pukaki is important from an economic point of view and is also significant for the energy security of the South Island of New Zealand. Tourism may be negatively impacted. Since sub-catchments future temperature is predicted to increase, it may have some impact on the Jollie River and Hooker glacier and surrounding ski fields where a lot of people travel for hiking or recreation purpose. Also, higher temperature means more intense rainfall storms that can cause frequent flooding and erosion issues in the Pukaki reservoir.

6.7 Limitations and Conclusion

The catchment runoff is obtained at the outlet of the catchment, but sub-catchment runoff is the average value over the sub-catchment. The sub-catchment precipitation calculated from the TopNet model is computed on the per unit area of the sub-catchment, while the runoff is computed per unit length of stream. All the simulations and sub-catchments flow are based on groundwater part, i.e., missing the surface runoff component, which can be 0-10% in these catchments as there is not much land use change. Large parts of the area of two study catchments (Ahuriri and Pukaki) are in the national parks (Ahuriri Conservation Park and Mount Cook National Park). The Hakataramea catchment is away from any major towns and land use is comprised of, primarily dairy and, sheep farming with water resources fully allocated therefore it is highly unlikely land use will change to have a significantly land use change in the study catchment.

This study is done using only anthropogenic climate change using GCMs recommended by Mullan et al. (2009). Natural climate variability, such as El Niño Southern Oscillation (ENSO) and Interdecadal Pacific Oscillation (IPO), are not considered in this study. GCM's sensitivity and emission scenario sensitivity is not considered in this study. In this chapter, the climate change impacts on future runoff in different types of catchments are evaluated. Glacial retreat is not considered in this study because Hakataramea and Ahuriri do not have significant glaciers, but the Pukaki catchment has more than 190 glaciers, including the large glaciers, Tasman and Murchison. This study is done by taking 20 years' reference data and SRES emission scenario, but the glacial retreat may vary year to year. Therefore, climate change impact on the glaciers of the Pukaki catchment could be an area of further research.

The variation in sub-catchment runoff is also investigated. It is found that catchment and sub-catchment runoff depend on temperatures, the amount of precipitation and especially whether that precipitation falls as rainfall and snowfall. The future flows in rainfall-dominated catchments are found to peak in winter when precipitation is largest. Snow-dominated basin flows peaked when temperatures caused a two-fold impact: an increase in future temperature caused more precipitation to fall as rainfall rather than snow and an increase in temperature caused more direct as well as rainfall-driven snowmelt. The amount of flow is found to be inversely related with SWE. A high SWE means more snow to melt later in spring or summer or to stay as a permanent snow until temperatures are high enough to melt it. A decrease in SWE is related to the loss of snow that is converted into runoff, hence an increase in runoff is observed.

Climate change has variable impacts on different catchments; therefore, each catchment needs an appropriate plan to use the water resources sustainably. The Hakataramea catchment has its highest flows in July of the 2090s, but the increase is small. This increase will not be enough to allow more water to be extracted in future because water is already over-allocated at present (ECAN 2012). Also, the Hakataramea River is a major salmon and inanga (*Galaxias maculatus*) spawning river and has many endangered species which restricts abstractions and transfers because that can alter the water quality.

The Ahuriri catchment has some snow, therefore the snow enhances an increase in the 2040s flow in spring but this shifts to late winter in the 2090s. More snowmelt in the 2040s will contribute as a runoff and the 2090s snowmelt will be added on top of that value. The Ahuriri catchment flows increase significantly, therefore it has the largest impact on conservation of endangered birds, invertebrates and plants because braided river beds and the wetlands created are their habitat. Also, the Ahuriri has unique landscape and many people use national parks for recreational or tourist purposes. Since both water peaks and volumes increase significantly in future, it will be a challenging job to manage braided river systems and preserve endangered species like black stilts. Careful planning to manage extra water is needed; however, the added water will be economically beneficial for hydroelectric power generation or any future water uses.

The Pukaki catchment is a snow-dominated catchment, therefore less runoff is found in winter in both present and future periods. However, future winter flows will be higher and that have a positive impact on the hydroelectric power generation and energy security of New Zealand. The increase in winter flows may also have some negative effects of flooding and erosion in the catchment. Lake Pukaki and Mount Cook are popular tourist attractions, therefore any change in future flows in the Pukaki catchment must be managed properly so there are little or no negative impacts.

It is important to perform climate change studies on a catchment basis rather than studying the whole basin. It is shown that an increase and decrease of flows in different catchments have completely different effects on different catchments. If climate change studies are performed on a catchment basis, then the right strategy needed for each catchment can be developed to mitigate harmful impacts in that catchment.

Sub-catchment-level studies are required to get a more precise idea of what is happening in each catchment: there is so much variability in sub-catchments’ runoff because of precipitation as well as snowmelt. Also, this can be particularly useful to solve local-scale problems or inter-catchment problem. For example, the future flows in the

Hakataramea catchment are very low and water cannot be extracted in the future due to several restrictions. However, if the sub-catchment runoff is known, the problem of water scarcity can be addressed partially by diverting water from sub-catchments with water surplus to the sub-catchments in drought-like condition. The sub-catchment is Strahler third order (nearly 7 km^2), so it can offer a less averaging effect and a better resolution in the estimation process.

Any significant climate change impact can change future temperature, rainfall and flows which can affect the habitat of species living in the Waitaki river basin including threatened and endangered, as well as species endemic to Waitaki. While in other areas of the world, the species may move to the suitable habitat, this adaptation may be difficult in New Zealand especially for flightless birds because the land is limited as New Zealand is an island country. Climate change risk for New Zealand are investigated in National Climate Change Risk Assessment for New Zealand (MfE 2020). This study suggests that the change in temperature and rainfall due to future climate change will pose extreme risk to availability of potable water supply as well as water quantity and quality in New Zealand. The study categorised risk is urgent (93 out of 100) and extreme This is important for the study catchments because lake Pukaki is source of municipal water supply (Chapter 2) and there are already concerns about the quality of water in the Hakataramea river.(Shaw and Palmer 2015). The same study also highlighted there is an urgent risk (73 out of 100) to indigenous ecosystem and indigenous species from invasive species from potential future climate change.

Chapter 7. Conclusions and Recommendations

This thesis investigated spatial variability in mountain catchments. While previous studies suggest variability in mountain catchments flows are related to elevation, soil and landcover, this thesis shows that precipitation variability due to rain shadow effect is the key factor for spatial variability in flows. These findings challenge previous studies and contribute to the literature by suggesting precipitation distribution should be considered in determining the spatial variability of flow in mountain catchments. This study demonstrates a striking relationship between precipitation and flow and shows an alpine catchment creates a strong orographic effect that affects the precipitation based on the distance from the main divide. This study confirms the importance of investigating the relationship between precipitation and flow before investigating other factors.

Many researchers studied the spatial variability with either lumped or distributed models or with elevation, soil type and land cover. Most of the studies in mountains used large catchments and only a few studies compared flows using lumped vs distributed models. There are no significant studies that evaluate the role of a main divide for catchments and sub-catchments flows. There is no significant study where the catchment size or scale effect is considered in determining spatial variability. This study confirms that spatial variabilities should be analysed in sub-catchment scales because there is high variability in alpine catchments so catchment-scale studies cannot capture spatial variability.

This study questioned the difference between climate change impacts on future flows in catchment scales compared with sub-catchment scales. While some studies have compared two or three representative sub-catchments (Poyck et al. 2011; Gawith et al. 2012), there are no significant studies based on climate change impacts on sub-catchment levels. This study contributes to the previous literature by demonstrating the spatial variability in future flows in sub-catchment scales, and therefore suggests that climate-change studies should focus on sub-catchment scales rather than catchment scales. The evidence from this study strongly suggests that climate change impacts on catchment scales are different to the effects on sub-catchment scales: this is important for intra-catchment water resource management. The sub-catchment level study will be useful to solve water resource problems locally if water can be diverted from sub-catchments with high runoff to sub-catchments with small runoff. The findings from this study at catchment level will be important for catchment water resources management because it shows the change in the magnitude and seasonality in future flows. The information of future catchment and sub-catchment flows is useful because water resources management can know beforehand whether water will be surplus or deficit in any particular location and any particular season.

One of the limitations of this work is the sparse rain-gauge density used in the study catchments. This sparse network can impact the precipitation estimation. The model used in this study assumes uniform hydrological fluxes in the sub-catchment; however, there may be a high variability of these fluxes in the Strahler third order sub-catchment (7 km^2) in spatially variable mountainous catchments. There may be some benefit to studying Strahler second order or first order sub-catchments; however, this will need large computing resources and time. Regardless, the sub-catchment areas will be smaller, and so precipitation and temperature input will be still from VCSN, with a 5 km x 5 km grid size, therefore accuracy will not increase significantly.

This study assumes that there will not be any significant land-use change in the study catchments: if the land use changes significantly, the same calibration cannot be used to estimate future flows. Further research may be done to quantify the sensitivity of effects of future land use change in streamflow under climate change. The catchments considered in this study are located far from urban areas, lie in the national parks and have large lakes and mountains: it is unlikely that there will be any significant land use change within the timeline of this study.

The model used in this study does not consider any glacier advancement or glacier retreat. This study focuses on long term average (20 years) variability in streamflow, but glacier retreat can be variable year to year. The Hakataramea and the Ahuriri catchments do not have significant glaciers but the Pukaki catchment has 190 glaciers, including two large glaciers – Tasman and Murchison (Sirguey 2010). Further study is recommended to investigate climate change effects on glacier retreat in the Pukaki catchment.

Further research studying spatial variability using radar rainfall in conjunction with rain-gauge data is recommended. The radar rainfall estimation is very useful in un-gauged catchments and in areas where the rain-gauge network density is very low. Radar rain estimation can supplement rain gauges to produce high-density data with high-spatial resolution. The quality of precipitation readings can be improved by using radar data and supplementing its information into VCSN; however, this means waiting number of years until sufficient data is collected from the rain radar located within the range of the study catchments and cannot be used to incorporate past data when there was only rain gauge and no rain radar data.

This study only considers climate change due to warming from SRES scenario and does not consider the natural climate variability such as El Niño Southern Oscillation (ENSO) or Interdecadal Pacific Oscillation (IPO). This study used 20 years of average data for present and future climates based on emission scenarios, therefore natural climate variability is not included in this study. The ENSO (2-7 years) is considered to yield some drier conditions on the East Coast of New Zealand (NIWA 2018) and thus further study is recommended. There is no significant evidence for IPO (15-25) because studies show only 2 or 3 IPO phases.

Similar research to confirm the study of this findings in other catchments is suggested. Similar studies can be done to test or confirm this result in any other alpine catchment or in monsoon catchments with similar rainfall. Further studies should also look at evaluating the impact of future land cover change in streamflow. Future flows will be different if landcovers change because of different evapotranspiration or infiltration. The sensitivity of land use change can be studied by evaluating the impact of land use change on future flows. Further research is suggested to model the future streamflow using dynamical downscaling instead of statistical downscaling, to test catchment or streamflow sensitivity to the downscaling. Another suggestion for further research is to test the sensitivity of climate change effects on streamflow with different GCMs and different emission scenarios.

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