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Climate Change and Alpine Catchment Discharge

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Abstract

This thesis examines the impact of predicted global climate change on alpine catchment discharge from the eastern Southern Alps of Canterbury. The reasons for this assessment are twofold. Firstly, the water resources of Canterbury and other drier parts of New Zealand are becoming limited due to demand for irrigation, hydroelectric generation and recreation. Secondly, studies overseas have shown water resources of alpine catchments to be highly sensitive to predicted global climate change, but as yet this subject has received little attention in New Zealand.

The research objectives are: (1) To investigate and choose a methodology to assess the impact of climate change on discharge from alpine catchments. (2) To predict the effects of potential climate change on alpine catchment discharge from the eastern Southern Alps of Canterbury.

The HBV3-ETH9 conceptual runoff model is chosen for seven reasons: easily met data input requirements, appropriate spatial and temporal scale, distributed snow and glacier representation, simple calibration and verification technique, accurate simulations of discharge in previous studies in several different environments, model availability and previous use for similar climate change studies. It is applied to four catchments with differing characteristics (Jollie, Hooker, Rangitata, and Rakaia). The model is calibrated and verified using daily inputs of precipitation, mean temperature and discharge. Climate change scenarios are generated from downscaled GCM results.

Model performance indicates the HBV3-ETH9 model can be applied successfully to alpine catchments in New Zealand under the current climate. Verification period model efficiency ($R^2$) values range from, 0.70 - 0.78 (Jollie), 0.58 - 0.81 (Hooker), 0.61 - 0.85 (Rangitata) and 0.45 - 0.83 (Rakaia). Model performance is largely related to representation of areal precipitation.

By the 2080's higher volumes of discharge are predicted in all seasons by all scenarios (except under the CSIRO scenario for summer). For example, mean seasonal discharge from the Jollie catchment using the HadCM2
scenario for the 2080’s increases by 1.5 m$^3$/s in autumn, 5 m$^3$/s in winter, 3 m$^3$/s in spring and 1.5 m$^3$/s in summer. The largest predicted increase in discharge is during late winter and spring, when substantially larger floods are likely. For example, late winter and spring floods double in peak volume under the 2080’s HadCM2 scenario for the Rangitata. An increased proportion of discharge will occur in winter and early spring. For example, mean monthly discharge as a proportion of mean annual discharge from the Jollie catchment during August jumps from 0.6 to 1.1, and during January drops from 1.7 to 1.5 using the HadCM2 scenario for the 2080’s. This is partially caused by a reduced proportion of precipitation falling as snow. For example, currently 40 per cent of precipitation falls as snow in the Hooker catchment, this reduces to 27 per cent using the CSIRO scenario for the 2080’s.

Future studies need to focus on further assessing the validity of climatic transferability of conceptual models. Physically based models driven by dynamically downscaled scenarios could reduce doubt surrounding climatic transferability. Applying such models to the alpine environment in New Zealand will require a long-term project to gather quality input data with high spatial and temporal resolution.
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Ramsay Glacier in the headwaters of the Rakaia catchment during winter.
To the memory of

Stacey

a much loved sister and dearly missed.
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Chapter 1

Introduction

1.1 Context

Recent research has shown that discharge from alpine catchments is highly sensitive to predicted global climate change (Singh and Kumar, 1997; Braun, Weber and Schulz, 2000; Morrison, Quick and Foreman, 2002). This is particularly the case where snow and ice play a major role in the discharge process. For many of New Zealand’s alpine catchments, such as the Hooker River shown in Figure 1.1, future climate change is likely to alter the precipitation input and the snow and ice cover. This will lead to changes in discharge volume and seasonal timing. As yet however, there has been little assessment regarding the sensitivity of New Zealand’s alpine catchment water resource to a changing climate.

Much of the water resource of the eastern South Island is generated in the alpine regions along the Main Divide of the Southern Alps. This is due to the distribution of precipitation (Figure 1.2) produced by the prevailing westerlies. Together the major alpine rivers shown in Figure 1.2 (Waitaki, Rangitata, Rakaia, Waimakariri, Hurunui, Waiau and Clarence) contribute 88 per cent of the Canterbury region’s surface runoff (Morgan, Bidwell, Bright, McIndoe and Robb, 2002), with a combined mean annual discharge of close to 1000 m³/s.

This water resource is utilised for a variety of very important economic, environmental, health, cultural and recreational activities (Morgan et al., 2002). Electricity generation on the Waitaki River alone contributes an annual average 7650 GWh to the national grid (Meridian Energy Limited, 2003). This is equal to 21 per cent of total generation in New Zealand for 2002 (Statistics New Zealand, 2003). Irrigation of 438,000 ha accounts for 83.4 per cent of water consumption in Canterbury, more than
Figure 1.1: Hooker River and its alpine catchment.

half of which comes directly from these alpine catchments (Morgan et al., 2002). The maximum allocated weekly rate of take from these catchments is more than 130 m$^3$/s (Morgan et al., 2002). The Rangitata Diversion Race (RDR) alone takes up to 31 m$^3$/s from the Rangitata, irrigating 64,000 hectares, generating an annual income in excess of $100 million (Rangitata Diversion Race Management Limited, 2001).

Meeting these and future water needs can only be achieved through a clear understanding of the variability of the resource and likely influences on it. Some influences are relatively well understood, such as the role of the cryosphere (Fitzharris and Garr, 1995; Fitzharris, Lawson and Owens, 1999) and precipitation distribution (Griffiths and McSaveney, 1983a; Sinclair, Wratt, Henderson and Gray, 1997). However, other influences such as the impact of global climate change are less well known. Expected global climate change is likely to greatly affect water resources of alpine catchments (Braun et al., 2000), but the topic has received little attention in New Zealand.

The Intergovernmental Panel on Climate Change (IPCC) released its Third Assessment Report (TAR) in 2001. This report states that:

There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities (IPCC, 2001).
Figure 1.2: The alpine catchment water resource, showing a significant precipitation increase towards the Main Divide of the Southern Alps (Bowden, 1983). Catchment information from Environment Canterbury (2003).
Further, the IPCC report indicates that temperatures will continue to increase throughout the 21st century, and this in turn will affect other aspects of the climate, including precipitation and atmospheric circulation patterns. The question is, how will predicted climate change affect the water resource generated in the alpine regions of the major Canterbury catchments?

The climate has a direct influence on discharge through precipitation and temperature changes, but also an indirect impact through its influence on the cryosphere and biosphere. To assess the impact of climate change on runoff all of the links must be included in the investigation. The links must also be considered at the appropriate time scale because the climate varies over a range of time scales. This thesis investigates the impact of predicted global climate change over the next century on selected alpine catchment discharges in Canterbury.

1.2 Rationale and Objectives of Thesis

Prediction is the ultimate goal of any science. Hydrology as a science is now in the position of having predictive ability. Quantitative hydrology of the previous 350 years (Biswas, 1970) has allowed modern hydrology to reach this point. The aim of this thesis is to use this predictive ability to demonstrate the potential influence of climate change on alpine catchment runoff.

Prediction allows for sensible planning, but planning can only be as good as the predictions it is based on. Therefore identification of the best tool to make predictions is important. Added to this is the importance of input data. Without the best input data, predictions are less reliable. The nature of climate change science is such that as improvements are made, the ability to generate realistic scenarios also improves. The objectives of this thesis are therefore:

- To investigate and present a methodology to assess the potential impact of climate change on discharge from alpine catchments.

- To predict the effects of potential climate change on alpine catchment discharge from the eastern Southern Alps of Canterbury.

The first objective reflects the need to focus on methodology in climate change studies as much as on the predictions themselves. This is because specific predictions may be considered out of date within a few years due to improvements in General Circulation Models (GCMs) or scenarios, but the methodology used to gain the prediction is likely
to remain robust. The second objective reflects the need to at least determine the sensitivity of the Canterbury water resource to climate change and to provide some results upon which to base future management decisions.

1.3 Thesis Structure

The remainder of this thesis contains five chapters and is structured as follows. Chapter 2 provides a literature review, which outlines the most important research concepts related to alpine catchment discharge and potential global climate change over the next century. Various approaches to modelling discharge are then reviewed and specific research questions this thesis will answer are identified. The methodology used in this thesis is outlined in Chapter 3, along with the rationale behind the methods. Results of the thesis are presented in Chapter 4.

A discussion of the results in relation to the research questions and the findings of others is presented in Chapter 5. Also included is a discussion of the methodology and what this means for future studies of alpine catchment resources in New Zealand. The thesis ends with a conclusion (Chapter 6) that summarizes the findings as related to the objectives. This includes an assessment of the methodology, and the potential consequences of long-term climate change on alpine catchment runoff from the eastern Southern Alps. Also identified in Chapter 6 are future research needs relating to this topic.
Chapter 2

Literature Review

2.1 Introduction

This chapter contains a review of the established knowledge relevant to the two objectives of the thesis topic. The chapter starts with a review of global climate change and this is then placed in the context of New Zealand. Next, the links between climate, catchments and discharge are reviewed. Approaches to modelling these links are investigated and previous studies focusing on climate change and discharge are explored in a methodological review. Research questions are then outlined to give further focus to the thesis.

2.2 Climate Change

2.2.1 Global Climate Change

The IPCC was established in 1988 and since then has released three Assessment Reports. These provide the most comprehensive analysis of climate change available. The latest, or Third Assessment Report (TAR) (IPCC, 2001) provides the best evidence yet that global climate change is real, and that humans are at least partially responsible for the changes. Climate change is predicted to continue into the 21st century (IPCC, 2001).

The climate changes expected for the future are most commonly based on GCMs. The IPCC (2001) concludes that "confidence in the ability of models to project future climate has increased". GCMs are able to produce expected changes in temperature and precipitation at the grid scale of the model (usually a 2.5 degree latitude and
longitude grid). These changes are based on scenarios of green house gas emissions. The most recent scenarios of green house gas emissions were produced by the Special Report on Emissions Scenarios (SRES) (Nakicenovic, Alcamo, Davis, de Vries, Flann, Gaffin, Gregory, Grübler, Jung, Kram, Rovere, Michaelis, Mori, Morita, Pepper, Pitcher, Price, Raihi, Roehrl, Rogner, Sankovski, Schlesinger, Shukla, Smith, Swart, van Rooijen, Victor and Dadi, 2000).

When the grid scale changes are analysed, a globally averaged surface temperature projection can be made. The globally averaged temperature changes predicted by a variety of GCMs under the full range of SRES scenarios show an increase of 1.4 °C to 5.8 °C by 2100 (IPCC, 2001). However the TAR also states in its technical summary that the “climate sensitivity is likely to be in the range of 1.5 to 4.5 °C” (IPCC, 2001). The wide range of temperature change predictions illustrates the high degree of uncertainty that surrounds any climate change impact evaluation. This is relevant when considering the second objective of this thesis.

With an increase in temperature, globally averaged water vapour, evaporation and precipitation are predicted to increase (IPCC, 2001). However precipitation is also strongly dependent on circulation patterns. Changes in these circulation patterns will largely determine regional changes in precipitation. Therefore at a regional scale, both increases and decreases of precipitation are predicted by GCMs (IPCC, 2001).

### 2.2.2 Global Climate Change and New Zealand

Climate trends in New Zealand are similar to those in most other parts of the world. Mean temperatures have risen by up to 0.1 °C per decade, but the detection of any rainfall trend is difficult and uncertain (Basher and Pittock, 1998). Several studies attempt to predict the future climate of New Zealand. Early work by Salinger (1982) used four different scenario generation methods, namely numerical models, extreme warm and cold year ensembles, dynamic/empirical reasoning and the maximum Holocene warming analogy. These methods of scenario generation produced a broad agreement that temperatures would be warmer countrywide, the North Island would be wetter, Canterbury would be wetter with less variability and Southland would be drier. Output of early, simple GCMs indicated that there would be a decrease in the strength of the westerlies and in the number of extra tropical lows (Lambert, 1995). Figure 2.1 from Bridgman (1998) shows how climate change in this way was predicted to effect New Zealand at a regional level. The predicted changes were based on a reduced equator to pole temperature gradient, a southward movement of all circulation systems and the subtropical highs moving poleward (Bridgman, 1998).
Although early work by Salinger (1982) focused on finding an appropriate analogy of a warmer climate, computer modelling (GCMs) is now the generally accepted approach for predicting future climate change (IPCC, 2001). Pittock and Salinger (1991) rightfully commented on the inability of early GCMs to predict precipitation changes. This inability was due to the high degree of spatial variability in precipitation over small distances and the coarse scale of the GCMs. GCMs have gone through a process of continued improvement as the nature of the global climate system is increasingly understood and more accurately represented. Recent development has led to coupled atmosphere-ocean GCMs that have the ability to:

simulate ocean currents and upwelling as well as atmospheric conditions
and simulate the exchanges of heat, momentum and moisture between the atmosphere and ocean (Wratt, Mullan and Renwick, 2000).

The development of these coupled GCMs has resulted in much of the previous scenario work in New Zealand being largely disregarded, because almost the opposite precipitation trends are now predicted. The improved coupled GCMs predict an increase in the strength of the mid-latitude westerlies and therefore predict a wetter west coast and drier east coast (Basher and Pittock, 1998). Figure 2.2 from Wratt et al. (2000), shows the most recent regional climate change scenarios for New Zealand. These are based on an average from the downscaling of four different transient, coupled, GCMs. Figure 2.2 also shows the seasonal differences of predicted climate change. Winter conditions are obviously more affected than summer.

Figures 2.1 and 2.2 show very different scenarios of climate under a warming world. This highlights the caution needed when working with scenarios. Improvement in scenario generation has occurred, but further improvement in GCMs may yet again see very large changes in climate scenarios at a regional level. Using the most recent estimates available (Mullan, Wratt and Renwick, 2001), New Zealand can expect to become warmer by between 1 and 2°C over the next 100 years. Precipitation will generally increase in the west and decrease in the east, due to an increase in the strength of the westerly flow.
Figure 2.1: Expected Climate change up to the mid-21st century under weaker mid-latitude westerlies (Bridgman, 1998).
Figure 2.2: Recent climate change scenarios for New Zealand based on the average of four GCMs, which predict an increase in the strength of the mid latitude westerlies (Wratt et al., 2000).
2.3 Climate, Catchment and Discharge Linkages

To understand how climate change over the next 100 years will influence discharge, the discharge formation processes must be examined. This illustrates those parts of discharge formation that are susceptible to a changing climate. Discharge formation processes can be separated into those that are climate based and those that are catchment based.

The hydrological cycle provides a useful conceptual framework to look into ideas of how the climate and discharge are linked, and is illustrated in Figure 2.3 (Hornberger, Raffensperger, Wiberg and Eshleman, 1998). This simple diagram does not show the influence of catchment characteristics (geomorphology) on discharge. The geomorphological unit of a catchment can be used to illustrate the links between the catchment and discharge as shown in Figure 2.4 (Gregory and Walling, 1973).

![Figure 2.3: The hydrological cycle (Hornberger et al., 1998).](image)

Even further detail can be added when hillslope hydrology is considered. Understanding how precipitation becomes discharge was considered by Arnell (2002), who suggested that there are four main processes. These are shown in Figure 2.5 (Arnell, 2002). Direct precipitation is the precipitation that falls on the channel...
system and produces an immediate response to flow. In most catchments the channel area is a small proportion of the total area so direct precipitation make only a small contribution to discharge. **Overland flow** (sometimes referred to as surface flow) is the precipitation that flows towards the channel on the surface. It has three parts, *infiltration excess overland flow* from water that exceeds the infiltration capacity of the soil, *saturation excess overland flow* from saturated catchment areas and *return flow* when soil water is forced to return to the surface. **Throughflow** is water that has infiltrated the soil and moves vertically and laterally in the soil layer. It is also divided into three parts, *unsaturated throughflow* is water moving in an unsaturated soil layer, *saturated throughflow* is water moving in a saturated soil layer (faster than unsaturated throughflow), *pipeflow* is water moving through the macropore network within the soil and sometimes called preferential flow (fastest soil water movement). **Groundwater discharge** is water released from a groundwater aquifer.

The various approaches to understanding discharge outlined above show the complex nature of the hydrological system. Each of the approaches has strengths and weaknesses when considering the impact of climate change on discharge. Therefore aspects from all the approaches are used to gain an understanding of climate change.
impacts. The rest of this Section considers the direct links between the climate and discharge, the way a catchment’s characteristics influence discharge and the influence of the cryosphere and biosphere.

### 2.3.1 Direct Linkages Between the Catchment and Discharge

The physical nature of a catchment can directly determine the volume and timing of discharge from that catchment. Taylor (1967) has shown that in New Zealand, geomorphological factors can be used to explain 85 per cent of the mean annual discharge and 97 per cent of the discharge/precipitation ratio. Hydrograph theory can be used to explain the influence of various geomorphological attributes on discharge. The most important components of the hydrograph that will be considered are shown by Figure 2.6 (Rodda, 1969). They are the rising limb, basin (or catchment) lag, peak, recession, storm runoff and base flow.

Size of catchment is the first consideration. All other factors being equal, the larger a catchment, the larger the discharge volume (Ward, 1975). With increasing size of catchment area, generally comes increasing spatial variability of climate and a

[Figure 2.5: Runoff generation processes (Arnell, 2002).]

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resultant decrease in catchment proportion contributing to the discharge at any given time (Black, 1996; Wilson, 1969). The effect is that peak discharge per unit area has been shown to decrease with increasing catchment size (Chorley, 1969). Figure 2.7 from Jones (1997) shows generalised hydrographs that result from increasing catchment size. The larger a catchment the more lag time, and higher the peak discharge.

The effect of catchment shape on the hydrograph can be explained through the time of concentration (Black, 1996). If a storm of uniform intensity covers the entire area, some catchment shapes act to concentrate the flood peak. Others increase the time of concentration, resulting in a reduced flood peak if the storm duration is less than the total time of concentration. This is shown in Figure 2.7 (Jones, 1997) where the long, thin catchment has a hydrograph with an increased lag and reduced peak compared to the circular catchment. There have been many methods put forward for measuring catchment shape as explained by Chorley (1969). Catchment shape as measured by the bifurcation ratio has been shown to have a controlling influence over the peakedness of the discharge hydrograph (Chorley, 1969). The absolute length of the channel system is related to catchment shape and also has some control over the lag time between the precipitation event and the peak discharge (Chorley, 1969).

Figure 2.6: Components of a discharge hydrograph (Rodda, 1969).
Channel gradient and mean basin slope angles are also important influences on the hydrograph of a catchment (Chorley, 1969). The relative importance of lateral and vertical movement of water is influenced by the slope angle (Ward, 1975; Wisler and Brater, 1959). Steeply sloping catchment areas tend to produce more overland flow, resulting in water reaching the channels more quickly (Ward, 1975; Thompson, 1999). Channel gradient then becomes an important factor in controlling the speed at which water moves to the catchment outlet. As shown in Figure 2.7 (Jones, 1997) the overall result is that a steeper catchment produces a hydrograph with a higher peak and less lag time.

A catchment's drainage network determines the efficiency of water movement from the catchment (Wisler and Brater, 1959). Therefore the characteristics of the hydrograph are dependent on the nature of the drainage network. A drainage network that, for example has a high density, will concentrate flow quickly and produce a hydrograph with a high peak and less lag time (Wisler and Brater, 1959; Black, 1996; Jones, 1997). This is shown by Figure 2.7 (Jones, 1997). Drainage patterns also affect lag times (Black, 1996). Lakes and swamps as part of the drainage network have the effect of reducing the peak of the hydrograph and increasing the lag time (Beckinsale, 1969; Ward, 1975).

The direction of the main channel defines a catchment’s orientation (Black, 1996) and is important when considering the storm input of precipitation. Storms coming
from different directions will interact with the catchment shape to produce different hydrographs for the same total input (Wilson, 1969). For example, a storm that moves up a long thin catchment will reduce the hydrograph peak, whereas a storm that moves down a long thin catchment will increase the hydrograph peak.

The amount of insolation a slope receives is determined in part by its aspect (Oke, 1987). Insolation on a slope influences the water balance of that slope and therefore the hydrograph (Black, 1996). In the Southern Hemisphere, slopes that face north receive more insolation than those that face south. The amount of insolation in turn influences the vegetation and soil of a slope. In general, the net result is more evapotranspiration on north facing slopes and therefore less discharge volume (Black, 1996). Soil and vegetation differences caused by insolation patterns also result in differences of discharge timing (Black, 1996). Aspect has a major influence on discharge timing where the cryosphere occupies part of a catchment (Wisler and Brater, 1959; Toebes, 1963).

Elevation or catchment relief is an important influence on discharge from a catchment. Precipitation, in general increases with altitude, while temperature decreases (Wilson, 1969; Wisler and Brater, 1959). Vegetation tends to be sparser and soil thinner at higher elevations due to the climate resulting in more rapid discharge (Black, 1996). Discharge is greatly complicated for a catchment that has elevations high enough to include a cryosphere component. The proportion of area within a catchment at different altitudes will influence the shape of the hydrograph produced by that catchment.

The soil within a catchment provides a further means of storage of water. The nature of this storage is determined by the depth, texture and structure of the soil profile. Soils of a sandy texture will allow greater infiltration rates and tend to generate less quickflow than soils of a clay texture with low infiltration rates (Ward, 1975). The structure of the soil profile also contributes to the infiltration rate with deep, uniformly permeable soils creating a hydrograph with high baseflow (Ward, 1975). Soils with low permeability layers near the surface result in a higher proportion of quick flow (Ward, 1975).

With the exception of changing areas of snow and ice, there is very little change to catchment characteristics that can be expected to be caused by climate change over the next 100 years. However the influence of the existing characteristics may not be the same under a changed climate. Some characteristics may become more influential in discharge formation and others less influential.
2.3.2 Direct Linkages Between Climate and Discharge

The direct links between climate and discharge are well known. The water balance equation can be used to illustrate these direct linkages.

\[ Q = P - E \pm \Delta S \]  

Where \( Q \) is discharge, \( P \) is precipitation, \( E \) is evaporation and \( \Delta S \) is change in storage. If change in storage is considered to be zero over many years the direct linkages between climate and discharge are precipitation and evaporation.

If precipitation increases, evaporation stays the same and there is no change in storage over the long-term then discharge must increase. In the same way if precipitation decreases discharge will also decrease. If the precipitation stays the same but evaporation increases and there is no change in storage, then discharge will decrease. The reverse is also true, if evaporation decreases and precipitation remains the same with no change in storage, discharge will increase. Any of these outcomes are possible with climate change.

Precipitation and evaporation are also themselves linked. If all other climatic variables remain the same, evaporation will increase as precipitation increases until the potential evaporation is reached. The reverse is also true, if precipitation decreases then evaporation will also decrease if all other climatic variables remain the same. Thus although there are direct links between the climate and discharge there are also links between the climatic variables themselves.

The water balance approach outlined above only gives a very basic explanation of the linkage between climate and discharge. More can be gained by a consideration of the characteristics of individual storm events and how these relate to discharge. For example, what is the effect of precipitation intensity, storm duration, areal distribution, direction of storm movement and type of precipitation?

Precipitation intensity is one of the factors that determines the proportions of a storm's precipitation that make up overland flow, interflow and groundwater flow (Ward, 1975). Surface runoff (overland flow) occurs if the intensity exceeds the infiltration rate (Raudkivi, 1979). If surface runoff occurs, the hydrograph peak will be higher because of the reduced time taken for the water to reach the channel (Ward, 1975). At reduced intensities, the infiltration capacity is not exceeded and interflow and groundwater flow make up the bulk of a hydrograph with a reduced peak and increased lag time (Wisler and Brater, 1959).
Duration of a storm event is important because infiltration capacity is reduced as the soil reaches saturation (Wisler and Brater, 1959). If saturation is reached then surface runoff can occur, resulting in a sharp increase in the hydrograph peak (Ward, 1975). In reality different parts of the catchment will reach saturation at different times. The greater the area of catchment at saturation the more surface runoff there will be and the higher the hydrograph peak (Raudkivi, 1979).

The area of a catchment that reaches saturation is also a function of the areal distribution of the storm event. It is very seldom that precipitation is distributed uniformly over a catchment (Wisler and Brater, 1959). The wider the area of catchment covered by a storm the greater the saturated area, and therefore the higher a hydrograph peak will be. However widely distributed storms tend to be less intense and therefore in reality produce lower hydrograph peaks, unless they are of long duration (Ward, 1975). A widely distributed, low intensity storm will produce mostly baseflow, whereas a highly intense localised storm will produce more surface runoff and a higher hydrograph peak (Wisler and Brater, 1959; Ward, 1975). The position of the high intensity storm is also important. The further from the catchment outlet the storm is the lower and broader the resultant hydrograph (Wisler and Brater, 1959; Raudkivi, 1979).

Storms are rarely stationary (Wisler and Brater, 1959). Therefore distribution of precipitation during a storm event is dynamic. Figure 2.8 (Ward, 1975) shows the effect this has on hydrograph shape. For a storm moving up an elongated catchment (storm A) the event hydrograph is broader and with lower multiple peaks. A storm that moves down a catchment (storm B) will produce a hydrograph that is less broad with a high peak.

The final consideration for how climate affects discharge is the type of precipitation. Precipitation that falls as snow is not available as runoff in the catchment system until melt has occurred. This creates a lag period that may be hours to years between the timing of precipitation and the timing of discharge. In general, hydrographs produced by snowmelt tend to have lower peaks and broader bases (Raudkivi, 1979). The role of the cryosphere in discharge formation is considered extensively in Subsection 2.3.3. Although the links between climate and discharge appear very simple when considered from a water balance approach there are other important considerations when climate change occurs. Individual storm characteristics have been shown to be an important determinant of discharge characteristics. Therefore changes in storm characteristics will be an important influence in changes to discharge from catchments. However as yet such changes are unknown for climates out to 2100 in the New Zealand context.
2.3.3 The Role of the Cryosphere

The Influence of the Cryosphere on Discharge

The cryosphere is an intrinsic part of the hydrological cycle. It can be considered as a storage component, with glaciers being long-term storage and snow cover being a seasonal storage component (Braun et al., 2000). If the cryosphere is considered as a storage component as above, time scale is important when assessing the influence that it has on discharge. Changes in discharge due to the cryosphere may occur at a daily, monthly, yearly or longer time scale (Braun et al., 2000). Figure 2.9 (Braun et al., 2000) shows how time scale can be used to assess the influence of the cryosphere on runoff.

Hours to days:

The current weather determines the intensity of rainfall and melt water production over hours to days (Braun et al., 2000).

New Zealand is considered to be a maritime climate and as such has highly variable weather. Consequently there are fluctuations of snow and glacier melt on a daily basis and these are highly correlated to temperature (Kirkbride, 1995). Discharge from alpine regions in New Zealand shows high daily variability (Fitzharris, 1979), although it appears there are uncertainties in assessing these variations in terms of snow and glacier melt compared to rainfall influence (Fitzharris et al., 1999).
Months to a year:

For the periods of months to a year the sequence of weather patterns will determine the build-up and melting of seasonal snow cover (Braun et al., 2000). Seasonal snow has the effect of delaying discharge that would otherwise have occurred immediately following precipitation until the snow melts. The discharge regime of a river is thus strongly determined by the influence of the cryosphere. The effect of this in New Zealand is shown by Figure 2.10 (Fitzharris, Owens and Chinn, 1992). The Manuherikia River shows the influence of seasonal snow, with a high spring mean discharge.

Several years to decades:

Long-term trends of precipitation and air temperature as integral measures of climate will influence the mass balance and spatial extent of glaciers (Braun et al., 2000). Glaciers provide long-term storage of precipitation and also strongly influence the discharge regime of a catchment. The Hooker River is a good example of this as shown

Figure 2.9: Discharge formation in a catchment influenced by the cryosphere (Braun et al., 2000).
Figure 2.10: Example discharge regimes of three New Zealand rivers. The Hooker River shows the influence of glaciers, the Manuherikia River seasonal snow and the Motu River precipitation variability (Fitzharris et al., 1992).
by Figure 2.10. If the spatial extent of the glaciers within a catchment changes due to long-term climatic trends then it can be expected that the hydrological characteristics (such as discharge regime) of the catchment will also be affected (Moore, 1992).

The Importance of the Cryosphere to Discharge in New Zealand

There is more than 50 km$^3$ of ice volume stored within New Zealand glaciers (Chinn, 1989). In most springs, there is about 30 km$^3$ of water stored as seasonal snow, much of it in the South Island (Fitzharris, 1979). This represents a very large water storage, which Fitzharris (1979) considered to be comparable to the size of controlled storage in New Zealand’s hydro lakes.

The delayed release of water stored in the cryosphere is a mixed blessing. Different users have different needs at different times of the year. In terms of hydroelectric generation, small seasonal variation in discharge is seen as having a positive impact on generation timing (Fitzharris, 1996). By contrast most alpine catchments have marked seasonal flow, with lowest discharge in winter. Unfortunately this is when electricity demand is highest. On the other hand run of the river irrigation users require a high summer discharge so that large seasonality in flow with high spring and summer discharge from snow and glacier melt is beneficial. Reduction in spring/summer seasonal flows due to less snow and ice may lead to run of the river supply no longer meeting irrigation demands (Griffiths, 1990).

For South Island mountain catchments, Fitzharris (1979) concluded that snow storage contributes to between 10 - 25 per cent of annual river discharge. Fitzharris (1979) estimates that more than one third of the discharge of the Clutha River at Roxburgh in spring and early summer comes from seasonal snowmelt. In some years, the exact contribution to discharge may be much greater than this. This is because seasonal snow has a high degree of year-to-year variability that is also shown in the discharge patterns. Fitzharris (1987) assessed that fluctuation in seasonal snow accounts for about 40 per cent of the variability in spring runoff.

The large valley glaciers in the South Island mountain catchments are in a state of retreat. As a consequence there is extra discharge from these catchments as a result of water released from long-term storage. Purdie and Fitzharris (1999) state that water released due to ice lost from glaciers represents six per cent of the annual inflow to Lake Pukaki. Most of the melt occurs in summer. Ice loss is greatest during dry hot summers and makes a significant contribution to Lake Pukaki inflows at times when river flow from other sources is low. Despite these findings, the exact contribution of
glacier wastage to river discharge is not well documented in New Zealand compared with overseas, where more precise studies (Hopkinson and Young, 1998) have been achieved.

Given the influence of the cryosphere on discharge from a catchment, it is important to consider the effect that climate change will have on the cryosphere. Any effect of climate change on the cryosphere will be important in determining the effect of climate change on discharge from an alpine catchment. Thus although climate change can directly affect discharge it can also indirectly affect discharge through changes in the cryosphere. The nature of the change in discharge will be determined in part by the characteristics of the cryosphere within the catchment.

**Climate Change and Glaciers**

"As climate changes, so do glaciers" (Lowell, 2000). The overall response of glaciers is a reflection of prior climate change. The rates of accumulation and ablation determine mass balance, which provides a direct link between the climate and glacier (Chinn, 1995). During a period of warming, ablation will exceed accumulation resulting in retreat of the glacial margin (Lowell, 2000). The opposite, whereby accumulation exceeds ablation occurs during climate cooling. Added to this is the effect of precipitation changes (Hooker and Fitzharris, 1999).

Globally, the Little Ice Age resulted in the advance of glaciers, but since then alpine glaciers have been retreating (Greene, Broecker and Rind, 1999). The retreat of glaciers and the upward shift of equilibrium line altitudes have been related to recorded climate shifts and show a strong relationship (Greene et al., 1999). Dyurgerov and Meier (2000) also show that glaciers have lost volume in response to global warming and that this loss of volume is more than a simple adjustment to the Little Ice Age.

In New Zealand the evidence shows that glaciers have reduced in size and volume dramatically since the 19th century (Chinn, 1996; Bishop and Forsyth, 1988). An interesting anomaly is the glacier response over the past two decades. Chinn (1999) notes that there has been a reversal in the trend of recession and many mountain glaciers have shown visible advances, while some western valley glaciers have also advanced. Only the large valley glaciers with pro-glacial lakes show strong recession in the last 20 years.

Chinn (1999) has suggested that the downward shift in the end of summer snow lines over the past 20 years represents a cooling of 0.47°C, but this assumes that all other factors such as rainfall have remained constant. Recent research (Clare, 2000)
has shown that Southern Hemispheric atmosphere circulation, sea surface temperature patterns and Southern Oscillation are all related to the elevation of the end of summer snow lines.

The New Zealand glacier response to climate change over the past century shows that temperature change alone does not account for the behaviour of glacial terminus position. Morphological processes (Kirkbride, 1993) and atmospheric circulation changes (Hooker and Fitzharris, 1999) are also related to the behaviour of glacial terminus position. Kirkbride (1993) and Purdie and Fitzharris (1999) have shown that the terminal position of the Tasman Glacier is strongly related to the morphology of the glacial terminus and calving of ice into the recently formed pro-glacial lake. The terminal position is largely de-coupled from the climate. This can also be considered to be the case for other large valley glaciers terminating into pro-glacial lakes in the eastern Southern Alps.

The retreat and recent advance phases of the Franz Josef Glacier on the western side of the Southern Alps was studied by Hooker and Fitzharris (1999). They linked the terminus behaviour to atmospheric circulation changes and climate variables. Specifically, the advance phase was characterised by more precipitation, cooler weather and more south-westerlies in the ablation season. These in turn were related to stronger westerlies in the accumulation season, a northward shift in the sub-tropical high pressure zone, more El Nino events and negative sea level pressure anomalies over New Zealand. The retreat phase had the opposite characteristics.

From this it can be concluded that future scenarios of global temperature rise may not adequately predict the behaviour of New Zealand’s glaciers. To predict the future response of glaciers in the Southern Alps would require an understanding of atmospheric circulation changes and the climatic variables associated with these, as well as the likely morphological influences on each specific glacier. As Hooker and Fitzharris (1999) concluded:

some maritime glaciers can advance even during global warming, if the suitable circulation patterns are favourable.

**Climate Change and Seasonal Snow**

In mountain snow basins, a change in climate will likely cause a change in the basin snow cover extent (Rango and Martinec, 1994).

Seasonal snow can be considered snow that accumulates and melts in the same year
As the above quote suggests, global climate change is likely to have a big impact on seasonal snow. Hemispheric remote sensing data suggests a recent significant decrease in seasonal snow on northern continents. This is associated statistically with higher temperatures. The decrease in snow cover is particularly evident in spring and early summer (Barry, Fallot and Armstrong, 1995). However, such anomalies have occurred in the past, even before recent warming trends, and seasonal snow cover worldwide shows no significant long-term trend as judged from station records Barry et al. (1995).

There are no long-term records of seasonal snow in New Zealand, but Fitzharris and Garr (1995) used a conceptual model to reconstruct past variability. They show that there is no long-term trend in the volume of water stored as seasonal snow within the Southern Alps. There is however, a high level of variability from year to year. Australian records (Duus, 1992) also show no overall trend, but there are high and low snowfall regimes, which last for 10 - 20 years.

The fact that there are no reliable records of seasonal snow makes it difficult to assess the impact of climate change on seasonal snow. Modelling by Rango and Martinec (1994) suggests that temperature change has a much more significant effect than a change in precipitation. A doubling of precipitation did not make up for a 2°C rise in temperature for seasonal snow depletion. Australian studies (Haylock, Whetton and Desborough, 1994) suggest that a 1°C rise in temperature could reduce snow cover duration by 50 per cent, and that a 50 per cent increase in precipitation is required to offset a 0.5°C warming. A 50 per cent increase in precipitation is unlikely, so it could be concluded that there will be reduced seasonal snow cover duration under global warming.

2.3.4 The Biosphere

The Influence of the Biosphere on Discharge

The biosphere can influence total discharge from a catchment because of the effect vegetation has on the water balance. If the water balance equation is given in its most basic form,

\[ P = E + Q \]  

it is seen that precipitation (P) is divided between evapotranspiration (E) and discharge (Q). At the catchment scale, vegetation exerts important controls over the total volume of water lost as evapotranspiration. The processes of evaporation, interception and transpiration are used below to demonstrate this.
Evaporation is simply the physical process of liquid water being changed to vapour (Bonan, 2002). This can happen on any surface within the catchment. The nature of the evaporative surface does however have an influence over the process through energy and aerodynamic factors (Arnell, 2002). Therefore the vegetation cover and type within a catchment will influence the process of evaporation.

Interception is the process where by vegetation prevents precipitation from reaching the ground. The components of interception are given in Figure 2.11 (Arnell, 2002). Gross precipitation can be evaporated from the surface of the vegetation, become stemflow or throughfall. This process can then occur at each of the vegetation surfaces until the water reaches the ground, or evaporation has taken place. The amount of water that is evaporated during this process is considered the interception loss.

Interception loss from tussock vegetation as reported by Campbell and Murray (1990) is 21 per cent of annual precipitation. However interception loss is also related to storm intensity and duration, with monthly values ranging from 10 to 45 per cent for tussock vegetation (Campbell and Murray, 1990). This reflects the role of the canopy storage capacity. Beech forest has interception loss values of around 30 per cent (Rowe, 1975; Rowe, 1983).

Interception does not always result in a loss. Horizontal interception (deposition of water on surfaces from fog (Penman, 1963)) can result in net gain from vegetation surfaces. In New Zealand there has been an ongoing debate as to the exact contribution of this process to the water balance in catchments where tussock vegetation occurs. Values as small as one per cent to as large as 10 per cent have been suggested in the literature as gains to the water yield caused by horizontal deposition (Ingraham and Mark, 2000).

Transpiration is the evaporation of water that has been drawn from the soil through a plant (Bonan, 2002). This process is regulated by the physiology of the plant (Bonan, 2002), but should be considered a physical process (Arnell, 2002). During photosynthesis, stomata are open so as to make carbon dioxide available, at the same time water can be evaporated from within the leaf through the stomata (Bonan, 2002). There can be considered to be a constant transfer of water from the soil to the atmosphere through the plant, following the water potential gradient (Bonan, 2002).

Evapotranspiration is the total amount of water lost from the catchment via evaporation (including interception loss) and transpiration. The water lost via each of the processes is strongly dependent on the type and cover of vegetation. As vegetation cover increases, evaporation becomes less dominant over transpiration, and interception plays an increasing role (Bonan, 2002).
Vegetation also has some control over the timing of discharge. This is due to the influence of vegetation on flow pathway, once precipitation reaches the ground. Vegetation can modify the soil texture and structure and this influences the infiltration rate and movement of water within the soil (The International Geosphere-Biosphere Programme, 1993). The different flow paths followed due to differing vegetation types cause different hydrograph shapes and timing (Ward, 1975).

**Climate Change and the Biosphere**

Having established that the biosphere has some influence over the volume and timing of discharge from a catchment, it is important to understand how climate change over the next 100 years could influence the biosphere. Will climate change cause vegetation changes at the community level, or in the physiology of plants? Will changes in vegetation, if any, change the evapotranspiration and thus discharge from a catchment?

The biogeographic distribution of vegetation is mainly determined by temperature and precipitation (Bonan, 2002). Changes in vegetation can be expected to match those of the climate. However lags may exist between climate change and vegetation change. This occurs where climate change is faster than the potential rate of vegetation change, as restricted by the life cycle of a given vegetation type (Bonan, 2002).
There is evidence that community level changes are occurring in the Northern Hemisphere. Kullman (2001) describes a multispecies tree-limit elevation advance of 100 m over the last century without "appreciable" time lag. Theurillat and Guisan (2001) in a review also showed that changes in distribution throughout the European Alps have occurred and that further change is likely.

In New Zealand, Wardle and Coleman (1992) provided evidence that upper limits of four native tree species are rising. However the rise is much smaller than that predicted by the recorded climate change. The possible reasons for this lag as given by Wardle and Coleman (1992) are that, the existing tree line may have been set during an earlier warm phase, seed dispersal ability, competition from other vegetation, frost damage of seedlings in the open and beech forest dependence on mycorrhizal infection. Cullen, Stewart, Duncan and Palmer (2001) dispute the evidence for tree limit rise given by Wardle and Coleman (1992) suggesting that the seedlings above the tree line represent a permanent population of low density with continuous turnover.

Halloy and Mark (2003) provide evidence for the vulnerability of alpine plant species to extinction in New Zealand due to climate change, but predict long lag times between climate change and changes in vegetation. Historical vegetation change in New Zealand, as shown by pollen analysis, is a process that has taken thousands of years (Vandergoes, Fitzsimons and Newnham, 1997; McGlone and Moar, 1998). From the above evidence it is unlikely that community vegetation change in New Zealand to predicted climate change over the next 100 years will be more rapid. Therefore changes in evapotranspiration due to community vegetation change caused by climate change over the next 100 years are unlikely.

However changes in vegetation may also happen at the physiological level and could occur much faster than community level changes. Increased CO₂ concentration, one of the drivers of climate change, along with increased temperatures has been shown to produce higher photosynthetic rates, decreased stomatal conductance (Beerling, 1999) and therefore decreased transpiration (Levis, Foley and Pollard, 2000). This means that it is likely water use efficiency in plants will improve.

CO₂ fertilization of plants is often assumed to produce an increase in biomass (Lockwood, 1999). This would logically increase the amount of transpiration and interception loss. However, it has been shown by Lockwood (1999) that in a closed canopy system no increase in biomass occurs. Therefore transpiration decreases and there is no increase in interception. This is especially the case were other nutrients are limiting factors to growth (Lockwood, 1999). Lockwood (1999) concludes:
enhanced atmospheric CO₂ levels could significantly suppress both potential
and actual evapotranspiration values and that for some vegetation covers
they will significantly change the relationship between the two.

There are no studies in New Zealand comparable to European studies (for example
Beerling (1999)) of physiology changes in plant species to CO₂ fertilization. Therefore
only inferences can be drawn about New Zealand species. Lockwood (1999) provides
evidence that low vegetation in areas with frequent rainfall will not have significant
changes in evapotranspiration, and as stated above, closed canopy systems are likely to
have reduced evapotranspiration. It is therefore unlikely that physiology level changes
in vegetation will result in significant evapotranspiration changes in New Zealand alpine
catchments.

The conclusion from the above review is that the biosphere is likely to adjust to
climate change and elevated levels of CO₂. However with respect to the water balance
over the next 100 years in alpine New Zealand catchments, there is no evidence to
suggest major changes in evapotranspiration due to vegetation changes. This assumes
the cultural influence on vegetation within these catchments does not change.

2.3.5 Summary of Climate, Catchment and Discharge Linkages

The linkages between discharge the climate and catchment have all been considered
separately. However, it is important to realise that discharge is the net result of all
the influences. Having said that, some influences have been shown to be more impor-
tant than others when considering the influence of climate change on alpine catchment
discharge over the next 100 years. Obviously precipitation change is the most impor-
tant, as it determines the potential amount of water available to discharge. How the
catchment characteristics interact with the changes in precipitation will also be impor-
tant. The cryosphere stands out as being very important because it is highly sensitive
to climate change and has a large influence over discharge and its timing in alpine
catchments. The biosphere, although having a large influence over discharge from a
catchment, is not thought to alter its influence significantly with climate change over
the next 100 years.
2.4 Modelling the Links Between the Climate, a Catchment and Discharge

There are four main types of hydrological model. They are empirical, water balance, conceptual and physically based models. The complexity of model increases from empirical through to physically based models.

**Empirical models** are those that relate the output of discharge statistically to other variables such as precipitation and temperature (Leavesley, 1999). They are often called black box models as they do not include hydrological processes, but are simple relationships between input and output (Davie, 2003). As the simplest model they have the least requirement for input data.

**Water balance models** use the water balance equation to account for water entering the catchment as precipitation until it leaves as either evapotranspiration or discharge (Leavesley, 1999). Water balance models can in theory be applied at any time step as long as the input data is available. They range in complexity depending on the level of treatment each of the water balance components receives (Leavesley, 1999).

**Conceptual models** "provide simplified representations of key hydrological processes using a perceived system" (Dawson and Wilby, 2001). This means that the models approximate or simplify the physical laws that govern discharge (Leavesley, 1999). As with water balance models conceptual models account for water from the moment it enters a catchment as precipitation until it leaves as discharge or evapotranspiration. The main difference is that most conceptual models are at a finer time scale and consider the flow paths in more detail, including vertical and lateral movement of water (Leavesley, 1999). Most conceptual models are lumped-parameter, meaning that they make approximations of state for the whole catchment that may or may not be homogeneous in state (Leavesley, 1999). However the models can also be distributed by subcatchments or elevation to make the perceived system more realistic (Leavesley, 1999).

**Physically based models** use the physical laws of mass and energy transfer to describe the precipitation-discharge process (Dawson and Wilby, 2001). These models operate at a much finer spatial scale than conceptual models and are usually dissected using a grid or topographically (Leavesley, 1999). In theory, very little calibration should be necessary, but this is seldom the case due to the difficulty of meeting input data requirements (Davie, 2003).
2.5 Global Climate Change and Water Resources

World wide there have been many studies investigating the impact of global climate change on hydrological resources. Only a representative sample is presented here to show the merits of the various approaches in order to select the most appropriate approach. Where possible examples are drawn from New Zealand studies. The studies are ordered according to the hydrological model type used. In addition to the four hydrological model types defined in Section 2.4, use of GCMs is included.

Braddock (1998) uses an empirical model to determine the influence of climate change on annual discharge from the Hooker catchment in the Southern Alps of New Zealand. A regression equation relating temperature and precipitation to discharge was created. Under the climate change scenarios used, her results indicate almost a 60 per cent increase in mean annual discharge could be expected by 2030 and almost a 90 per cent increase in mean annual discharge by 2070.

The advantage of using such an approach is the relatively simple data requirements. However empirical models are not considered appropriate for hydrological climate change studies (Leavesley, 1999). This is because the model function reflects the relationship between inputs and outputs for the current climate and catchment conditions. Extending this relationship to different climate and catchment conditions is "questionable" (Leavesley, 1999). Consequently empirical models cannot be considered an effective way to fulfil the objectives of this thesis.

Water balance models are used by Griffiths (1990) and Garr (1992) in New Zealand to investigate the influence of climate change on water resources. These studies use mean annual and mean monthly water balances respectively and show that water resources in New Zealand are sensitive to changes in temperature and precipitation. The simplistic nature and limited input data requirements of water balance models as used by Griffiths (1990) and Garr (1992) are their main advantages. The limitation of this approach as seen by Leavesley (1999) is the need to calibrate the model parameters to observed values from within the catchment that may not stay constant with a changing climate. Yearly and monthly water balance models also have the limitation of not being able to account for changes in precipitation-runoff characteristics at smaller time steps (Leavesley, 1999). Water balance models although applicable to climate change studies, and widely used in recent overseas studies (Kwadijk and Rotmans, 1993; Guo, Wang, Xiong, Ying and Li, 2002), are not considered the most robust approach (Leavesley, 1994).
Many studies have considered it appropriate to use conceptual hydrological models for climate change impact assessment (for example, (Singh and Kumar, 1997; Braun et al., 2000; Loukas, Vasiliades and Dalezios, 2002)). Conceptual models are used to investigate how climate change will influence discharge regime (Yu, Yang and Wu, 2002), floods (Loukas and Quick, 1999), runoff generation processes (Loukas et al., 2002) and water resources in catchments with a high degree of influence from the cryosphere (Moore, 1992; Singh and Kumar, 1997; Braun et al., 2000; Morrison et al., 2002). In New Zealand a conceptual model is used to consider the effects of climate change on river protection (Leong, Jordan and Ibbitt, 1992). The advantage of conceptual models is the greater attention given to physical process and the higher temporal resolution (Leavesley, 1999). The disadvantages include the increased number of parameters that need to be estimated, or calibrated, and the increased data input requirements (Leavesley, 1999).

Physically based models are applied in relatively few climate change impact studies (Leavesley, 1999). Recent examples include Legesse, Vallet-Coulomb and Gasse (In Press) and Oltchev, Cermak, Gurtz, Tishenko, Kiely, Nadezhdina, Zappa, Lebedeva, Vitvar, Alberston, Tatarinov, Tishenko, Nadezhdin, Kozlov, Ibrom, Vygodskaya and Gravenhorst (2002), where both climate and land-use changes were considered. Physically based models have the advantage of being process based and as such are the most appropriate for climate change studies (Leavesley, 1999). The limitation of this modelling approach is the need for quality catchment and climate data at the spatial and temporal scale needed for model parameterisation and validation (Leavesley, 1999).

Arora and Boer (2001) provide a good example of GCM use to investigate the influence of global climate change on water resources. The advantage of using GCM output is that only one model is required for both climate and discharge simulation. This makes scenario studies relatively easy to implement. Arora and Boer (2001) illustrate the limitations in the direct application of GCMs to hydrological studies. The coarse scale of the GCM means that regional distribution of precipitation is poorly simulated and consequently the resulting discharge is also poorly simulated. GCMs cannot therefore be considered an appropriate approach to climate change impact studies in New Zealand, where alpine catchments are smaller in scale than the grid size of GCMs.

Of all the modelling approaches available, conceptual models are considered to be the most appropriate for this study. This is because conceptual models have relatively simple data input requirements while still replicating the key hydrological processes. There is also the choice of many different conceptual hydrological models that have been developed worldwide. Model choice for this thesis is justified in Section 4.4 within the methodology.
2.6 Research Questions

The objectives as given in Chapter 1, are repeated here:

- To investigate and present a methodology to assess the potential impact of climate change on discharge from alpine catchments.

- To predict the effects of potential climate change on alpine catchment discharge from the eastern Southern Alps of Canterbury.

In light of the above literature review it becomes clear that four specific research questions can now be raised. These are:

- Can discharge from catchments in the eastern Southern Alps be modelled successfully for the present climate using a conceptual hydrological model?

- How will global climate change affect the annual water yield from alpine catchments in the eastern Southern Alps?

- How will global climate change affect the seasonal discharge regime of catchments in the eastern Southern Alps?

- How will global climate change affect the hydrograph characteristics of catchments in the eastern Southern Alps?

The first question is inherent in any modelling study in that there is uncertainty regarding the ability of relatively simple models to simulate a complex system. The next two questions reflect the likely changes that are detectable using a conceptual modelling approach. Annual water yield is important because it is the total resource that has the potential to be managed. The discharge regime is important because different users have needs associated with seasonality. This has management implications regarding run of the river versus stored supply. The last question is important regarding floods and low flow periods from catchments.
2.7 Chapter Summary

This Chapter has considered the established knowledge of climate change and how this relates to discharge from alpine catchments. Global climate change is occurring and will continue over the next century. In New Zealand, temperatures are predicted to increase over the next 100 years by between 1 and 2°C. Precipitation in general is likely to increase in the west and decrease in the east. Catchment discharge volume and timing has the potential to be affected by this climate change. Precipitation and cryosphere changes will be the most important factors in alpine catchments. To model the expected changes in discharge, conceptual hydrological models provide the best tool. This is because they have relatively simple data input requirements, while still considering the key hydrological processes.
Chapter 3

Methodology

3.1 Introduction

This chapter outlines the research strategy and modelling method used to investigate the research questions identified in the previous chapter. First the research strategy is explained, and then the rationale for catchment selection is set out. An explanation of the choice of model is followed by detail of the chosen model structure and parameters. Calibration and verification methods are explained. Then collection and preparation of the model input data is described. Climate change scenario generation is explained and then the methods for examining the difference between the discharge of the current climate and the discharge of the scenario climate.

3.2 Research Strategy

This study is a climate change impact assessment of alpine catchment water resources. Figure 3.1 shows a climate change impact assessment flow chart and is consistent with the general framework developed by Working Group Two of the IPCC (Frederick, 1994). Step one, define the problem, has already been achieved in the previous chapters through the process of literature review and identification of research questions. Details of step two, select method, are covered in this chapter and steps three through to nine are covered in the following three chapters.
Figure 3.1: Flow chart of a climate change impact assessment (Frederick, 1994).
3.3 Catchments

Four catchments have been chosen as being appropriate to this thesis. They are the Jollie River, Hooker River, Rangitata River (above its gorge) and Rakaia River (above its gorge). The Jollie catchment is chosen due to the influence of seasonal snow on the river regime, with very little influence from glaciers within the catchment. The Hooker catchment is chosen because of the high proportion of glacier area within the catchment. The Rakaia and Rangitata catchments are chosen for their larger size, and the influence of both seasonal snow and glaciers in each. Figure 3.2 shows the location of each of the catchments included in the modelling. Catchment characteristics are described in the results chapter.

3.4 Modelling Approach

As shown in the previous chapter there are a number of modelling approaches to predict runoff from a catchment. Based on the evidence presented in that chapter conceptual models are considered to be the best option. Of the numerous conceptual models available worldwide, the HBV3-ETH9 model is selected for the following reasons.

- Model availability.
- Easily met data input requirements.
- Distributed snow and glacier representation.
- Appropriate spatial and temporal scale.
- Simple calibration and verification technique.
- Previous use for similar climate change studies.
- Accurate model simulations of discharge in previous studies in several different environments.

3.5 Structure and Parameters of the Model

The HBV3-ETH9 conceptual runoff model is a variant of the original HBV3 model structure as developed by Bergström (1975). The HBV3 model was developed for catchments where snow accumulation and melt are important factors in the runoff
Figure 3.2: Catchment locations.
regime. The basic structure of the HBV3 model is the same as that for the earlier HBV models (Bergström and Forsman, 1973), except that a snow routine is added. The HBV3 model, according to Braun and Renner (1992), was then developed further by Jensen (1982) and Braun (1985) and named the HBV3-ETH model. Yet more development and revision has led to the HBV3-ETH9 model as used by Braun et al. (2000). This version includes a snow and glacier routine and incorporates a graphical user interface with the model structure and can be run on a PC through the operating system Microsoft Windows 98. Copies of the model are available from the Commission for Glaciology in Munich, Germany.

As shown by Figure 3.3, the HBV3-ETH9 model structure keeps to the original aims of HBV modelling as set out by Bergström and Forsman (1973), which were:

- That the model algorithm should be logical and physically relevant.
- The hydrograph should be simulated as accurately as possible.
- The number of parameters should be kept to the minimum needed to give accurate runoff representation.
- Where ever possible parameters should be measurable or related to catchment characteristics.
- Input data should be that which is generally available.

The model uses the inputs of daily precipitation totals and mean daily temperatures to calculate the principle output of daily discharge. It also calculates the mass balance of glacial areas and the water equivalent of the snow pack. The model structure consists of a snow pack and glaciated area routine that is distributed with elevation and aspect, providing input to a lumped soil moisture routine and two layered response function that is also lumped. As such, the model can be classified as a semi-distributed conceptual model. Each of the routines and parameters listed in Table 3.1 are explained below. The parameter values outlined below are based on literature review. Exact values as used in the modelling process are given in the results (Chapter 4). Many were determined through the calibration process, as outlined in the next section. Specific details of mathematical equations are left out, for this detail see Braun et al. (1992), Braun and Renner (1992) or Bergström (1976) for example.
Figure 3.3: The HBV3-ETH9 model structure (adapted from Braun et al., 1992).
Table 3.1: Input parameters of the HBV3-ETH9 model (adapted from (Konz, 2003)).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCF</td>
<td>Rainfall correction factor</td>
<td>-</td>
</tr>
<tr>
<td>SCF</td>
<td>Snowfall correction factor</td>
<td>-</td>
</tr>
<tr>
<td>CMin</td>
<td>Minimum value of degree day factor</td>
<td>mm °C⁻¹ d⁻¹</td>
</tr>
<tr>
<td>CMax</td>
<td>Maximum value of degree day factor</td>
<td>mm °C⁻¹ d⁻¹</td>
</tr>
<tr>
<td>T0</td>
<td>Threshold value for transition from rain to snow, melt and general temperature correction</td>
<td>°C</td>
</tr>
<tr>
<td>RMult</td>
<td>Ice melt correction coefficient</td>
<td>-</td>
</tr>
<tr>
<td>RExp</td>
<td>Aspect correction coefficient</td>
<td>-</td>
</tr>
<tr>
<td>CWH</td>
<td>Water retention in snow pack</td>
<td>-</td>
</tr>
<tr>
<td>CRFR</td>
<td>Refreezing coefficient</td>
<td>-</td>
</tr>
<tr>
<td>PGrad</td>
<td>Precipitation gradient</td>
<td>% 100 m⁻¹</td>
</tr>
<tr>
<td>TGrad</td>
<td>Temperature gradient</td>
<td>°C 100 m⁻¹</td>
</tr>
<tr>
<td>ETMax</td>
<td>Maximum evapotranspiration</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>LP</td>
<td>Limit for potential evapotranspiration</td>
<td>mm</td>
</tr>
<tr>
<td>FC</td>
<td>Maximum soil moisture storage</td>
<td>mm</td>
</tr>
<tr>
<td>BETA</td>
<td>Empirical coefficient controlling the soil moisture outflow</td>
<td>-</td>
</tr>
<tr>
<td>LUZ</td>
<td>Limit for fast drainage from the upper zone storage</td>
<td>mm</td>
</tr>
<tr>
<td>WET</td>
<td>Catchment wet areas (for example, lakes and swamps)</td>
<td>Decimal fraction</td>
</tr>
<tr>
<td>CPerc</td>
<td>Percolation capacity into lower zone storage</td>
<td>mm d⁻¹</td>
</tr>
<tr>
<td>K0</td>
<td>Storage discharge constant</td>
<td>-</td>
</tr>
<tr>
<td>K1</td>
<td>Storage discharge constant</td>
<td>-</td>
</tr>
<tr>
<td>K2</td>
<td>Storage discharge constant</td>
<td>-</td>
</tr>
<tr>
<td>K3</td>
<td>Storage discharge constant</td>
<td>-</td>
</tr>
</tbody>
</table>
3.5.1 Snow and Glacier Routine

The meteorological inputs of daily precipitation and mean daily temperature are used to govern the build up and melt of the snow pack and glaciers via eleven parameters; RCF, SCF, PGRAD, TGRAD, TO, CMAX, CMIN, RMULT, REXP, CWH and CRFR. These parameters are essential in the accurate modelling of the river regime as influenced by the snow pack.

RCF and SCF are the rainfall and snowfall correction factors respectively. These parameters are used to correct for such things as rain gauge systematic error, interception and representative rainfall amount. The two parameters are different corrections, depending on the precipitation phase. Systematic error of rain gauges is relatively well understood; this includes wind induced, evaporation and wetting losses as well as instrument specific properties (Ungersböck, Rubel, Fuchs and Rudolf, 2001). Interception is dependent on the type of vegetation covering a surface and precipitation event characteristics (Ward and Robinson, 2000). Values of interception in New Zealand for tussock vegetation and Beech forest are 20 and 30 per cent respectively as reported by Pearce and McKerchar (1979) and Rowe (1975). Correcting for the representative rainfall amount is based on the idea that a rain gauge records events at a point rather than the total or areal precipitation of the catchment. Griffiths and McSaveney (1983a) have studied precipitation distribution across the Southern Alps showing that mean annual precipitation peaks at the ridge crest. They also show that precipitation is a function of both elevation and distance from the ridge crest. This variation of precipitation over each catchment is taken into account by the precipitation correction factors under the assumption that each event has the same distribution pattern.

The meteorological input data is then corrected for elevation distribution through constant lapse rates of precipitation and temperature (PGRAD and TGRAD respectively). Temperature lapse rates as used in similar modelling studies are in the order of -7.0 °C km⁻¹ (Woo and Fitzharris, 1992; Fitzharris and Garr, 1995; McAlevey, 1998). Neale (1996) reports lapse rates of -5.6 °C km⁻¹ (dry bulb) and -7.9 °C km⁻¹ (wet bulb) for the Mount Cook region. Ruddell (1995) gives seasonally variable lapse rates from a low of -5.5 °C km⁻¹ in January to a high of -7.2 °C km⁻¹ in September, also in the Mount Cook region. Precipitation gradients are not as simple as temperature gradients. As stated above, precipitation is not only a function of elevation but also distance from the ridge crest in the study area. Identifying a precipitation gradient is difficult given that they are highly variable as reported by Singh and Kumar (1997). A value of around two per cent increase per 100 m increase in elevation is a best estimate for the study area based on Griffiths and McSaveney (1983b).
TO is the temperature threshold for melt and the temperature below which rain is defined as snow and added to the snow pack. TO is not always set at 0°C. This is because TO can also be used as a general temperature correction. The temperature as recorded at the climate station site may not be representative of the temperature for that elevation throughout the whole catchment. Therefore TO can be used to correct for the representative temperature creating a more accurate representation of the build up and melt of the snow pack. TO is a parameter that is catchment specific and can only be set during the calibration process.

A degree-day melt factor that varies seasonally between CMAX and CMIN is used as input to calculate melt of snow and ice. There are several reported degree-day melt factors in the literature for New Zealand snow packs. Recent work at high elevations (2440m) by Cutler (2002) shows that an average value of 3.4 mm °C⁻¹ d⁻¹ represents melt on most days. However Cutler (2002) also notes that a value of 9 mm °C⁻¹ d⁻¹ is required to account for melt during days of northwesterly wind flow. Moore and Owens (1984a) in an application of the HBV model in New Zealand used a single value of 4 mm °C⁻¹ d⁻¹. In a study of the mass balance of the Franz Josef Glacier, Woo and Fitzharris (1992) used a variable rate of between 3 and 6 mm °C⁻¹ d⁻¹ depending on the time since fresh snow. Other values as reported in New Zealand include: 3-12 mm °C⁻¹ d⁻¹ (McAlevey, 1998), 2.3 mm °C⁻¹ d⁻¹ but 11.5 mm °C⁻¹ d⁻¹ during northwesterly storm events (Neale, 1996) and 5 mm °C⁻¹ d⁻¹ (Twaddle, 1995).

Snow and ice have different degree-day melt factors. Ice has much higher melt rates than snow due to the reduced surface albedo (Braun and Renner, 1992). This is accounted for in the model by the parameter RMULT, which is a multiplicative factor increasing the melt of ice areas in the catchment. Typical values of this parameter are 1.3 (Braun et al., 1992) or 1.5 (Braun and Renner, 1992; Moore, 1993).

To account for the effect of melt caused by slope aspect, the parameter REXP is used. This is another multiplicative factor that increases melt for those slopes that face north and decreases melt for south facing slopes (Southern Hemisphere). This is a new function within the present version of the model. Typical values are not available within the literature, so this parameter can only be assigned in the calibration process.

When snow melts, the water that is released is held within the snow pack until a critical threshold of water holding capacity is reached (Ward and Robinson, 2000). CWH is the model parameter that accounts for this process. Melt water is held within the snow pack until the fractional water holding capacity is reached. This is the same for water added to the snow pack through rain on snow events. The U.S. Army Corps
of Engineers (1998) suggest that quantification of the liquid water holding capacity is difficult due to differing physical characteristics of snow packs, but that fractional values are between 0.02 and 0.05 for a snow pack at 0°C. Fractional values for the water holding capacity of snow as used by others in modelling studies include; 0.0 (Moore and Owens, 1984b), 0.04 (Gottlieb, 1980), 0.05 (Moore, 1993; Braun et al., 1992), 0.1 (Braun and Renner, 1992), 0.01 (Braun and Renner, 1992).

Liquid water held within the upper part of the snow pack begins to refreeze if the air temperature drops below the freezing point (Bengtsson, 1982). If the refreezing process is not included in the degree-day snowmelt approach the simulated melt will occur too rapidly (Bengtsson, 1982). The process of refreezing is determined by the parameter CRFR, termed the coefficient of refreezing. Studies of snowmelt in New Zealand have shown that a refreezing coefficient does not improve model fit (Moore and Owens, 1984b). However Moore and Owens (1984b) do state that the refreezing process may need to be accounted for in a runoff model. Values as used by Braun et al. (1992) and Braun and Renner (1992) range from 0.2 to as high as 3.0. Bengtsson (1982) indicates that higher refreezing values occur when there are larger diurnal differences in temperature.

3.5.2 Soil Moisture Routine and Response Function

Rain and melt is added to a lumped soil moisture routine and a response function that consists of two layers, upper zone storage and lower zone storage. The movement of water through the soil moisture routine and response function to exiting the conceptual system of the HBV3-ETH9 model is controlled by another eleven parameters (ETMAX, LP, FC, BETA LUZ, CPERC, K0, K1, K2, K3 and WET).

The first layer the water enters is the soil moisture storage layer. Evaporation occurs from this layer. The potential evaporation rate varies seasonally and is controlled by the parameter ETMAX. The actual evaporation is a function of the potential evaporation and the soil moisture storage. Evaporation occurs at the potential rate when the soil moisture storage is above the threshold value set by LP (limit for potential evaporation). At soil moisture levels below LP, evaporation is reduced below the potential.

The soil moisture storage limit is set by the parameter FC, which is a conceptual representation of the field capacity of the soil. The closer to the limit set by FC that the soil moisture storage gets, the more water is released into the next layer down, the upper zone storage. The parameter BETA controls this release into the upper zone storage.
Bergström and Graham (1998) refer to BETA as an index of heterogeneity. The higher the value of BETA, the more homogeneous are the catchment’s soil properties. BETA is another parameter found via the calibration process.

Water can exit four different ways from the upper zone storage; fast discharge, intermediate discharge, ground water losses and percolation to the lower zone storage. Fast discharge is controlled by the parameter \( K_0 \), and occurs when the upper zone storage exceeds the value set by the parameter \( L_{UZ} \). Intermediate discharge rate is set by the parameter \( K_1 \), and occurs continuously when there is water in the upper zone storage. Ground water losses are represented by the parameter \( K_3 \). Percolation to the lower zone storage is at a constant rate from the upper zone storage as set by \( CPERC \) (percolation capacity). The lower zone storage can also be added to through the parameter \( WET \). \( WET \) is the proportion of the catchment area made up of lakes and swamps. Precipitation inputs from these areas are entered directly into the lower zone storage.

Water exits the lower zone storage by slow discharge. The parameter \( K_2 \) controls the rate of slow discharge. The total surface water discharge is provided using the three storage discharge constants \( K_0, K_1 \) and \( K_2 \). The discharges controlled by these constants are summed and recorded as the calculated (modelled) catchment discharge.

3.6 Calibration of the Model

The total number of years that are available for modelling is determined by the availability of the essential data (precipitation, mean temperature and mean runoff all at a daily time step). Calibration requires as many years as possible to achieve estimation of parameters under as wide a range of conditions as possible. To include as many hydrological events as possible in the calibration period, it is defined as all but the last five available modelling years (these form the verification period). For the Hooker catchment only six hydrological years are available, these are divided in two, the first three for calibration and the final three for verification.

Calibration involves finding parameter values which provide the best model performance. A two-step process is used to obtain the best parameter values for the chosen catchments. Step one involved a literature search to evaluate the parameters, both from previous HBV modelling studies and other sources. Many of the values obtained are outlined in the above section. Step two involved a further calibration of these initial parameters so as to give improved performance of the model.
Performance of the model is judged in three ways. The first and most important way is through a visual inspection of the hydrograph output of the model. Model parameters are adjusted to give a more realistic shape of the hydrograph output. The second method is an R\textsuperscript{2} efficiency criterion as put forward by Nash and Sutcliffe (1970) (a full explanation is given in Appendix A). An R\textsuperscript{2} value of 1 denotes a perfect fit, meaning that the model explains all of the variation in discharge as recorded. The third method uses accumulated differences between the measured and modelled discharge to evaluate performance. The accumulated difference plot is useful in showing systematic error, such as insufficient areal precipitation input or the incorrect modelling of the snow pack.

Snow and mass balance data should also be used wherever possible to constrain snow routine parameters to more realistic values. This is required because the conceptual model effectively allows endless amounts of water to be derived from ice melt. As shown by Moore (1993), under-representation of areal rainfall and consequent snow pack build up, can be accounted for in runoff predictions by over-estimation of ice melt. Although the model predicts the recorded discharge accurately it is not necessarily an accurate physical representation of the processes or the catchment's water balance. To remove the ambiguity surrounding parameter calibration, and to ensure an accurate representation of the physical processes, calibration using observed snow pack and mass balance data (end of summer snow lines) is also desirable where possible. In effect the parameters are constrained to values that provide both accurate runoff prediction as well as snow pack prediction as suggested by Braun and Aellen (1990).

Once the best possible parameter values are found the model is termed “calibrated”. However this does not mean that the model is able to predict discharge outside of the calibration period. To do this the model needs to be independently verified.

### 3.7 Verification of the Model

Verification is achieved by using a different set of input data than that used in the calibration procedure. This provides an independent test of the model. The last five of the available hydrological years are used for the verification period, except in the Hooker catchment where the last three years are used because only a total of six years is available.

Ideally, the verification input data should include the potential range of climate values likely to affect the catchment, so as to provide a true test of the model's ability
to predict discharge. This may not necessarily be the case however, when the model is used to predict runoff for some future, altered climate. However, the model is deemed “verified”, if there is no major change in the model performance between the calibration period and the verification period.

3.8 Input Data Collection and Preparation

The essential input data required by the model for each catchment is complete sets of daily precipitation, mean daily temperature and mean daily runoff. However, complete sets of data are not always available for the chosen catchments. Therefore, years that had few gaps in these sets were selected for each of the data inputs. As well as the climate and runoff data the model also requires the hypsographical detail of each catchment for the distributed snow and glacier routine.

3.8.1 Temperature

Mean daily temperature is approximated using the average of the daily maximum and minimum temperatures. Maximum and minimum temperatures are recorded at several sites within or near to each of the catchments except for the Rangitata. Temperature data from the Mount Cook climate station is used for the Hooker and Jollie catchments. Data from this station is also considered the nearest approximation to temperature in the Rangitata catchment. For the Rakaia catchment it is necessary to use a record from the station at Craigieburn Forest. This is near, but outside of the catchment. Some other temperature data is available from within the catchment, but it did not fit the period of discharge record.

Missing values for temperature data at the Mt Cook site are approximated using a linear multiple regression relationship with the climate station operated by Lake Tekapo Air Safaris. The regression equation had an $R^2$ value of 0.89. Missing Craigieburn Forest temperature values are estimated using regression with Arthurs Pass climate station values. This regression equation had an $R^2$ value of 0.84.

3.8.2 Precipitation

Precipitation is recorded at various sites within each catchment. Precipitation sites are chosen based on the completeness of their records. Sites and years without complete rainfall measurement records are discarded. Precipitation is much more variable in
space and time than temperature, and missing values cannot be approximated as easily through regression.

A tipping bucket rain gauge operated in the Jollie catchment from 1972 until 1999 and provides a complete record for the modelling years. The Hooker catchment has a tipping bucket rain gauge which has operated since 1993. This is at the same site as the river discharge measurements. Within the Rangitata, precipitation is recorded via a tipping bucket rain gauge at Mistake Flat. However this record is of little value due to the many gaps. Instead the data for Erewhon is selected because, it is central to the catchment and the data is of good quality. This data collected at Erewhon is from a manual gauge, and occasionally in the record the time period of observation is greater than 24 hours. In these cases, the recorded rainfall is divided evenly between the missing days. If extensive gaps are present in the record for a particular year, then that year is excluded from the analysis. The Rakaia catchment has several rainfall stations but few records are complete, especially those closer to the Main Divide. The data used here is from the manual Glenthorne rainfall station. Data is treated as for the Erewhon gauge.

3.8.3 Discharge

Various authorities record discharge data for each of the catchments. Stage recorders sited in stilling well towers are used to measure water level for discharge from the Jollie, Rangitata and Rakaia catchments. The Hooker stage is measured using an ultra sonic sensor installed on the bridge at Hooker Corner (Tuck, pers. comm. 2003). Figures 3.4 to 3.7 show the recording sites for each of the catchments.

Stage-discharge relationships then convert the recorded stage values to discharge values for each of the rivers. Accuracy of the discharge data is dependent on the accuracy of the stage-discharge relationship. Error is introduced where non-constant stage-discharge relationships exist, such as for the natural riverbed environments of these recording sites. Further error exists where the stage-discharge relationship is extended beyond the maximum gauged discharge.

In general, the discharge records are relatively complete compared to the meteorological records. Major gaps in the record resulted in that year being excluded from modelling. Gaps of up to several days are approximated using the average discharge of the three days either side of the gap.
Figure 3.4: Flow recording site for the Jollie catchment.

Figure 3.5: Flow recording site for the Hooker catchment.
Figure 3.6: Flow recording site for the Rangitata catchment.

Figure 3.7: Flow recording site for the Rakaia catchment.
3.8.4 Hypsographical Data

The model requires a table of hypsographical data as input to the distributed snow and glacier routine of the model. This table divides the catchment into 200-meter elevation bands and three direction classes: (1) east, west and horizontal, (2) south and (3) north. The proportion of area within the catchment that faces each of the three direction classes is then given for each of the 200-meter elevation bands. The proportion of glaciated area within the catchment is likewise entered for the three direction classes in each of the 200-meter elevation bands.

The required input is developed using the Arc GIS package. First, the catchment boundaries are defined. Then a Triangular Irregular Network (TIN) model is created for each of the catchments based on the contour information from the NZMS 260, 1:50,000 map series. From this TIN model, raster images of aspect and elevation are created. These raster images are then used to calculate the area for each of the three aspect classes in each of the 200-meter elevation bands. This procedure is repeated for the glaciated area of each catchment, as defined by the NZMS 260 1:50,000 map series.

3.9 Generation of Climate Change Scenarios

To predict the impact of climate change on a system it is necessary to generate a climate change scenario. Many methods have been proposed for the generation of such scenarios, but as yet no single method has been adopted as best practice. This section outlines the possible methods put forward in the literature for generating climate change scenarios, with emphasis placed on impact studies of hydrological systems using a modelling approach. Figure 3.8 diagrammatically shows four methods that are applicable to hydrological modelling. A brief critique of each method is put forward and a method is chosen based on its applicability to this study.

3.9.1 Hypothetical Scenario

The first possible scenario type is a hypothetical scenario. Hypothetical scenarios are generated without the use of GCM data. They are not based on a prediction of the changing climate, but rather are useful in that they outline the sensitivity of the system to change. They are generally created by altering a historic climate time series by given amounts of temperature or precipitation. For example an existing temperature record can be changed by adding $\pm 1^\circ$C to each of the values, and a precipitation record
altered by adding ± 10 per cent to each of the days with rain. This method ensures that the natural variability of the present climate is retained within the impact study. However, it fails to provide meaningful results in terms of how expected climate change will actually alter the system. Generally, the approach is simplistic because it does not take into account the potential for seasonal variation - it changes the historic time series in a homogeneous manner. Guo et al. (2002) and Legesse et al. (In Press) are examples of the hypothetical scenario generation method used in a hydrological impact study.

3.9.2 Raw GCM Data Based Scenario

A second scenario method is to use the information directly from the output of a GCM. GCMs are the most generally accepted way to predict climate change under forcing from greenhouse gases (Bárdossy, 1997). They provide information about how a climate will react to forcing of various greenhouse gases through complex mathematical calculations (Harvey, 2000). The information that is provided by a GCM can be used, either as direct input to a hydrological model, or the degree of change as forecast by the GCM can be used to statistically alter a historic time series of data. This altered time series then provides input for a hydrological model, so as to predict the change between the

Figure 3.8: Methods for generating climate change scenarios.
reference period (historic time series) and the scenario time period. Lahmer, Pfützner and Becker (2001), Morrison et al. (2002) and Etchevers, Golax, Habets and Noilhan (2002) are good examples of using raw GCM data to modify historic time series of meteorological parameters in a hydrology impact study. Using the raw information from a GCM has problems though. The coarse resolution of the GCMs restricts the ability of the models to represent climate change variables at a regional scale (Menzel and Bürger, 2002). Wilby, Hay and Leavesley (1999) studied the implications of using raw GCM data in climate change scenarios for impact studies in hydrology. They show that the accuracy of historic runoff predictions can be improved by downscaling of GCM data.

Mpelasoka, Mullan and Heerdegen (2001) point out that it is important to ensure that impact assessments use data at the same spatial and temporal scale at which impacts are likely to occur. Downscaling is the process of going from the coarse resolution data of a GCM to more meaningful, higher resolution data applicable to regional impact studies. Downscaling can be achieved either through statistical (empirical downscaling) or dynamic (regional climate models) means.

### 3.9.3 Statistical Downscaling Scenario

Statistical downscaling is the third way to derive a climate change scenario, and involves setting up empirical relationships between GCM output and local meteorological variables such as temperature and rainfall. As Bárdossy (1997) points out, the most important assumption of this method is that the empirical relationship between the local variable and the GCM variable remains the same with a changing climate. Statistical downscaling can provide, either a time series of meteorological data for direct input to a hydrological model, or as above, a forecast of change that can be used to alter a historic time series of meteorological data, which is then used as input. Cannon and Whitfield (2002) show that in British Columbia, Canada, empirical downscaling of large scale atmospheric conditions, like those predicted by a GCM, are capable of predicting changes in stream flow resulting from climate change. Many studies use the statistical downscaling scenario generation method for hydrological impact assessment including Bárdossy (1997), Kaleris, Papanastasopoulos and Lagas (2001), Bárdossy, Stehlík and Caspary (2001), Menzel and Bürger (2002).
3.9.4 Dynamic Downscaling Scenario

The fourth method of scenario generation is through dynamic downscaling. This involves using regional climate models that are able to simulate regional climatic variables based on input from a GCM. In this way they provide the link between the coarse resolution data of a GCM and that for the local climate. The regional climate model is able to provide a time series of temperature and precipitation data based on the greenhouse gas scenario used by the GCM. Again this time series can be used a number of ways, either as direct input, or as forecast change between the reference period and the climate change prediction period. As outlined by Wilby et al. (1999), one of the constraints of using regional climate model downscaling, is that it is more data intensive and computationally demanding than empirical techniques. Braun et al. (2000), in an alpine hydrology impact study, used statistical information about climate change from a regional climate model to alter a historic reference period climate record. For example, if the regional climate model predicted more convective precipitation events, these were added into the record. Similarly if more "hot" days were forecast for summer, then the temperature record was adjusted accordingly.

3.9.5 Scenario Choice

Of the four climate change scenario generation methods outlined above, only three are seen as being potentially applicable to this study. Raw GCM data would not accurately predict climate change at the scale of this study. Alpine climates in New Zealand vary much over a scale smaller than that represented by the GCMs (Mpelasoka et al., 2001). Of the other three methods, the deciding factor in choice of scenario generation is data availability. If no data is available, then the best method is to use a hypothetical scenario that outlines the sensitivity of the system to change. However, some statistically downscaled data for New Zealand is available.

Wratt et al. (2000) provide climate change maps for New Zealand based on statistically downscaled data. These maps for summer and winter are based on the average change as given by downsampling four GCM’s. Mpelasoka et al. (2001) also give maps based on statistical downscaling that follow similar trends but are different in specific details, showing the need to be careful in climate scenario generation.Mpelasoka et al. (2001) use two different statistical methods to downscale data produced by the Hadley Center Global Climate Model (HadCM2), which is a state of the art, transient-coupled-atmosphere-ocean GCM. This data is at a seasonal time scale. Although not
providing monthly data, these methods are better than setting up hypothetical scenarios. The spatial scale is also applicable to this study, and allows for regional differences in predicted climate change.

The most recent statistical downscaling of transient GCM’s for New Zealand is that of Mullan et al. (2001). The regional climate simulation from this downscaling approach can be considered to be more reliable than that of Mpelasoka et al. (2001), in that more climate stations are involved in the downscaling process. This study also includes six transient GCM’s (CSIRO, HadCM2, CCC, Japan, GFDL, MPI), rather than just the one as in Mpelasoka et al. (2001). It allows for a more realistic scenario generation, by showing the full range of climate change predictions between different models.

It is therefore considered that the best method to generate climate change scenarios, is to use statistically downscaled data based on the analysis described in Mullan et al. (2001). The data shows percentage changes, from the current climate (1970-1990), of temperature and precipitation for the periods 2020-2040 (6 models) and 2070-2099 (4 models). Three climate-recording sites used in the statistical downscaling are within the catchments used in this study. They were, H307711 Hermitage (precipitation and temperature), H31241 Harper (precipitation) and H31352 Lake Coleridge (temperature).

The downscaled data from these three sites are used to provide three scenarios for each catchment. One based on the CSIRO model, one on the HadCM2 model and a third on the average change of all the models included in the analysis by Mullan et al. (2001). The CSIRO and HadCM2 models are singled out because the results they give are contrasting, although both have realistic representation of the current climate for the Australasian region (Mullan, pers. comm. 2003). HadCM2 shows a much greater increase in the strength of the westerlies across the Southern Alps, and corresponding changes in precipitation. The north-south temperature gradient of the HadCM2 model is also much larger than the CSIRO model (Mullan, pers. comm. 2003).

The information for each model about temperature and precipitation changes at a monthly time step was supplied by Mullan (pers. comm. 2003). This data is used to adjust the reference period data for each catchment, creating the three climate change scenarios. Temperature changes as predicted for the Hermitage site, are used for the Hooker, Jollie, and Rangitata catchments. Temperature changes as predicted for the Lake Coleridge site, are used for the Rakaia catchment. Precipitation changes as predicted for the Hermitage site, are used for the Hooker and Jollie catchments.
The precipitation changes for the Rangitata and Rakaia rivers are taken as being the mean of the changes for the Hermitage and Harper sites, as this is considered closer to the areal precipitation for these catchments.

3.10 The Impact of Climate Change on Discharge

The resultant changes in discharge as predicted by the climate change scenarios are analysed in four ways, based on visual inspection of graphs. This method, backed up by simple statistics, such as percentage difference, is chosen because of its simplicity.

The first type of analysis compares the hydrograph responses of the modelled scenarios with those for the reference period. This leads to ideas as to how the climate change scenarios will alter discharge on a day-to-day basis. Ideas on how the changes in temperature and precipitation will alter the seasonality of discharge are developed, based on the perceived hydrograph changes. Also shown is the possible effect climate change will have on flood peaks and base flow.

The second way of analysis follows Menzel and Bürger (2002) and is used to illustrate the change in discharge regime. Graphs of mean monthly discharge for the reference period and the climate change scenarios are compared. Line graphs of mean monthly discharge as a proportion of mean annual discharge are also used to show changes in discharge regime.

The third way of analysis shows the cumulative discharge for the reference period and each of the climate scenarios. By showing cumulative discharge, changes in discharge timing (regime) and total annual water yield can be illustrated.

The fourth way of analysis compares seasonal discharge response. This follows the methods of Wilby et al. (1999) and the recommendations of Mullan (pers. comm. 2003). These seasonal changes show most realistically, given the confidence limits of climate scenario generation, what can be expected for the future climate.

3.11 Summary

This chapter has outlined the research strategy and methods used to answer the research questions put forward in the previous chapter. The research strategy can be summarised as a climate change impact assessment on runoff from alpine catchments. In brief, the methods used are as follows.

1. Selection of an appropriate model (HBV3-ETH9).
2. Collection and preparation of necessary input data.

3. Identification of likely model parameters.


5. Verification of the model on independent data.

6. Selection of an appropriate climate change scenario generation method.

7. Generation of climate change scenarios.

8. Run model with climate change scenario data.

9. Analysis of difference between current climate runoff generation and scenario climate runoff generation.
Chapter 4

Results

4.1 Introduction

This chapter gives the results of the HBV3-ETH9 climate change modelling experiment. It is divided into four sections, one for each of the catchments studied. In each section the catchment is briefly introduced, the input parameters of the model are given and the results pertaining to the specific catchment are provided using the four analysis methods described in the previous chapter.

4.2 Jollie Catchment

4.2.1 Catchment Characteristics

The Jollie catchment has an area of 140 km² with less than 4 km² of glaciers, but substantial amounts of seasonal snow (Braddock, 1998). Discharge from the catchment flows into the Waitaki hydroelectric system via the Tasman River and Lake Pukaki. The catchment is approximately 15 km east of and almost parallel to the Main Divide of the Southern Alps. The gauging station is at an altitude of 580 m and the highest peak is The Nuns Veil at 2749 m giving a total elevation range of 2169 m. The base rock geology of the catchment consists of greywacke and argillite. Vegetation ranges from tussock grassland at low elevation to scree and bare rock above about 1500 m.

Figure 4.1 shows the hypsography of the catchment. Approximately 50 per cent of the catchment is above 1400 m. In terms of aspect, 65 per cent of the catchment faces east, west or is horizontal, 13 per cent faces north and 22 per cent faces south. The glacial area of the catchment is found above 1900 m with 60 per cent of the glacial
area facing south and the other 40 per cent split between east facing, west facing and horizontal slopes. Also shown by Figure 4.1 is the position of the only rain gauge in the catchment at an elevation of 610 m.

### 4.2.2 Climate Change Scenarios

The climate change scenarios used for the Jollie catchment are given in Table 4.1. Each of the scenarios of temperature and precipitation change are named after the GCM used to create them. The Multiple Model Average (MMA) scenario is explained in the methodology. Temperature changes are given as increases or decreases in degrees Celsius while precipitation changes are given as per cent differences. The CSIRO scenario for the 2080’s predicts the largest temperature changes, while the HadCM2 scenario for the 2080’s predicts the largest precipitation changes. The CSIRO and HadCM2 models produce very different climate change scenarios. For example where the CSIRO model is predicting small decreases in winter precipitation for the 2080’s, the HadCM2 model is predicting large increases.

### 4.2.3 Calibration and Verification

Table 4.2 gives the R² values of model efficiency for the Jollie River during the calibration and verification periods for the present climate. The calibrated model parameters used to derive these modelling results are displayed in Table 4.3. R² values for the calibration period range from 0.56 to 0.88, while the range for the verification period is 0.70 to 0.78.

Figure 4.2 displays recorded and modelled hydrographs for the 1993-94 hydrological year. Recorded versus modelled hydrographs for the other hydrological years during the verification period can be seen in Appendix B. The hydrological year 1993-94 is a typical result for the verification period, with an R² value of 0.78. Model performance is strong throughout the entire year. The model underestimates several of the floods, while overestimating several others. Base flow is generally well represented, with the exception of August where model estimates drop below recorded base flow.

The cumulative difference between recorded discharge and modelled discharge for the hydrographs in Figure 4.2 is shown by Figure 4.3. This illustrates that for the year 1993/94, the model underestimates autumn and winter discharge, while it overestimates spring and summer discharge. Cumulative difference plots for the other years within the verification period are given in Appendix B. The seasonal cycle shown above
Figure 4.1: Jollie catchment hypsography and glacial extent.
Table 4.1: Climate change scenarios for the Jollie catchment (temperature changes in degrees Celsius ($\Delta T$) and precipitation changes as per cent differences($\Delta P$)). Each scenario is named after the GCM used to generate it. Source: derived from Mullan et al. (2001).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\Delta T$ (°C)</th>
<th>Month</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Jan</td>
<td>Feb</td>
</tr>
<tr>
<td>CSIRO</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>2030's</td>
<td>-12.6</td>
<td>-6.6</td>
</tr>
<tr>
<td>CSIRO</td>
<td>1.8</td>
<td>1.9</td>
</tr>
<tr>
<td>2080's</td>
<td>2.7</td>
<td>5.9</td>
</tr>
<tr>
<td>HadCM2</td>
<td>-0.2</td>
<td>0.0</td>
</tr>
<tr>
<td>2030's</td>
<td>13.6</td>
<td>11.5</td>
</tr>
<tr>
<td>HadCM2</td>
<td>0.8</td>
<td>1.1</td>
</tr>
<tr>
<td>2080's</td>
<td>8.0</td>
<td>-1.2</td>
</tr>
<tr>
<td>MMA</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>2030's</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>MMA</td>
<td>1.1</td>
<td>1.3</td>
</tr>
<tr>
<td>2080's</td>
<td>15.9</td>
<td>13.8</td>
</tr>
</tbody>
</table>
only exists in half the modelled years. Appendix B also shows the model sometimes underestimates the discharge for the entire year, while in other years the cumulative difference fluctuates about zero. Except for 1991, the cumulative difference stays within 100 mm for all hydrological years during the verification period.

A scatter plot of the hydrograph data presented in Figure 4.2 is given in Figure 4.4. This illustrates a high level of confidence in model representation of discharge from the Jollie catchment. There are no major outliers, with the majority of points being distributed evenly above and below the perfect fit line. The base flow values are however mostly just below the perfect fit line. Scatter plots for the other hydrological years within the verification period are given in Appendix B.

Table 4.2: $R^2$ values of model efficiency for the Jollie catchment during the calibration and verification periods.

<table>
<thead>
<tr>
<th>Year</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Calibration</strong></td>
<td></td>
</tr>
<tr>
<td>1984</td>
<td>0.75</td>
</tr>
<tr>
<td>1985</td>
<td>0.82</td>
</tr>
<tr>
<td>1986</td>
<td>0.88</td>
</tr>
<tr>
<td>1987</td>
<td>0.74</td>
</tr>
<tr>
<td>1988</td>
<td>0.56</td>
</tr>
<tr>
<td><strong>Verification</strong></td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>0.78</td>
</tr>
<tr>
<td>1990</td>
<td>0.70</td>
</tr>
<tr>
<td>1991</td>
<td>0.71</td>
</tr>
<tr>
<td>1992</td>
<td>0.78</td>
</tr>
<tr>
<td>1993</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Table 4.3: Calibrated input parameters of the HBV3-ETH9 model for the Jollie catchment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCF</td>
<td>1.35</td>
</tr>
<tr>
<td>SCF</td>
<td>1.35</td>
</tr>
<tr>
<td>CMin</td>
<td>3.60 mm °C⁻¹ d⁻¹</td>
</tr>
<tr>
<td>CMax</td>
<td>4.35 mm °C⁻¹ d⁻¹</td>
</tr>
<tr>
<td>T0</td>
<td>-0.90 °C</td>
</tr>
<tr>
<td>RMult</td>
<td>1.00</td>
</tr>
<tr>
<td>RExp</td>
<td>1.80</td>
</tr>
<tr>
<td>CWH</td>
<td>0.025</td>
</tr>
<tr>
<td>CRFR</td>
<td>0.55</td>
</tr>
<tr>
<td>PGrad</td>
<td>3.30 % 100 m⁻¹</td>
</tr>
<tr>
<td>TGrad</td>
<td>-0.73 °C 100 m⁻¹</td>
</tr>
<tr>
<td>ETMax</td>
<td>3.6 mm d⁻¹</td>
</tr>
<tr>
<td>LP</td>
<td>90 mm</td>
</tr>
<tr>
<td>FC</td>
<td>90 mm</td>
</tr>
<tr>
<td>BETA</td>
<td>0.25</td>
</tr>
<tr>
<td>LUZ</td>
<td>46 mm</td>
</tr>
<tr>
<td>WET</td>
<td>0.02</td>
</tr>
<tr>
<td>CPerc</td>
<td>2.50 mm d⁻¹</td>
</tr>
<tr>
<td>K0</td>
<td>0.125</td>
</tr>
<tr>
<td>K1</td>
<td>0.045</td>
</tr>
<tr>
<td>K2</td>
<td>0.055</td>
</tr>
<tr>
<td>K3</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Figure 4.2: Recorded discharge versus modelled discharge for the Jollie catchment - example of the hydrological year 1993/94.

Figure 4.3: Cumulative difference between recorded discharge and modelled discharge for the Jollie catchment - example of the hydrological year 1993/94.
4.2.4 Hydrograph Responses to Climate Change

The hydrograph responses to the predicted climate change for the 2030’s in the Jollie catchment are shown in Figure 4.5. These changes are based on the reference year 1993/94 as used in the previous subsection. Figure 4.5 shows that there is very little difference between the current climate and predicted future climate hydrographs. There is very little difference either in base flow or peak discharge volumes for any of the scenarios when compared to the modelled flow for the reference year.

The predicted hydrograph responses for the 2080’s are given in Figure 4.6. Again these changes are based on the reference year 1993/94. The most obvious change illustrated is that the winter and spring discharges are higher for all three scenarios. Base flow increases most for the HadCM2 modelled scenario and least for the CSIRO modelled scenario. This is also the case for winter and spring flood events. The HadCM2 scenario shows these events are up to twice as large compared to the modelled discharge for the current climate. The CSIRO scenario predicts these events as being only slightly larger. The summer and autumn discharge appears to change very little between the present climate and the predicted climate for the 2080’s for all of the modelled scenarios.
Figure 4.5: Modelled hydrographs for the Jollie catchment’s present climate (reference year 1993/94) and for the 2030’s using different climate scenarios.

Figure 4.6: Modelled hydrographs for the Jollie catchment’s present climate (reference year 1993/94) and for the 2080’s using different climate scenarios.
4.2.5 Cumulative Discharge Response

The cumulative discharge response to the climate change scenarios for the 2030’s is shown in Figure 4.7. When compared to the modelled cumulative discharge as the reference, it can be seen that the HadCM2 and the MMA scenarios predict an increase in the cumulative discharge. The greatest divergence of cumulative totals from the current climate occurs during August. The CSIRO scenario predicts very little difference in cumulative discharge compared to the current climate over the year with a small decrease in total cumulative discharge.

Figure 4.8 shows the predicted cumulative discharge from the Jollie catchment under the climate change scenarios for the 2080’s. A large change in cumulative discharge is predicted by all three scenarios. The CSIRO scenario predicts a relatively small increase in total cumulative discharge of about 250 mm. Most of this occurs by the end of October during the hydrological year. The HadCM2 and MMA scenarios predict an increase in cumulative discharge of around 550 mm compared to the modelled verification period climate. The greatest difference occurs during winter where cumulative discharge diverges rapidly from the modelled cumulative discharge total.

Figure 4.7: Mean cumulative discharge from the Jollie catchment for the current climate and using different climate scenarios for the 2030’s.
4.2.6 Discharge Regime Response

The predicted discharge regime response for the 2030’s is shown in Figures 4.9 and 4.10. Figure 4.9 shows recorded and modelled mean monthly discharge and mean monthly discharge for the three modelled scenarios of the 2030’s using the verification period as the reference climate. Under the modelled HadCM2 scenario, mean monthly discharge increases during all months except November and April. This increase is most evident during August. The CSIRO modelled scenario for the 2030’s shows very little change from the present climate. For the period October to February small decreases in mean monthly discharge are predicted and for the period March to September small increases are predicted. The MMA scenario predicts small increases in mean monthly discharge all year round.

When the mean monthly discharge is shown as a proportion of mean annual discharge (Figure 4.10), the effect of the above changes on the seasonal discharge regime is emphasized. Using the modelled discharge regime as the reference, the proportion of discharge increases for the period June to September and decreases for the period November to February. This is the case for all of the modelled climate change scenarios for the 2030’s.

Figure 4.11 shows mean monthly discharge for climate change scenarios of the
2080’s. Large changes in discharge are predicted. The HadCM2 modelled scenario for the 2080’s shows an all year round increase in mean monthly discharge, especially for the period June to October. The largest increase is predicted for the month of August, when mean monthly discharge more than doubles from 5 cumecs to 11 cumecs. The CSIRO modelled scenario predicts increases for the period February to October, with the largest increases during the period August to October. For the period November to January the CSIRO modelled scenario predicts small decreases.

The mean monthly discharge as a proportion of mean annual discharge under the modelled scenarios for the 2080’s is shown in Figure 4.12. Using the modelled discharge regime as the reference, it can be seen that during the period June to September the proportion of discharge increases. This increase is most marked for the HadCM2 and MMA scenarios and least marked for the CSIRO scenario. During the period November to February, all three climate change scenarios show a decrease in the proportion of discharge.

Figure 4.9: Jollie catchment mean monthly discharge predicted for the 2030’s.
Figure 4.10: Jollie catchment discharge regime predicted for the 2030’s.

Figure 4.11: Jollie catchment mean monthly discharge predicted for the 2080’s.
4.2.7 Seasonal Discharge

The response of seasonal discharge predicted for the 2030’s is shown in Figure 4.13. Using modelled mean seasonal discharge as the reference, the HadCM2 scenario shows an increase in mean seasonal discharge for all seasons. The largest increase in mean seasonal flow is during the winter. The CSIRO scenario predicts small decreases for spring and summer and small increases for autumn and winter. The MMA scenario predicts small increases in mean seasonal discharge for all seasons.

Figure 4.14 shows the seasonal discharge response under the climate change scenarios for the 2080’s. The HadCM2 scenario predicts increases for all seasons. The largest increase is in winter, with a doubling in mean discharge from just under 5 cumecs to just under 10 cumecs. The CSIRO scenario also predicts increases of up to 1.5 cumecs in all seasons. These are smaller than those of the HadCM2 scenario, except in autumn. The MMA scenario also shows an increase in mean seasonal discharge of between 2 and 4 cumecs across all seasons.
Figure 4.13: Jollie catchment mean seasonal discharge predicted for the 2030’s.

Figure 4.14: Jollie catchment mean seasonal discharge predicted for the 2080’s.
4.2.8 Summary of Results for the Jollie Catchment

The calibrated version of the HBV3-ETH9 model provides a consistently good fit of recorded versus modelled discharge for the present climate as represented by the calibration and verification periods. The climate change scenarios for the 2080's of temperature and precipitation change generated by the GCMs predict that discharge will increase all year round, this results in a higher cumulative discharge from the catchment under all modelled scenarios. Late winter and early spring discharge is predicted to increase most. The HadCM2 scenarios give the largest increases in discharge compared with the present climate. The seasonal discharge regime of the Jollie catchment is also altered under modelled climate change scenarios for the 2080's. A higher proportion of discharge is predicted to occur during winter and early spring with a lower proportion during late spring and early summer.

4.3 Hooker Catchment

4.3.1 Catchment Characteristics

The Hooker River flows from a 25 km long section of the Main Divide of the Southern Alps. The catchment has a total area of 104 km$^2$ of which 46 km$^2$ is glaciated. The total elevation range of the catchment is 3054 m, with the gauging station at 700 m and the highest mountain, Mt Cook (Aoraki), at 3754 m. The base rock geology consists of greywacke and argillite. Vegetation ranges from native scrub at low elevations to scree and bare rock above about 1200 m. Discharge from the catchment flows into the Waitaki hydroelectric system via the Tasman River and Lake Pukaki.

Figure 4.15 shows the hypsography of the catchment. Approximately half of the catchment area is above 1600 m. The catchment has 61 per cent of the area facing east, west or being horizontal. Only 13 per cent of slopes face north, and 26 per cent face south. As shown by Figure 4.15, the Hooker is a heavily glaciated catchment. 58 per cent of glacier area faces east, west or is horizontal. Only 11 per cent faces north and 31 per cent faces south. Also shown in Figure 4.15 is the relative position of the rain gauge and the Hermitage, Mt Cook climate station.

4.3.2 Climate Change Scenarios

The climate change scenarios for the Hooker catchment are the same as those used for the Jollie catchment. These scenarios have been given in Table 4.1.
Figure 4.15: Hooker catchment hypsography and glacial extent.
4.3.3 Calibration and Verification

R² values of model efficiency for the Hooker catchment during the calibration and verification period are given in Table 4.4. Table 4.5 contains the calibrated model parameters used to derive these values. Calibration period R² values range from 0.57 to 0.72, while verification period R² values range from 0.58 to 0.81.

A typical year does not exist within the verification period because of the shorter length of record and high variability. Therefore the hydrological year of 1999/2000 has been used as an example. Figure 4.16 displays recorded and modelled hydrographs of 1999/2000. Appendix B contains recorded versus modelled hydrographs for the other years within the verification period. For 1999/2000 the model performs well with an R² value of 0.81. Discharge is well estimated except for flood peaks. This can also be said for the other two years within the verification period.

Figure 4.17 displays the cumulative difference between recorded and modelled discharge for the example hydrological year of 1999/2000. Autumn discharge is underestimated, while discharge is overestimated for the rest of the year. Underestimated flood peaks show as little spikes in the downward trend. Cumulative difference figures for the other hydrological years within the verification period are given in Appendix B. Peak cumulative differences for the other hydrological years within the verification period are higher than the 400 mm for the 1999/2000 hydrological year, reaching more than 500 mm. No pattern of cumulative difference exists within the verification period for the Hooker catchment.

A scatter plot of recorded versus modelled discharge is presented in Figure 4.18. This illustrates a poor representation of flood discharge volumes by the HBV3-ETH9 model for the Hooker catchment. High discharge values are consistently below the perfect fit line, getting further from it for higher recorded discharge values. A high degree of scatter exists, even at low discharge volumes. Remaining scatter plots for years from the verification period for the Hooker catchment are presented in Appendix B.
Table 4.4: $R^2$ values of model efficiency for the Hooker catchment during the calibration and verification periods.

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Figure 4.16: Recorded discharge versus modelled discharge for the Hooker catchment - example of the hydrological year 1999/2000.
Table 4.5: Calibrated input parameters of the HBV3-ETH9 model for the Hooker catchment.

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Figure 4.17: Cumulative difference between recorded discharge and modelled discharge for the Hooker catchment - example of the hydrological year 1999/2000.

Figure 4.18: Scatter plot of recorded discharge versus modelled discharge for the Hooker catchment - example of the hydrological year 1999/2000.
4.3.4 Hydrograph Responses to Climate Change

Hydrograph response to predicted climate change for the 2030’s is shown in Figure 4.19. The reference hydrograph is the hydrological year 1999/2000. Only very small changes are evident for the three modelled scenarios. Winter flood peaks increase slightly, while winter base flow remains unchanged. Summer flood peaks also increase under all three modelled climate change scenarios.

Figure 4.20 shows predicted hydrograph changes based on modelled climate change scenarios for the 2080’s. All three of the modelled scenarios shown similar changes to the reference modelled hydrograph. Flood peaks show an increase all year round. Winter flood peaks increase from about 10 cumecs to between 40 and 50 cumecs, with the HadCM2 scenario producing the largest winter discharge volumes. Winter base flow increases in volume and decreases in duration. The CSIRO scenario predicts the largest late spring and autumn increases in discharge volumes. The MMA scenario predicts hydrograph changes in the middle of the range set by the HadCM2 and CSIRO scenarios.

![Figure 4.19: Modelled hydrographs for the Hooker catchment’s present climate (reference year 1999/2000), and for the 2030’s using different climate scenarios.](image-url)
Figure 4.20: Modelled hydrographs for the Hooker catchment’s present climate (reference year 1999/2000), and for the 2080’s using different climate scenarios.

4.3.5 Cumulative Discharge Response

Shown in Figure 4.21 is the cumulative discharge response of the Hooker catchment to climate change scenarios for the 2030’s. All three scenarios predict similar changes. Using modelled cumulative discharge as the reference, an increase of about 1000 mm total cumulative discharge is predicted. Error between recorded and modelled cumulative discharge is large, with modelled cumulative discharge being under estimated.

The cumulative discharge response of the Hooker catchment using climate change scenarios for the 2080’s is given in Figure 4.22. Again, all three scenarios predict similar changes in cumulative discharge from the Hooker catchment. Cumulative discharge increases under all scenarios by around 2500 mm. This represents an increase of total discharge from the catchment of around one third compared to the current modelled discharge. Cumulative totals diverge all year round. The scenarios predict one third more cumulative discharge by the end of August compared to the modelled current climate.
Figure 4.21: Mean cumulative discharge from the Hooker catchment for the current climate and using different climate scenarios for the 2030’s.

Figure 4.22: Mean cumulative discharge from the Hooker catchment for the current climate and using different climate scenarios for the 2080’s.
4.3.6 Discharge Regime Response

The discharge regime response predicted for the 2030’s is shown in Figures 4.23 and 4.24. Figure 4.23 shows recorded and modelled mean monthly discharge for the verification period along with modelled mean monthly discharge under climate change scenarios. All three scenarios predict an increase in mean monthly discharge all year round compared to the modelled verification period. A strong seasonal trend in discharge is still evident. As Figure 4.24 shows, there is very little change between the modelled discharge regime and predicted discharge regime under the climate change scenarios.

Mean monthly discharge predicted by climate change scenarios for the 2080’s is given in Figure 4.25. Again all three scenarios predict increases in mean monthly discharge all year round. The HadCM2 scenario predicts a near doubling of mean monthly discharge for the period of June to September. An increase in mean monthly discharge of about 10 cumecs is predicted by the HadCM2 scenario during almost all other months. The CSIRO scenario predicts the largest increases to occur during the period from September to December. The smallest increases predicted by the CSIRO scenario occur during the period of June to August. The MMA scenario follows closely to that of the HadCM2 scenario. Changes predicted by all three scenarios are much larger than differences between the recorded and modelled mean monthly discharges for the verification period.

Figure 4.26 illustrates the predicted discharge regime using climate change scenarios for the 2080’s. Proportionally, discharge decreases for the period of December to February for all scenarios. The HadCM2 and MMA scenarios predict an increase in proportion of discharge for the period of May to September. For the CSIRO scenario a small increase in proportion is predicted for the period of September to November.

4.3.7 Seasonal Discharge

The response of seasonal discharge using modelled climate change scenarios for the 2030’s is shown in Figure 4.27. Each of the scenarios predict an increase in mean seasonal discharge for all four seasons compared to the modelled reference period mean seasonal discharge. The HadCM2 scenario indicates that mean seasonal discharge will increase by almost a third in winter. This scenario also indicates that mean spring and summer discharge will increase by about 5 cumecs. Mean seasonal discharge increases to a lesser extent under the CSIRO scenario in all seasons except autumn when compared to the HadCM2 and MMA scenarios. The MMA scenario predicts very similar mean seasonal discharge to the HadCM2 scenario.
Figure 4.23: Hooker catchment mean monthly discharge predicted for the 2030’s.

Figure 4.24: Hooker catchment discharge regime predicted for the 2030’s.
Figure 4.25: Hooker catchment mean monthly discharge predicted for the 2080’s.

Figure 4.26: Hooker catchment discharge regime predicted for the 2080’s.
Figure 4.28 shows mean seasonal discharge response using climate change scenarios for the 2080’s. Large changes in mean seasonal discharge are predicted by each of the three scenarios. The HadCM2 scenario predicts that mean winter discharge will almost double from 10 cumecs to just under 20 cumecs. The HadCM2 scenario also predicts mean spring discharge to increase by 10 cumecs, summer by 9 and autumn by 7 when compared to current climate modelled mean seasonal discharge. The CSIRO scenario of temperature and precipitation changes predicts winter will show the smallest increase in mean seasonal discharge and spring the largest. Mean spring discharge is predicted under the CSIRO scenario to increase almost one third from 23 cumecs to just over 35 cumecs. Mean summer discharge also shows a large increase under the CSIRO scenario of 12 cumecs with autumn increasing 10 cumecs. The MMA scenario predicts a large winter increase, doubling mean discharge. Increases of around 10 cumecs for the other three seasons are predicted by the MMA scenario.

![Graph showing mean seasonal discharge across seasons and climate scenarios](image-url)

Figure 4.27: Hooker catchment mean seasonal discharge predicted for the 2030’s.
Figure 4.28: Hooker catchment mean seasonal discharge predicted for the 2080’s.

4.3.8 Summary of Results for the Hooker Catchment

Overall the calibrated version of the HBV3-ETH9 model provides inconsistent results for the Hooker catchment with some high values of model efficiency but also some low values. GCM generated climate change scenarios of temperature and precipitation changes indicate that for all scenarios and all year round mean discharge will increase from the Hooker catchment. This increase in discharge will be large with around a quarter more mean annual discharge under all three climate change scenarios for the 2080’s. The three different scenarios from the GCM models all predict very similar changes for the mean seasonal discharge from the Hooker catchment in the 2080’s. Under scenarios for the 2080’s spring discharge is predicted to increase the most in terms of volume but winter discharge increases the most in proportion to current winter discharge.

4.4 Rangitata Catchment

4.4.1 Catchment Characteristics

The Rangitata River flows from a 20 km long section of the Main Divide to the Pacific Ocean via glaciers, braided river bed, a gorge and further braided river bed across the
Canterbury plains. It has a total area of 1460 km² above the gauging station, with 38 km² of glaciers. The total elevation range of the catchment is 2495 m with the gauging station at 380 m, and the highest peak being Mt D'Archiac at 2875 m. The geology consists of greywacke and argillite. Vegetation ranges from tussock grassland and patches of beech forest at low elevation to scree and bare rock above about 1500 m. The main uses of the river are for recreation and irrigation of which the Rangitata Diversion Race is the largest abstraction with a capacity of 31 cumecs at the intake.

Figure 4.29 shows the hypsography of the catchment. Approximately half of the catchment area is above 1200 m. Within the catchment, 57 per cent of the slopes face east, west or are horizontal. North facing slopes make up just 19 per cent of the area and south facing slopes 24 per cent of the area. South facing slopes account for 47 per cent of the glacier area. East, west and horizontal slopes have 45 per cent of the glacier area, and north facing slopes just 8 per cent of the glacier area.

### 4.4.2 Climate Change Scenarios

The scenarios used for the Rangitata catchment are given in Table 4.6. The temperature changes are given as increases or decreases in degrees Celsius while the precipitation changes are given as per cent differences. It can be seen that there is a large variation among the GCM predicted climate change values for each scenario. For example, where the CSIRO model is predicting small decreases in precipitation during June, July and August for the “2080’s”, the HadCM2 model is predicting large increases and the MMA scenario is predicting moderate increases.

### 4.4.3 Calibration and Verification

Efficiency criterion $R^2$ values for the calibration and verification periods are shown in Table 4.7. These values are based on calibrated model parameters for the Rangitata catchment as given by Table 4.8. $R^2$ values for the calibration period range from 0.52 to 0.88, while the range for the verification period is 0.65 to 0.85.

Figure 4.30 shows hydrographs of recorded and modelled discharge for the 1992/93 hydrological year (hydrographs of recorded and modelled discharge for the other years within the verification period can be found in Appendix B). This is a typical year for the verification period with an $R^2$ value of 0.74. There is a reasonable agreement between recorded and modelled discharges. The model underestimates winter base flow and several summer flood peaks.
Figure 4.29: Rangitata catchment hypsography and glacial extent.
Table 4.6: Climate change scenarios for the Rangitata catchment (temperature changes in degrees Celsius ($\Delta T$) and precipitation changes as per cent differences($\Delta P$)). Each scenario is named after the GCM used to generate it. Source: derived from Mullan et al. (2001).

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<th>Jul</th>
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Table 4.7: $R^2$ values of model efficiency for the Rangitata catchment during the calibration and verification periods.

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<td>1991</td>
<td>0.61</td>
</tr>
<tr>
<td>1992</td>
<td>0.74</td>
</tr>
<tr>
<td>1993</td>
<td>0.71</td>
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<tr>
<td>1994</td>
<td>0.85</td>
</tr>
<tr>
<td>1995</td>
<td>0.65</td>
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</tbody>
</table>
Table 4.8: Calibrated input parameters of the HBV3-ETH9 model for the Rangitata catchment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>RCF</td>
<td>1.18</td>
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<tr>
<td>SCF</td>
<td>1.16</td>
</tr>
<tr>
<td>CMin</td>
<td>3.80 mm °C⁻¹ d⁻¹</td>
</tr>
<tr>
<td>CMax</td>
<td>4.10 mm °C⁻¹ d⁻¹</td>
</tr>
<tr>
<td>T0</td>
<td>-0.50 °C</td>
</tr>
<tr>
<td>RMult</td>
<td>1.45</td>
</tr>
<tr>
<td>RExp</td>
<td>1.80</td>
</tr>
<tr>
<td>CWH</td>
<td>0.05</td>
</tr>
<tr>
<td>CRFR</td>
<td>0.85</td>
</tr>
<tr>
<td>PGrad</td>
<td>3.20 % 100 m⁻¹</td>
</tr>
<tr>
<td>TGrad</td>
<td>-0.60 °C 100 m⁻¹</td>
</tr>
<tr>
<td>ETMax</td>
<td>3.30 mm d⁻¹</td>
</tr>
<tr>
<td>LP</td>
<td>170 mm</td>
</tr>
<tr>
<td>FC</td>
<td>270 mm</td>
</tr>
<tr>
<td>BETA</td>
<td>0.20</td>
</tr>
<tr>
<td>LUZ</td>
<td>45 mm</td>
</tr>
<tr>
<td>WET</td>
<td>0.03</td>
</tr>
<tr>
<td>CPerc</td>
<td>1.55 mm d⁻¹</td>
</tr>
<tr>
<td>K0</td>
<td>0.160</td>
</tr>
<tr>
<td>K1</td>
<td>0.120</td>
</tr>
<tr>
<td>K2</td>
<td>0.010</td>
</tr>
<tr>
<td>K3</td>
<td>0.009</td>
</tr>
</tbody>
</table>
Cumulative difference between recorded and modelled discharge (1992/93) is shown by Figure 4.31. This shows that cumulative difference has a seasonal cycle with winter discharge being under represented, while late spring and early summer discharge is over represented. The effect of under representing summer flood peaks is also evident in the cumulative difference, which reaches a peak in late summer. This seasonal cycle is typical of cumulative differences during the verification period and other examples can be seen in Appendix B.

A scatter plot of recorded versus modelled discharge (1992-93) is presented in Figure 4.32. It demonstrates that the model has a poorer representation of flood peaks than other discharge values. This is shown by an increased scatter with increased discharge values. A large number of values fall below the perfect fit line for low flow values. There is only one major outlier, that of the under estimated December flood. Scatter plots for the other years during the verification period are given in Appendix B.

![Figure 4.30: Recorded discharge versus modelled discharge for the Rangitata catchment - example of the hydrological year 1992/93.](image-url)
Figure 4.31: Cumulative difference between recorded discharge and modelled discharge for the Rangitata catchment - example of the hydrological year 1992/93.

Figure 4.32: Scatter plot of recorded discharge versus modelled discharge for the Rangitata catchment - example of the hydrological year 1992/93.
4.4.4 Hydrograph Responses to Climate Change

The Rangitata hydrograph responses to predicted climate change for the 2030's are shown in Figure 4.33. These changes are based on the reference year 1992/93. The CSIRO scenario predicts very little change in the hydrograph from the modelled reference year. The HadCM2 and MMA scenarios predict an increased level of peak discharge compared to the modelled current climate particularly in spring. Base flow appears to remain largely unchanged for all three of the climate scenarios.

Predicted changes for the 2080's as shown by Figure 4.34 show variability among scenarios. All three scenarios show that the strong seasonal pattern of discharge will continue. The HadCM2 and MMA scenarios predict that winter and spring flood peaks will increase. During late winter and early spring some of these peak discharge values nearly double. The CSIRO scenario also predicts increased winter and spring floods but to a lesser extent. Base flow values during the winter period remain unchanged compared to the modelled values. All three scenarios predict relatively minor changes to summer and autumn discharge.

![Figure 4.33: Modelled hydrographs for the Rangitata catchment's present climate (reference year 1992/93), and for the 2030's using different climate scenarios.](image-url)
Figure 4.34: Modelled hydrographs for the Rangitata catchment’s present climate (reference year 1992/93), and for the 2080’s using different climate scenarios.

4.4.5 Cumulative Discharge Response

Cumulative discharge response of the Rangitata under scenarios for the 2030’s is shown in Figure 4.35. It confirms that the CSIRO scenario predicts very little difference in discharge from the reference modelled cumulative discharge. The HadCM2 and MMA scenarios show higher cumulative annual discharge of 300 and 250 mm respectively than the reference cumulative annual discharge. The HadCM2 scenario gives the highest cumulative total while the CSIRO scenario gives the lowest.

Figure 4.36 shows the cumulative discharge response under scenarios for the 2080’s. All three scenarios show an increase in cumulative discharge total from the modelled cumulative total. The cumulative totals diverge most rapidly from the modelled total during August for the HadCM2 and MMA scenarios. As in the scenarios for the 2030’s, the HadCM2 scenario gives the highest cumulative discharge and the CSIRO scenario the lowest. There is a greater range of totals under scenarios for the 2080’s with the HadCM2 scenario cumulative total being 400 mm higher than the CSIRO scenario. The HadCM2 scenario predicts 500 mm more annual discharge from the Rangitata catchment compared to the current climate.
Figure 4.35: Mean cumulative discharge from the Rangitata catchment for the current climate and using different climate scenarios for the 2030’s.

Figure 4.36: Mean cumulative discharge from the Rangitata catchment for the current climate and using different climate scenarios for the 2080’s.
4.4.6 Discharge Regime Response

The response of the discharge regime to climate change is shown in Figures 4.37 through to 4.40. Figure 4.37 shows mean monthly discharge of the recorded and modelled verification period as well as mean monthly discharge for the three scenarios during the 2030’s. There are no large differences between the reference period (verification period) and the 2030’s. Modelling error is as great as the predicted changes for many of the months. Using the modelled flow as the reference, it can be seen that in the period March through to November mean monthly discharge increases slightly with future climate change. In the period December through to February both increases and decreases in mean monthly discharge occur depending on the scenario.

Figure 4.38 displays mean monthly discharge as a proportion of mean annual discharge. The scenarios for the 2030’s indicate that the proportion of mean annual discharge increases for the months of June through to September with the largest increase in August. The months of December through to February show that the proportion of mean annual discharge decreases with the largest decrease in January.

Figure 4.39 shows mean monthly discharge under climate change scenarios for the 2080’s. Larger differences are shown between the reference period and the 2080’s than for the 2030’s. Using the modelled discharge as the reference, March through to July show slight increases in mean monthly discharge. August through to November show large increases in mean monthly discharge while December through to February again shows increases or decreases, depending on the scenario chosen.

Figure 4.40 displays mean monthly discharge as a proportion of mean annual discharge using climate change scenarios for the 2080’s. Changes in discharge regime as predicted by the scenarios are similar to those for the 2030’s, with increases in the proportion of mean annual discharge for the period June through to September and decreases for the period December through to February. The largest increase is in August and the largest decrease is in January.

4.4.7 Seasonal Discharge

The response of seasonal discharge using climate change scenarios for the 2030’s is shown in Figure 4.41. Using the modelled discharge (verification period) as the reference, there is a slight increase in autumn, winter and spring mean seasonal discharge for future climates. Mean seasonal discharge in summer decreases under the CSIRO scenario but increases under the HadCM2 scenario and remains unchanged under the MMA scenario.
Figure 4.37: Rangitata catchment mean monthly discharge predicted for the 2030’s.

Figure 4.38: Rangitata catchment discharge regime predicted for the 2030’s.
Figure 4.39: Rangitata catchment mean monthly discharge predicted for the 2080’s.

Figure 4.40: Rangitata catchment discharge regime predicted for the 2080’s.
Figure 4.42 shows the seasonal discharge response under climate change scenarios for the 2080's. Autumn shows a relatively minor increase, winter an increase and spring a large increase in mean seasonal discharge. Summer again shows a decrease under the CSIRO scenario, but an increase under the HadCM2 scenario, and no change under the MMA scenario. The CSIRO scenario shows a change of discharge pattern with spring becoming the season with highest mean discharge, as opposed to summer under the current climate. This scenario retains a low winter discharge. The HadCM2 and MMA scenarios show an evening up of the mean spring and summer discharges, and of the mean autumn and winter discharges.

<table>
<thead>
<tr>
<th>Season</th>
<th>Recorded</th>
<th>Modelled</th>
<th>CSIRO</th>
<th>HadCM2</th>
<th>MMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>autumn</td>
<td>80</td>
<td>60</td>
<td>120</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>winter</td>
<td>60</td>
<td>40</td>
<td>100</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>spring</td>
<td>100</td>
<td>80</td>
<td>140</td>
<td>160</td>
<td>180</td>
</tr>
<tr>
<td>summer</td>
<td>120</td>
<td>100</td>
<td>160</td>
<td>180</td>
<td>200</td>
</tr>
</tbody>
</table>

Figure 4.41: Rangitata catchment mean seasonal discharge predicted for the 2030’s.

4.4.8 Summary of Results for the Rangitata Catchment

The calibrated version of the HBV3-ETH9 model provides a reasonable fit of recorded versus modelled discharge for the present climate as represented by the calibration and the verification periods. Under future climate change scenarios, discharge is most predominantly altered during spring. Higher peak discharges are predicted during spring under all scenarios, especially for the 2080’s. These changes are generally beyond the range of modelling error. Total annual discharge increases under all scenarios except for the CSIRO 2030’s scenario. The discharge regime of the Rangitata catchment changes, with a greater proportion of discharge occurring during spring and a smaller proportion occurring during summer.
4.5 Rakaia Catchment

4.5.1 Catchment Characteristics

The Rakaia catchment covers an area of 2585 km², of which 58 km² is glaciated. A 60 km length of the Main Divide of the Southern Alps makes up the north west boundary of the catchment area. The gauging station at the gorge is at 280 metres above sea level and the highest peak is Mt Arrowsmith at 2795 m. This gives the catchment a total elevation range of 2515 m. The basement rock type is mainly greywacke. Vegetation within the catchment is diverse, ranging from improved pasture to forest patches. Tussock associations make up large areas of the catchment. Above about 1500 m, the tussock associations start to make way to herb fields, scree and bare rock.

Figure 4.43 shows the hypsography of the Rakaia catchment above the Gorge. More than 50 per cent of the Rakaia catchment is below 1000 m in elevation. Within the catchment, 60 per cent of the slopes face east, west or are horizontal. Only 18 per cent face north and 22 per cent face south. The largest glaciers extend to as low as 1000 m terminating in pro glacial lakes. The glaciers in the catchment mostly face south making up 37 per cent of the glacial area. North facing glaciers make up just 10 per cent of the glacial area. The remaining 53 per cent of glacial area is split between the east and west facing slopes or is horizontal. Also shown in Figure 4.43 is the position of the rain gauge relative to the rest of the catchment.
Figure 4.43: Rakaia catchment hypsography and glacial extent.
4.5.2 Climate Change Scenarios

Climate change scenarios as used for the Rakaia catchment are given in Table 4.9. As with the other three catchments, the scenarios created by three different GCMs show variability, especially with the predicted changes in precipitation. The temperature changes predicted for the Rakaia catchment for the 2080's are also slightly higher than for the catchments further south.

4.5.3 Calibration and Verification

Table 4.10 displays $R^2$ values of model efficiency for the calibrated HBV3-ETH9 model of the Rakaia catchment. As shown, modelling results are inconsistent. $R^2$ values for the calibration period range from as low as 0.40 to as high as 0.84. Verification period $R^2$ values range from 0.45 to 0.83. Calibrated parameter values for the Rakaia catchment are given in Table 4.11.

Hydrographs of recorded and modelled discharge for the hydrological year 1992/93 are shown in Figure 4.44. The hydrological year 1992/93 is used because it is a typical modelling result for the catchment. It has an $R^2$ value of 0.68. Recorded versus modelled hydrographs for the other years within the verification period are given in Appendix B. Typical HBV3-ETH9 modelling traits for the Rakaia catchment as shown by Figure 4.44 include under estimation of base flow and under estimation of flood peaks throughout the year. This has the effect of cumulative modelling difference always being positive as shown by Figure 4.45 for the example hydrological year. The cumulative difference usually ranges from 100 mm to 300mm during the verification period as shown by the other cumulative difference figures within Appendix B.

A scatter plot of recorded and modelled discharge for the example hydrological year (1992/93) is given in Figure 4.46. This illustrates the under estimation of flood peaks by the model with all of the high discharge values being below the line of perfect fit. Base flow values are also clustered below the line of perfect fit. There is a large scatter of points particularly for discharge above base flow.
Table 4.9: Climate change scenarios for the Rakaia catchment (temperature changes in degrees Celsius ($\Delta T$) and precipitation changes as per cent differences ($\Delta P$)). Each scenario is named after the GCM used to generate it. Source: derived from Mullan et al. (2001).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Month</th>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
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<tbody>
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<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
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<td>ΔP (%)</td>
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<td>-10.6</td>
<td>-5.7</td>
<td>2.6</td>
<td>1.2</td>
<td>-4.0</td>
<td>-4.0</td>
<td>-4.1</td>
<td>-8.1</td>
<td>-6.7</td>
<td>-0.9</td>
<td>3.2</td>
<td>-6.3</td>
</tr>
<tr>
<td><strong>CSIRO</strong></td>
<td>ΔT</td>
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<td>1.9</td>
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<td>2.0</td>
<td>2.0</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
<td>1.9</td>
<td>1.9</td>
<td>1.8</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>2080's</td>
<td>ΔP</td>
<td></td>
<td>1.9</td>
<td>4.7</td>
<td>9.4</td>
<td>2.7</td>
<td>1.2</td>
<td>-8.1</td>
<td>-5.0</td>
<td>-1.9</td>
<td>12.8</td>
<td>15.8</td>
<td>11.4</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>HadCM2</strong></td>
<td>ΔT</td>
<td></td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.5</td>
<td>0.8</td>
<td>0.9</td>
<td>0.7</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>2030's</td>
<td>ΔP</td>
<td></td>
<td>8.8</td>
<td>7.0</td>
<td>2.4</td>
<td>3.5</td>
<td>8.4</td>
<td>13.8</td>
<td>22.6</td>
<td>24.6</td>
<td>16.8</td>
<td>6.9</td>
<td>0.4</td>
<td>8.8</td>
</tr>
<tr>
<td><strong>HadCM2</strong></td>
<td>ΔT</td>
<td></td>
<td>1.1</td>
<td>1.2</td>
<td>1.3</td>
<td>1.2</td>
<td>1.5</td>
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<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>2080's</td>
<td>ΔP</td>
<td></td>
<td>4.1</td>
<td>3.3</td>
<td>-1.2</td>
<td>5.9</td>
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<td>27.7</td>
<td>40.4</td>
<td>41.6</td>
<td>28.8</td>
<td>20.1</td>
<td>11.5</td>
<td>15.2</td>
</tr>
<tr>
<td><strong>MMA</strong></td>
<td>ΔT</td>
<td></td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>0.9</td>
<td>1.0</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>2030's</td>
<td>ΔP</td>
<td></td>
<td>3.0</td>
<td>3.2</td>
<td>2.5</td>
<td>3.4</td>
<td>6.1</td>
<td>7.6</td>
<td>13.0</td>
<td>9.4</td>
<td>7.0</td>
<td>2.0</td>
<td>2.7</td>
<td>4.3</td>
</tr>
<tr>
<td><strong>MMA</strong></td>
<td>ΔT</td>
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<td>1.6</td>
<td>1.7</td>
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<td>2.0</td>
<td>2.1</td>
<td>1.9</td>
<td>1.7</td>
<td>1.4</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>2080's</td>
<td>ΔP</td>
<td></td>
<td>13.0</td>
<td>11.2</td>
<td>9.3</td>
<td>7.7</td>
<td>14.5</td>
<td>18.1</td>
<td>24.1</td>
<td>20.7</td>
<td>16.3</td>
<td>11.7</td>
<td>10.2</td>
<td>12.9</td>
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</table>
Table 4.10: R^2 values of model efficiency for the Rakaia catchment during the calibration and verification periods.

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<tr>
<th>Year</th>
<th>R^2</th>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
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<td>1988</td>
<td>0.65</td>
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<tr>
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<td>0.64</td>
</tr>
<tr>
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<td></td>
</tr>
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<td>1993</td>
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<tr>
<td>1994</td>
<td>0.83</td>
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</tbody>
</table>

Figure 4.44: Recorded discharge versus modelled discharge for the Rakaia catchment - example of the hydrological year 1992/93.
Table 4.11: Calibrated input parameters of the HBV3-ETH9 model for the Rakaia catchment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
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</tr>
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<td>CMax</td>
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</tr>
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<td>RExp</td>
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</tr>
<tr>
<td>CRFR</td>
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</tr>
<tr>
<td>PGrad</td>
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<td>TGrad</td>
<td>-0.70 °C 100 m^{-1}</td>
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<tr>
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</tr>
<tr>
<td>LP</td>
<td>150 mm</td>
</tr>
<tr>
<td>FC</td>
<td>200 mm</td>
</tr>
<tr>
<td>BETA</td>
<td>0.10</td>
</tr>
<tr>
<td>LUZ</td>
<td>19 mm</td>
</tr>
<tr>
<td>WET</td>
<td>0.09</td>
</tr>
<tr>
<td>CPerc</td>
<td>2.7 mm d^{-1}</td>
</tr>
<tr>
<td>K0</td>
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<td>K2</td>
<td>0.040</td>
</tr>
<tr>
<td>K3</td>
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</table>
Figure 4.45: Cumulative difference between recorded discharge and modelled discharge for the Rakaia catchment - example of the hydrological year 1992/93.

Figure 4.46: Scatter plot of recorded discharge versus modelled discharge for the Rakaia catchment - example of the hydrological year 1992/93.
4.5.4 Hydrograph Responses to Climate Change

Using the hydrological year 1992/93 as the reference, Figure 4.47 shows the changes expected using climate change scenarios for the 2030's. Only very small differences are predicted. During the period of spring, floods are predicted to increase in size by the HadCM2 and MMA scenarios. The CSIRO scenario does not predict this increase. For the rest of the year there are no noticeable changes between the modelled current climate and the future climate under the three scenarios.

Figure 4.48 displays the situation under climate change scenarios for the 2080's. Again using the modelled current climate as the reference, the HadCM2 modelled scenario predicts an increase in the volume of winter and spring peak discharges. Base flow under the HadCM2 scenario increases only slightly in winter and spring. Summer and autumn discharge remain unaltered under the same scenario. The CSIRO scenario shows the same pattern of change, but smaller increases in peak discharge volumes. The MMA scenario predicts very similar changes to the HadCM2 scenario.

![Figure 4.47: Modelled hydrographs for the Rakaia catchment's present climate (reference year 1992/93), and for the 2030's using different climate scenarios.](image-url)
Figure 4.48: Modelled hydrographs for the Rakaia catchment’s present climate (reference year 1992/93), and for the 2080’s using different climate scenarios.

4.5.5 Cumulative Discharge Response

Displayed in Figure 4.49 is the cumulative discharge response of the Rakaia catchment under climate change scenarios for the 2030’s. Recorded and modelled cumulative discharge do not show a strong agreement. Modelled cumulative discharge under estimates recorded cumulative discharge during the entire year. When the scenarios are compared to modelled discharge it is seen that the CSIRO scenario predicts very little change in cumulative discharge. The HadCM2 and MMA scenarios on the other hand predict an increase in total cumulative discharge of about 250 mm. These two scenarios show the greatest divergence from modelled cumulative discharge during August.

The cumulative discharge response under climate change scenarios for the 2080’s is shown in Figure 4.50. The CSIRO scenario predicts an increase in cumulative discharge of 250 mm. The MMA and HadCM2 scenarios also predict increases in cumulative discharge of 500 mm and 600 mm respectively. As for the 2030’s, the greatest divergence of cumulative discharge for the scenarios from modelled cumulative discharge occurs during August. This is true for all three climate change scenarios for the 2080’s.
Figure 4.49: Mean cumulative discharge from the Rakaia catchment for the current climate and using different climate scenarios for the 2030’s.

Figure 4.50: Mean cumulative discharge from the Rakaia catchment for the current climate and using different climate scenarios for the 2080’s.
4.5.6 Discharge Regime Response

Predicted mean monthly discharge from the Rakaia catchment in the 2030's is given with recorded and modelled mean monthly discharge for the current climate in Figure 4.51. Relatively minor changes are predicted by each of the modelled scenarios. In general, slight increases in mean monthly discharge are expected for almost all months under the HadCM2 and MMA scenarios of climate change. The only large increase these two scenarios show is for the month of August. The CSIRO scenario shows a small increase in mean monthly discharge for the period of April to November, but a small decrease for the period of December to February.

When the mean monthly discharge is shown as a proportion of mean annual discharge as in Figure 4.52, only small changes in the discharge regime are predicted. Small mean monthly discharge proportion decreases are predicted by all scenarios for the period of December to February compared to the modelled discharge for the current climate. Small proportion increases are predicted by all scenarios for the period of June to September, with the largest proportion increase in August.

The effect of climate change scenarios on the mean monthly discharge from the Rakaia catchment for the 2080's is given in Figure 4.53. The HadCM2 and MMA scenarios predict very similar patterns of change. Large increases in mean monthly discharge are predicted for the period of May to October compared to the modelled current climate. Small increases are predicted for all other months except February where a small decrease is predicted. The CSIRO scenario of climate change predicts a small decrease of between 15 and 45 cumecs in mean monthly discharge for the period from December to February. For the rest of the months a small increase is predicted by the CSIRO scenario, with the largest increases of about 50 cumecs during the period from August to November.

Figure 4.54 displays changes to the discharge regime expected from these changes in mean monthly discharge for the 2080's. The proportion of discharge during December to March decreases. During the period of June to October, mean monthly discharge as a proportion of mean annual discharge increases. August has the largest increase in proportion of mean annual discharge. All climate scenarios predict a similar pattern of change, however the HadCM2 scenario predicts the largest changes and the CSIRO scenario the smallest changes.
Figure 4.51: Rakaia catchment mean monthly discharge predicted for the 2030’s.

Figure 4.52: Rakaia catchment discharge regime predicted for the 2030’s.
Figure 4.53: Rakaia catchment mean monthly discharge predicted for the 2080's.

Figure 4.54: Rakaia catchment discharge regime predicted for the 2080's.
4.5.7 Seasonal Discharge

The response of seasonal discharge for the Rakaia catchment under climate change scenarios for the 2030's is shown in Figure 4.55. Changes predicted are small in comparison to mean seasonal discharges of the current climate. The HadCM2 scenario does however predict an increase in mean winter discharge of nearly 50 cumecs compared to modelled mean winter discharge for the current climate. Each of the scenarios predict increases for mean seasonal discharge in all seasons except for mean summer discharge under the CSIRO scenario.

Figure 4.56 displays predicted mean seasonal discharge under climate change scenarios for the 2080's. The largest changes are predicted for winter and spring. Under the HadCM2 scenario, mean winter discharge increases nearly 100 cumecs and mean spring discharge 50 cumecs. The CSIRO scenario predicts mean winter discharge to increase by about 30 cumecs and spring discharge by about 50 cumecs. The MMA scenario predicts an increase of around 70 cumecs in winter and 50 cumecs in spring. Mean summer discharge remains similar compared to modelled mean summer discharge for the current climate. The CSIRO scenario predicts that mean summer discharge will decrease slightly. All three of the climate change scenarios for the 2080's predict a small increase in mean autumn discharge.

Figure 4.55: Rakaia catchment mean seasonal discharge predicted for the 2030’s.
4.5.8 Summary of Results for the Rakaia Catchment

The results of the calibrated version of HBV3-ETH9 model for the Rakaia catchment are inconsistent during the calibration and verification periods. Under climate change scenarios for the Rakaia catchment, discharge is most predominantly predicted to change during August. A large increase in mean monthly discharge is predicted by all three scenarios during this month for the 2080’s. Total cumulative discharge increases under all scenarios of climate change except for the CSIRO scenario for the 2030’s. The discharge regime is predicted to change under climate change scenarios for the 2080’s with a higher proportion of discharge in winter and spring than under the current climate. Only the CSIRO scenarios predict a decrease in mean discharge for any season, with this being mean summer discharge both for the 2030’s and 2080’s.

4.6 Chapter Summary

The HBV3-ETH9 runoff model produces consistent results for the Jollie and Rangitata catchments over the calibration and verification periods. The Rakaia and Hooker catchments produce less satisfactory modelling results. The climate change scenarios predict an increase in discharge from all catchments, with the largest changes predicted
for the 2080's. Discharge regimes show very little change under the scenarios for the 2030's. Climate change scenarios for the 2080's predict a greater proportion of annual discharge to occur during winter and spring, with a smaller proportion in summer. Only the CSIRO scenario predicts summer discharge to decrease from the Rangitata and Rakaia catchments. Results for the Hooker catchment predict large increases in summer discharge. Winter and spring discharge are predicted to increase from all catchments.

Table 4.12 gives a summary of per cent changes in seasonal discharge from each catchment under the MMA scenario for the 2080's. It shows that, in terms of per cent change, winter discharge is most affected, and summer discharge is least affected. The greatest change (per cent) is predicted for the Hooker catchment, while the smallest change is predicted for the Rakaia Catchment. It is important to note that summer discharge is not predicted to increase from the Rangitata or Rakaia catchments. Appendix C gives a full comparison between the three scenarios and four catchments.

Table 4.12: Summary table giving per cent changes in seasonal discharge from each catchment under the MMA scenario for the 2080's.

<table>
<thead>
<tr>
<th></th>
<th>Jollie</th>
<th>Hooker</th>
<th>Rangitata</th>
<th>Rakaia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>28</td>
<td>42</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Summer</td>
<td>11</td>
<td>32</td>
<td>-1</td>
<td>0</td>
</tr>
<tr>
<td>Autumn</td>
<td>26</td>
<td>36</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>Winter</td>
<td>82</td>
<td>85</td>
<td>69</td>
<td>61</td>
</tr>
<tr>
<td>Spring</td>
<td>22</td>
<td>32</td>
<td>25</td>
<td>23</td>
</tr>
</tbody>
</table>
Chapter 5

Discussion

5.1 Introduction

Recent studies overseas have shown alpine catchment discharge to be highly sensitive to predicted global climate change (Braun et al., 2000; Morrison et al., 2002). Yet in New Zealand, the response of alpine catchment water resources to climate change has received little attention in the literature. This thesis attempts to address this gap by investigating the potential effect of climate change on discharge from the eastern Southern Alps.

The Chapter starts with a discussion of modelling catchment discharge from the eastern Southern Alps and what can be learnt from the application of the HBV3-ETH9 model. The results of this thesis provide good evidence that alpine catchment discharge in the eastern Southern Alps can be modelled effectively with the HBV3-ETH9 conceptual runoff model. Variability in the results needs to be addressed to provide improved modelling performance. Also discussed are the likely causes of error in the model and options for improvement. Potential for wider application of the HBV3-ETH9 model is then considered. The effect of climate change on alpine catchment discharge is then explored along with a methodological discussion. Finally, a pathway is proposed for selecting the best methodology to investigate the impact of climate change on the water resources of any catchment.
5.2 Modelling Alpine Catchment Discharge

5.2.1 Application of the HBV3-ETH9 Model

Model error has two possible sources. The first is model function whereby the model incorrectly replicates the real processes. The second is input data of a poor quality. To improve model performance it is important to identify the most likely sources of error (either function or input data based).

Precipitation

For any hydrological model to be successful in predicting discharge, the input precipitation must be correct. Unless the precipitation input is accurate, the modelled discharge will inevitably be inaccurate. Therefore the first place to investigate cause for model error must be precipitation input.

The HBV3-ETH9 model uses point precipitation from a single rain gauge and correction factors (RCF, SCF, PGrad) to calculate areal precipitation. This method accepts that rainfall is too variable in space and time to measure accurately for model input. Therefore the only way to know how much rain fell on a catchment is to record discharge, hence the need for a calibration process in hydrological modelling.

The calibration process assumes that all storms have the same precipitation distribution pattern across the catchment. Therefore the same correction factor can be applied for all storms as recorded by the rain gauge to produce the areal precipitation total. It is unlikely all storms have the same distribution pattern. Accordingly, the calibration process producing a single correction factor is unlikely to produce an accurate areal precipitation total.

The Jollie catchment produces the best model performance. A likely reason, is that it has a more uniform distribution of precipitation than the other catchments. It is approximately 15 km east and almost parallel to the Main Divide of the Southern Alps. Hence is not subject to the same intense horizontal precipitation gradient as the other three catchments, which border the Main Divide and extend east.

Precipitation input to the model is supposed to be representative of the whole catchment (Konz, 2003). This is difficult in catchments where large precipitation gradients exist. The model structure as used only accounts for an altitudinal precipitation gradient, not for any horizontal gradient of decrease with distance from the Main Divide associated with spillover. A potential solution for this problem is to re-organise the structure of the model so as to create sub-catchments of uniform precipitation input. These could then be linked to give total discharge from the macro-catchment.
A second potential reorganisation of model structure could use more than one precipitation correction factor. A different precipitation correction factor could be assigned based on wind direction or type of storm. This would improve accuracy of precipitation input and thus model performance.

Changing the model structure, may however not be the best option. A better solution may be to create a synthetic series of precipitation data (Konz, 2003). This would require working out the areal precipitation of individual events to generate a precipitation time series. This would then be used as model input. The lack of high-resolution measured precipitation data would make this task difficult.

Andréassian, Perrin, Michel, Usart-Sanchez and Lavabre (2001) agree that hydrological models give better performance and reduced variability in performance (higher R² values) with improved areal precipitation estimates. They also show that calibrated parameter values can also be sensitive to imperfect precipitation data. In effect, some parameters settings compensate for the under or over estimation of areal precipitation. This is also considered to be the case by (Moore, 1993) in an application of a different version of the HBV model.

El Niño - Southern Oscillation (ENSO) is known to influence precipitation distribution in New Zealand (Kidson, 1996). Yet there is no relationship between model performance and the Southern Oscillation Index (SOI) (see Appendix E). Further, comparison of R² values between the four catchments reveals an unrelated pattern throughout the modelled years (see Appendix E). This implies that there is no overriding phenomenon affecting model performance.

This leads to the premise that, within catchment areal precipitation variability is a likely cause of poor model performance and variability in performance. Further evidence for this includes:

- Strong model performance and low variability in performance for the Jollie catchment.
- Weaker model performance and increased variability in performance for the Hooker and Rakaia catchments.

Understanding the relationship between the recorded precipitation and areal precipitation is one of the keys to accurate hydrological modelling. If the relationship is constant, simple within model correction is adequate. However, if the relationship is variable, further work will be required to provide high performance modelling results.
Temperature

Although the climate record available requires that mean daily temperature be estimated from daily maximum and minimum values, this may be a poor reflection of the true mean temperature on some days. Highly variable weather as in the Southern Alps means that the length of time associated with the daily maximum and minimum may not be equal. Therefore there may be error generated by using estimated mean daily temperatures. There is a need for higher temporal resolution of temperature data for the Southern Alps. Data loggers can easily record temperature data. Having hourly data available would improve the estimation of mean daily temperature. This would improve model accuracy through improved modelling of the snow pack.

Mass Balance and Snow Data

The model simulates mass balance of glaciers and seasonal snow within the catchments. This modelling cannot however be adequately verified. This is because there is no snow course data available within the study area. Modelled snow pack is compared to end-of-summer snow lines but this does not confirm the models ability to accurately represent the snow pack.

The degree-day method of modelling snow ablation, although simplistic, has been used successfully in previous studies in the South Island (for example Moore and Owens (1984b). This model has not been tested here, but it is proposed that the modelled snow pack must be within acceptable error limits given the accuracy of modelled discharge. Future studies should however investigate how well the modelled snow pack compares with the actual snow pack as derived from thorough field measurements of snow accumulation and melt.

Temporal Resolution

The HBV3-ETH9 model was run at a daily time step, as this was the temporal resolution of the available input data (precipitation, temperature and discharge). Greater accuracy could be achieved with a shorter time step. This has been suggested before by Moore (1984) after his alpine hydrological modelling study in the Craigieburn Range (New Zealand). Moore and Owens (1984a) recommend a time step of three hours or less for data collection and modelling. Shorter time steps would better match the temporal variability of hydrologically important processes such as snow accumulation and melt.
Discharge

Measured discharge for each of the four catchments has been taken as correct, but this may not be the case. Each discharge-gauging site is natural riverbed and subject to change. This has the potential to alter the stage-discharge relationship and thus introduce error. This can happen during a single event. Even discharge recorded by a well maintained weir or flume may have an error of up to five per cent (Beven, 2000). A gauging site with a moveable natural riverbed, will have an error considerably greater than a weir or flume (Beven, 2000). The possible extent of recorded discharge error must be taken into consideration when evaluating R² values.

The desired recording standard of Environment Canterbury (Rangitata discharge values) is ± 8 per cent of the actual value 95 per cent of the time (Gray pers. comm., 2003). It is possible that the recorded discharge meets the ± 8 per cent figure for periods of moderate flow where many gaugings confirm the stage discharge relationship. However, there is likely to be considerable error in the recorded peak discharge values where extrapolation of the rating curve has taken place. For example, maximum recorded discharge for the Rangitata is 2964 m³/s, while the maximum gauged discharge is only 1405 m³/s (Gray pers. comm., 2003). Therefore peak discharge values are likely to have error greater than 8 per cent.

Tuck (pers. comm., 2003) considers the recorded Hooker discharge (ultrasonic sensor) to be within ± 5 per cent. Given the sources of error in recording discharge, this is perhaps a little optimistic for peak discharge values. An error of 10 per cent or greater is perhaps a better estimate for these values.

Three of the catchments studied (Jollie, Hooker and Rangitata) are largely uninfluenced by human development, but the Rakaia has a hydro power station. Water is diverted from the Wiberforce and Harper tributaries and stored in Lake Coleridge. This means that the hydrograph as recorded is not the natural discharge hydrograph of the catchment. Unfortunately a corrected record was not available. The exact influence of the power station on discharge is unknown, but discharge from the power station peaks at around 40 cumecs (Bowden, 1983). It is likely that modelling results for the Rakaia catchment could be improved using a record corrected for the influence of the Coleridge power station.
Baseflow Representation

The results indicate that the model has a poor representation of baseflow for both the Rangitata and Rakaia catchments. As shown in Figures 4.30 and 4.44 baseflow is generally underestimated. Gauging runs by Environment Canterbury indicate that the total water discharging from each of the sub catchments in the headwaters during baseflow is less than the discharge recorded at Klondyke (Gray pers. comm., 2003). This indicates that water is being stored in the deep sediment in the braided section of the catchment above the gorge and released slowly as baseflow. The baseflow function of the model is unable to replicate the shape of the hydrograph created by this process.

Another possibility also exists to explain the poor baseflow representation. Baseflow generally occurs during winter. The model has no representation of the freeze thaw cycle that would slowly release water from the soil adding to a higher than predicted baseflow and lower flood peaks in winter. Possible evidence for this is shown in Figure 4.30 where winter flood peaks are overestimated, while baseflow is underestimated.

Flood Representation

Large flood peaks are poorly estimated with frequent underestimation. It is possible that larger storms have more variable precipitation, leading to variable modelling results. Another possibility is that melt is incorrectly estimated during northwesterly storm events where the degree-day factor has been shown to be substantially higher than the values used for modelling (Cutler, 2002). A definitive reason for the models poor representation of flood peaks requires more detailed precipitation data and analysis.

5.2.2 Model Efficiency

Braun et al. (2000) were able to achieve R² values of 0.86 to 0.90 during verification using the HBV3-ETH9 model in alpine catchments within the Oetztal Alps. Bergström (1976) using earlier versions of the HBV model achieved R² values ranging from 0.10 to 0.97 in a range of different catchments. Moore (1993) in an application of a version of the HBV model in British Columbia, Canada, achieved R² values ranging from 0.53 to 0.92.

In New Zealand, Moore and Owens (1984a) applied a version of the HBV3 model to Camp Stream in the Craigieburn Range. R² values of 0.72 to 0.81 were achieved during the calibration, but model performance during verification was poor with R² values
being 0.52 to 0.53. The short period of data available for calibration and verification was a limiting factor along with the model structure being unable to account for the total discharge through parameter adjustment. It is likely that the HBV3-ETH9 model applied to the same data would produce better results through its precipitation and groundwater loss correction.

Grimmond (1980) applied the Martinec Model to the Fraser catchment (Central Otago, New Zealand), which is heavily influenced by seasonal snow. Two different calibrated versions of the model produced $R^2$ values of -0.75 to 0.72 and -0.04 to 0.63. Turner (1986) applied a Soil Moisture Accounting model and the Martinec Model again to the Fraser catchment. Again the results were poor, with $R^2$ values for the Soil Moisture Accounting model during the verification period ranged from -0.85 to 0.27 and for the Martinec Model ranged from -0.42 to 0.28.

Table 5.1 compares the model efficiency results of the current study to those of comparable studies overseas and within New Zealand. It can be said that the HBV3-ETH9 model performs less well than in comparable studies overseas. However when compared to studies in New Zealand it has performed strongly. The HBV3-ETH9 model has produced results that are consistent between the calibration and verification periods for all four catchments. From year to year, the Hooker, Rangitata and Rakaia catchments produce a range of $R^2$ values. However, the Jollie catchment produces consistently high $R^2$ values.

In past studies, it seems many hydrological modellers in New Zealand have regarded the precipitation as recorded by a rain gauge to be a good estimation of the actual precipitation for the whole catchment. This is not the case and may in part explain previous poor model performance results. However recorded precipitation is likely to have a relationship with the areal precipitation of the catchment. Therefore, a model either, requires input of precipitation data that has been synthetically adjusted, or needs to be able to account for the relationship between point precipitation and areal precipitation within its own structure.

### 5.2.3 Potential for Wider Application

A hydrological model that can accurately predict discharge based on a few key, simple, inputs would be highly beneficial to hydrologists researching the alpine catchment water resource in New Zealand. As we come to understand more and more the climate variability on a yearly, decadal and even longer time period, it becomes possible to predict with more certainty associated changes in water resources.
Table 5.1: Comparison of model efficiencies (calibration period = CP and verification period = VP).

<table>
<thead>
<tr>
<th>Author</th>
<th>Area</th>
<th>Model</th>
<th>Model efficiency ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CP</td>
<td>VP</td>
</tr>
<tr>
<td>Bergström (1976)</td>
<td>Norway</td>
<td>HBV-3</td>
<td>0.88</td>
</tr>
<tr>
<td>Moore (1993)</td>
<td>Coast Mountains, Canada</td>
<td>Adapted HBV-3</td>
<td>0.79 - 0.91</td>
</tr>
<tr>
<td>Braun et al. (2000)</td>
<td>Oetztal Alps, Austria</td>
<td>HBV3-ETH9</td>
<td>0.87 - 0.93</td>
</tr>
<tr>
<td>Grimmond (1980)</td>
<td>Central Otago, New Zealand</td>
<td>Martinec</td>
<td>-0.75 - 0.72</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>-0.04 - 0.63</td>
</tr>
<tr>
<td>Moore and Owens (1984a)</td>
<td>Craigieburn Range, New Zealand</td>
<td>HBV-3</td>
<td>0.72 - 0.81</td>
</tr>
<tr>
<td>Turner (1986)</td>
<td>Central Otago, New Zealand</td>
<td>Martinec</td>
<td>0.29 - 0.71</td>
</tr>
<tr>
<td>Current Study</td>
<td>Southern Alps, New Zealand</td>
<td>HBV3-ETH9</td>
<td>0.56 - 0.88</td>
</tr>
<tr>
<td></td>
<td>Jollie catchment</td>
<td></td>
<td>0.57 - 0.72</td>
</tr>
<tr>
<td></td>
<td>Hooker catchment</td>
<td></td>
<td>0.52 - 0.88</td>
</tr>
<tr>
<td></td>
<td>Rangitata catchment</td>
<td></td>
<td>0.40 - 0.84</td>
</tr>
<tr>
<td></td>
<td>Rakaia catchment</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In general, climate data has been recorded for longer periods than discharge data. This means that climate variability is better understood than the corresponding discharge variability. For example the Interdecadal Pacific Oscillation (IPO) affects the climate of New Zealand and has shown up in the climate records. Discharge data does not however exist for the corresponding time period, so it is not known how the IPO influences discharge. The HBV3-ETH9 model could be used to predict the changes in water resource under each phase of the IPO cycle.

The discharge record, for any catchment where climate data exists, could be extended. This is limited to catchments where calibration and verification are possible. A long-term synthetic discharge record could be used to give a better idea of such things as variability in drought and flood frequency.

A model of real time snow pack development and melt coupled to a hydrological model would allow for better planning and management of stored water resources. It would take the guesswork out of predicting the volume of water stored as snow that contribute to spring and summer discharge. Half way through summer it would be possible to know how much water was still likely to come from melt.

5.3 Potential Effect of Climate Change on Discharge

This section focuses on the modelling results under the climate change scenarios as presented in Chapter 4. Inferences are also drawn about the impact on the total alpine catchment water resource in Canterbury. The results of this study are compared to those of others and water resource management issues are considered.

5.3.1 Changes in Annual Water Yield

The results show that annual water yield from each of the modelled catchments will increase with current expected climate change. In the Jollie, it is predicted to increase by between 15 to 30 per cent by 2080, and in the Hooker by between 35 to 40 per cent by 2080. The annual water yields from the Rangitata and Rakaia are predicted to increase by between 10 to 25 per cent by 2080. These increases are beyond the range of modelling error in all except for the Rakaia where a 10 percent increase is at the same level as model error.

However the results are problematic, especially for the Hooker catchment. When the water balances for each catchment (Appendix D) are analysed, it can be seen that significant amounts of the discharge are made up from negative glacier mass
balance. For example, in the Hooker catchment under the CSIRO scenario for the 2080’s, 2264 mm of the 9769 mm discharge comes from negative glacier mass balance. Such supply from long-term water storage would not be sustained for long. The total discharge must decline as the glacial area shrinks.

Therefore it is important to also consider the total precipitation input for each scenario versus the current climate. Three scenarios for the Hooker catchment predict reduced precipitation input (CSIRO 2030’s, MMA 2030’s and CSIRO 2080’s). Although the modelling predicts an increased discharge of about 25 per cent using the CSIRO 2080’s scenario, it is more than likely that discharge will in fact be reduced in line with the precipitation once glacial area has shrunk. This behaviour has been demonstrated by Braun et al. (2000), where simulated discharge increases with fixed present day glacial extent and global warming, but decreases if reduced glacial area is taken into account. The increased discharge is in reality the release of glacial water storage. Once glacial water storage runs out, discharge then decreases.

The model then may be more appropriate for catchments where glaciers play a less dominant role in the water balance, unless glacial area changes are considered. This would require a dynamic glacier mass balance model. Verifying such a model would be difficult at present, given the lack of mass balance measurements for glaciers in the Southern Alps.

The verification period for each catchment is used to represent the current climate when analysing the results. The verification period is only five years long for the Jollie, Rangitata and Rakaia catchments, and only three years long for the Hooker catchment. This is a problem because the verification period may be a poor representation of the current climate. This shows the importance of high quality, long-term data records. On reflection, using the entire calibration and verification period to represent the current climate may have been more appropriate.

5.3.2 Changes in Seasonal Discharge Regime

The results show that the discharge proportion will increase in winter and early spring and decrease in summer by 2080 for all catchments. Although the proportion of discharge decreases in summer, total summer discharge only decreases under the CSIRO scenario for the Rangitata and Rakaia catchments. It is likely that the summer discharge from the Hooker catchment is over estimated for the 2080’s. This is because much of the water released by the unsustainable negative glacier mass balances is part of the modelled summer discharge. Summer discharge for the other three catchments is likely to be only slightly over estimated.
To explain the change producing a greater proportion of winter and spring discharge two factors need to be addressed. The first is the proportion of precipitation falling as snow. This is shown in Table 5.2 and taken from analysis of the water balance components given in Appendix D. Under all of the climate change scenarios the proportion of precipitation falling as snow decreases. Therefore there is a smaller proportion of water stored as seasonal snow and released in spring and summer. Although the proportion of snowfall decreases, the total snowfall does not always decrease (see Appendix D).

The second factor is the climate scenarios themselves. Under the HadCM2 and MMA scenarios the greatest precipitation increases occur during winter and early spring. The CSIRO scenario on the other hand predicts a precipitation decrease for winter and large increase in spring. The result is that the CSIRO scenario produces large increases in spring discharge while only minor increases in winter discharge as shown in Figure 4.40.

Changes in seasonal discharge are therefore the result of two factors:

- Large precipitation increases in winter and early spring (HadCM2 and MMA scenarios) and spring (CSIRO scenario).
- Predicted temperature increase resulting in a smaller proportion of precipitation falling as snow.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Jollie</th>
<th>Hooker</th>
<th>Rangitata</th>
<th>Rakaia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current climate</td>
<td>31</td>
<td>40</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>CSIRO 2030’s</td>
<td>27</td>
<td>34</td>
<td>36</td>
<td>26</td>
</tr>
<tr>
<td>HadCM2 2030’s</td>
<td>30</td>
<td>39</td>
<td>39</td>
<td>27</td>
</tr>
<tr>
<td>MMA 2030’s</td>
<td>28</td>
<td>36</td>
<td>36</td>
<td>26</td>
</tr>
<tr>
<td>CSIRO 2080’s</td>
<td>20</td>
<td>27</td>
<td>28</td>
<td>19</td>
</tr>
<tr>
<td>HadCM2 2080’s</td>
<td>26</td>
<td>35</td>
<td>34</td>
<td>22</td>
</tr>
<tr>
<td>MMA 2080’s</td>
<td>23</td>
<td>30</td>
<td>30</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 5.3: Comparison of climate change studies.

<table>
<thead>
<tr>
<th>Author</th>
<th>Area</th>
<th>Model type</th>
<th>Key findings</th>
</tr>
</thead>
</table>
| Griffiths (1990) | New Zealand              | Water balance and “contributing specialists” | • No Change in annual discharge close to the Main Divide and up to 40 % decrease east of the Main Divide.  
• Less water in late spring and early summer caused by less snow.  
• Temporal runoff pattern change with snowmelt about one month earlier. |
| Garr (1992)     | South and central Southern Alps | Water balance      | • Under the “most likely” scenario, annual discharge increases 12 %.  
• Winter and spring discharge increase for the central Southern Alps.  
• Summer discharge decreases.                                                                                           |
| Braddock (1998) | Hooker catchment         | Empirical          | • 80 % increase in annual discharge by 2070.                                                                                               |
| Current study   | Central Southern Alps    | Conceptual         | • Annual discharge increase ranging from 10 - 40 %.  
• An increase in the proportion of winter and early spring discharge, and a decrease in the proportion of summer discharge.  
• Increases in winter and spring peak discharges.                                                                   |
5.3.5 Water Resource Management Issues

Infrastructure and river protection works are often designed to estimates of flood size recurrence, which are based on historical discharge values. With a changing climate predicted to increase discharge values, the historical records should be considered a poor predictor of future flood risk. It is likely that for any given flood size, recurrence times will shorten for the alpine catchments studied, and infrastructure design specifications may need to be re-evaluated. Leong et al. (1992) found that a 15 per cent increase in precipitation during an event would result in a 20 per cent increase in peak flow, and a ‘100 year flood’ would become a ‘33 year flood’. A precautionary approach may be needed if the life expectancy of a piece of infrastructure is more than 50 years.

Electricity generation is likely to benefit from predicted global climate change. There will be more generation potential as a result of the increased annual discharge. Increased winter discharge will help improve the alignment of peak electricity consumption with water availability. This is similar to the findings of Garr (1992). In general, it can be said that there will be no negative effect on the ability to generate electricity using the alpine catchment water resource. However, managers will have to be aware of the increased flood risk.

Irrigation users are not likely to benefit from the increased annual discharge. The major increases in discharge come during the winter and spring months when it is of little use. Under the CSIRO scenario it is likely that irrigation users will suffer increased water shortages due to the decreased summer discharge. The only way to ensure water supply may be harvesting and storage of extra discharge during spring. Competition for the summer water resource will continue between consumptive and instream users.

5.4 Predicting the Effects of Climate Change

This section discusses methodological insights gained from this research. The processes of selecting a hydrological model and scenarios for a climate change impact study are considered. Use of the HBV3-ETH9 model for climate change impact studies is appraised and the scenarios used for the current study are also assessed. A qualitative assessment of the error involved in such hydrological impact studies is made. Finally, a methodological selection process is proposed for assessing the impact of climate change on catchments.
5.4.1 Selecting a Hydrological Model

The Literature review shows that there is a clear order of preference in selecting model type for impact studies. Empirical models should not be used. The order of preference is, (i) physically based models, (ii) conceptual models, (iii) water balance models. Model choice is not just about this order of selection as input data availability also needs to be considered. It determines the feasibility of applying any particular model to a given catchment. In general, input requirements are easier to meet down the model type preference list. Model validation is the next consideration. If the model cannot be validated for the current climate, it cannot be used to predict discharge for the future climate.

A physically based model was not chosen for this study because of input data requirements and limited previous use of such models in New Zealand. However, it should be considered the ultimate objective of hydrologists in New Zealand to apply climate scenarios to a physically based model. Such an application will not be possible until there has been extensive research applying and validating such a model in New Zealand's alpine catchments. A research catchment may need to be established to collect and maintain a database on the right temporal and spatial scale.

Model Appraisal for Climate Change Impact Studies

Braun et al. (2000) considered the HBV3-ETH9 conceptual runoff model to be “especially suited to the investigation of hydrological consequences of climatic changes”. However, it is necessary to consider the climatic transferability of the model. The less climatically transferable the model is, the greater doubt is placed on the results. Further, the strength of the approach is dependent on how well the model simulates the major processes and interactions within the catchments. Model appraisal is considered in order of water movement through the model structure (see Figure 3.3).

Meteorological input variables are corrected by the parameters RCF, SCF, and T0. The relationship between the measured variable and the 'actual' value for that variable, averaged over the whole catchment is assumed to remain constant with a changing climate. Given that the distribution of precipitation is likely to change and temperature changes are not expected to be uniform, there is perhaps a problem with this assumption. For example, the relationship between the point measured precipitation and the areal catchment precipitation may change. This could happen through a change in the direction of dominant storm activity, or a change to spillover characteristics of precipitation along the Main Divide.
The snow and glacier routine is separated into two parts, the seasonal snow pack and melt water produced from glacial areas. Considering the seasonal snow pack first, the degree-day approach to modelling seasonal snow works well where melt is a function of temperature (Konz, 2003). The only reason for doubting the climatic transferability of the parameters within this method is related to the energy balance for melt. For example, if sensible heat flux density, which is currently the dominant energy source for melt (Cutler, 2002), became less dominant to say the net all-wave radiation flux density, then the degree-day factor would change. This would result in the model being non-climatically transferable.

No research has considered how the energy balance of melting snow is likely to change under predicted global climate change, but it can be discussed qualitatively. If cloud cover increases with increasing precipitation, it is likely to decrease the net all-wave radiation flux density, increasing the importance of turbulent energy flux for melt. This will increase the contribution of sensible heat flux density for melt. Therefore the relationship between measured temperature and melt will change (degree-day factor). The potential effect of global climate change on the energy balance of snowmelt needs to be quantified.

The model, as used, does not have a dynamic representation of glacial area. The glacier area represented under the various climate scenarios remains the same as under the current climate. This is clearly a poor assumption. Glacial area is likely to be reduced under a warmer climate. The exact extent of this glacial area reduction is unknown because each individual glacier reacts differently to climate. Glacier response to climate change in the studied catchments is beyond the scope of the current study. It is definitely an important issue for refinement of the results.

The sensitivity of the soil moisture routine parameters to climate change is difficult to assess. The first consideration is evaporation. The structure of the model requires potential evaporation to remain unchanged for the climate change scenario runs. However, actual evaporation can change depending on modelled soil moisture under the climate scenarios. In general, this resulted in modelled evaporation increasing slightly under the climate change scenarios (see Appendix D). Evaporation is a small part of the water balance in the catchments studied and any change to evaporation is likely to have a small impact as suggested in the literature review. Griffiths (1990) also assumed no significant change in evaporation in his study of the influence of climate change on annual water yield in New Zealand.
The model parameters FC and BETA are representations of catchment field capacity and the release of water from the soil. If the pattern of precipitation distribution changes, these calibrated parameters could be in error. This is because these parameters are for the catchment averaged conditions under the current climate. If one area of the catchment receives more of the precipitation input, as happens for the Rakaia and Rangitata, the calibrated parameters will represent the release of water from that part of the catchment. If the area of the catchment producing the most significant proportion of the discharge changes, it is likely FC and BETA will also change.

The response function is designed to replicate the shape of the discharge hydrograph, which is a function of many catchment and climate characteristics as shown in Chapter 2. Many of these, including some catchment characteristics, are specific to the current climate. The climatic transferability of the parameters controlling the response function is likely to be questionable. Hence the daily model output needs to be treated with caution.

Using a lumped model where changes are not expected to be uniform is a problem. For example, the model uses one value of precipitation input for catchments with non-uniform precipitation, and assumes that this relationship will continue to hold for future climates. By their nature lumped models are limited in their ability to deal with non-uniform change of input values.

Calibration implies uncertainty for climatic transferability of hydrological models (Bonell, van Dam and Jones, 1999). There must be doubts about the climatic transferability of any conceptual model. However, results from the HBV3-ETH9 conceptual discharge model, are still considered to be indicative of likely change under predicted global climate change.

### 5.4.2 Scenario Generation

There is a clear order of preference for scenario generation. Hypothetical scenarios can be used where GCM data is not available, but if GCM data is available the order of preference is: (i) dynamically downscaled scenarios (regional climate model), (ii) empirically downscaled scenarios and (iii) raw GCM scenarios.

The scenario generation data currently available in New Zealand, and used for this study, is empirically downscaled results from GCMs. Recent research has been working towards a regional climate model for New Zealand (Bhaskaran, Renwick and Mullan, 2002). This model requires further refinement before it is able to produce an accurate representation of New Zealand’s climate variables. It could then potentially
be used to develop dynamically downscaled scenarios of climate change. This should be considered the ultimate goal for future climate change impact studies in New Zealand.

**Scenario Appraisal**

The strength of any given climate scenario is its ability to represent future climates. The scenarios used in the current study are percentage changes in precipitation and degrees Celsius changes in temperature from the reference climate period (1970–1990). These predicted changes are then used to adjust the historic time series of climate data. This retains the natural variability of the current climate. The only problem with this is that the variability of the climate may be altered by global climate change.

Such scenarios are least realistic for precipitation change. The method as used, in effect, increases the intensity of storm where precipitation increase is expected (and decreases the intensity of the storm where precipitation is expected to decrease). This may be unrealistic. The method does not consider possible changes in storm frequency and duration as might be expected under an intensification of the hydrological cycle. It could be improved by using meteorological time series of statistically downscaled data. This would be a synthetic temperature and precipitation time series that would have climatic variability as predicted by the GCM. Discharge characteristics could then be compared to the baseline climate discharge characteristics.

Statistical downscaling is based on an empirical relationship. In the same way that an empirical hydrological model predicts discharge (output) from inputs (such as precipitation and temperature), statistical downscaling creates outputs of climate variables based on their empirical relationship to inputs from GCMs. This approach is flawed. Just as empirical hydrological models are limited in their use for climate change studies, because the climatic transferability of the empirical relationship is questionable (Leavesley, 1999), so to one must question the climatic transferability of the statistical downscaling approach (Bhaskaran et al., 2002). Although statistical downscaling is a commonly used method, and has been shown to be applicable to studies of climate change and hydrology (Cannon and Whitfield, 2002), its use must be questioned.

Dynamic downscaling is a better approach. This is because the regional climate models used in dynamic downscaling predict the climate in their own right using physical processes rather than statistical relationships (Bhaskaran et al., 2002). As they become available, dynamically downscaled scenarios should be used as direct input to hydrological models, rather than per cent change values used to alter historic time series of climate data. This is to retain climatic variability as predicted by the GCM.
A major difficulty is predicting changes in discharge hydrographs brought about by changes in storm direction that may accompany climate change. This is a linkage problem between the scenarios and the hydrological model. Parameters that control the shape of the discharge hydrograph in the model are set for the current climate. Changes in storm direction under climate change may produce discharge hydrographs of different shape. Thus the parameters that control hydrograph shape may not be climatically transferable.

5.4.3 Uncertainty

Kaleris et al. (2001) postulated that there are two steps for quantification of climate change impact on water resources and each step is a source of error. Those steps are:

- "To predict the change of the local hydrological variables such as temperature and precipitation at the basin scale due to modifications of general circulation in the atmosphere."

- "To predict the runoff variation, which is due to changes of the hydrological variables."

Uncertainty exists for each of these steps. Step one can be broken down into two parts, GCM and downscaling uncertainty. It has to be acknowledged that predicting the future climate for a specific location, a specific number of years into the future, is subject to a huge and immeasurable uncertainty.

Step two also has two parts with related uncertainties. Model discharge error and climatic transferability. Model discharge error is measurable and can be removed through model and input data improvement. Climatic transferability, as shown above, is hard to quantitatively assess.

In summary, there is a large degree of uncertainty in climate change impact predictions such as those given by this study. These uncertainties are identifiable, but often not quantifiable. Some of these uncertainties can be removed by methodological improvement, but much of the uncertainty result from limitations in our ability to predict future climates.

5.4.4 Methodological Selection Process

Following the experience of the current study, Figure 5.1 demonstrates a pathway for selecting the best approach to assess the impact of climate change on discharge from
any given catchment. There is no single answer. This reflects the different levels of
data, model and scenario availability. Selection should follow the most appropriate
path until limited by input data, model or scenario availability. The end use of the
output should also be considered. For example, is it necessary to use a daily time step
model structure when investigating annual water yield? Where possible, studies should
work towards achieving the ultimate end goal of physically based hydrological models,
with dynamic downscaled climate scenarios, and an hourly temporal resolution.

This selection process alone does not guarantee reliable results because the modeller
will still have to make judgement calls about the influence of climate change on param-
eters within the chosen model. This is not an easy process. As shown earlier in this
thesis, there is still much uncertainty surrounding such things as, evapotranspiration
and cryosphere changes.
Figure 5.1: Methodological selection process showing the choice path for investigating the impact of climate change on water resources.
Chapter 6

Conclusion

6.1 Overview

This thesis has focused on the impact of global climate change on the alpine catchment water resource of the eastern Southern Alps in Canterbury, New Zealand. The reasons for this focus are twofold. Firstly, the significance of this water resource to the Canterbury region and New Zealand as a whole. Secondly, studies overseas have shown that alpine catchment water resources are highly sensitive to predicted global climate change, but as yet this subject has received little attention in New Zealand.

Two objectives formed the foundation of this thesis. They are:

1. To investigate and present a methodology to assess the impact of climate change on discharge from alpine catchments.

2. To predict the effects of potential climate change on alpine catchment discharge from the eastern Southern Alps of Canterbury.

These objectives are achieved by undertaking a review of the existing literature (Chapter 2) and setting specific research questions (Section 2.6). These questions are:

- Can discharge from catchments in the eastern Southern Alps be modelled successfully for the present climate using a conceptual hydrological model?

- How will global climate change affect the annual water yield from alpine catchments in the eastern Southern Alps?

- How will global climate change affect the seasonal discharge regime of catchments in the eastern Southern Alps?
How will global climate change affect the hydrograph characteristics of catchments in the eastern Southern Alps?

To answer these questions, a methodology (Chapter 3) based on the research strategy of a climate change impact assessment is established. It involves: the selection of a suitable hydrological model (HBV3-ETH9), successfully modelling the discharge under the current climate, and lastly modelling the discharge under plausible future climate change scenarios. The results are presented in Chapter 4 and discussed in Chapter 5. The main findings are summarised below.

6.2 Main Findings

There are several key findings with regard to the first objective, these are:

- There is a clear order of preference for selection of methods within hydrological climate change impact studies. Where data and model availability make it possible, physically based models, with dynamically downscaled climate scenarios should be used at a daily time scale.

- There is unquantifiable uncertainty in the results of hydrological climate change impact studies. Some of this uncertainty stems from the nature of climate scenarios generated from GCM data. Further uncertainty stems from the issue of climatic transferability of calibrated models.

- The HBV3-ETH9 model was chosen for seven reasons: easily met data input requirements, appropriate spatial and temporal scale, distributed snow and glacier representation, simple calibration and verification technique, accurate simulations of discharge in previous studies in several different environments, model availability and previous use for similar climate change studies.

With regard to hydrological modelling of alpine catchments in New Zealand there are five key findings, these are:

- The HBV3-ETH9 conceptual hydrological discharge model is successfully applied to a range of alpine catchments in the eastern Southern Alps of Canterbury. Firstly, the Jollie, which is a small catchment (140 km²) with seasonal snow but very little glacial area (4 km²). Secondly, the Hooker, also a small catchment (104 km²), but highly glacial (46 km²). Thirdly, the Rangitata, a large catchment...
(1460 km²) with glaciers (38 km²) and seasonal snow. Lastly, the Rakaia, also a large catchment (2585 km²) with glaciers (58 km²) and seasonal snow.

- Although modelling performance (as measured by R² values) is weaker than that of comparable studies overseas, it is stronger than comparable New Zealand studies. Calibration and verification period R² values are consistent. Verification period R² values range from, 0.70 - 0.78 for the Jollie catchment, 0.58 - 0.81 for the Hooker catchment, 0.61 - 0.85 for the Rangitata catchment and 0.45 - 0.83 for the Rakaia catchment.

- Within catchment areal precipitation variability is a probable cause of poor model performance and variability in performance. It has been demonstrated that, where a single rain gauge has a consistent relationship with a catchment’s areal precipitation, simple within model precipitation correction factors can be applied. This leads to consistent and strong model performance (for example, the Jollie catchment). Poor model performance stems from using a single rain gauge with a variable relationship to areal catchment precipitation (for example, the Hooker catchment).

- The degree-day method of modelling snow accumulation and ablation seems to be appropriate for hydrological models in Southern Alps catchments. This is shown by strong modelling performance in four catchments where the cryosphere influences discharge. It is possible the method could be further improved by using synoptically variable degree-day factors.

- Temporal resolution greater than the daily time step used in this study could improve model performance. This is because key hydrological processes in the alpine zone, such as the representation of precipitation as rain or snow, occur at a much finer than daily time scale. Finer temporal resolution modelling is currently restricted by the need for collection of finer temporal resolution input data.

This thesis considers four different catchments and applies six different climate scenarios to each. Each scenario has its own predicted influence on discharge. However there are a few features that all scenarios have in common.

- Only small changes in discharge are predicted by the 2030’s, while by the 2080’s large changes are predicted. For example, total cumulative discharge from the
Jollie catchment using the CSIRO scenario does not change by the 2030's while by the 2080's it increases by 250 mm.

- Higher levels of discharge are predicted in all seasons by all scenarios (except under the CSIRO scenario during summer). For example, mean seasonal discharge from the Jollie catchment using the HadCM2 scenario for the 2080's increases by 1.5 m$^3$/s in autumn, 5 m$^3$/s in winter, 3 m$^3$/s in spring and 1.5 m$^3$/s in summer.

- The greatest increases in discharge are predicted for winter and spring. For example, mean winter and spring discharge from the Hooker catchment are predicted to increase by 10 m$^3$/s using the HadCM2 scenario for the 2080's.

- Larger late winter and spring floods are likely by the 2080's. For example, late winter and spring floods double in peak volume under the 2080's HadCM2 scenario for the Rangitata.

- The discharge regime will change with increased proportion of annual discharge in winter and early spring and less discharge proportionally in summer and autumn. For example, mean monthly discharge as a proportion of mean annual discharge from the Jollie catchment during August jumps from 0.6 to 1.1, and during January drops from 1.7 to 1.5 using the HadCM2 scenario for the 2080's.

- The proportion of precipitation falling as snow decreases by 2080. For example, currently 40 per cent of precipitation falls as snow in the Hooker catchment, this reduces to 27 per cent using the CSIRO scenario for the 2080's.

There are three key water resource implications.

- Flood recurrence times for a flood of any given size are likely to shorten for the studied catchments.

- Electricity generation will benefit with increased potential generation and a better alignment with peak consumption.

- Run of the river irrigation users will not benefit from the increased annual discharge with most of the increase being during late winter and spring. Under the CSIRO scenario they could suffer increased water shortages during summer, making water harvesting more important.
6.3 Future Research Directions

This thesis has addressed a gap in the literature by providing an assessment of the impact of predicted global climate change on alpine catchment discharge from the eastern Southern Alps of Canterbury. It provides a basis for improvement in future assessments of the influence of global climate change on New Zealand alpine catchment discharge. Removing shown systematic error and data limitations would provide an impetus for future research in this area.

- Validation of the snow pack modelling within the HBV3-ETH9 model is essential to validate the physical correctness of the model. To achieve this the model would have to be run in conjunction with snow course measurements. This will allow more ‘correct’ determination of other parameters within the model structure by first providing a more accurate account of the snow pack.

- Development of dynamically downscaled scenarios will remove the doubt associated with climatic transferability of empirical downscaling relationships. These would be required at a daily time scale to be able to test for changes in base flow, flood magnitude and frequency.

- A climate change impact study using a physically based hydrological model would provide increased confidence in the results. A physically based hydrological model with no calibration would provide the ultimate evidence that the model was climatically transferable.

- Physically based models as yet are not as applicable to areas with data limitations such as the Southern Alps. Hence conceptual models may still have to be used for future studies. Investigation of the sensitivity of model parameters to climate change will continue to be an important line of research. The fundamental question that needs to be answered is: are conceptual models climatically transferable?

- An increased understanding of areal precipitation is required to improve hydrological modelling performance. Hydrological models using a single point source precipitation input (such as HBV3-ETH9), could benefit from the creation of catchment based, synthetic, areal precipitation time series.

- The best way to achieve many of the above research directives is through development of a long-term project to monitor and research alpine catchment discharge
in New Zealand. This would allow data collection at the spatial and temporal scale necessary to achieve higher quality results. A very intensive study of one or two representative alpine catchments would help more extensive studies of alpine water resources in New Zealand.
References


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Appendix A

Model Efficiency Criterion

The $R^2$ value is known as the Nash-Sutcliffe efficiency criterion as proposed by Nash and Sutcliffe (1970). The value of $R^2$ can range between negative infinity and one, with one being a perfect agreement between the observed and modelled discharge. It is calculated as follows.

$$R^2 = \frac{F_o^2 - F^2}{F_o^2}$$

With $F^2$ (sum of squares of the residuals) and $F_o^2$ (initial variance) calculated as,

$$F^2 = \sum_{t=0}^{T} (Q_r(t) - Q_c(t))^2$$

and

$$F_o^2 = \sum_{t=0}^{T} (Q_r(t) - \bar{Q}_r)^2$$

where $Q_r(t) =$ observed discharge at time $t$, $Q_c(t) =$ modelled discharge at time $t$, $T =$ total period of time and $\bar{Q}_r =$ mean of the observed discharge over time $T$. 

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Appendix B

Modelling Results

This Appendix presents model results for years within the verification period that are not given within Chapter 4.

B.1 Jollie Catchment

The Section contains the model results for the Jollie catchment. The hydrological years 1989, 1990, 1991 and 1992 are presented here. The hydrological year 1993 has been presented in Chapter 4.

B.2 Hooker Catchment

This Section contains the model results for the Hooker catchment. The hydrological years 2000 and 2001 are presented here. The hydrological year 1999 has been presented in Chapter 4. Please note, the scales of the graphs are not uniform between the two years.

B.3 Rangitata Catchment

This Section contains the model results for the Rangitata catchment. The hydrological years 1991, 1993, 1994 and 1995 are presented here. The hydrological year 1992 has been presented in Chapter 4.
B.4 Rakaia Catchment

This Section contains the model results for the Rangitata catchment. The hydrological years 1990, 1991, 1993 and 1994 are presented here. The hydrological year 1992 has been presented in Chapter 4.
Figure B.1: Jollie catchment model results (1989). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.2: Jollie catchment model results (1990). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.3: Jollie catchment model results (1991). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.4: Jollie catchment model results (1992). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.5: Hooker catchment model results (2000). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.6: Hooker catchment model results (2001). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.7: Rangitata catchment model results (1991). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.8: Rangitata catchment model results (1993). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.9: Rangitata catchment model results (1994). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.10: Rangitata catchment model results (1995). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.11: Rakaia catchment model results (1990). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.12: Rakaia catchment model results (1991). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.13: Rakaia catchment model results (1993). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Figure B.14: Rakaia catchment model results (1994). A) Recorded versus modelled hydrographs, B) cumulative difference plot, C) scatter plot.
Appendix C

Comparison of Seasonal Results

This Appendix gives a comparison of seasonal results between catchments and scenarios for the 2080's.
Table C.1: Comparison of seasonal results between catchments and scenarios for the 2080’s. Results given as per cent changes in discharge between the modelled verification period and each climate change scenario.

<table>
<thead>
<tr>
<th></th>
<th>Jollie</th>
<th>Hooker</th>
<th>Rangitata</th>
<th>Rakaia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CSIRO</td>
<td>HadCM2</td>
<td>MMA</td>
<td>CSIRO</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>32</td>
<td>28</td>
<td>41</td>
</tr>
<tr>
<td>Summer</td>
<td>0</td>
<td>13</td>
<td>11</td>
<td>32</td>
</tr>
<tr>
<td>Autumn</td>
<td>22</td>
<td>18</td>
<td>26</td>
<td>41</td>
</tr>
<tr>
<td>Winter</td>
<td>31</td>
<td>98</td>
<td>82</td>
<td>43</td>
</tr>
<tr>
<td>Spring</td>
<td>17</td>
<td>31</td>
<td>22</td>
<td>54</td>
</tr>
</tbody>
</table>
Appendix D

Catchment Water Balances

Catchment water balances are given in this Appendix for the current climate (verification period) and under each of the climate change scenarios.
Table D.1: Modelled annual water balance components for the Jollie catchment averaged over the verification period (1989-1993) for the current climate and each of the climate scenarios. All measurements are in millimetres, including snow which is in millimetres water equivalent. Discharge does not include groundwater losses.

<table>
<thead>
<tr>
<th></th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Snow balance</th>
<th>Glacier balance</th>
<th>Soil and groundwater balance</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snow</td>
<td>Rain</td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current climate</td>
<td>698</td>
<td>1530</td>
<td>2228</td>
<td>331</td>
<td>1</td>
<td>68</td>
</tr>
<tr>
<td>CSIRO 2030's</td>
<td>561</td>
<td>1547</td>
<td>2108</td>
<td>329</td>
<td>0</td>
<td>-35</td>
</tr>
<tr>
<td>HadCM2 2030's</td>
<td>770</td>
<td>1808</td>
<td>2578</td>
<td>344</td>
<td>2</td>
<td>110</td>
</tr>
<tr>
<td>MMA 2030's</td>
<td>648</td>
<td>1704</td>
<td>2352</td>
<td>337</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>CSIRO 2080's</td>
<td>470</td>
<td>1827</td>
<td>2297</td>
<td>342</td>
<td>0</td>
<td>-124</td>
</tr>
<tr>
<td>HadCM2 2080's</td>
<td>736</td>
<td>2064</td>
<td>2800</td>
<td>351</td>
<td>0</td>
<td>54</td>
</tr>
<tr>
<td>MMA 2080’s</td>
<td>613</td>
<td>2036</td>
<td>2649</td>
<td>350</td>
<td>0</td>
<td>-20</td>
</tr>
</tbody>
</table>
Table D.2: Modelled annual water balance components for the Hooker catchment averaged over the verification period (1999-2001) for the current climate and each of the climate scenarios. All measurements are in millimetres, including snow which is in millimetres water equivalent. Discharge does not include groundwater losses.

<table>
<thead>
<tr>
<th></th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Snow balance</th>
<th>Glacier balance</th>
<th>Soil and groundwater balance</th>
<th>Discharge</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Snow</td>
<td>Rain</td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current climate</td>
<td>3660</td>
<td>5453</td>
<td>9113</td>
<td>602</td>
<td>940</td>
<td>-72</td>
</tr>
<tr>
<td>CSIRO 2030’s</td>
<td>2797</td>
<td>5316</td>
<td>8113</td>
<td>603</td>
<td>625</td>
<td>-1162</td>
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<td>604</td>
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Table D.3: Modelled annual water balance components for the Rangitata catchment averaged over the verification period (1991-1995) for the current climate and each of the climate scenarios. All measurements are in millimetres, including snow which is in millimetres water equivalent. Discharge does not include groundwater losses.

<table>
<thead>
<tr>
<th></th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Snow balance</th>
<th>Glacier balance</th>
<th>Soil and groundwater balance</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snow</td>
<td>Rain</td>
<td>Total</td>
<td>Snow</td>
<td>Total</td>
<td>Snow</td>
</tr>
<tr>
<td>Current climate</td>
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<td>1540</td>
<td>2583</td>
<td>361</td>
<td>57</td>
<td>-7</td>
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Table D.4: Modelled annual water balance components for the Rakaia catchment averaged over the verification period (1990-1994) for the current climate and each of the climate scenarios. All measurements are in millimetres, including snow which is in millimetres water equivalent. Discharge does not include groundwater losses.

<table>
<thead>
<tr>
<th></th>
<th>Precipitation</th>
<th>Evaporation</th>
<th>Snow balance</th>
<th>Glacier balance</th>
<th>Soil and groundwater balance</th>
<th>Discharge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Snow</td>
<td>Rain</td>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Current climate</strong></td>
<td>961</td>
<td>2239</td>
<td>3200</td>
<td>274</td>
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<td>2957</td>
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Appendix E

Model Performance and ENSO

This Appendix compares the model efficiency ($R^2$) values to the SOI phase.
Table E.1: $R^2$ values of model efficiency for each modelled year compared to the SOI phase.

<table>
<thead>
<tr>
<th>Hydrological year</th>
<th>Jollie</th>
<th>Hooker</th>
<th>Rangitata</th>
<th>Rakaia</th>
<th>SOI phase</th>
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<td>-</td>
<td>-</td>
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<tr>
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<td>-</td>
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</tr>
<tr>
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<td>-</td>
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