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Combined snow and streamflow modelling to estimate impacts of climate change on water resources in the Clutha River, New Zealand

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Abstract

Global climate is changing in response to increased greenhouse gas concentrations in the atmosphere. This change may have multiple hydrological effects. The most obvious effect of climate change on hydrology is through changes in rainfall patterns, but hydrology is also strongly affected by changing temperatures (e.g., changes in evapotranspiration and snowfall). In this paper we focus on the effects of climate change on the Clutha River, in the South Island of New Zealand. We present an analysis of the projected weekly averaged flows of the Clutha at Balclutha, comparing the current situation (1980-1999) with two future time periods (2030-2049 and 2080-2099) for one "middle of the road" emission scenario, A1B, using data from the IPCC Fourth Assessment Report.

The investigation used the distributed hydrological model TopNet, which includes a snow model. The model was validated against 20-year streamflow records for three locations in the catchment. Climate predictions of 12 different Global Circulation Models for the A1B scenario (as well as the average of those 12) were used as input to the model.

In the future scenarios annual precipitation increases in this catchment. The total yearly streamflow increases as a response (~6% for 2040 scenario and ~10% for 2090 scenario); however the relative contribution of snowmelt to streamflow decreases. The most striking change is in the seasonality of streamflow. Streamflow in winter and spring increases substantially, whereas stream-flow in summer and autumn is relatively unchanged. Two factors contribute to this effect: 1) total precipitation increases over winter and spring (up to 40% in some areas of the catchment for the 2090 scenario), whereas it remains constant or decreases slightly over summer and autumn in some areas, and 2) during winter and spring, precipitation falls more often as rainfall (rather than snow) in the future scenarios.

Introduction

The fact that climate is changing is widely accepted. Many studies consider the extent to which climate is changing (IPCC, 2007; Sansom and Renwick, 2007; Ministry for the Environment, 2008), and estimate the impacts of different climate scenarios on, for example, snow and hydrology (Bavay *et al.*, 2009; Stahl *et al.*, 2008; Bormann, 2009; Jiang *et al.*, 2007; Buytaert *et al.*, 2009; Young *et al.*, 2009). To translate climate change scenarios to the potential reaction of the environment, model assessments of future climate impacts have become a standard tool (Bavay *et al.*, 2009).

In this research we use a combined snow and streamflow model to examine the hydrological impacts of climate change for the Clutha catchment, in the South Island of New Zealand. The Clutha is the largest catchment in New Zealand and an economically important river for New Zealand. The Clutha hosts two hydropower stations, providing 14% of New Zealand's hydropower generation capacity (Ministry of Economic Development, 2009). It provides water for irrigation in one of New Zealand's driest regions, and the water demand is expected to grow with the increasing number of dairy farms and other agriculture. Furthermore the lakes and their surroundings have an important recreational value, which gives the area a very high potential for development.

The streamflow regime of the Clutha could be affected not only by climate change through changes in rainfall, but also directly by changes in temperature, in particular through changing snow patterns, and changing evapotranspiration. The headwaters of the Clutha catchment receive a substantial amount of snow, which accounts for part of the streamflow generation. Snow is very sensitive to climate change, especially snow cover in mountain regions (Stewart, 2009).

Several studies have investigated the effect of climate change on mountain snow cover, both from measured data (Stewart, 2009; Mote *et al.*, 2005) and model studies (Hendrikx *et al.*,submitted; Lapp *et al.*, 2005). These studies typically predict pronounced changes in the snow pack. These changes include permanent snow lines retreating, snow accumulation moving to higher altitudes and changing timing of snow melt.

Studies have also been carried out to quantify the impact of climate change on snow, water resources and floods (Bavay *et al.*, 2009; Stewart, 2009; Horton *et al.*, 2006; Barnett *et al.*, 2005). Results are unanimous that climate change will have a significant effect on snow pack and hence streamflow regime, which will also react to changes in precipitation and evapotranspiration demand. For example, Bavay *et al.* (2009) found that under climate change scenarios snow melt would occur during a short time in late spring (as opposed to a more prolonged period under current conditions), producing a high volume but short runoff peak. Stewart (2009) analysed worldwide changes in snowpack over the last few decades and emphasized that mountain regions receive higher annual precipitation under climate change, which can influence the snowpack, with the amount and timing of melt changing in the same or opposite direction as warming alone would indicate. Impacts of climate change on mountain snow accumulation and melt must therefore be interpreted as a simultaneous response to both temperature and precipitation change in the context of the characteristics of a particular location. Earlier, Horton *et al.* (2006) found that for glacierized catchments, the simulated regime modifications are mainly due to an increase in mean temperature and its corresponding effect on snow accumulation and melting processes. The hydrological regimes of catchments located at lower altitudes were more strongly affected by changes in seasonal precipitation. Horton *et al.* (2006) additionally found that the predicted climate change scenarios resulted in a significant decrease of the total annual discharge and in a shift of the monthly maximum discharge to earlier periods of the year, due to the combined impact of increased temperature and decreased precipitation in the Swiss Alps, resulting in changes to snow melting processes. Borman (2009) concluded that for five regions in Germany, which vary in present and projected climate, the seasonal variability in runoff and soil moisture will increase. Barnett *et al.* (2005) showed that the model-predicted changes of seasonal shifts in streamflow are already being seen in the observed data.

The aim of this paper is to extend previous work on the hydrological effects of climate change on snow and to assess the total impact of climate change on the streamflow behaviour of the Clutha, of which snow melt is one of the determining factors. The paper focuses on the Clutha as a whole, with Balclutha being the furthest downstream station studied. The following research questions will be investigated:

- How will annual streamflow patterns in the Clutha River change as result of projected climate change?
- What are the causes of these changes and what are their relative magnitudes?

To estimate the effects of climate change on the water resources in the Clutha we will compare for current conditions and the future scenarios:

- input precipitation and the fraction that falls as snow;
- changes in the contribution of snow melt to streamflow;
- total yearly streamflow at Balclutha, both quantities and timing;
- seasonality of streamflow at Balclutha.

The study was undertaken using TopNet, a distributed hydrological model based on TOPMODEL concepts, combined with kinematic wave river routing and an integrated snow model (Clark *et al.*, 2008; Beven and Kirkby, 1979; Beven, 1997; Clark *et al.*, 2009). Projected changes in New Zealand's climate are used based on the A1B scenario of greenhouse gas emissions (IPCC, 2007). Changes are specified for 2040 and for 2090, relative to the climate of 1990. A 20-year period is used for all climate runs (e.g., a period of 1980–1999 for the current climate). For uncertainty estimation, climate change scenarios from 12 different Global Climate Models (GCMs) are used (Mullan and Dean, 2009), as well as the average of the 12 GCMs.

In this paper we first describe the catchment and the model used for the combined snow and streamflow modelling. The calibration and current catchment behaviour are discussed. Next, the chosen climate scenarios are explained and the effects on the water resources in the Clutha are presented, including uncertainty estimation within the model, caused by differences in the 12 GCM climate change projections for the same emission scenarios.

Last, the changes are summarized and future research directions are discussed.

Study area

This study assesses possible future changes in water resources for the Clutha catchment, located in the South Island of New Zealand (Fig. 1). The South Island is a very diverse area, with immense differences in weather and geography. The main geographical feature of the South Island is the Main Divide, the Southern Alps that run from north-east to south-west along the spine of the island, dividing the wet west from the dry east. The Clutha catchment lies on the south-east side of the Divide. Mean annual rainfall varies from over 5000 mm in the headwaters to less than 500 mm around the geographical centre of the catchment (see Fig. 2). The spatial extent of seasonal snow is governed by the winter altitude of the snow-line, which is highly variable at inter-annual scales, but according to Fitzharris *et al.* (1999) averages around 1000 m in winter in this region. Chinn (2001) has documented 576 glaciers in the Clutha catchment, including several larger glaciers such as the Dart, Therma and Volta Glaciers. The glaciers have mean elevations at approximately 2000 m (Chinn, 2001), but make up a very small proportion of the total Clutha catchment by area. With a mean flow of approximately 600 m^3s^{-1} the Clutha River is New Zealand's largest river by volume and it drains 21,960 km^2. The catchment is characterised by its large lakes: Lake Wakatipu, Lake Wanaka and Lake

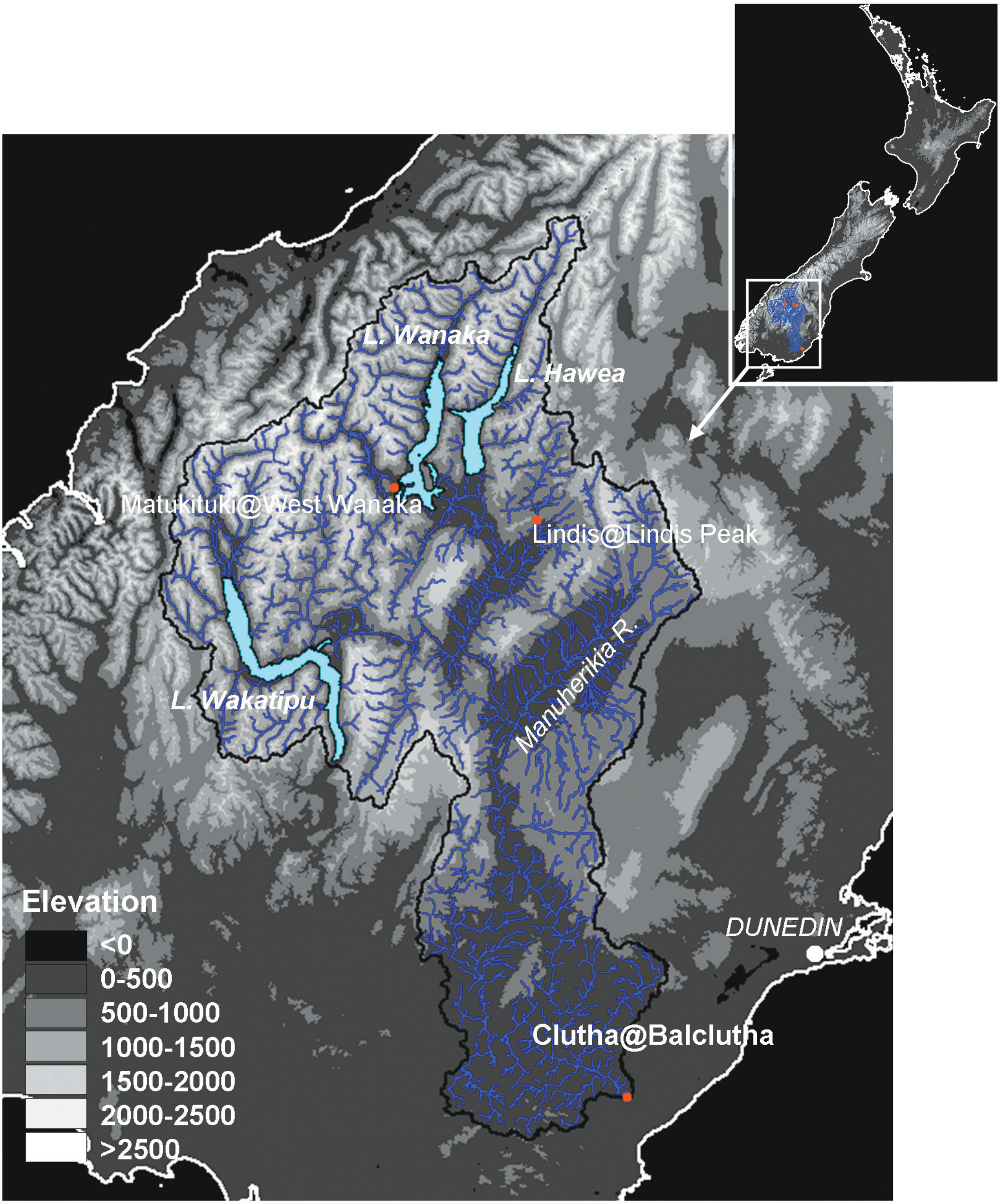

Figure 1 – The Clutha catchment showing the elevation distribution (metres), location of the major lakes and the stream network. Clutha at Balclutha is the outlet of the catchment, and flow recording sites on two key tributaries, Matukituki at West Wanaka and Lindis at Lindis Peak, are also shown.

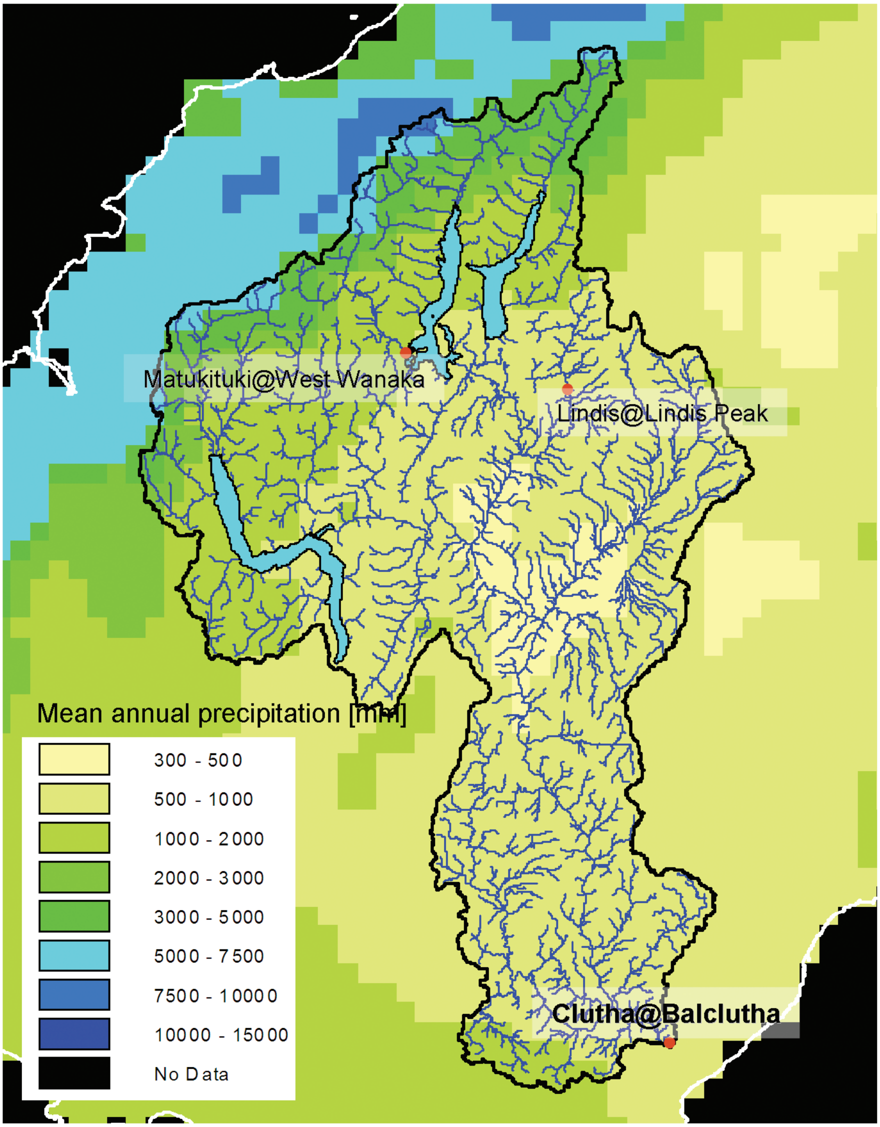

Figure 2 – Mean annual precipitation for the Clutha catchment.

Hawea, as well as the hydropower dams at Clyde and Roxburgh. Lake Hawea's outflow is significantly modified for hydropower production, whereas Lake Wanaka and Lake Wakatipu have natural outflow regimes.

The Clutha catchment is a catchment of opposites: in the northwest it stretches out well into the Alps, with strong alpine influences on the upstream catchments (i.e., high precipitation, partly falling as snow). The southeast side, further downstream, is much drier, especially the Manuherikia and Lindis tributaries. In this study we consider water availability in the Clutha as a whole. Additional detail on within-catchment and within-year variability is given in the section on model calibration, where results are shown for the Matukituki at West Wanaka (an example of a wet catchment with low flows in winter) and for the Lindis at Lindis Peak (an example of a dry catchment with low flows in summer), as well as for the Clutha at Balclutha (the whole catchment).

Methods

Model description

TopNet uses a spatially explicit representation of the Clutha catchment, based on subcatchment boundaries. Subcatchments are defined based on Strahler order, here Strahler order 3, resulting in 2343 subcatchments.

A schematic representation of TopNet is shown in Figure 3. TopNet operates in three steps:

1) In the first step input data, such as precipitation and temperature, is read in and disaggregated to the subcatchment hourly scale (i.e., spatially from station data/ gridded data to subcatchment scale and, if necessary, temporally from daily rainfall data to hourly rainfall data).
2) When input per subcatchment has been calculated, the water balance is solved for each subcatchment for each timestep. In this step the snow module is utilised; it is explained in more detail below. The model calculates water storage in the catchment, divided as canopy storage, snowpack storage, soil storage, shallow aquifer storage and overland flow storage. A detailed description of the water balance can be found in Clark *et al.* (2008) and Clark *et al.* (2009).
3) In the last step streamflow is routed, using a one-dimensional Lagrangian kinematic wave routing scheme, through the stream network to the basin outlet (Clark *et al.*, 2008).

The snow module in TopNet is based on the temperature index method. The module tracks snow quantity in the subcatchment, defined as Snow Water Equivalent (SWE), which is controlled by rate of snow accumulation, the snow melt rate, and the rate of sublimation. Snow is especially sensitive to temperature, so for the snow calculations each subcatchment is divided into elevation bands (100 m vertical distance for the Clutha), which have differing air temperatures calculated using a standard

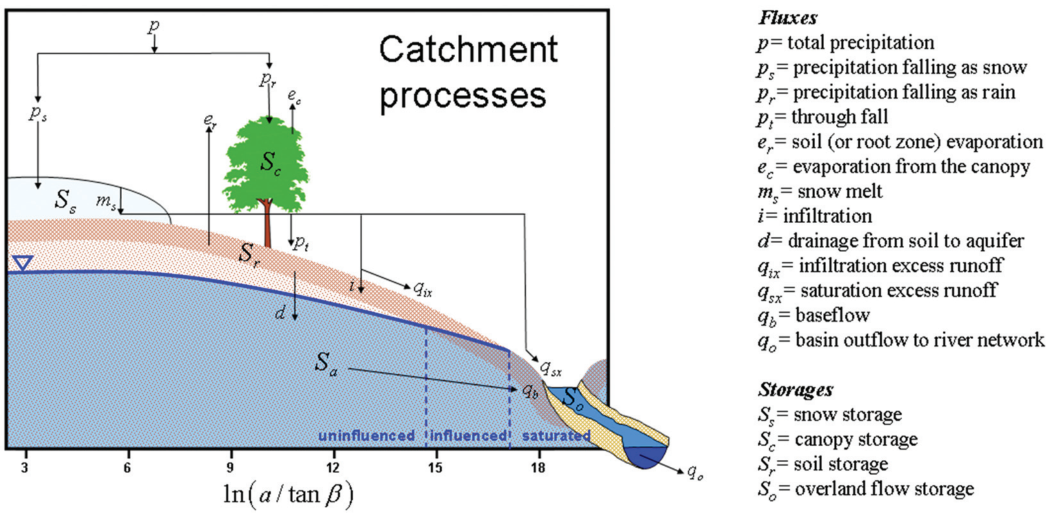

Figure 3 – Schematic representation of TopNet; the topographic index ln(α/ *tan*β) increases towards the stream, indicating areas of topographic convergence and areas where the water table intersects the soil zone.

lapse rate. Snow accumulation and melt is calculated per elevation band and summed to give totals for each subcatchment.

A temperature threshold in the model defines whether precipitation falls as rain or snow. Snow melt is to a large extent controlled by temperature, but a constant relationship between melt and temperature ignores many important melt processes (Clark *et al.*, 2009). Therefore a time-varying melt factor has been introduced, which takes into account seasonality (availability of energy for melt), enhanced melt during rain-on-snow events and changes in albedo (Clark *et al.*, 2009).

Model calibration – theory

For each subcatchment initial values of spatial parameters (e.g., elevation distribution, wetness index, soil hydraulic conductivity, infiltration capacity, overland flow velocity) are estimated based on the New Zealand River Environment Classification (Snelder and Biggs, 2002), the New Zealand Land Resource Inventory and the New Zealand Land Cover Database (Newsome *et al.*, 2000). These initial values do not produce reliable simulations of streamflow, and need to be modified by a parameter calibration process. For model calibration a subset of the spatial parameters are modified, mainly a combination of parameters that define the soil hydraulic properties. The initial spatial distribution for the parameters is preserved, while the parameters in the whole catchment are adjusted uniformly, using a spatially constant set of parameter multipliers. This method provides a necessary reduction in the dimensionality of the parameter estimation problem.

The snow model parameters have been pre-calibrated against a range of measurements (Clark *et al.*, 2009), including 1) measurements of snow water equivalent, 2) water balance estimates of snow storage (Fitzharris and Grimmond, 1982; McKerchar *et al.*, 1998; Woods *et al.*, 2006; Tait *et al.*, 2006), and 3) classification of snow regions (Owens and Fitzharris, 2004; Technical Subcommittee on Snow, 1969). Within the snow model, only the seasonality of the melt factor was varied for the model calibration of the Clutha, by changing the day of the year where the melt factor is highest and the day where it is lowest. In this analysis we set the melt factor minimum to August 5th and the maximum to February 4th.

The model calibration was evaluated for three locations in the Clutha catchment: Balclutha, Matukituki and Lindis (see Figure 1 for locations). The downstream location Balclutha will be used to assess the impacts of climate change, and the results at Matukituki and Lindis are used to improve the distributed model performance. Matukituki is a typically "wet" catchment, with strong alpine influences, whereas Lindis is one of the driest catchments in the Clutha.

The calibration used a semi-automatic method where (5000) initial parameter sets were generated to cover the feasible parameter space for the hydrological parameters. These parameter sets were run from October 1993 until the end of 1994, in order to catch the high flow at the beginning of 1994. From these 5000 parameter sets the highest performing 20 parameter sets for each of the locations (i.e., 60 in total) were then run for a 20-year period (1980–1999), for visual inspection of model output. For the eight best hydrological parameter sets, the seasonality of the melt factor was varied. Model evaluation was based on the following performance measures:

- Nash-Suthcliffe (NS) scores of hourly streamflow were used to assess overall model performance, with a tendency to emphasise flood peaks, on the basis of which the 60 highest performing parameter multiplier sets were selected.
- Cumulative plots of rainfall and modelled versus observed streamflow allow for an estimation of actual (modelled) evapo-

transpiration and an assessment of total volume of streamflow.
- A 20-year average of weekly moving averaged streamflow (modelled versus observed) allows for seasonality of streamflow patterns to be evaluated, including timing of snow melt.

Model calibration – input data

The hydrological/snow model was calibrated using historical precipitation and temperature data from the Virtual Climate Station Network (VCSN) (Cichota *et al.*, 2008; Tait *et al.*, 2006; Tait and Turner, 2005), a compilation of daily climate variables since 1972 for regular gridded points all across New Zealand. The VCSN precipitation data was corrected for spatial bias, based on a water balance approach (Woods *et al.*, 2006). To adjust the recorded daily maximum and minimum temperature data to mean sea level, a fixed 5°K km^{-1} lapse rate was used, consistent with the estimate of Norton (1985), reflecting the humid conditions in New Zealand (Clark *et al.*, 2009). The temperature data at mean sea level were interpolated using a bi-variate spline, after which the temperatures were adjusted back to the subcatchments and elevation bands. In this study, uncertainty in observed data (rainfall, temperature, flow) was not modelled, although sources of data uncertainty have been identified in New Zealand catchments such as the method of interpolating between raingauges and stage-discharge relationships used to calculate flow (McKerchar and Pearson, 1997; McMillan *et al.*, 2010a; 2011), and other sources may directly affect the snow model, such as temperature lapse rate. However, in this study, the uncertainties regarding which IPCC scenario will best approximate future climate, and which GCM is most accurate, were assessed as most important.

Model calibration – robustness

Where a hydrological model is used to forecast river flows in a future climate, it is important to note that this may require the model to be used outside the range of conditions represented in the rainfall, snow and flow data used for calibration. We therefore need to have confidence that the model dynamics will function correctly in the extended set of forecast conditions. This situation can be particularly problematic for 'black-box' models where the model behaviour cannot be linked directly to the physical processes in the catchment. However, the TopNet model has a relatively strong physical basis, and considerable effort has been made to ensure that the dominant rainfall-runoff dynamics are adequately represented by the model. For example, the soil water dynamics of TopNet have been compared with a small-scale 3D Richards Equation model (McMillan *et al.*, 2010b). During calibration, further care is taken to ensure that the model remains realistic: model parameters are bounded to ensure they lie between physically reasonable limits, and model behaviour is checked using multiple diagnostics, including seasonal patterns and model water-balance (refer to previous section).

Model calibration – results and discussion

A qualitative assessment based on expert judgment of all performance measures (see previous section, Model calibration – theory) was used to select an "optimal" parameter set. Figures 4 and 5 show the calibration results for the final parameter set.

Figure 4 shows cumulative plots of the 20-year average of weekly moving averages of precipitation and measured versus observed streamflow for Balclutha, Lindis and Matukituki. The average annual total volume of streamflow at Balclutha is very well predicted by the model. At Lindis it is also very well predicted. At Matukituki the average annual streamflow is slightly underestimated. However, for all measurement locations the percentage differences between modelled and observed streamflow volumes are very small.

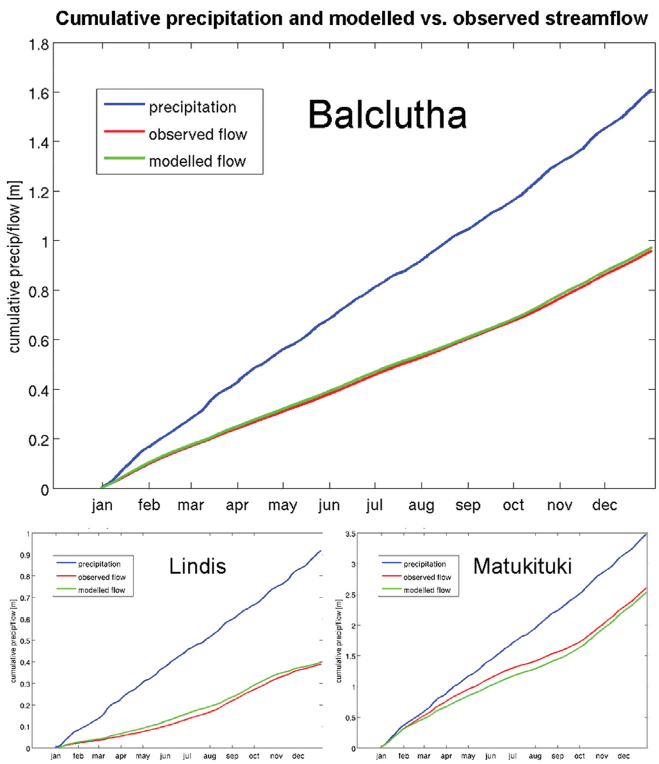

Figure 4 – 20-year average cumulative plot of weekly averaged streamflow for Balclutha, Lindis and Matukituki

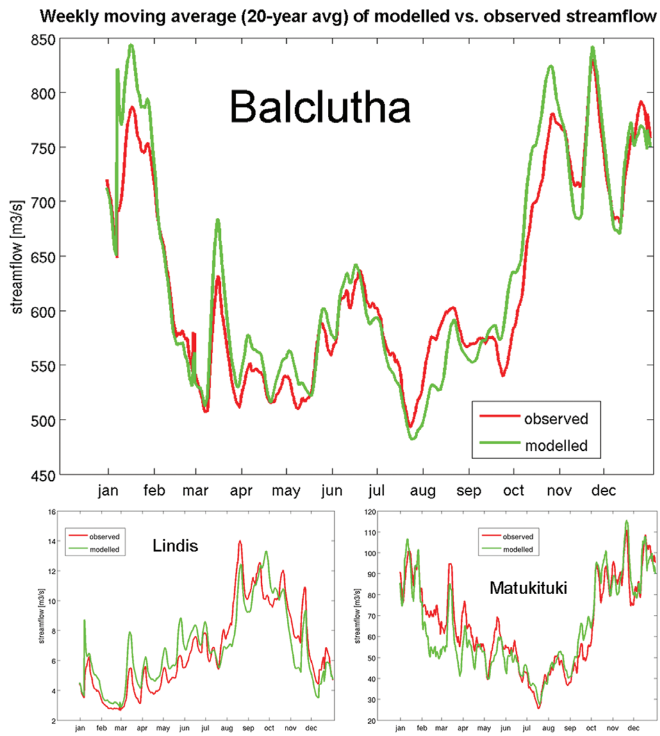

Figure 5 – 20 year average of weekly moving averages of streamflow at Balclutha, Lindis and Matukituki. Nash-Suthcliffe scores are 0.90, 0.81 and 0.86, respectively.

Figure 5 shows the 20-year averages of weekly averaged streamflow (modelled versus observed) for Balclutha, Lindis and Matukituki. This figure shows that the seasonality of streamflow is also very well predicted at all three measurement locations. The Nash-Suthcliffe scores are 0.90, 0.81 and 0.86 for Balclutha, Lindis and Matukituki respectively.

At Lindis a small offset in timing during the year can be observed (a slight overestimation of streamflow volumes in the months March-July and a slight underestimation of streamflow volumes in the months August-December). At Matukituki the model underestimates streamflow volumes, especially in late summer/autumn (February-May), whereas the model overestimates streamflow volumes slightly in late winter (September-October). The underestimation of streamflow in late summer/autumn might be a result of a component of streamflow that is derived from glacier melt rather than snow melt, as there is no representation of glaciers in the model. Chinn (2001) calculated the melt water released due to glacier melting resulting from climate change and estimated this to be between 0.5 and 1 m^3s^{-1} for the Clutha as a whole, when annualized over a 50-year period. This amount is consistent with the magnitude of the underestimate in flow presented in our modeling results, which is 0.62 m^3s^{-1} averaged over all non-flood periods.

It is worth emphasizing that the same set of parameter multipliers is used for the entire Clutha catchment. With this one set of parameter multipliers, the geographic range of streamflow regimes within the Clutha can be simulated, from the dry Lindis catchment with flows that have their minimum in summer, through to the wet Matukituki, whose flows are least in winter. The different regimes can be simulated with the same parameter set because TopNet includes a range of runoff generating mechanisms, which are activated differently, depending on the local climate and catchment characteristics.

Climate change scenarios – theory

Most climate change scenarios are derived from Global Climate Models (GCMs), mathematical models that simulate the behaviour of the global atmosphere and/or ocean. GCMs can be used to simulate current (and past) climate, and also to study future climate scenarios, under different emission scenarios. From the 17 GCMs that were analysed previously, 12 are significantly more accurate in predicting New Zealand climate, based on tests using historical data (Ministry for the Environment, 2008). Those 12 models are used in this study.

GCM predictions cannot be used directly in most climate impact studies, as their grid scale is too coarse. There are several ways of downscaling the results of GCMs, from relatively simple statistical methods which extract change parameters from GCMs and apply those to measured data (i.e., delta-change method) (Mullan *et al.*, 2001; Ministry for the Environment, 2008), to more complicated methods, e.g., embedding a Regional Climate Model (RCM) into a GCM (Drost *et al.*, 2007; Durman *et al.*, 2001). Both types of method have previously been used to assess climate change impacts in New Zealand (e.g., Hendrikx *et al.*, submitted; McMillan *et al.*, 2010a).

Methods based on Regional Climate Models have greater potential to represent the physical processes of interest on a relevant scale and hence simulate them directly (Durman *et al.*, 2001). However, these models currently require significant bias correction to be applied to model results (Boé *et al.*, 2009) and therefore, the statistical delta-change method is chosen for this study.

Climate change scenarios – input data

The method used to define the changes to rainfall and temperature is described in the Ministry for the Environment (MfE) Guidance Manual for Local Government in New Zealand (Ministry for the Environment, 2008). The change scenarios used in this study are derived from statistical downscaling of output from 12 GCMs, and are supplemented by initial analyses from two simulations using NIWA's Regional Climate Model. Ministry for the Environment (2008) provides seasonal and annual percentage changes in precipitation for different stations in New Zealand. In this study emission scenario A1B is used, a "middle of the road" scenario. In Ministry for the Environment (2008) monthly changes are specified for 2040 (an average for a 20-year period from 2030-2049), and for 2090 (2080-2099 average), relative to the climate of 1990 (1980-1999 average).

An empirical method is used to adjust the daily precipitation series, taking into account the mean monthly changes, as well as an adjustment to the distribution to increase the most extreme daily amounts (Ministry for the Environment, 2010). Average monthly precipitation changes are shown in Figure 6 (12-model average for 2040) and Figure 7 (12-model average for 2090). The Clutha catchment boundary is marked with a black line. Figure 6 shows a slight increase in precipitation for most months in the 2040 scenario, except for July-September, where the increase is much more pronounced (up to 25 percent in some areas of the catchment), and except for January, where a slight decrease is predicted. A similar but stronger trend was revealed for the 2090 scenario. In the summer months (January-February) the

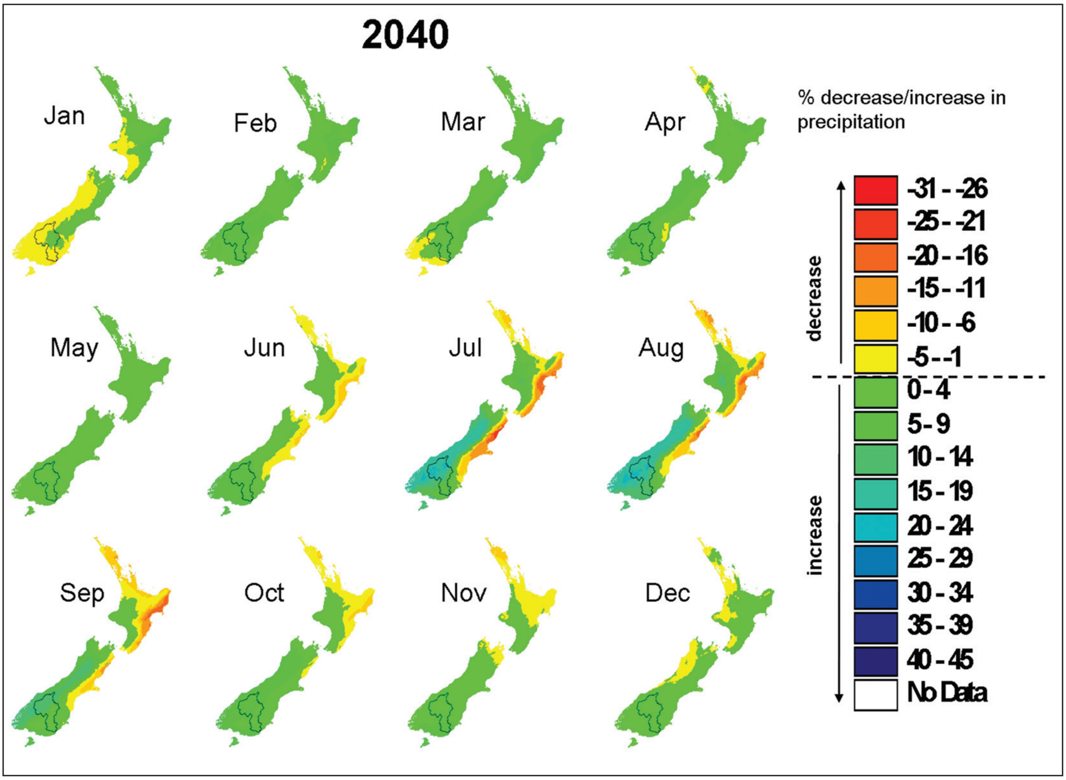

Figure 6 – Percentage change in average monthly precipitation for 2040 scenario (12-model average).

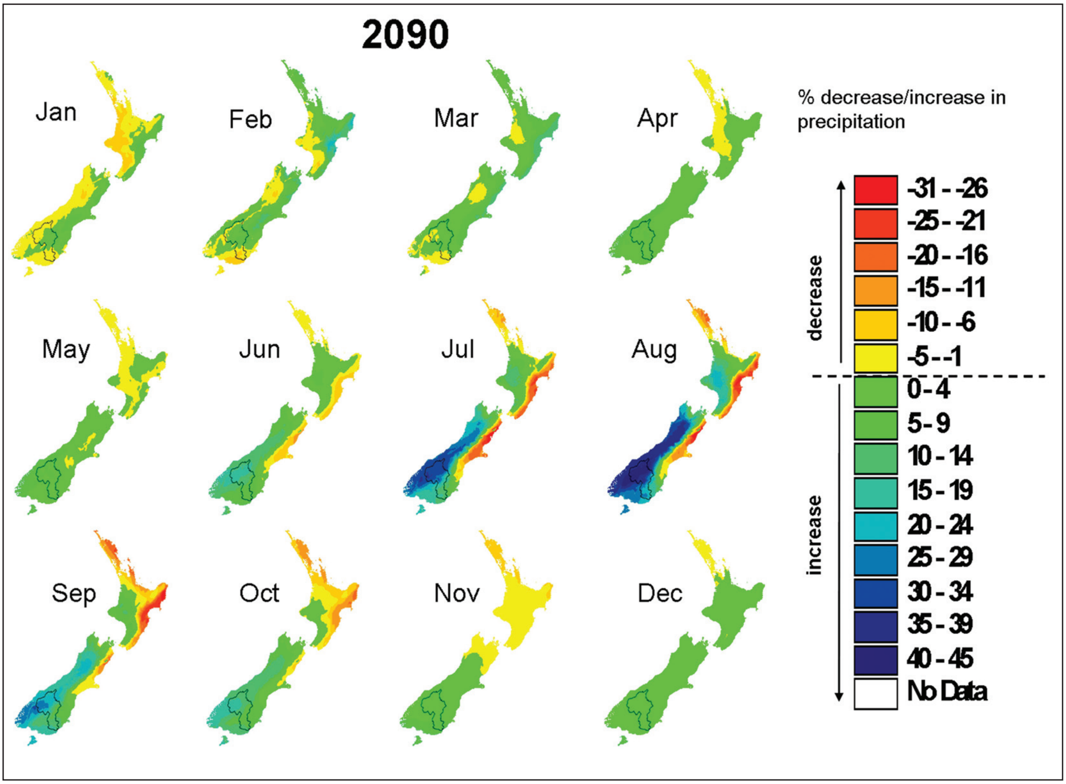

Figure 7 – Percentage change in average monthly precipitation for 2090 scenario (12-model average).

within-catchment differences increase; the central part of the catchment receives slightly more rain, whereas the lowest parts of the catchment become drier. In the winter and spring months precipitation increases up to 40%. For temperature, monthly additive offsets are used directly from Ministry for the Environment (2008).

The primary analysis of climate change impacts on streamflow was carried out using the 12-model average precipitation and temperature changes to give a best single estimate of streamflow changes. Further to this, the analysis was re-done using each of the 12 model predictions for precipitation and temperature individually, to estimate the uncertainty of the streamflow predictions due to choice of GCM.

Results and discussion

Figures 8 to 11 show the predicted impact of climate change on Clutha river flows for each of the 12 GCMs and the average of the 12 GCMs for the A1B emissions scenario for the periods centred around 2040 and 2090.

Figures 8 and 9 show predicted cumulative catchment rainfall, streamflow and snowmelt at Balclutha, for 2040 and 2090 respectively. The figures show an increase in total precipitation for both future time periods, relative to the 1980-1999 period. Total streamflow volume also increases, whereas total snowmelt decreases. Therefore a substantially smaller proportion of the streamflow is generated by snowmelt in future scenarios. This is further illustrated by Figure 10, which shows average monthly snow accumulation as a part of total precipitation at ground surface (i.e., precipitation minus any canopy interception) for the current, 2040 and 2090 scenarios (12-model average). This figure shows a consistent decline in snow accumulation for all months, and especially in late autumn and winter (May-August). Total precipitation remains reasonably constant for summer and autumn, but increases substantially over winter and spring.

Figures 8 and 9 also show the variability of the results within the 12 different GCMs. Most of the individual climate runs show a very similar general picture: increase in total precipitation, increase in total streamflow, and decrease in total snowmelt. However, the range of increase in total average annual precipitation is approximately 0% to 14% for 2040 and -2% to 25% for 2090 (only one of the 12 GCMs predicts a reduction in precipitation for the Clutha). The predicted increase in streamflow ranges from circa 0% to 13% for 2040 and -2% to 20% for 2090 (again only one GCM predicts a negative

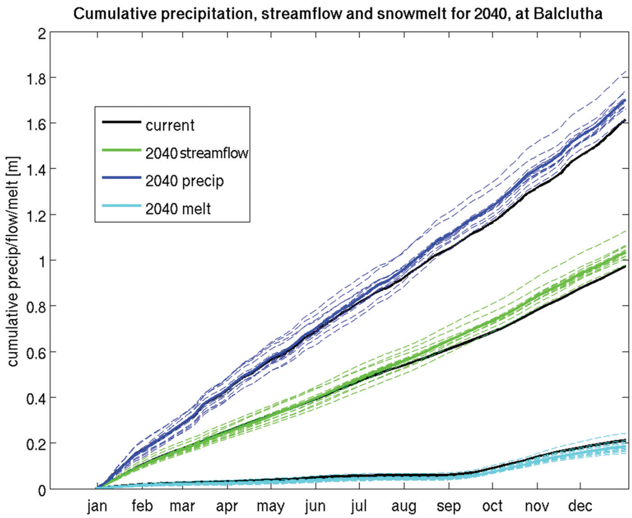

Figure 8 – Cumulative precipitation (dark blue), streamflow (green) and snowmelt (light blue) for 2040, compared to the current scenario (black). The dashed lines are the results of each of the 12 individual climate runs; the solid lines are the results of the 12-model average run.

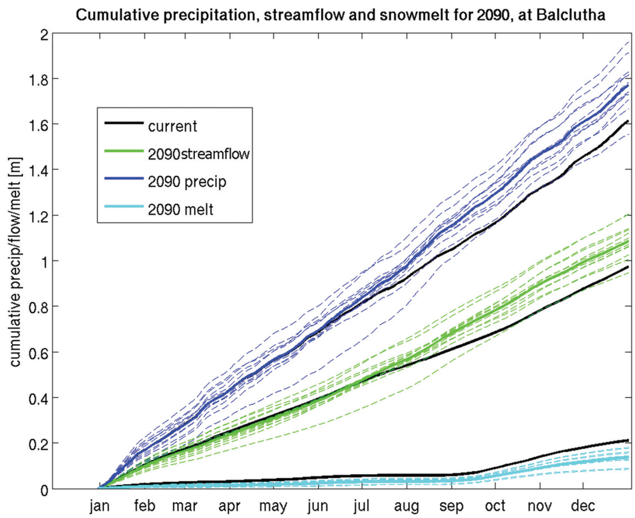

Figure 9 – Cumulative precipitation (dark blue), streamflow (green) and snowmelt (light blue) for 2090, compared to the current situation (black). The dashed lines are the results of each of the 12 individual climate runs; the solid lines are the results of the 12-model average run.

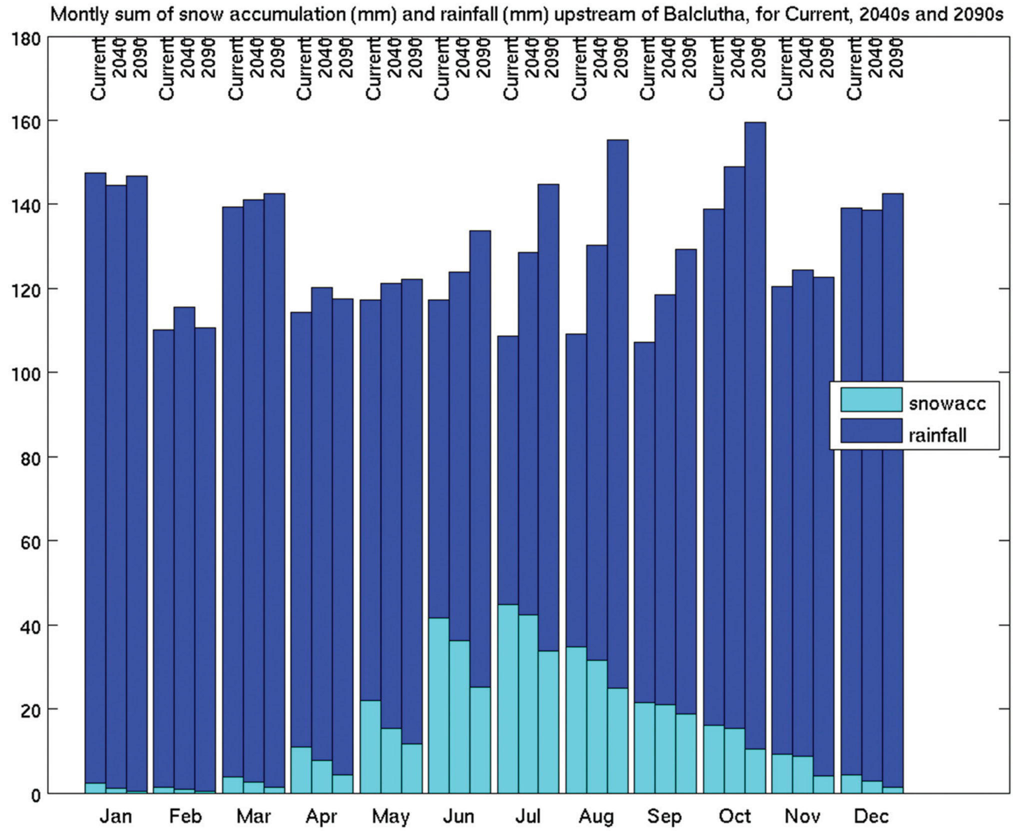

Figure 10 – Average monthly rainfall and snow accumulation for current, 2040 and 2090 (for 12-model average). The total length of the bars represents the total precipitation at ground surface (i.e., input precipitation minus any canopy interception).

change). Average annual total snowmelt change ranges from -25% to 10% for 2040 (only one run predicts a positive change) and -60% to 5% for 2090.

Figure 11 shows the seasonality of predicted streamflow for the current, 2040 and 2090 scenarios. In winter and spring, especially late June-early October, all individual GCM runs predict increased streamflow relative to the current climate. For the remainder of the year, flows from individual GCM runs for 2040 and 2090 are both above and below the flows for the current climate; on average, relatively little change is predicted in these months.

The same pattern can be observed for precipitation in Figures 8 and 9, i.e., some GCM predictions show a decrease of precipitation for the months January-May and November-December, whereas other GCM predictions show an increase of precipitation in those months. In winter and spring all 12 GCM simulations predict increased precipitation. The strong increase in winter and spring streamflow is a combination of the increased winter and spring precipitation and a decrease in snow accumulation (Fig. 10), causing more precipitation to run off directly. The direction and magnitude of change in precipitation and (seasonality of) streamflow is consistent from current to 2040 and then to 2090 – i.e., the system is behaving as we

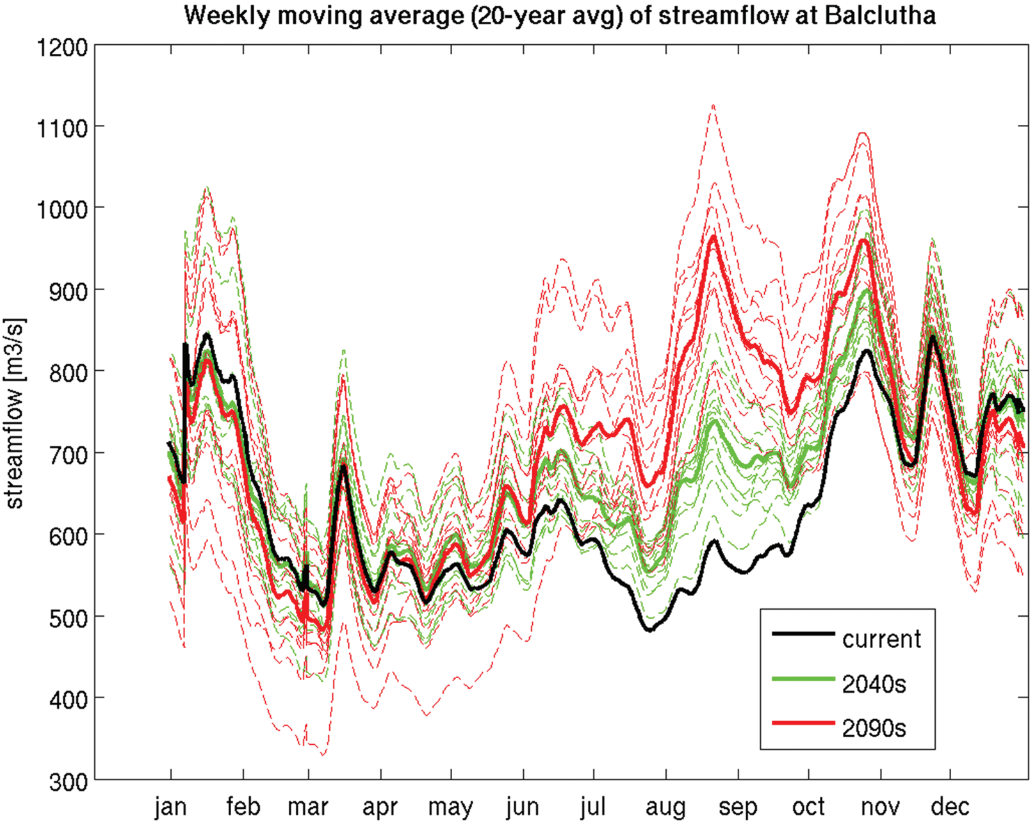

Figure 11 – 20-yearly average of weekly moving averaged streamflow at Balclutha for 2040 (green) and 2090 (red), compared to the current scenario (black). The dashed lines are the results of the 12 individual climate runs; the solid lines are the results of the 12-model average run.

would expect from first principles, and in a consistent manner.

The IPCC fourth assessment report (IPCC, 2007) provides a summary of international findings on the effects of climate change on water resources in snow-influenced catchments, which can be used to put the results from the Clutha into a global context. In the high latitudes of North America and Eurasia, overall runoff was found to increase by 10 to 40% by 2050 in the A1B scenario (Milly *et al.*, 2005). Our results suggest that the changes may be less extreme in New Zealand, predicting changes of 0 to +13% by 2040. A shift in seasonality of river flows where much winter precipitation currently falls as snow was a consistent international finding (e.g., Barnett *et al.*, 2005). At low elevations, peak seasonal flow was found to occur at least a month earlier (Jasper *et al.*, 2004; Knowles and Cayan, 2004). This is consistent with our results (Fig. 11) that the highest spring flows may now occur in mid-October rather than mid-November.

Our results are broadly consistent with projections of snow-fed water resources given by Fitzharris and Garr (1996), who suggested that proportionately more runoff is very likely from South Island rivers in winter, and less in summer. The main types of water use that could be affected by the projected changes in Clutha River flows are hydro-electric power generation and irrigation. At present, demand for electricity tends to peak in winter to provide domestic heating (Renwick *et al.*, 2010), so more water in future for hydro-electric generation during winter would reduce dependence on hydro-storage lakes to transfer spring runoff into the next winter. However, demand patterns can also change over time (warming climate may reduce winter heating demand; expansion of irrigated agriculture may can lead to increased summer demand for electricity to pump water), so further analysis is needed to explore these consequences. The possibility of slightly lower river water availability in summer (Fig. 11, December, January and February), a time of higher irrigation demand, could have adverse effects on agricultural production, but an analysis of changes in demand for water would also be necessary, as well as consideration of changes in frequency of drought years. The investigation reported in Ministry of Agriculture and Forestry (2011) provides an example of this type of analysis. If the net effect on future water reliability is negative, then it could be mitigated to some extent by storage of the projected additional winter and spring runoff.

Conclusion and future research

Climate projections from 12 different GCMs, and the average of the 12, were used to drive the hydrological model TopNet and hence predict changes in streamflow for the Clutha River at Balclutha under the moderate A1B emission scenario, for future 20-year time periods centred on 2040 and 2090. The hydrological model was evaluated using streamflow records in three locations in the catchment and was found to perform well in reproducing both flow volumes and seasonality of flow.

The consistent trend shown by both the 12 individual model runs, and the 12-model average, is that total annual precipitation will increase under the A1B scenario. As a result, yearly streamflow volumes also increase (mean predicted change of ~6% for 2040 scenario and ~10% for 2090 scenario), but the percentage contribution of snowmelt decreases significantly. The main predicted increase in streamflow occurs in winter and spring (this is true for all 12 GCM simulations and for both future time periods). Despite the predicted reduction in snowmelt contribution, we found no substantial reduction in spring or summer flows for the 12-model average, as the reduced snowmelt was offset by (slightly) higher future rainfall totals. However, the individual predictions vary from a circa 10% decrease to a 10% increase of total streamflow in January-April for 2040, and a circa 50% decrease to 25% increase of total streamflow in January-April by 2090.

We envisage at least two major areas where further research is needed: 1) expanding the study area to cover other regions of New Zealand, including impacts on many more river basins, and on groundwater-dominated systems, which we have not considered here; 2) increasing our understanding on uncertainty of the results. To address the latter, it is first necessary to use a range of emission scenarios (low-medium-high), and this will give a wider range of predictions for the future. Furthermore, it may be possible to decrease the uncertainty of the results by using predictions of a Regional Climate Model (e.g., Drost *et al.*, 2007) directly as input to the hydrological simulations, once the Regional Climate Model predictions are improved further and require less bias correction.

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