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The effects of climate change on runoff in the Lindis and Matukituki catchments, Otago, New Zealand

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Abstract

Climate change linked to anthropogenic emission of greenhouse gases is projected to have substantial effects on Earth's water resources. Changes in the amount and timing of runoff are environmentally, socially and economically important. While many studies worldwide focus on the hydrological effects of projected climate change, there have been few such studies in the Otago region of New Zealand, an important region for hydropower and agriculture. This investigation examines the effects of projected climate change on runoff in Otago, focusing on two tributaries of the Clutha River: the Lindis and the Matukituki. Runoff in these two catchments was modelled using the semi-distributed hydrological model TopNet. This hydrological model uses projections from 12 different General Circulation Models (GCMs), based on the moderate A1B emissions scenario, for two future time periods: 2030-2049, and 2080-2099. For each time period, projected monthly runoff totals were produced for each catchment. GCM ensemble mean annual runoff increased in both catchments in both future time periods by 20.4% for the Lindis for the 2080-2099 period and by 12.8% for the Matukituki. All 12 GCM ensemble members show increasing annual runoff for the Lindis in the 2080-2099 scenario (ranging from 6.4 to 37.5%), with just one ensemble member showing a decrease for the Matukituki (range: –4.0 to +26.7%). Uncertainty between GCMs is greater for mean monthly runoff, with no clear signal either side of the baseline in a number of months. However, all GCMs indicate large increases in July-August runoff, which has the effect of amplifying the seasonal cycle of runoff for the Lindis while reducing it for the Matukituki. These changes in seasonality are consistent with projected increases in winter precipitation, as well as a larger proportion of this precipitation falling as rain rather than snow.

Keywords

climate change, runoff, runoff seasonality, Clutha

Introduction

Projected changes in 21st century climate are expected to alter substantially catchment hydrology throughout much of the world (Bates *et al.*, 2008; Todd *et al.,* 2011). Changes in climate are known to influence catchment hydrology through changes in the amount and timing of precipitation (Meehl *et al.,* 2007), evapotranspiration (Kingston *et al.,* 2009) and consequent community vegetation changes (Ishidaira *et al.*, 2008).

Runoff in the Clutha catchment, Otago, New Zealand, is expected to be particularly responsive to climate change, given the extent of its seasonal snowpack and the sensitivity of this reservoir to changes in temperature (Clark *et al.*, 2009; Stewart, 2009).

There have been numerous studies globally which have addressed the effects of climate change on runoff. Despite a robust thermodynamic response to a warming climate being identified, typically characterised as 'the wet get wetter and dry get drier' (Meehl *et al.,* 2007), substantial uncertainty remains over the response of runoff to such changes in climate (e.g., Todd *et al.,* 2011). This is in large part due to differences in the precipitation climate change signal between General Circulation Models (GCMs), which are often not even consistent in the direction of change (e.g., Kingston and Taylor, 2010; Kingston *et al.,* 2011). Instances where unanimity in the direction of change in future runoff is present typically occur in catchments that are strongly influenced by seasonal storage and release of frozen water. In such catchments, changes in runoff timing are linked to reductions in snow accumulation and increased rates of snowmelt (Horton *et al.*, 2006; Andréasson *et al.*, 2004). In the Clutha catchment, increases in winter precipitation are projected to combine with the effects of higher temperatures on snowpack to greatly affect the annual runoff regime (Poyck *et al.*, 2011).

Possible changes in catchment hydrology associated with climate change are of fundamental importance to both human and natural systems (Kundzewicz *et al.*, 2008). The Clutha River is particularly important from a human perspective: it drives several large hydro-electric power plants, including the country's third largest, the Clyde Dam (432 MW). Water is also drawn from the catchment for irrigation, particularly in the dry interior (Otago Regional Council, 2009; Poyck *et al.*, 2011). Notwithstanding these considerations, relatively few papers have investigated the possible effects of climate change on catchment hydrology in New Zealand (Fowler, 1999; Poyck *et al.*, 2011), although more studies can be found in the 'grey literature' (e.g., Garr, 1992; Lill, 2003; McMillan *et al.,* 2010; Sturman *et al.,* 2011). Of this previous work, a key study was that of Poyck *et al.* (2011), who considered the response of the Clutha catchment as a whole to climate change. This investigation looks to extend the work of Poyck *et al.* (2011) by examining the effects of climate change on catchment hydrology in two climatically and hydrologically distinct sub-catchments of the Clutha: the Lindis and the Matukituki.

Model assessments have become a standard tool for hydrological impact studies and their performance has developed through greater understanding of hydrological processes, continuously improving model structure and higher quality input data (Bates *et al.*, 2008). This investigation uses a model assessment of the hydrological impacts of climate change with the specific objectives of:

1) Forming projections of the influence of climate change on runoff in the hydrologically distinct Lindis and Matukituki catchments.
2) Investigating the controls on hydrological change in the Lindis and Matukituki catchments stemming from both climate and catchment characteristics.

These objectives reflect the need to further understand the possible effects of climate change on hydrology within the Clutha catchment. They also address the need to form climate change projections of hydrological impact in both the Lindis and Matukituki catchments themselves. As such, this investigation will provide useful information for future water resource planning.

This paper begins with a description of the study catchments and the approach used to model their hydrology. The procedure by which this hydrological model was linked to General Circulation Model (GCM) output is then outlined. Projections of the effects of climate change on runoff, precipitation, snow water equivalent, actual evapotranspiration and infiltration excess runoff are presented in the context of both hydrological model and GCM uncertainty. These results are discussed, with emphasis placed on differences in response between the two study catchments. Finally, conclusions are drawn and directions for further research are highlighted.

Study area

This study focuses on two sub catchments, the Lindis and the Matukituki, which feed New Zealand's largest volume river, the Clutha. The Lindis and Matukituki sub catchments are chosen for investigation because of their differing geographies in terms of location, topography, climate and land use.

The Matukituki catchment is situated within the western margins of the Clutha catchment on the main divide of the Southern Alps (Fig. 1). The combination of orographic enhancement of precipitation and the dominant westerly circulation result in high precipitation in the Matukituki catchment (mean annual precipitation up to 5000 mm: Fig. 1). As such, the Matukituki is one of the key contributors to Clutha river flow (along with other alpine sub catchments on the western margins of the Clutha catchment such as the Rees and the Dart). The mountainous topography of the Matukituki catchment also results in a significant seasonal snowpack, as well as a number of glaciers (Chinn, 2001). This seasonal reservoir results in low flows in winter and higher flows in late spring and summer (Fig. 2; Poyck *et al*., 2011).

The Lindis catchment is situated east of the Matukituki catchment in the lee of the Southern Alps, and in consequence is far drier than the Matukituki (mean annual precipitation between 500-1000 mm; Fig. 1). Whilst not technically part of the Southern Alps, and with a lower mean elevation than the Matukituki catchment, the Lindis catchment still encompasses semi-mountainous terrain ranging in elevation from 220 m above sea level (asl) to a maximum of 1925 m asl. The upper part of the Lindis catchment receives substantial precipitation between June and November; however the lower catchment is one of the driest areas in the Clutha (Otago Regional Council, 2009). Although the Lindis catchment does receive seasonal snow, there are no glaciers and the overall influence of snow storage and release on annual streamflow is small in comparison to the Matukituki. Peak flow for the Lindis occurs from August-October, associated with high precipitation input and seasonal snow melt. Due in part to the small seasonal storage of snow (relative to the Matukituki), the Lindis catchment experiences low flows in summer (Fig. 2; Poyck *et al*., 2011).

The physiographic differences between the Lindis and Matukituki catchments result in substantially different runoff regimes. These same differences will also affect how runoff reacts to climate change, and as such provide the context in which the results of this study are discussed.

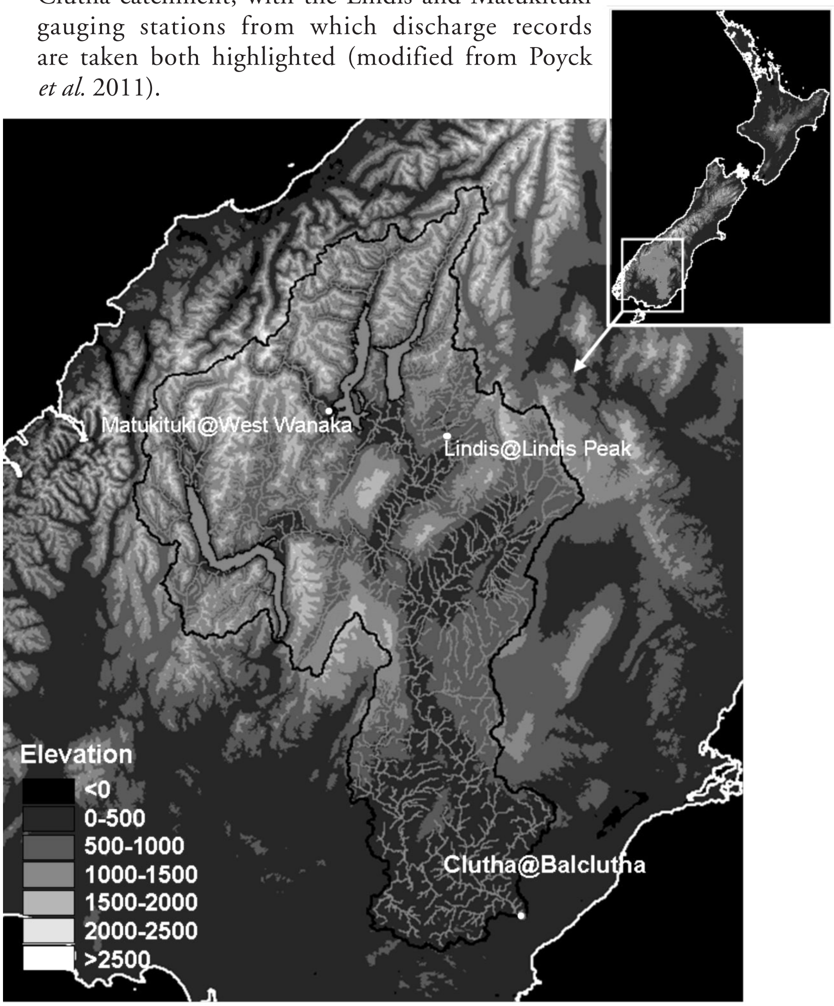
Methods

Hydrological model

The TopNet hydrological model was developed at NIWA and subsequently set up and run for the Clutha catchment as reported by Poyck *et al.* (2011). Here follows a brief description of the TopNet model (see Poyck *et al.* 2011 and Clark *et al.* 2009 for more detail). TopNet proceeds in three steps:

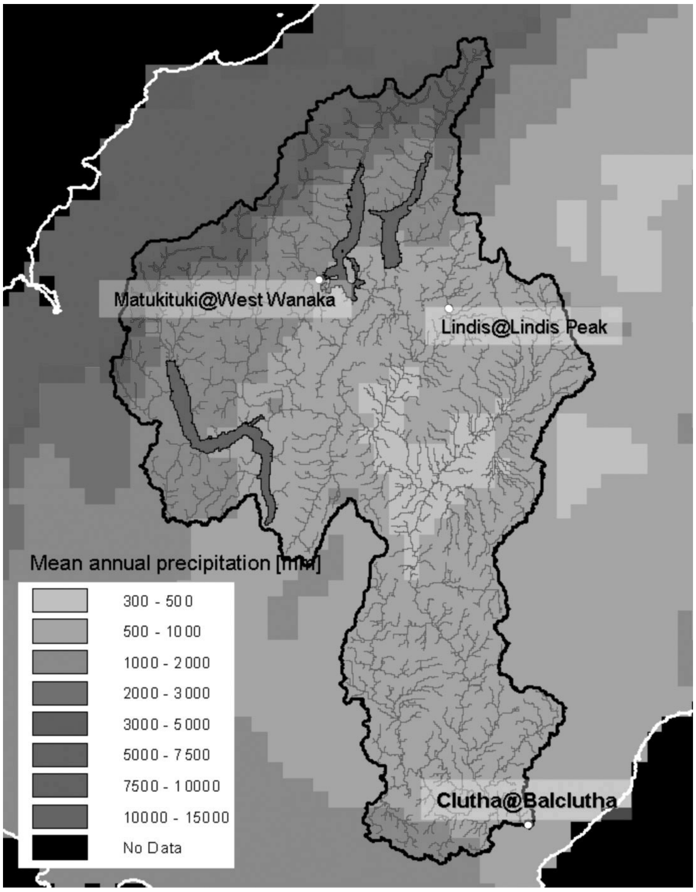
1) Input data such as precipitation are disaggregated to the sub-catchment spatial scale (defined by Strahler order 3) and hourly timescale.
2) These input data are used to simulate the water balance for each hourly time step in each sub-catchment.

Figure 1 – Location of the Clutha catchment within New Zealand (inset), elevation (left) and precipitation (right) distribution and major stream networks in the Clutha catchment, with the Lindis and Matukituki gauging stations from which discharge records are taken both highlighted (modified from Poyck *et al.* 2011).



3) The calculated streamflow is routed through the channel network using a one-dimensional Lagrangian kinematic wave river routing scheme.

Snow is accounted for using an index method to calculate snow water equivalent. This method models snowfall and snowmelt based on air temperature, which is calculated as a function of altitude using a standard lapse rate of 5 K km^{-1} (Poyck *et al.*, 2011). Snowfall and snowmelt are calculated in the model for each 100 m elevation band and then aggregated across the catchment. Seasonal changes in melt factor caused by factors such as albedo, rainfall and aerosol deposition are also incorporated (Clark *et al.*, 2009; Hock, 2003; Barringer, 1989; Rango and Martinec, 1994).



Initial spatial model parameter values were estimated based on the New Zealand Land Resource Inventory, the New Zealand Land Cover Database (Newsome *et al.*, 2000), and the New Zealand River Environment Classification (Snelder and Biggs, 2002). Climate data were taken from historical temperature and precipitation records from the Virtual Climate Station Network (VCSN). These climate data were spatially interpolated over the study catchment using a bi-variate spline applied to calculations of sea level potential temperature (Tait *et al.*, 2006).

The initial TopNet parameter values did not produce accurate simulations and therefore needed calibration. The model was calibrated as described by Poyck *et al.* (2011) for the entire Clutha catchment. A short summary of the methods employed is presented here. The calibration process used a semi-automatic parameter adjustment method, in which the feasible parameter space was sampled for a subset of parameters related to soil hydraulic properties. Because of the size of the model, it was necessary to limit the dimensionality by preserving the spatial distribution of parameters and adjusting them uniformly. This was achieved by applying the same parameter multipliers to each of the 2,343 sub catchments of the Clutha. Through this semi-automatic method, 5,000 parameter sets were evaluated against measured discharge in the Lindis and Matukituki sub catchments, as well as the Clutha catchment as a whole (using streamflow data from the Clutha at Balclutha). Each of these 5,000 parameter sets was run for the period October 1993-December 1994, and the 60 best performing parameter sets

(20 from each catchment) were then run for the 20-year period from 1980-1999. Of these sets, the eight best hydrological parameter sets were further parameterised through the addition of a seasonally variable melt factor. Using a combination of performance assessments, a qualitative expert judgment was employed to select an 'optimal' parameter set from the eight best performing sets.

Hydrological model performance was assessed in this investigation using both the standard and logarithmic formulation of the Nash Suthcliffe efficiency (E). The logarithmic transformation of E (lnE) reduces the sensitivity of E to high flows and increases the influence of low flows on this statistic (Krause *et al.*, 2005). The use of a combination of objective functions complies with the recommendations of Krause *et al.* (2005) in order to account for objective function bias. Model performance was also assessed qualitatively through visual inspection of model output against observed runoff.

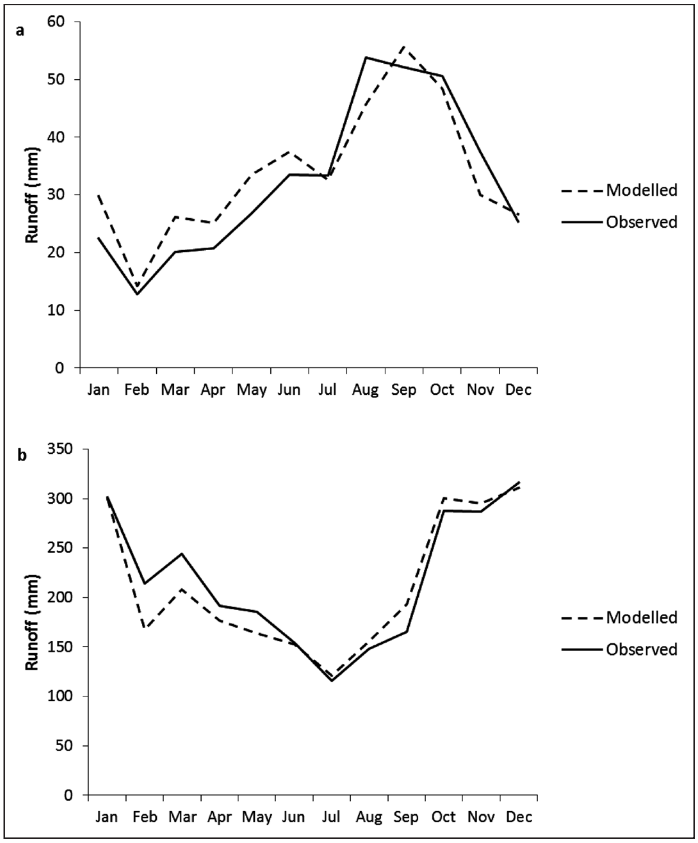


Figure 2 – Mean monthly modelled and observed runoff in (a) the Lindis and (b) the Matukituki catchments for the 1980-1999 baseline period.

Climate scenarios

In addition to hydrological model uncertainty, GCM uncertainty is a key consideration in the formulation of runoff projections (Todd *et al.*, 2011; Poyck *et al.*, 2011). An ensemble approach using the projections of a number of different GCMs is therefore recommended when attempting to analyse the possible effects of climate change on runoff (Boé *et al.*, 2009; Andréasson *et al.*, 2004; Todd *et al.*, 2011; Davies and Prudhomme, 2009). In this study, an ensemble of 12 different GCMs was used in order to account for uncertainty associated with GCM structure, following Poyck *et al.* (2011). These 12 GCMs were selected from a group of 17, as they were found to be substantially more accurate in simulating historical climate records in New Zealand (Ministry for Environment, 2008). These climate models utilised the SRES A1B emissions scenario as a 'middle-of-the-road' estimate of future greenhouse gas emissions (Lopez *et al.*, 2011).

In order to assess the magnitude of uncertainty between the 12 GCMs, projections resulting from each individual GCM were compared against ensemble mean projections in both the Lindis and Matukituki catchments for both future time periods. This method allows for nonlinearity in the hydrological response to climate forcing and provides an indication of whether projected runoff changes are robust to the uncertainty among GCMs, whilst also describing the magnitude of this uncertainty over the annual cycle.

High-resolution climate scenario data were generated through statistical downscaling of GCM output, supplemented by analysis of simulations from the NIWA Regional Climate Model, as described by Poyck *et al.* (2011). The statistically downscaled GCM data were used as input to the hydrological model TopNet. TopNet was used to model an historical time period between 1980 and 1999 (henceforth referred to as the baseline period), and two future time periods: 2030-2049 and 2080-2099 (henceforth referred to as the 2040 and 2090 time periods, respectively). Discharge data were converted into runoff depth per unit area in order to allow clear comparison between catchments and with other hydrological variables.

Results

Hydrological model performance

Modelled and observed runoff for the baseline time period are compared in Figure 2. As shown by Poyck *et al.,* (2011), Figure 2 demonstrates that the calibrated model produces a reasonably good representation of catchment runoff in both the Lindis and Matukituki catchments during the baseline time period. In the Matukituki catchment, however, the model underestimates runoff in late summer and autumn (with a maximum underestimation of 20% in February), and slightly overestimates runoff in late winter and spring (by up to 16% in September). In the Lindis catchment, the model overestimates runoff between December and June/July (up to 32%) and underestimates runoff in July, August, and September-November (up to 20%).

Statistical analyses of model performance using the standard and logarithmic formulations of E are presented in Table 1. Values for E and lnE are further assessed based on the classification scheme proposed by Henriksen *et al.* (2008). Values of E can be seen to support the assessment that on a monthly basis TopNet performs well in both the Lindis and Matukituki catchments, as shown previously for weekly data by Poyck *et al.* (2011). In addition, further analyses here show that values for lnE are higher than E in both catchments. This shows that while TopNet was calibrated with the aim of maximising only the standard formulation of E (thus placing emphasis on fitting high flow portions of the dataset), the calibrated model also simulates low flows well.

Projected change in annual runoff

Changes in mean annual runoff are generally greater in the 2090 period compared to 2040 (Fig. 3). In the Lindis catchment, the range of increase in annual runoff for the 2090 period is between 6.4% and 37.5%, with an ensemble mean of 20.4%. In the Matukituki catchment the range of increase in annual runoff is between -4.0% and +26.7%, with an ensemble mean of 12.8% (note that different

Table 1 – Standard and logarithmic formulations of the Nash-Sutcliffe efficiency (E; assessed against the classification scheme of Henriksen et al. (2008)) for monthly river flow in the Lindis and Matukituki catchments.

	Nash-Sutcliffe (E)	Classification	Ln E	Classification
Matukituki	0.68	Very Good	0.72	Very Good
Lindis	0.69	Very Good	0.79	Very Good

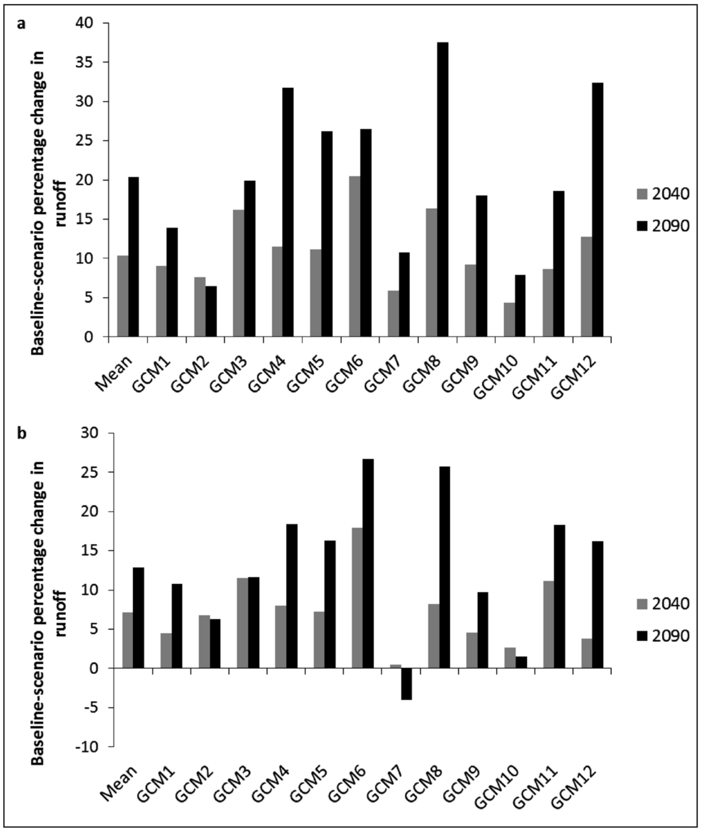


Figure 3 – Percentage change in 20-year averaged runoff compared with the baseline for each of the 12 GCMs and ensemble means for (a) the Lindis, and (b) the Matukituki.

GCMs produce the extreme values, according to catchments and time period considered).

The increasing availability of water at an annual time-scale is broadly consistent with understanding of how the global hydrological cycle is likely to be affected by climate change (i.e., wet get wetter; Meehl *et al.*, 2007), as demonstrated by global-scale hydrological modelling studies (e.g., Milly *et al.*, 2005; Nohara *et al.*, 2006). These increases in annual runoff are also consistent with the findings of previous New Zealand-based studies (Braddock, 1998 ; Garr and Fitzharris, 1994; Lill, 2003). Poyck *et al.* (2011), using the same GCMs as this study, found that ensemble mean projections of runoff for entire Clutha basin led to increases of 10% by 2090, somewhat smaller than those projected for the Matukituki and especially the Lindis. This is likely to reflect both the relatively large hydrological influence of seasonal snowpack in the Lindis and Matukituki catchments, and their location closer to or in (for the Matukituki) the zone of spillover precipitation from the Main Divide, where larger increases in precipitation are expected (Wratt and Mullan, 2008).

Projected change in seasonal runoff

Figures 4 and 5 show projected change in monthly Matukituki and Lindis runoff for the 2040 and 2090 time periods, using individual GCM forcing as well as the ensemble mean. It is clear that the choice of GCM determines the direction of change in both future time periods during late spring, summer and autumn in both the Lindis and Matukituki catchments. During the months of July and August in the Lindis, and June-October in the Matukituki, scenarios from all 12 GCMs lead to increased runoff. In the Matukituki catchment, the largest increases in runoff occur close to the annual runoff minimum (minimum in July, maximum increase in August), indicating that climate change will moderate the annual runoff regime here. By contrast, peak runoff increases in the Lindis catchment coincide approximately with the annual maximum runoff, leading to an amplification of the seasonal cycle in this case. The seasonality of these changes in

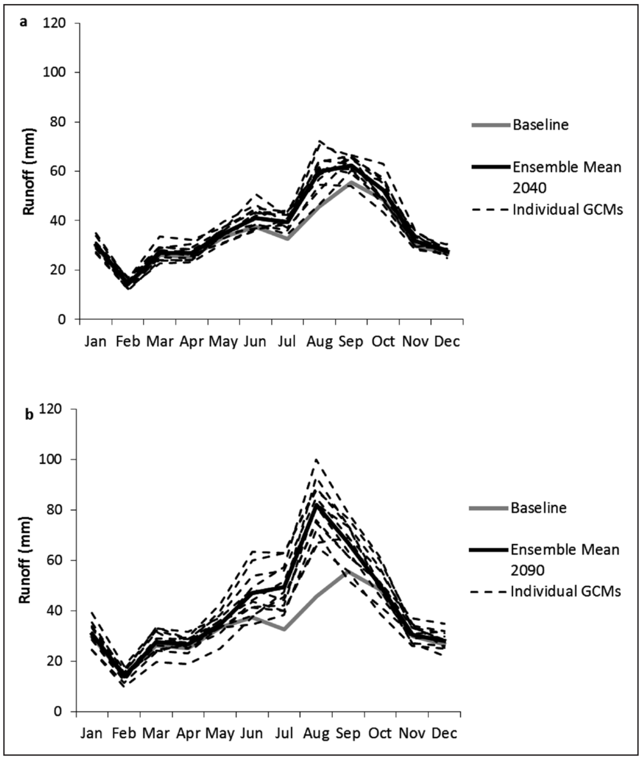


Figure 4 – 20 year mean monthly runoff by individual GCM and ensemble mean for the Lindis catchment in (a) the 2040 period and (b) the 2090 period.

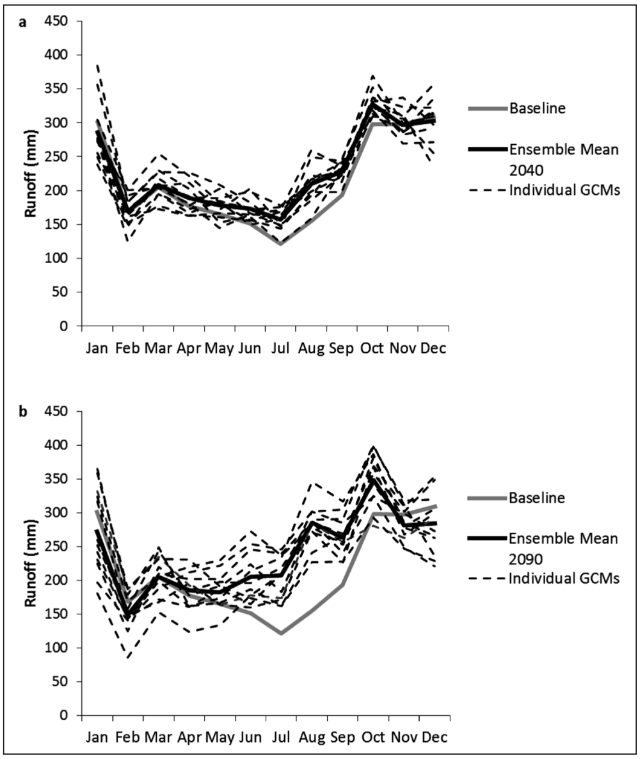


Figure 5 – 20 year mean monthly runoff by individual GCM and ensemble mean for the Matukituki catchment in (a) the 2040 period and (b) the 2090 period.

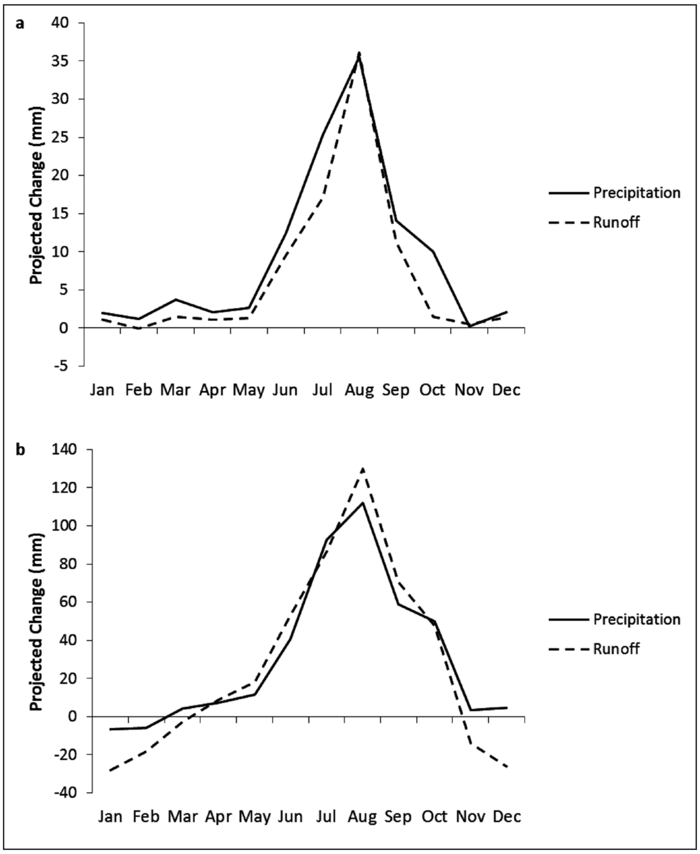


Figure 6 – 20 year mean monthly change in precipitation and runoff between the baseline and 2090 time period for (a) the Lindis and (b) the Matukituki catchments.

Table 2 – Percentage of 20 year averaged annual total precipitation contributing to actual evapotranspiration (AET), catchment runoff (Q) and catchment storage (S) for the baseline, 2040 and 2090 time periods.

	AET as % of precipitation	**Runoff as % of precipitation**	**Storage as % of precipitation**
Matukituki Baseline	23.2	77.2	0.3
Matukituki 2040	22.6	77.8	0.4
Matukituki 2090	22.3	78.2	0.5
Lindis Baseline	51.3	50.0	1.4
Lindis 2040	49.8	51.5	1.3
Lindis 2090	48.3	52.9	1.2

runoff is consistent with the findings of Poyck *et al.* (2011), Lill (2003) and Garr and Fitzharris (1994).

Comparing projections of seasonal change in runoff with projected changes in precipitation (Fig. 6) suggests that it is not just changing precipitation that is driving changes in runoff (for either catchment). As expected, changes in runoff and precipitation show similarities over the annual cycle in both study catchments. However, in the Matukituki catchment, the increase in runoff over the winter months is greater than the increase in precipitation; conversely decreases in runoff during the summer months are not matched by decreases in precipitation. In the Lindis catchment, increases in precipitation are slightly greater than increases in runoff from January-July and September-October, with little difference at other times (Fig. 6a).

Differences in runoff response to changing precipitation can in part be understood through closer examination of the different components of the water balance for each catchment (i.e., precipitation, actual evapotranspiration, runoff and storage; Table 2). The disparity between the increase in precipitation and smaller increase in runoff in the Lindis may

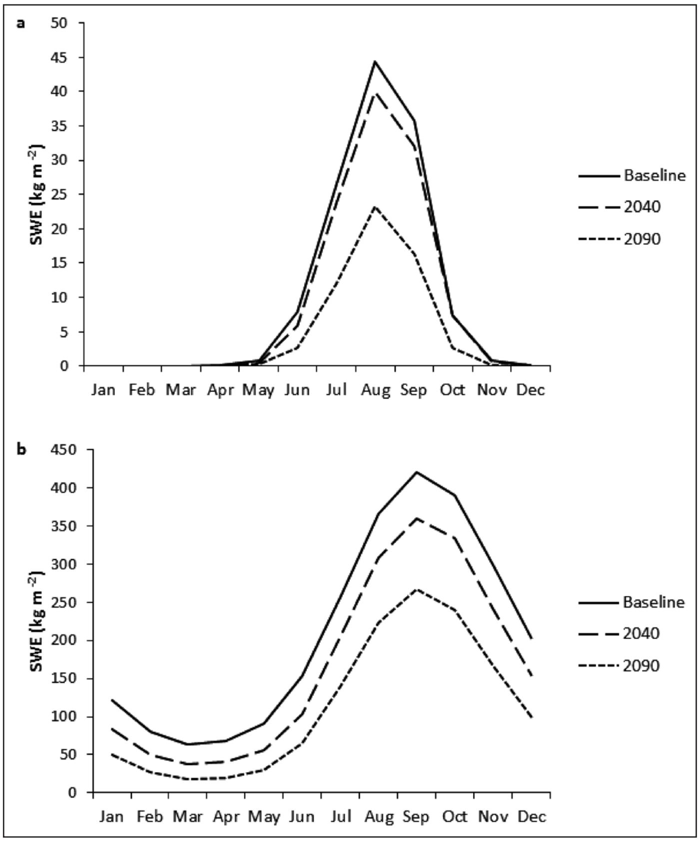


Figure 7 – 20 year mean monthly snow water equivalent (SWE) for the baseline, 2040 and 2090 time periods for (a) the Lindis and (b) the Matukituki catchments.

partly reflect the relatively large influence of evapotranspiration on the water balance in the Lindis compared to the Matukituki. Approximately 50% of precipitation entering the Lindis catchment leaves the system through evapotranspiration in the baseline and both future scenarios, limiting the influence changing precipitation will have on river flow. In contrast to the Lindis, only 22% (approximately) of precipitation in the Matukituki leaves as evapotranspiration, making this catchment far more sensitive to changes in precipitation.

Further explanation for the disparity between changes in precipitation and runoff can be found by examination of changes in catchment snow-water equivalent (SWE; Fig. 7), particularly for the Matukituki catchment. Increased temperatures lead to a change in the snow-to-rain ratio. During the winter half-year in particular, this will lead to an increased occurrence of rain as opposed to snow, thus providing an explanation for the greater increases in runoff compared to precipitation at this time of year. This is because any precipitation that occurs is more likely to begin passing through the catchment towards the stream straightaway, rather than being stored as snow. As well as ensuring that less snowfall occurs, higher temperatures will mean that any snow that does accumulate within the catchment will remain frozen for a shorter amount of time, again resulting in reduced snow storage (Fig. 7b). In turn, reduced snow storage means that the influence of meltwater input on streamflow will be lessened. This reduced influence is particularly apparent in spring and early summer, when the majority of the winter snowpack would usually melt. This mechanism, combined with a small increase in actual evapotranspiration, appears to be primarily responsible for the November-December decrease in Matukituki runoff that occurs despite a small increase in precipitation (Fig. 6b). In contrast to the Matukituki, the relatively small size of the seasonal snowpack present in the Lindis is likely to explain why this effect is not as apparent in this catchment.

Table 3 – 20 year averaged annual runoff, infiltration excess runoff (IER) and IER as a percentage of runoff during the baseline for the 2040 and 2090 time periods in the Lindis and Matukituki catchments.

	Runoff (mm)	Infiltration Excess Runoff (mm)	IER as a % of runoff
Matukituki Baseline	2543.6	85.9	3.4
Matukituki 2040	2724.5	102.1	3.8
Matukituki 2090	2869.8	117.2	4.1
Lindis Baseline	405.3	5.9	1.5
Lindis 2040	447.4	7.9	1.8
Lindis 2090	488.0	9.9	2.0

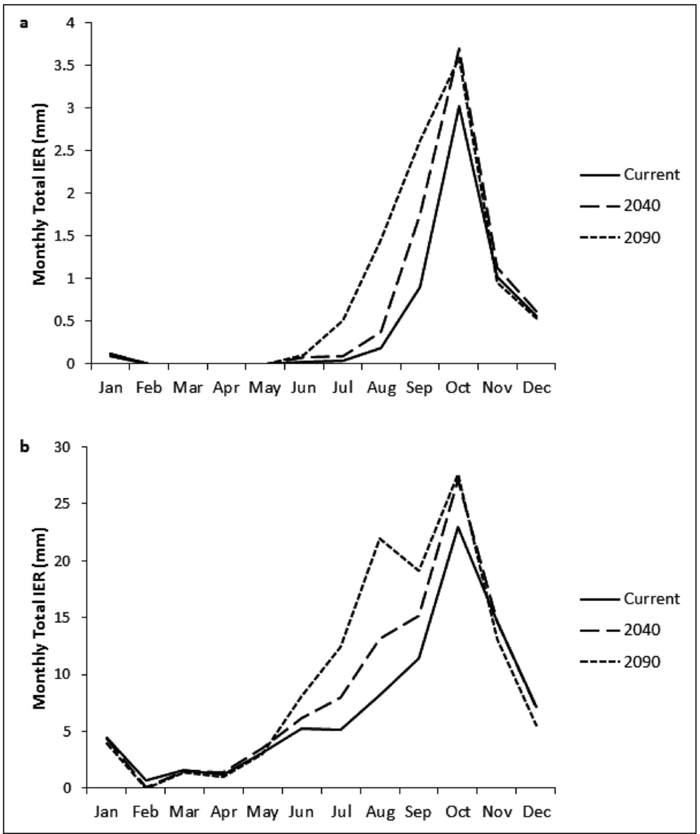


Figure 8 – 20 year mean monthly infiltration excess runoff (IER) in the baseline, 2040 and 2090 time periods for (a) the Lindis and (b) the Matukituki catchments.

Extreme events

Infiltration excess runoff occurs when rainfall rate exceeds the soil infiltration capacity, and can be an important runoff component during flood events. Infiltration excess runoff is shown to increase in both future time periods (Table 3, Fig. 8), and is also projected to increase slightly as a proportion of total runoff. Increases in infiltration excess runoff are concentrated in the winter and early spring, which is consistent with the time of maximum (relative and absolute) increase in precipitation (Fig. 6). Given the seasonal changes in Matukituki runoff discussed in the previous section, the sharp increase in Matukituki infiltration excess runoff during winter is also thought to be associated with the changing incidence and storage of snow in this catchment. The proportion of precipitation that occurs as rain increases markedly in July and August, meaning that rain-on-snow melt events will occur more frequently. There are additional factors that could increase the incidence of infiltration excess runoff in reality, but which are not modelled in Topnet, such as the occurrence of rain on frozen ground. This could become more common as rainfall increases while mean monthly temperatures (although higher) remain below 0°C in parts of the catchment. Both rain-on-snow and rain on frozen ground are conducive to the occurrence of excess runoff, and are likely to become more common under climate change. Increases in infiltration excess runoff mean that storm rainfall is transported more quickly to the river channel and could lead to increased flooding in both catchments (but particularly the Matukituki) over the winter and spring months.

Conclusions

The findings of this investigation are based on the response of the TopNet hydrological model to forcing from GCM projections of change in 21st century climate. TopNet was able to produce very good representations of observed runoff in both catchments in the baseline period. While small divergences can be seen during parts of the annual cycle, the model performs very well on a monthly basis in relation to the classifications scheme of Henriksen *et al*. (2008). TopNet can therefore be accepted as a satisfactory model for catchment hydrology in the Lindis and Matukituki catchments under the baseline climate.

In light of the acceptable performance of TopNet, two general conclusions can be drawn regarding the effects of climate change on runoff in the Lindis and Matukituki catchments. The first conclusion relates to mean annual runoff which is projected to increase 7% by 2040 and 12.8% by 2090 in the Matukituki catchment, while larger increases of 10% by 2040 and 20.4% by 2090 are projected in the Lindis catchment. These changes are proportionally greater than those expected downstream at Balclutha (6% and 10% respectively; refer to Poyck *et al*., 2011), showing the important localised effects of climate change on catchment hydrology. Annual precipitation is projected to increase by a similar proportion in both catchments in both future time periods. Increases in runoff as a proportion of the water balance are, however, larger in the Lindis catchment than the Matukituki catchment. This is due primarily to decreases in the proportion of input precipitation which is lost to evapotranspiration.

The second general conclusion relates to seasonal runoff. Winter and spring runoff is projected to increase substantially in both catchments. This increase appears to occur over a slightly longer period of the year in the Matukituki catchment, where small decreases in summer runoff can also be seen. Little change in runoff is expected during the summer in the Lindis catchment. Increases in winter and spring precipitation, coupled with reductions in seasonal snowpack, account for increases in runoff over these seasons. Both the persistence of winter and spring increases in runoff and the slight decreases expected during summer can be explained by changes in the seasonal snowpack in the Matukituki catchment. These runoff changes were not seen in projections for the Lindis catchment because its highly seasonal snowpack only affects runoff between May and November.

In generating these findings, a further relevant hydrological change was identified. Infiltration excess runoff is projected to increase both in absolute terms and as a proportion of total precipitation. These increases may be associated with changes in the snow-to-rain ratio in both catchments. Importantly, increases in infiltration excess runoff coincide with the annual high flow period in both catchments, suggesting a higher likelihood of flood occurrence at this time of year under climate change. This is likely to have implications for flood management, as well as operation of hydro-electric generation facilities within the wider Clutha catchment.

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