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Modelling climate change impacts on inflows, lake storage and spill in snow-fed hydroelectric power catchments, Southern Alps, New Zealand

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Abstract

Climate change impacts on water resources and increasing demand for renewable electricity will have significant impacts on the management of hydroelectric power catchments globally. In New Zealand, where 55% of electricity currently comes from hydroelectricity generation, rainfall over the major South Island hydroelectric power catchments is expected to increase in coming decades, and the seasonality and volatility of that rainfall is expected to change.

This paper uses a change factor methodology linked to a model cascade to estimate changes to hydroelectric power catchment inflows in 12 regions of New Zealand. These future river flows are then put through an all of New Zealand electricity system model to examine impacts on flows downstream of the hydroelectric power stations, lake storage, and spill in the large South Island hydroelectric power catchments.

An overall 2% increase in annual hydroelectric power catchment inflows over the whole of New Zealand is projected between 2020 and 2050. Seasonal impacts are projected to be larger, with total New Zealand inflows projected to be 10% higher in winter and 6% lower in summer by 2050. Projected changes to inflows are equivalent to between -3% of current total summer New Zealand electricity generation and +5% of winter generation. The four main snow-fed hydroelectric power catchments in the Southern Alps (Pukaki, Tekapo, Clutha, and Manapouri) are predicted to get higher inflows than currently in winter, and lower inflows in summer, with a small increase in annual flows.

Modelled changes to inflows and catchment management results in, on average, higher modelled lake storage levels in the snow-fed hydroelectric power catchments in the South Island, which are predicted to spend more time at full lake levels and less time at low lake levels in 2050 than in 2020. The changing inflows, combined with higher storage levels and changes in the electricity system, results in a potential doubling of modelled spill from the large South Island hydroelectric power scheme lakes by 2050.

These significant seasonal changes to inflows will better match electricity demand, but the increase to annual spill levels is projected to more than offset any increases in annual inflows over the study period.

Keywords

climate change; hydrology; lake inflows; river flows; renewable electricity; hydro storage; hydro spill

Introduction

Climate change

Climate change is affecting temperature and rainfall regimes around the world, and this will have significant impacts on water resources internationally (IPCC, 2021). Changes to seasonal and annual rainfall totals, the magnitude of floods, and the severity and duration of droughts are already being experienced and are projected to continue to change (IPCC, 2021). This will result in a need for adaptive management of water resources by water users, such as hydroelectricity managers (Caruso *et al.,* 2017a; Abera *et al.,* 2018; de Queiroz *et al.,* 2016; Savelsberg *et al.,* 2018; Shu *et al.,* 2018; Ouédraogo *et al.,* 2019).

Projected changes to temperatures and rainfall as a result of climate change have been well documented globally (IPCC, 2021) and in New Zealand (Ackerly *et al.,* 2012; Ministry for the Environment [MfE], 2018). The projected global impacts of climate change on water resources have high spatial variation, with some areas expected to receive less rainfall and others more (Shu *et al.,* 2018), and evaporation is expected to increase (Konapala *et al.,* 2020). Generally, New Zealand is expected to get wetter in the west and south over time, and drier in the north and east. Temperatures are expected to increase by between 0.7 and 1 degree Celsius by mid-century, relative to 1986–2005 (MfE, 2018).

River flows

Changes to temperature and rainfall as a result of climate change will impact river flows globally (Arnell and Reynard, 1996; Strauch *et al.,* 2015; Peres *et al.,* 2019; Mukundan *et al.,* 2019; Anandhi *et al.,* 2011) and in New Zealand (Collins, 2020; Collins *et al.,* 2018; Caruso *et al.*, 2017b; Poyck *et al.,* 2011; Jobst *et al.,* 2018; Zammit and Woods, 2011). The relationship between temperature, precipitation, and river flow is important to project changes to river flows (Baig *et al.,* 2021; Tsakiri *et al.,* 2014; Patel *et al.,* 2016; Kostic *et al.,* 2016; Fu *et al.,* 2007).

Seasonal changes to both the timing and magnitude of runoff will be particularly noticeable in mountainous regions with significant glacier and snow cover, as changes to both temperature and precipitation are predicted to impact snow cover extent and, therefore, melt regimes (Collins, 2020; Bombelli *et al.,* 2018; Soncini *et al.,* 2016). Many rivers in New Zealand are significantly impacted by snow melt, in particular those of the largest hydroelectric power generation catchments (henceforth, hydropower catchments) in the South Island (McKerchar, 1998; Kerr, 2013). Snow cover extent in these catchments is projected to reduce by approximately 20% by the 2040s and 40–80% by the 2090s (Hendrikx and Hreinnson, 2012).

The Waitaki catchment, in the central South Island of New Zealand, which encompasses Lakes Tekapo and Pukaki (and other lakes), has the largest proportion of stored seasonal snow of any of the hydropower catchments; approximately half of Lake Pukaki summer inflows come from snow melt (McKerchar, 1998*;* Kerr, 2013). The Clutha and Waiau catchments (the latter of which encompasses the Manapouri power scheme) both have smaller, but still significant, proportions of snow melt in their hydropower lake inflows (McKerchar, 1998; Kerr, 2013). This, combined with peak rainfall in summer in the headwaters, results in a strong seasonal cycle of inflows to these lakes (e.g., Lake Pukaki average summer inflow is 210 $m^3 s^{-1}$ and average winter inflow is 60 $m^3 s^{-1}$). Hydroelectricity supplies approximately 55% of New Zealand electricity demand, and the three main hydropower catchments in the Southern Alps (Waitaki, Clutha, and Waiau) provide 37% of demand. However, the seasonal cycle of inflows into these lakes is the converse of the demand for electricity generation, which is higher in winter and lower in summer, and therefore to meet demand significant storage of water in the lakes from summer through to winter is required. Understanding future changes to the inflow regimes is vitally important for long-term planning of electricity supply.

Melting glacier ice has been found to make up 6% of Waitaki catchment inflows (Purdie and Fitzharris, 1999) and lesser amounts in other snow-fed catchments. Glacial ice volume in the Southern Alps is expected to reduce by approximately 24% between 2020 and 2050 under a mid-range emissions scenario (Anderson *et al.,* 2021). It is projected that glacial ice volume will continue decreasing at a rate similar to that experienced over the past century (Anderson *et al.,* 2021).

Significant increases in both the mean annual flood and mean annual low flow are expected across much of the south and west of the South Island by 2100, while lower flows across the distribution are expected in the north and east of the North Island (Collins, 2020). Increases in mean annual flows are projected for rivers sourced in the snow-fed catchments of the Southern Alps (Collins, 2020; Poyck *et al.,* 2011; Caruso *et al.,* 2017b; Zammit and Woods, 2011).

Uncertainty in these projections is thought to be large, and the largest contributor to the uncertainty in the snow-fed catchments was found to be from the snow projections (Jobst *et al.*, 2018). Uncertainties around climate change runoff projections are generally large and this is well documented in the literature surrounding river flow projections (Jobst *et al.*, 2018; Wambura *et al.*, 2015). Methods for reducing uncertainty in runoff projections include using ensemble prediction techniques and regional-scale hydrological models (Lehner *et al.*, 2019).

Changes to hydropower catchment management

Changes to energy production in hydropower catchments globally as a result of climate change has been shown to be highly spatially and temporally variable (Bombelli *et al.,* 2018; van Vliet *et al.,* 2016). Seasonal changes to energy generation due to seasonal changes in river flow under climate change are expected to be significant (Vicuña *et al.,* 2011; Savelsberg *et al.,* 2018).

River flows in hydropower catchments will undergo a two-fold transformation in coming decades. Firstly, their hydrological regimes will be modified by climate change, particularly lake inflows in mountain catchments, due to both changing rainfall and changing snow and ice melt (Ackerley *et al.*, 2012; Hendrikx and Hreinnson*,* 2012). Secondly, electricity demand is expected to increase significantly due to electrification of both transport and industrial processes, and intermittency of electricity supply is expected to increase due to higher levels of renewable energy (Ahmad and Zhang, 2020; de Queirox *et al.,* 2016; Savelsberg *et al.,* 2018).

In New Zealand, annual electricity demand is expected to increase by 30% (Ministry of Business, Innovation and Employment, 2019) to 70% (Transpower, 2021) by 2050. Fifty-five percent of New Zealand's electricity is generated by hydroelectric power. Hydroelectricity can act as the 'battery bank' (Castro, 2020) that firms up the intermittency of renewable generation sources, and therefore is vitally important in an electricity system with increasing proportions of renewable electricity. Hydroelectricity managers will have to adapt to both the changing hydrological regime and the changing electricity demand by adapting their use of lake storage, spill, and generation (Bombelli *et al.,* 2018), which will impact lower catchment river flows. Spill is the volume of water released without producing electricity when river flows exceed the hydraulic capacity of the system.

Lake storage will have to be carefully managed to cope with significantly larger flood flows (Renwick *et al.*, 2010), and the large headwater hydropower storage lakes could help to control and mitigate potential increased annual flows and increased flood risk to downstream areas (Caruso *et al.,* 2017b). It has been projected that hydropower lake storage levels will be far more variable in future (Mason *et al.*, 2010; Caruso *et al.,* 2017b).

Increases to spill from hydropower reservoirs are an unavoidable consequence of incorporating increased levels of renewables into a generation system, as increased extreme precipitation events are a predicted consequence of a warming climate (Mason *et al.*, 2010; Caruso *et al.,* 2017b; Tarroja *et al.*, 2016). However, predictions of increased drought in some parts of the world will likely lead to lower hydropower lake storage levels and spill levels (Kopytkovskiy *et al.*, 2015).

Electricity generation has national social and economic significance for New Zealand. It is vital that significant electrification of transport and industry (Climate Change Commission, 2021) and significant changes expected in renewable energy 'fuels' (wind, water, snow melt) come together to provide a secure, sustainable, and affordable energy sector (the energy trilemma; World Energy Council, 2020). Understanding how river flows will change over time and how this will integrate with the entire electricity system to impact river management is essential for the supply of electricity in New Zealand.

It should be noted here that exploration by the New Zealand government into the possible construction of a pumped storage scheme to firm up intermittent renewable generation is currently underway. If it goes ahead, this scheme will impact the findings of this paper, as the modelling undertaken here does not include this scheme.

The purpose of this study is to assess the potential impacts of climate change by mid-century on the inflows to New Zealand hydropower catchments, and in particular to the inflows, storage, and spill in the large snow-fed South Island hydropower catchments. A modelling chain is applied, which is based on the combined use of Regional Climate Model (RCM) output of rainfall projections (Ackerley *et al.,* 2012), snow model output of melt estimates (Fitzharris and Garr, 1995), projections of changes to snow water equivalent in the New Zealand mountains under climate change (Hendrikx and Hreinnson, 2012), a Change Factor Methodology (CFM) model to predict lake inflows (Hansen *et al.*, 2017) and an all of New Zealand electricity system model (LPCon) (Powell, 2021; Andrews, 2018).

Methodology

Study areas

The modelling in this study incorporates 40 hydroelectric power generation stations, spread over New Zealand, summarised into 12 distinct hydrological regions (Fig. 1). These 40 stations represent every currently grid-connected hydroelectric power station in New Zealand, with a total installed capacity of 5,470 MW. No new large hydroelectric power stations are projected to be built between 2020 and 2050 in national electricity models (Transpower, 2021; Ministry of Business, Innovation and Employment, 2019). This methodology acknowledges the spatial coherence of river flow records within regions (Salinger and Mullan, 1999) and the regional nature of projected climate change impacts. Each of the 12 regions has an 87-year history of observed hydrological flows. The term 'RoR' denotes 'run of river', which generally denotes a region with run-of-river hydroelectric power stations and little storage, and region names are derived from the electricity system model used, LPCon.

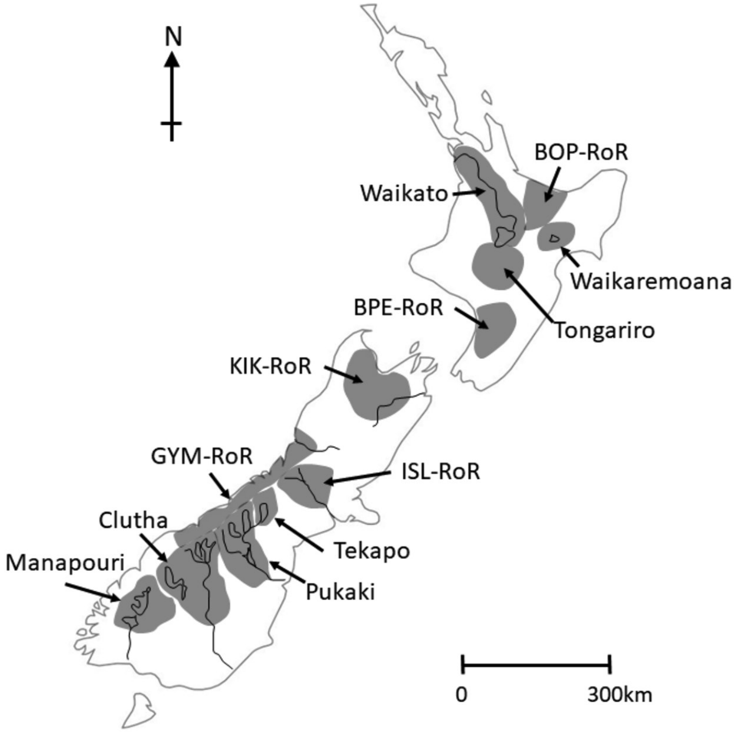

Figure 1 – Locations of the 12 New Zealand hydropower catchment regions used in this study.

Three catchments are focused on in this paper: Waitaki (Tekapo and Pukaki regions in Fig. 1), Clutha, and Waiau (Manapouri region in Fig. 1) catchment. The Waitaki catchment has eight hydroelectric power generation stations along its length (Tekapo A and B; Ohau A, B, and C; Benmore; Aviemore; and Waitaki), with a combined capacity of 1750 MW. The Clutha catchment has two hydroelectric power generation stations, Clyde and Roxburgh, with a combined capacity of 580 MW. The Manapouri scheme consists of two main storage lakes, Te Anau and Manapouri, with a generation capacity at Manapouri station of 850 MW.

Modelling framework

A modelling chain is applied to downscale climate variables from Global Circulation Model (GCM) scale (~100 km) to RCM scale (~27 km), and then further to a statistical model, CFM (Hansen *et al.,* 2017), to ascertain climate change impacts on river flows (Peres *et al.,* 2019; Eisner *et al.,* 2017). River flow projections are then utilised in an all of New Zealand electricity system model to ascertain changes to storage and spill in the studied catchments. In studies of climate change impacts on hydroelectricity systems there is a need to derive both rainfall and river flows from GCM projections and then energy or catchment management from changes to river flows. Chains of models are often used to ascertain changes throughout the component parts of the process (Guo *et al.,* 2021; Wagner *et al.*, 2017).

To project river flows, statistical methods are used to quantify the relationship between rainfall and subsequent river flows (Strauch *et al.,* 2015; Fontaine *et al.,* 1992; Wohl *et al.,* 2012; Tsakiri *et al.,* 2014; Baig *et al.,* 2021; Kostic *et al.,* 2016). A statistical method of projecting climate change impacts on catchment river flows, which relies on this relationship, is to apply a delta-change or Change Factor Methodology (CFM) (Diaz-Nieto and Wilby 2005; Anandhi *et al.,* 2011; Karamouz *et al.,* 2013; Hansen *et al.,* 2017; Ouédraogo *et al.,* 2019). CFM uses the differences or ratios of projected change between a base period and future period in the independent variables (e.g., rainfall and temperatures from GCMs and RCMs, snow melt) to project change over the same time period in the dependent variable (i.e., river flow). Future river flow scenarios are generated by a multiplicative factor applied to the observed meteorological or historical hydrological time series (Anandhi *et al.,* 2011; Karamouz *et al.,* 2013; Hansen *et al.,* 2017).

This method is particularly useful where good long-term observational records exist of the dependent variable, as the statistical characteristics of the historical record (e.g., variance) can be retained and adjusted proportionally for future conditions. Assumptions of stationarity of the relationship between independent and dependent variables are made in this study (Hansen *et al.,* 2017; Schlef *et al.*, 2018). The seasonal variability of meteorological and hydrological variables requires the use of multiple factors applied to different seasons (Hansen *et al.*, 2017).

Rainfall projections

The International Panel on Climate Change (IPCC) uses five Shared Socioeconomic Pathways (SSPs 1–5) to represent the impact on the climate, from low (1) to high (5) emissions pathways. The Sixth Assessment Report (AR6) (IPCC, 2021) scientific literature denotes SSP2 as the most likely scenario. This pathway has a radiative forcing of 4.5 Wm^{-2} (equivalent to Representation Concentration Pathway (RCP) 4.5 from IPCC, 2013 and 2014) and a projected temperature range by end of century of 2.5–2.7°C above pre-industrial levels.

To estimate the impact of climate change on New Zealand, NIWA derives data from six GCMs, for the four RCPs, as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (IPCC, 2013). The global models have a resolution of approximately 100–300 km, and GCM output variables are downscaled initially with an RCM, the HadRM3P regional atmosphere model (resolution ~27 km) (Ackerley *et al.,* 2012; Sood and Mullan, 2020). This process produces projections of such variables as rainfall and temperature out to 2100 for each GCM and for each RCP, to enable the closer examination of the regional impacts of climate change (MfE, 2018; NIWA, 2022). This current study estimates low emissions (RCP 2.6), mid-range emissions (RCP 4.5) and high emissions (RCP 8.5) impacts on river flows to 2050 and uses projections from the average of the six GCMs.

Snow melt changes

Few spatially extensive snow simulation models are available in New Zealand (Fitzharris and Garr, 1995; Clark *et al.,* 2011). Snow accumulation and melt is modelled using Snowsim, a model that calculates seasonal snow accumulation and ablation in the Southern Alps (Fitzharris and Garr, 1995). The base assumptions and input data in this model have been updated (unpublished) and the model is in active use in industry in New Zealand. The model is based on daily temperature and precipitation data from long-established climate stations proximal to the Southern Alps. Output is given as a daily specific net balance of Snow Water Equivalent (SWE) stored at five elevation bands from 1000 to > 2200 metres over several major river catchments.

Daily melt climatologies (1998–2018), in GWh, from Snowsim at different times of the year for the Pukaki, Tekapo, Clutha and Manapouri catchments are used as the baseline measure of snow melt in the catchments. Using the average estimate of a 25% reduction in stored snow water equivalent (SWE) by 2050 (from Hendrikx and Hreinnson, 2012), 25% of modelled melt water is redistributed from summer melt water to winter throughflow in the projected 2050 inflow record. The water is subtracted from the historical inflow record proportionate to the rate it would have melted (in summer) and redistributed to the 2050 projected inflows proportionate to the rate it would have accumulated in the recent past (in winter). Using one figure (25%) for reduction in snow water equivalent over multiple spatially and topographically variable catchments is a broad assumption, but snow is an important component of inflows in these catchments and the method adopted is based on the best available information at this time.

South Island glacial ice melt input to hydropower lake inflows is predicted to remain fairly constant in coming decades (Anderson *et al.,* 2021), so is not explicitly accounted for here.

Evaporation

Although decreases in evaporation over time have been documented in New Zealand (Roderick and Farquhar, 2005), and projected changes to evaporation due to climate change are documented in the international literature (Konpala *et al.*, 2020), variability amongst projections is wide and no local projections of likely changes to evaporation are available. Changes in evaporation are therefore not accounted for in this study, although it is acknowledged that this will lead to greater uncertainties in estimating inflows from rainfall and snow melt.

Floods and droughts

Flood volumes in New Zealand are expected to increase in coming decades, but significant uncertainty exists around the magnitude of these changes (MfE, 2018). Warmer air can hold more moisture, and increased wind speeds, projected in coming decades (MfE, 2018), are expected to enhance orographic uplift and spillover over the Southern Alps (Sinclair *et al.,* 1997).

The combined result of the above climate change forcing is that larger extreme rain volumes are expected in coming decades (MfE 2008; Collins, 2020). Although these studies do not offer evidence of any change to frequency of flood events, a recommended conservative estimate for modelling purposes is that most rain events are likely to be 8% larger under a 1°C warming from current temperatures (MfE, 2010), which is expected by mid-century. Changes in precipitation rates do not linearly translate to changes to floods, as many topographical and storage characteristics, as well as antecedent conditions, snowpack, and other factors mean it is not a linear relationship (Breinl *et al.*, 2021). However, due to the weekly granularity of the modelling in this study, increases in rainfall and runoff are assumed to be commensurate. Therefore, the flood hydrograph discharges are scaled up by 8% (MfE, 2018) in this study.

Generally, little change in drought severity or duration is expected in New Zealand's largest hydropower catchments over the next three decades (MfE, 2018). Where drier conditions *are* projected in parts of the East Coast and Northland, inflow volumes are relatively small, and in all catchments, rainfall changes have been applied to an 87-year distribution of inflows, encapsulating significant droughts and wet periods. Therefore, low flows in the hydropower catchments are not adjusted for in particular.

Model cascade methodology

A model cascade is employed to encapsulate climate change impacts in the 2050 projected inflow record for each regional dataset. This cascade is employed separately for each of the twelve hydrological regions, for three emissions scenarios (RCP 2.6, 4.5 and 8.5). This process is outlined in Figure 2. Sections a, b, and c (as shown on Fig. 2) are described in more detail below.

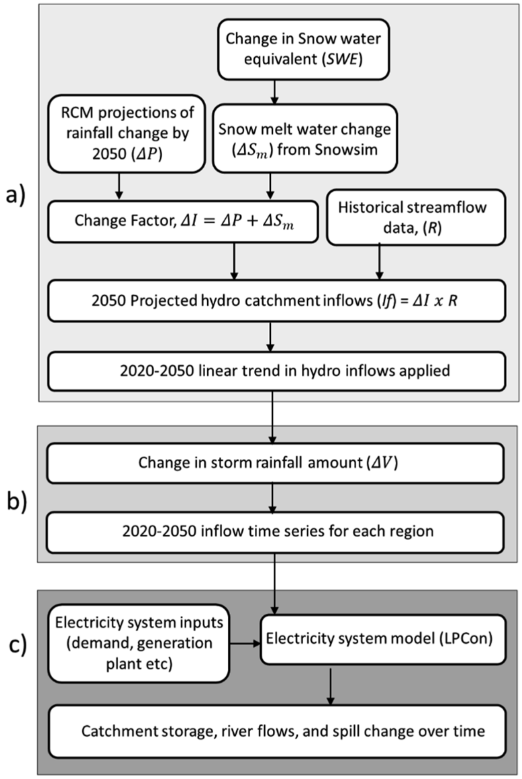

Figure 2 – The model cascade for determining projected 2050 hydropower catchment inflows for input to LPCon, and the electricity system inputs and outputs. The letters to the left denote modelling stages: a) is the process to capture seasonal and annual changes to inflows, b) is the process to capture increased short-duration rainfall amounts, and c) is the electricity system modelling inputs and outputs.

a) Seasonal and annual changes to inflows from rainfall and snow melt

Multiplicative change factors are used to estimate the seasonal and annual changes to inflows from projected changes to rainfall and snow melt. These are calculated using the following general equations, for each region and each week of the 2050 year (relative to 2020):

$$CF\left(\Delta I\right)_i = \frac{Future_i}{Base_i} \quad (1)$$

$$If_i = CF\left(\Delta I\right)_i \times R_i CF\left(\Delta I\right)_i = \frac{Future_i}{Base_i} \quad (2)$$

where $CF(\Delta I)_i$ is the multiplicative change factor (in this case change in inflows, ΔI), for the ith time step (week) in the future time period, which is a ratio calculated from the difference between the future value and the base value for each constituent variable (in this case, seasonal rainfall (ΔP) and snow melt (ΔS_m), summed). If_i is future (2050) inflow for the ith time step (week), and R_i is the recent (2020) historical average inflow (adapted from Hansen, 2017).

A linear trend is then applied between 2020 and 2050 values to create a 2020–50 time series. This method is applied to each of the 87 years of historical inflow records used in LPCon.

b) Increased rainfall amounts

An 8% increase in volatility is incorporated into the 2050 daily records to represent projected increases to rainfall events and a linear trend is applied, from 0% change in 2020 to 8% change by 2050, for twelve regional river flow records. For each region the 0% to 8% volatility is applied to each of the 87 hydrological sequences, out to 2050.

It should be noted that the only change to annual volume of water into catchments is precipitation changes from RCM projections. Changes to volatility and snow melt simply temporally redistributes catchment inflows. However, this redistribution in time is particularly important in relation to electricity generation modelling, because hydropower storage capacity is limited, flood events are optimally captured in storage rather than spilled, and seasonal hydropower inflows are currently anti-correlated with demand, with peak inflows occurring in summer and peak demand occurring in winter.

c) Electricity modelling

The electricity system model used in this study is the Linear Program Convolution Model (LPCon), created and owned by Meridian Energy Ltd and used on licence by this study. LPCon is a simulation model of the New Zealand power system that is capable of assessing medium- to long-term views of electricity supply and demand at 166 grid exit points (GXPs) across New Zealand (Andrews, 2018; Powell, 2021). The model's current settings enable simulations to run over the coming 30-year time period.

The LPCon model is a two-phase power system optimisation and simulation model. Because hydroelectric power generation dominates the generation within the New Zealand power system, the first modelling phase (the optimisation phase) involves a stochastic optimisation technique to determine reservoir operating guidelines, or water values, for the water stored in each of the hydropower reservoirs within the model, for each week in the model run. This optimisation is completed for the 30-year duration of the model run, for the set of 87 hydrological sequences, historical wind and solar production records, and a range of other persistent planning uncertainties, such as low/high demand or generation plant failure. Given reservoir operating guidelines, the second modelling phase (the simulation phase) is a sub-weekly deterministic snapshot of supply and demand at each GXP and portrays how the power system might be expected to operate through time, using linear programming to represent key elements of the weekly dispatch process, optimising for least cost to the entire electricity system. This process seeks to supply demand at each GXP using the cheapest available generation, after taking into account transmission, voltage support, reserves and other costs to the system of using that generation.

The model has representation of all New Zealand hydropower catchments, including run-of-river hydropower, hydropower storage characteristics, hydrological constraints, cascading releases, minimum flows, consent conditions, and spill. All variables output from the model have 87 potential future states, which are derived from 87 possible outcomes based on the 87 hydrological sequences. This enables the exploration of both dry and wet outcomes. More detail on this model can be found in Powell (2021) and Andrews (2018).

Results

Rainfall projections

Rainfall changes were calculated for each model region, for each week of 2050 (relative to 2020), for low, mid-, and high emissions scenarios. Changes to rainfall under mid-emissions scenarios are shown in Table 1. It can be seen that rainfall generally gets higher in the south and west over time, and lower in the north and east. The biggest seasonal shifts in rainfall occur in the Pukaki, Tekapo, GYM-RoR and ISL-RoR regions (drier in spring and autumn, and wetter in winter), as well as the Waikaremoana and BOP-RoR regions (drier in spring, wetter in autumn). The biggest positive change is a 4.7% increase in July rainfall in the Manapouri catchment by 2050, and the biggest negative change is 3.2% drier in Waikaremoana in spring.

Snow melt projections

Snow melt adjustments are needed for the Pukaki, Tekapo, Clutha, and Manapouri regions, because these hydropower catchments have a non-negligible portion of annual lake inflows derived from snow

Table 1 – Change in rainfall (%) in each of the LPCon regions 2020–50, and their corresponding rainfall projection region from NIWA (2022).

LPCon region	Manapouri	Clutha	Pukaki	Tekapo	GYM-RoR	ISL-RoR	KIK-RoR	BPE-RoR	Tongariro	Waikaremoana	BOP-RoR	Waikato
Niwa (2022) region used	Queenstown / Invercargill	Queenstown	Westport	Westport	Westport	Westport	Nelson/ Westport	Wellington / New Plymouth	Taupo	Napier	Tauranga	Taupo
1-Jul	4.5	4.2	3.4	3.4	3.4	3.4	3.1	0.8	0.5	0.1	-0.5	0.5
8-Jul	4.6	4.3	3.6	3.6	3.6	3.6	3.3	0.7	0.5	0.0	-0.6	0.5
15-Jul	4.7	4.4	3.7	3.7	3.7	3.7	3.3	0.7	0.6	-0.1	-0.7	0.6
22-Jul	4.7	4.3	3.6	3.6	3.6	3.6	3.2	0.6	0.5	-0.1	-0.8	0.5
29-Jul	4.5	4.1	3.4	3.4	3.4	3.4	3.0	0.5	0.4	-0.3	-0.9	0.4
5-Aug	4.3	3.9	3.1	3.1	3.1	3.1	2.6	0.2	0.2	-0.6	-1.1	0.2
12-Aug	4.1	3.6	2.7	2.7	2.7	2.7	2.1	0.0	0.0	-0.9	-1.2	0.0
19-Aug	3.7	3.2	2.2	2.2	2.2	2.2	1.6	-0.3	-0.3	-1.2	-1.4	-0.3
26-Aug	3.4	2.8	1.6	1.6	1.6	1.6	1.0	-0.7	-0.6	-1.5	-1.6	-0.6
2-Sep	3.0	2.2	1.0	1.0	1.0	1.0	0.2	-1.0	-0.9	-2.0	-1.9	-0.9
9-Sep	2.7	1.8	0.4	0.4	0.4	0.4	-0.4	-1.4	-1.2	-2.3	-2.1	-1.2
16-Sep	2.4	1.5	0.0	0.0	0.0	0.0	-0.9	-1.7	-1.5	-2.6	-2.3	-1.5
23-Sep	2.1	1.1	-0.5	-0.5	-0.5	-0.5	-1.4	-1.9	-1.7	-2.9	-2.4	-1.7
30-Sep	1.8	0.8	-0.8	-0.8	-0.8	-0.8	-1.8	-2.1	-1.9	-3.1	-2.6	-1.9
7-Oct	1.7	0.6	-1.1	-1.1	-1.1	-1.1	-2.0	-2.3	-2.0	-3.2	-2.6	-2.0
14-Oct	1.6	0.6	-1.2	-1.2	-1.2	-1.2	-2.1	-2.3	-2.1	-3.2	-2.6	-2.1
21-Oct	1.6	0.5	-1.2	-1.2	-1.2	-1.2	-2.1	-2.3	-2.1	-3.2	-2.6	-2.1
28-Oct	1.6	0.6	-1.1	-1.1	-1.1	-1.1	-2.0	-2.2	-2.1	-3.0	-2.4	-2.1
4-Nov	1.6	0.6	-1.0	-1.0	-1.0	-1.0	-1.8	-2.1	-2.0	-2.7	-2.2	-2.0
11-Nov	1.6	0.7	-0.9	-0.9	-0.9	-0.9	-1.5	-1.9	-1.9	-2.3	-2.0	-1.9
18-Nov	1.6	0.8	-0.7	-0.7	-0.7	-0.7	-1.1	-1.7	-1.8	-1.8	-1.6	-1.8
25-Nov	1.7	1.0	-0.4	-0.4	-0.4	-0.4	-0.7	-1.5	-1.7	-1.3	-1.3	-1.7
2-Dec	1.7	1.1	-0.2	-0.2	-0.2	-0.2	-0.3	-1.2	-1.6	-0.8	-0.9	-1.6
9-Dec	1.8	1.3	0.1	0.1	0.1	0.1	0.1	-1.0	-1.5	-0.3	-0.6	-1.5
16-Dec	1.8	1.4	0.3	0.3	0.3	0.3	0.5	-0.8	-1.4	0.2	-0.3	-1.4
23-Dec	1.8	1.5	0.4	0.4	0.4	0.4	0.8	-0.6	-1.3	0.6	0.0	-1.3
30-Dec	1.9	1.6	0.6	0.6	0.6	0.6	1.0	-0.4	-1.2	0.9	0.3	-1.2
6-Jan	1.9	1.6	0.6	0.6	0.6	0.6	1.2	-0.3	-1.2	1.2	0.4	-1.2
13-Jan	1.9	1.6	0.7	0.7	0.7	0.7	1.2	-0.2	-1.1	1.3	0.5	-1.1
20-Jan	1.8	1.6	0.6	0.6	0.6	0.6	1.2	-0.2	-1.1	1.3	0.6	-1.1
27-Jan	1.8	1.6	0.6	0.6	0.6	0.6	1.2	-0.1	-1.1	1.4	0.7	-1.1
3-Feb	1.7	1.6	0.4	0.4	0.4	0.4	1.1	0.0	-1.2	1.4	0.8	-1.2
10-Feb	1.7	1.5	0.3	0.3	0.3	0.3	1.0	0.1	-1.2	1.5	0.8	-1.2
17-Feb	1.6	1.4	0.1	0.1	0.1	0.1	0.8	0.2	-1.2	1.5	0.9	-1.2
24-Feb	1.5	1.3	-0.2	-0.2	-0.2	-0.2	0.6	0.3	-1.2	1.5	1.0	-1.2
2-Mar	1.3	1.3	-0.4	-0.4	-0.4	-0.4	0.4	0.4	-1.3	1.5	1.1	-1.3
9-Mar	1.2	1.2	-0.7	-0.7	-0.7	-0.7	0.2	0.5	-1.3	1.5	1.2	-1.3
16-Mar	1.2	1.1	-0.9	-0.9	-0.9	-0.9	0.0	0.6	-1.3	1.6	1.3	-1.3
23-Mar	1.1	1.0	-1.0	-1.0	-1.0	-1.0	-0.1	0.7	-1.3	1.6	1.3	-1.3
30-Mar	1.0	1.0	-1.1	-1.1	-1.1	-1.1	-0.2	0.8	-1.3	1.6	1.4	-1.3
6-Apr	1.0	1.0	-1.2	-1.2	-1.2	-1.2	-0.2	0.8	-1.3	1.6	1.4	-1.3
13-Apr	1.1	1.0	-1.2	-1.2	-1.2	-1.2	-0.2	0.9	-1.3	1.5	1.4	-1.3
20-Apr	1.1	1.1	-1.1	-1.1	-1.1	-1.1	-0.2	0.9	-1.3	1.5	1.4	-1.3
27-Apr	1.3	1.3	-0.8	-0.8	-0.8	-0.8	0.0	0.9	-1.2	1.4	1.3	-1.2
4-May	1.6	1.5	-0.5	-0.5	-0.5	-0.5	0.3	0.9	-1.0	1.3	1.1	-1.0
11-May	1.9	1.8	0.0	0.0	0.0	0.0	0.6	0.9	-0.9	1.2	1.0	-0.9
18-May	2.3	2.2	0.4	0.4	0.4	0.4	1.0	0.9	-0.7	1.1	0.8	-0.7
25-May	2.7	2.5	1.0	1.0	1.0	1.0	1.4	0.9	-0.5	0.9	0.5	-0.5
1-Jun	3.1	3.0	1.6	1.6	1.6	1.6	1.8	0.8	-0.2	0.7	0.3	-0.2
8-Jun	3.5	3.3	2.2	2.2	2.2	2.2	2.2	0.8	0.0	0.5	0.0	0.0
15-Jun	3.9	3.7	2.7	2.7	2.7	2.7	2.6	0.8	0.2	0.4	-0.2	0.2
22-Jun	4.2	4.0	3.1	3.1	3.1	3.1	2.9	0.8	0.3	0.3	-0.3	0.3

melt (McKerchar *et al.*, 1998; Kerr, 2013). Only one snow melt adjustment was applied for all emissions scenarios, as there was no information available on the potential impact of different emissions scenarios on snow melt.

Twenty-five percent of snow melt in the Pukaki, Tekapo, Clutha, and Manapouri catchments (Hendrikx and Hreinnson, 2012) is subtracted from the historical inflow record proportionate to the rate it would have melted and redistributed to the 2050 projected inflows proportionate to the rate it would have accumulated in the 1998–2018 climatology (from Snowsim modelling; Fitzharris and Garr, 1995). This adjustment results in rainwater flowing through into the hydropower lakes in winter rather than being stored in the snowpack and released in summer. The proportion of snow melt redistributed in each of the snow-fed catchments is shown in Figure 3.

Water is expressed as GWh of potential energy in this study to align with the use of the electricity system model. A GWh of water in a given catchment is the amount of water that results in 1 GWh of energy when flowed through the generation turbines in that catchment, for any given time period. The conversion unit to convert $m^3 s^{-1}$ to GWh is known as a k-factor; it is specific to each generation station and is impacted by hydraulic head, which changes with hydropower storage levels.

The reassigned snow melt water equates to 409 GWh of water in the Pukaki and Tekapo catchments combined, 146 GWh in the Clutha catchment, and 13 GWh in the Manapouri catchment. The 409 GWh that needed to be redistributed seasonally in the Tekapo and Pukaki catchments is assigned proportional to their average annual inflows (40% and 60%, respectively).

Inflow projections

The impact of different emissions scenarios on inflows was found to be small in the time frame of this study. Although impacts on inflows are significant overall, the 30-year

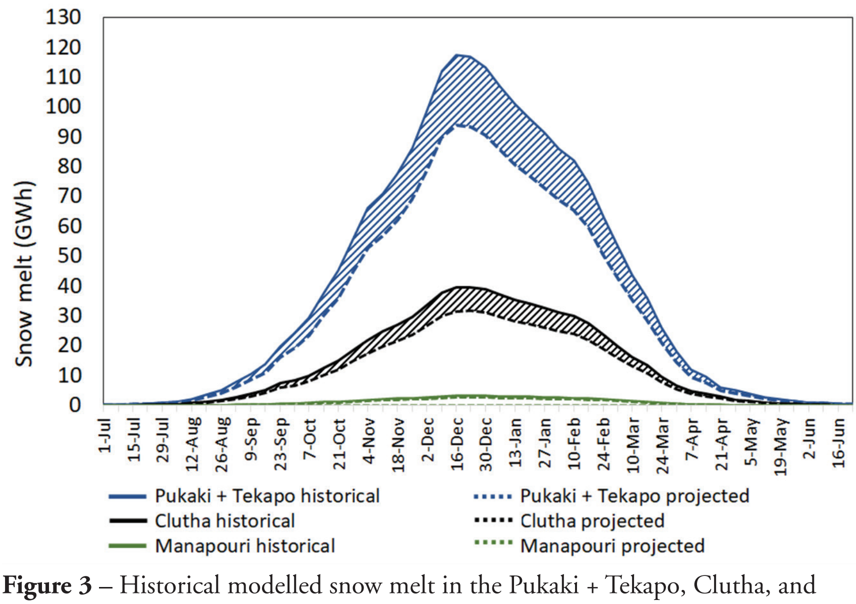

Figure 3 – Historical modelled snow melt in the Pukaki + Tekapo, Clutha, and Manapouri catchments (GWh) from Snowsim, and projected 2050 snow melt. Shaded areas show volume of water needing seasonal redistribution.

period examined was not long enough for clear distinctions between different emissions scenarios to emerge, distinct from that which is already 'locked in' by past emissions. The largest difference between inflow projections for different emissions scenarios is in the South Island mountainous hydropower catchments. However, even in these catchments the difference in inflows under the different scenarios is small (and scenarios are not statistically significantly different from one another) (Fig. 4). Henceforth, mid-range emissions scenario outcomes only are discussed, although different emissions scenarios will be explored in future work.

Mid-range emissions scenario change factors for each week for the twelve LPCon regions can be seen in Table 2. These change factors are applied the 87 historical hydrological sequences for 2050. A linear trend is then applied between each hydrological sequence between 2020 and 2050.

Although all regions generally show reductions in inflows in spring and summer and increases in winter, the timing and magnitude of these changes vary from region to region. The biggest changes between 2020 and 2050 inflows are seen in the seasonal inflows in the snow-fed catchments of Manapouri, Clutha, Pukaki and Tekapo.

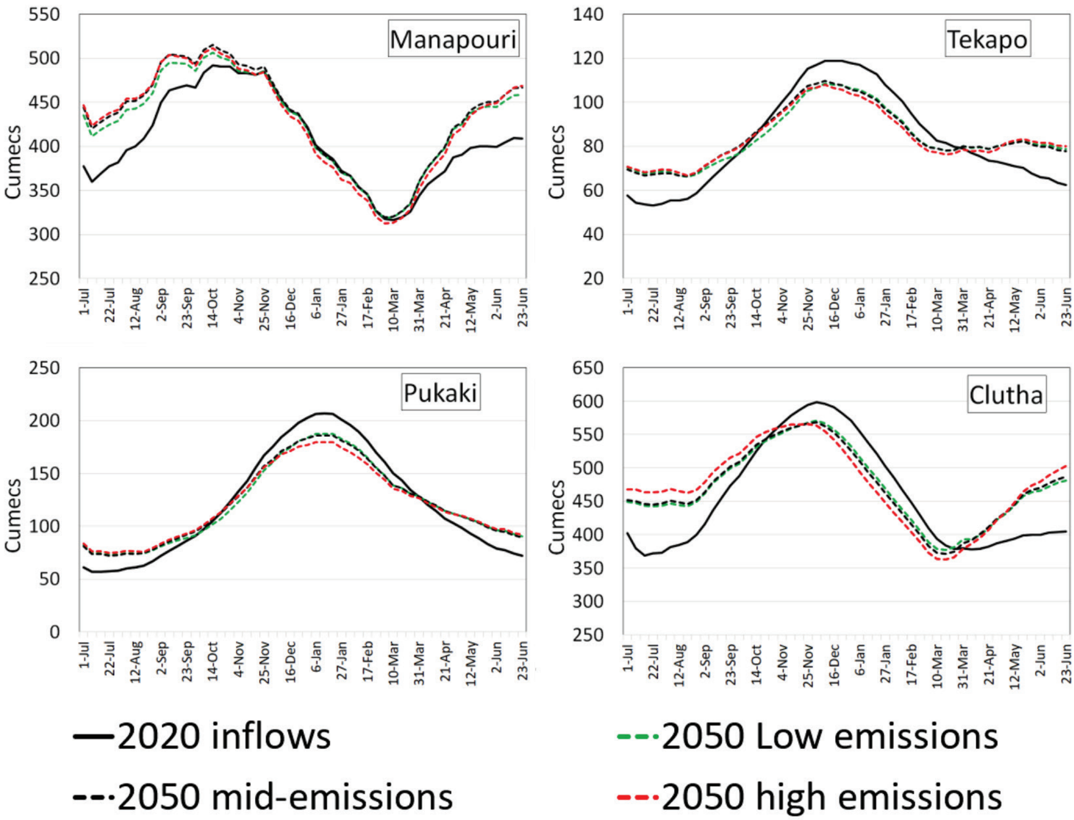

Figure 4 – Projected 2050 weekly average inflows for low-, mid-, and high-range emissions scenarios, for four main snow-fed hydropower catchments, South Island.

Table 2 – Inflow change factors for each LPCon region for each week of the year (% change) – mid-range emissions scenario.

Week	Manapouri	Clutha	Pukaki	Tekapo	GYM-RoR	ISL-RoR	KIK-RoR	BPE-RoR	Tongariro	Waikaremoana	BOP-RoR	Waikato
1-Jul	18%	27%	32%	32%	4%	3%	3%	2%	1%	3%	-1%	2%
8-Jul	17%	23%	29%	29%	4%	3%	3%	2%	1%	3%	-1%	2%
15-Jul	16%	22%	29%	28%	4%	3%	3%	2%	1%	3%	-1%	2%
22-Jul	16%	21%	27%	27%	4%	3%	3%	2%	1%	2%	-2%	1%
29-Jul	15%	19%	25%	24%	4%	3%	3%	2%	0%	2%	-2%	1%
5-Aug	14%	17%	23%	22%	3%	2%	2%	2%	0%	2%	-2%	1%
12-Aug	14%	17%	22%	22%	3%	2%	2%	2%	0%	1%	-2%	0%
19-Aug	13%	16%	21%	20%	3%	2%	2%	2%	0%	1%	-2%	0%
26-Aug	12%	15%	19%	18%	3%	2%	2%	1%	-1%	0%	-2%	0%
2-Sep	11%	13%	16%	15%	2%	1%	1%	1%	-1%	0%	-3%	-1%
9-Sep	9%	11%	13%	12%	2%	1%	1%	1%	-1%	0%	-3%	-1%
16-Sep	8%	10%	11%	10%	2%	1%	0%	0%	-2%	-1%	-3%	-1%
23-Sep	7%	8%	9%	9%	1%	1%	0%	0%	-2%	-1%	-3%	-2%
30-Sep	6%	6%	6%	5%	1%	0%	0%	0%	-2%	-1%	-3%	-2%
7-Oct	5%	3%	3%	3%	1%	0%	-1%	0%	-2%	-1%	-4%	-2%
14-Oct	3%	1%	1%	0%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
21-Oct	3%	0%	-1%	-1%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
28-Oct	2%	-2%	-2%	-3%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
4-Nov	2%	-3%	-4%	-4%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
11-Nov	1%	-4%	-5%	-6%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
18-Nov	1%	-5%	-6%	-7%	1%	0%	-1%	0%	-2%	-1%	-3%	-2%
25-Nov	0%	-5%	-7%	-8%	1%	0%	-1%	0%	-2%	0%	-3%	-2%
2-Dec	1%	-6%	-7%	-8%	1%	0%	-1%	1%	-2%	0%	-3%	-2%
9-Dec	0%	-6%	-7%	-8%	1%	0%	-1%	1%	-2%	1%	-3%	-2%
16-Dec	0%	-6%	-8%	-9%	1%	0%	0%	1%	-2%	1%	-2%	-2%
23-Dec	0%	-6%	-8%	-9%	1%	0%	0%	1%	-2%	2%	-2%	-1%
30-Dec	0%	-6%	-8%	-9%	1%	0%	0%	2%	-2%	2%	-2%	-1%
6-Jan	0%	-7%	-9%	-10%	1%	0%	0%	2%	-1%	3%	-2%	-1%
13-Jan	0%	-8%	-10%	-11%	1%	0%	0%	2%	-1%	3%	-1%	-1%
20-Jan	-1%	-9%	-11%	-12%	1%	0%	0%	2%	-1%	4%	-1%	-1%
27-Jan	-1%	-10%	-12%	-12%	1%	-1%	0%	2%	-1%	5%	-1%	-1%
3-Feb	-2%	-10%	-12%	-12%	1%	-1%	1%	3%	-1%	5%	-1%	-1%
10-Feb	-1%	-11%	-12%	-12%	1%	-1%	0%	3%	-1%	6%	-1%	-1%
17-Feb	-1%	-10%	-12%	-12%	1%	-1%	0%	3%	-1%	7%	-1%	0%
24-Feb	0%	-8%	-10%	-10%	1%	-1%	0%	3%	-1%	7%	0%	0%
2-Mar	0%	-6%	-8%	-8%	0%	-1%	0%	4%	-1%	7%	0%	0%
9-Mar	2%	-4%	-5%	-5%	0%	-1%	0%	4%	-1%	7%	0%	0%
16-Mar	2%	-2%	-4%	-4%	0%	-1%	0%	4%	-1%	7%	0%	0%
23-Mar	3%	-1%	-2%	-2%	1%	0%	0%	4%	-1%	7%	0%	0%
30-Mar	3%	1%	0%	0%	1%	0%	0%	4%	0%	7%	0%	0%
6-Apr	5%	2%	2%	3%	1%	0%	0%	4%	0%	7%	0%	0%
13-Apr	5%	4%	5%	5%	1%	0%	1%	4%	0%	6%	0%	0%
20-Apr	7%	7%	8%	8%	1%	1%	1%	4%	0%	6%	0%	1%
27-Apr	8%	9%	11%	10%	2%	1%	2%	4%	1%	6%	0%	1%
4-May	9%	11%	14%	13%	2%	2%	2%	4%	1%	5%	0%	1%
11-May	10%	14%	16%	15%	2%	2%	2%	3%	1%	5%	0%	1%
18-May	12%	15%	19%	18%	3%	2%	2%	3%	1%	5%	0%	1%
25-May	13%	17%	21%	20%	3%	3%	2%	3%	1%	4%	0%	2%
1-Jun	14%	19%	23%	23%	3%	3%	3%	3%	1%	4%	0%	2%
8-Jun	15%	21%	26%	26%	3%	3%	3%	3%	1%	4%	0%	2%
15-Jun	15%	22%	27%	28%	3%	3%	3%	3%	1%	4%	0%	2%
22-Jun	16%	22%	28%	28%	4%	3%	3%	2%	1%	4%	-1%	2%

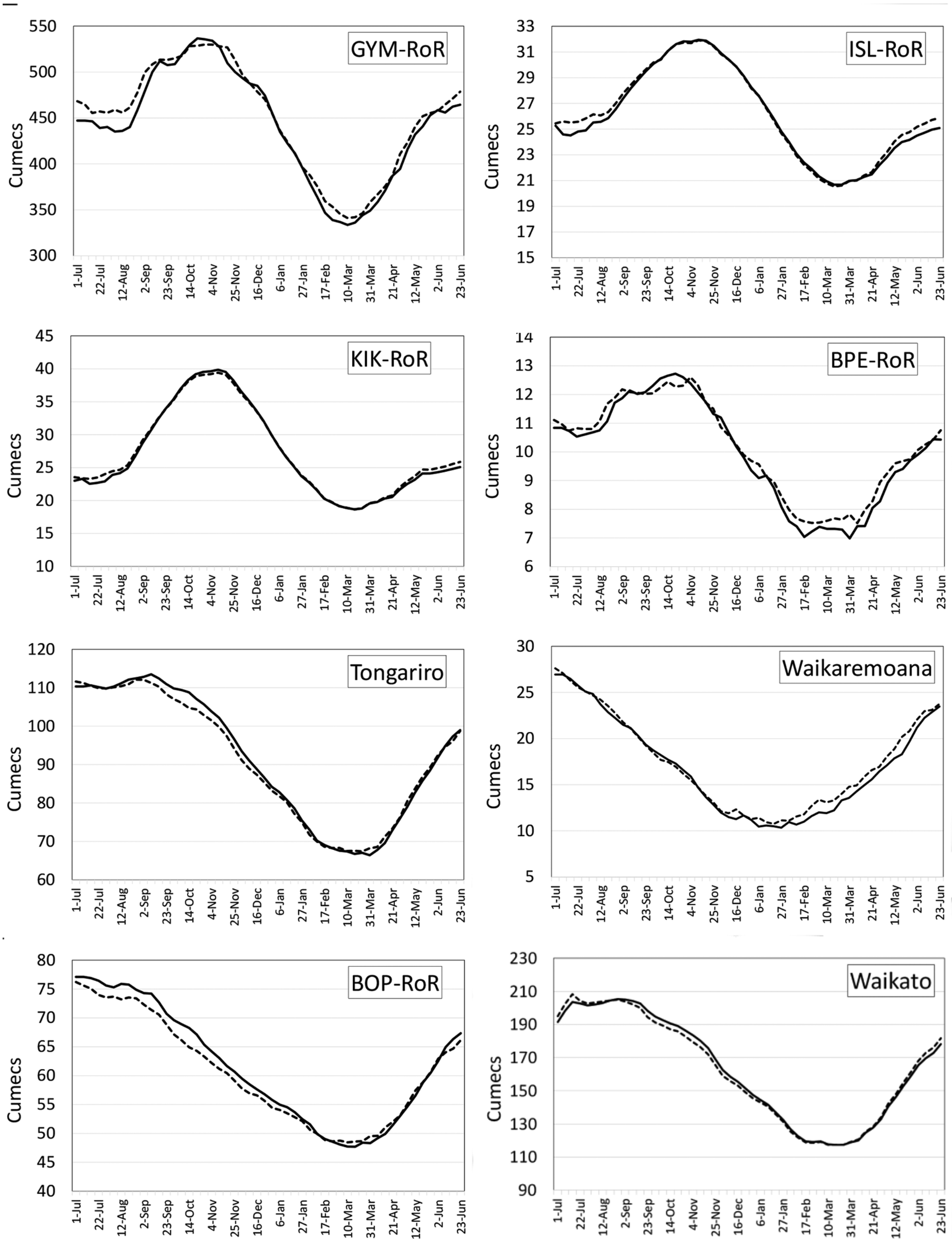

Figure 5 – Current (solid line) and 2050 (dotted line) smoothed average weekly hydropower lake inflows for 8 hydrological regions over 87 hydrological sequences. Note different y-axis scales.

After increased volatility is then applied, the resulting inflow projections are formed for 12 hydrological regions, for 87 hydrological sequences on a weekly time resolution, for the period 2020–50.

Summary graphs of the inflows for each region in 2020 and 2050, averaged over 87 hydrological sequences, can be seen in Figure 5 (except for the South Island snow-fed catchments, which are in Fig. 4). These are displayed in $m^3\ s^{-1}$, to show the true relativity between catchments. Flow ($m^3\ s^{-1}$) values are converted to GWh of potential energy for input into LPCon, by multiplying $m^3\ s^{-1}$ in any given catchment by the k-factor for that catchment. The total change, in GWh, of New Zealand hydropower inflows between 2020 and 2050 is shown in Figure 6.

Annual New Zealand total hydropower catchment inflows (approximately 23,000 GWh) are projected to increase by 2% (450 GWh) by 2050. This represents approximately 1% of New Zealand total annual electricity generation in 2020 of 43,000 GWh. Total projected New Zealand hydropower inflows for 2050 under any emissions scenario are not significantly different ($p > 0.05$) from base (2020) inflows.

However, it is projected that seasonal impacts will be larger, with total New Zealand hydropower catchment inflows projected to be 10% higher in winter, 1% higher in spring, 6% lower in summer, and 4% higher in autumn. The differences in inflows between 2020 and 2050 are significantly different ($p < 0.05$) for both winter and summer inflows, but not for spring or autumn.

South Island snow-fed hydropower catchments

Inflows into the headwaters of the South Island snow-fed hydropower catchments show the largest changes of any New Zealand hydropower catchments in the modelling. These changes can be seen in Figure 5 and are summarised in Table 3 into seasonal and annual changes for a mid-range emissions scenario.

It can be seen that all lakes have moderate increases in annual inflows, from 4% to 6%, between 2020 and 2050. These increases in annual inflows are not statistically significant ($p > 0.05$) relative to the natural variability of historical inflows. The total increase in annual inflows in these four catchments is 430 GWh, which makes up most (95%) of the nett change to annual total New Zealand inflows (450 GWh).

However, seasonal changes are projected to be large over this time period, with Pukaki and Tekapo catchments expected to get 26% wetter in winter and 10% drier in summer.

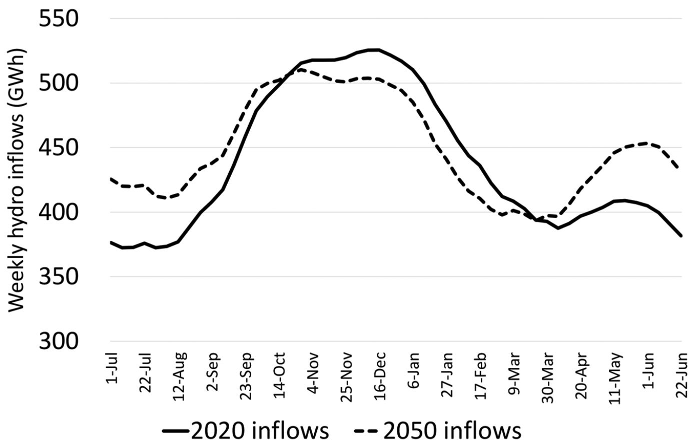

Figure 6 – Total weekly New Zealand hydropower inflows (smoothed), averaged over all 87 hydrological sequences, 2020 (solid line) vs 2050 (dashed line).

Table 3 – Seasonal and annual modelled changes to inflows into the snow-fed South Island hydropower catchments between 2020 and 2050 (%) for a mid-range emissions scenario.

	Pukaki	Tekapo	Clutha	Manapouri
Winter	26%	26%	19%	15%
Spring	2%	2%	2%	4%
Summer	-10%	–10%	–9%	–1%
Autumn	7%	7%	6%	6%
Annual	6%	6%	4%	6%

Clutha and Manapouri changes are expected to be in the same direction as these, but of smaller magnitudes. All four of these snow-fed catchments had statistically significant differences in seasonal inflows between 2020 and projected 2050 inflows ($p < 0.05$).

Electricity modelling results

Changes to both the electricity demand and supply (wind, water) will result in changes to how hydropower catchments are managed in New Zealand in coming decades, with resultant changes to the use of hydropower storage and spill levels.

This paper focuses on the hydrological impacts of changes to inflows and the changes to management of the hydropower catchments. The electricity system modelling includes a large number of assumptions of changes to demand, transmission, and generation, which are not outlined here, but are outlined in Andrews (2018) and Powell (2021). The electricity demand projections and percent renewable generation are shown in Figure 7.

Total New Zealand demand is projected to climb from approximately 43 TWh today to approximately 62 TWh in 2050 in this model projection, largely due to the decarbonisation imperative leading to widespread electrification of transport and industry. The proportion of renewable electricity on New Zealand's national grid is projected to reach 100% by 2033 in this model setup.

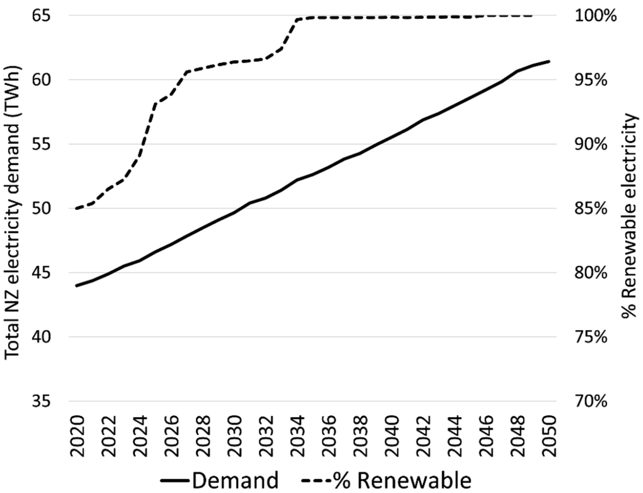

Figure 7 – Projected total New Zealand electricity demand and % renewable electricity 2020–50, from LPCon modelling.

Hydropower lake storage

Model projections of hydropower lake storage generally show increasing levels of storage over time. Storage levels increase across the distribution in Pukaki and Tekapo, from low to high storage levels, but the range of utilised storage decreases over time, i.e., the lakes sit at empty less often in the future, and at full more often, and average annual storage increases over time. The range of the average storage (over 87 sequences) decreases by 21% in Lake Pukaki and 23% in Lake Tekapo. Increasing modelled hydropower storage in Lake Pukaki can be seen in Figure 8, and the other snow-fed lakes follow a similar pattern.

The same increase in average storage over time is seen in Lake Hawea (the main hydropower storage lake in the Clutha catchment) model results, with less time spent at minimum storage in the 2030s to 2050s than in the 2020s. Lake Hawea is already currently managed to spend more time at absolute maximum and absolute minimum storage than the other lakes in this study, and this pattern continues in future, so the range does not decrease as much over time as the other lakes (-6%). Lake Manapouri also has more time spent above minimum storage in the 2030s to 2050s than at present. The range the average storage fluctuates by on an annual basis decreases by 24% between 2020 and 2050.

Average storage at the lakes increases by 37% at Lake Pukaki between 2020 and 2050, 35% at Lake Tekapo, 17% at Lake Hawea, and 24% at Lake Manapouri. These hydropower storage lakes spend less time at empty storage level (average of 4% less time), and more time at full storage level (average of 10% more time) in the future than in the 2020s, as can be seen in Figure 9.

Spill changes

Minimum, mean, and maximum weekly spill at Lakes Pukaki, Tekapo, Hawea, and Manapouri all increase across all 87 hydrological sequences between 2020 and

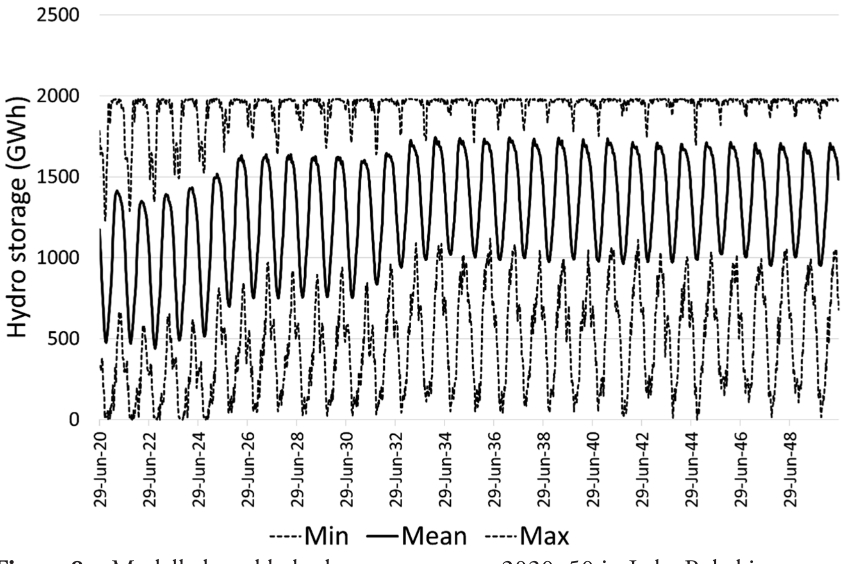

Figure 8 – Modelled weekly hydropower storage 2020–50 in Lake Pukaki: minimum, mean and maximum of 87 hydrological sequences based on past history, trended for climate change, and modified through hydropower scheme management.

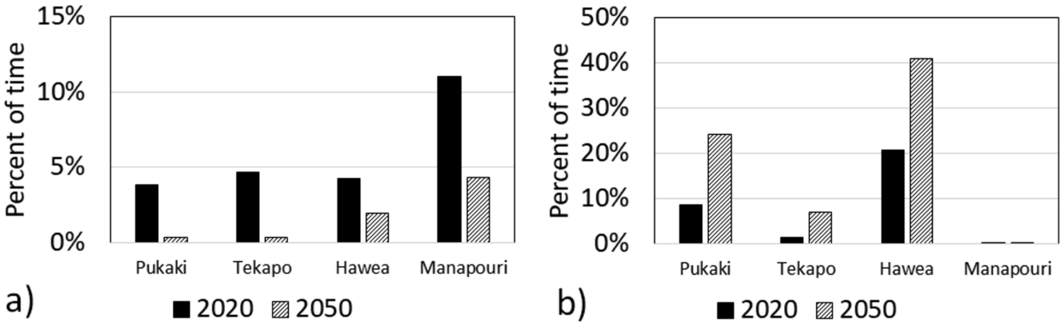

Figure 9 – Percent of time at a) empty storage (average of 87 hydrological sequences) and b) full storage (average of 87 hydrological sequences) for Lakes Pukaki, Tekapo, Hawea (Clutha), and Manapouri, for 2020 and 2050.

2050. Lake Pukaki modelled spill from 2020 to 2050 can be seen in Figure 10; the other lakes follow a similar pattern.

In more detail, Lake Pukaki spill for the maximum, mean, and minimum of the 87 hydrological sequences is shown for 2020 and 2050 (Fig. 11); the other lakes follow a similar pattern. It can be seen that spill is greatly increased in 2050 relative to 2020.

Spill is predicted to more than double by 2050 in the combined South Island hydropower catchments of Pukaki, Tekapo, Clutha, and Manapouri. Modelled spill at these four lakes increases from 485 GWh in 2020 to 1087 GWh in 2050, an increase of 602 GWh and equal to 6.3% of current generation from those catchments (see Table 4).

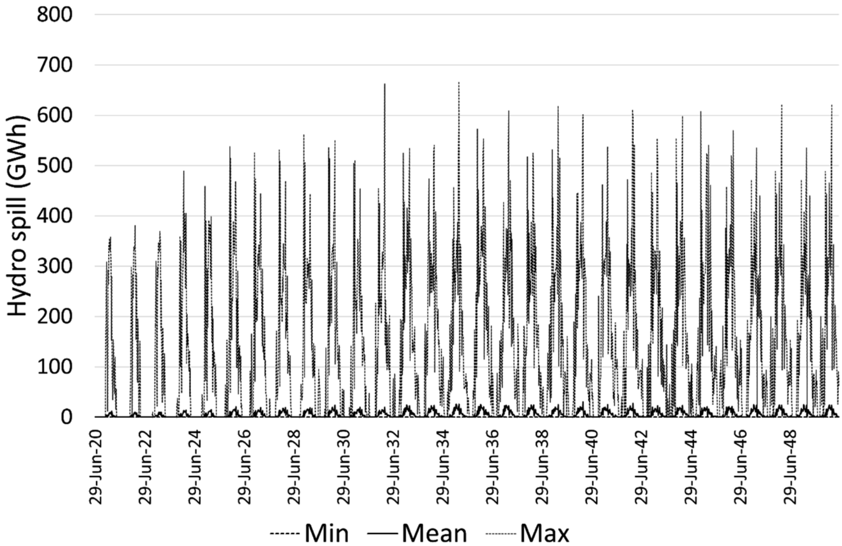

Figure 10 – Weekly modelled spill for Lake Pukaki, 2020–50. Minimum, mean and maximum (and linear trend of maximum) of 87 hydrological sequences based on past history, trended for climate change, and modified through hydropower scheme management.

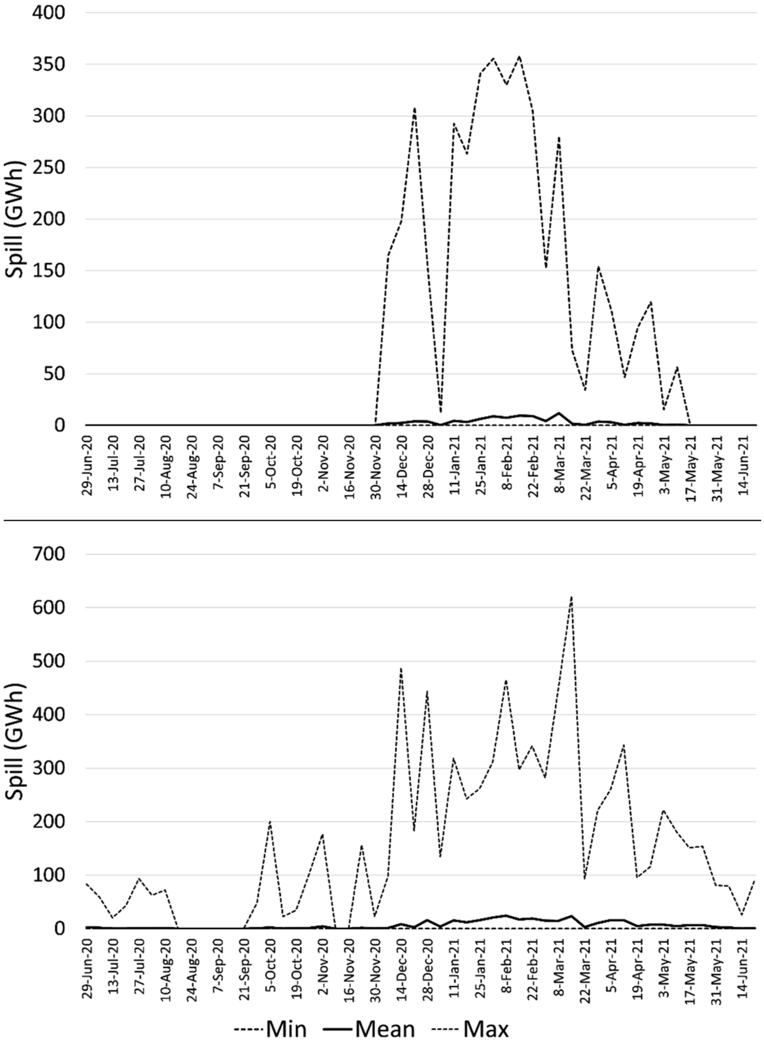

Figure 11 – Lake Pukaki weekly total modelled spill for 2020/21 (top) vs 2049/50 (bottom) – minimum, mean, and maximum of 87 hydrological sequences.

Table 4 – Modelled spill from major hydropower storage lakes in the Waitaki (Pukaki and Tekapo), Clutha (Hawea), and Manapouri catchments 2020 vs 2050, averaged over 87 hydrological sequences (GWh), and relative to current generation from that catchment.

	2020	**2050**	**% of generation 2020**	**% of generation 2050**
Lake Pukaki & Tekapo	133	500	1.8%	6.0%
Lake Hawea	56	117	1.5%	3.1%
Lake Manapouri	296	40	5.8%	9.2%
Total	485	1087	2.8%	6.3%

Discussion

Uncertainty

Uncertainties around climate change runoff projections are generally large, and this is well documented in the literature surrounding river flow projections (Jobst *et al.*, 2018; Wambura *et al.*, 2015; Lehner *et al.*, 2019). The main sources of uncertainty in this study stem from the use of the average of the six GCMs, NIWA's regional downscaling of these ocean-atmosphere state variables to local rainfall, the use of a single snowpack change trajectory, and the error around flood size changes. The model cascade methodology used also has the potential to impose an additive effect on the individual errors already mentioned. The significance of these uncertainties is a weakness of this study.

This study does explore the impact of different emissions scenarios, and looks for statistical significance in the changes found, relative to natural variability. The assumption is made that historical natural variability of inflows is represented by the use of an 87-year history of inflows for each catchment, although a longer record, were one available, would undoubtedly yield some changes to the 87-year distribution.

This study also explores scenarios of potential future states of the electricity system for different model setups. Profitability of generation plant dictates which new generation will be built according to need and on a least-cost basis, and as such a 'most likely' future scenario is arrived at based on estimates of supply and demand. This modelling process has significant uncertainty also but is simply meant to project one 'likely' future amongst many uncertainties.

Future work already underway will explore uncertainties around these future trajectories in greater depth, based on a spread of global models and a distributed hydrological model, Topnet (Collins *et al.*, 2018).

Hydropower catchment inflows

Climate change impacts on inflows to forty New Zealand hydroelectric power generation stations, encompassed in twelve regions, are modelled using a model cascade. Results show an overall 2% increase in annual hydropower catchment inflows over the whole of New Zealand between 2020 and 2050, which equates to an increase of 450 GWh. This increase in inflows is equivalent to approximately 1% of the total annual generation in 2020 of 43,000 GWh.

Seasonal impacts are projected to be larger, with total New Zealand hydropower catchment inflows projected to be 10% higher in winter and 6% lower in summer by 2050, and this is a statistically significant and largely beneficial shift, with New Zealand seasonal electricity demand currently anti-correlated with total New Zealand inflows. Projected changes to the volume of inflows are equivalent to between -3% of current total summer New Zealand electricity generation and +5% of winter generation.

Different emissions scenarios were shown to not yield significantly different inflow projections over the time period studied. This will be explored further in future work.

The largest snow-fed South Island hydropower catchments are particularly affected, because, in addition to expected rainfall changes, they receive a significant proportion of their inflows from snowmelt, resulting in large seasonal changes to inflows as temperatures warm in coming decades. All four catchments focused on (Pukaki, Tekapo, Clutha, and Manapouri) have moderate increases in annual inflows, from 4% to 6% between 2020 and 2050. The total increase in annual inflows in these four catchments sum to 430 GWh, which is 95% of the change to annual total New Zealand inflows. This finding is in contrast to those of international studies that have found annual river flows in mountainous catchments are projected to decrease, e.g., by 16–35% in

Chile (Vicuña *et al.*, 2011) and 5% in the Italian Alps (Bombelli *et al.,* 2018).

Seasonal changes in this study's catchments are projected to be large over this time period, with statistically significant changes in the Pukaki and Tekapo catchments for winter (26% wetter) and summer (10% drier). Clutha and Manapouri changes are expected to be in the same direction as these, but of smaller (but still significant) magnitudes. Internationally, changes in seasonal river flows in snow-fed catchments of -25% to -32% (summer, Chile) and +29% to +34% (winter, Chile) are projected for end of century (Vicuña *et al.*, 2011). Swiss hydropower inflows are projected to change by -22% (summer) and +39% (winter) by mid-century (Savelsberg *et al.,* 2018). Although estimates vary widely, the trend found here of higher winter inflows and lower summer inflows in future in snow-fed catchments is reflected in these international studies.

The results of this study are compared to other recent studies projecting changes to Southern Alps-sourced river flows in Figure 12. Although the studies differ in catchments, periods of projections, and methodologies, it can be seen that all studies project river flows in large, eastward-flowing Southern Alps snow-fed catchments changing in the same direction by mid-century. That is, large increases occur in winter inflows and smaller decreases or no changes to flows occur in summer. All studies project moderate (3–10%) increases in annual flows.

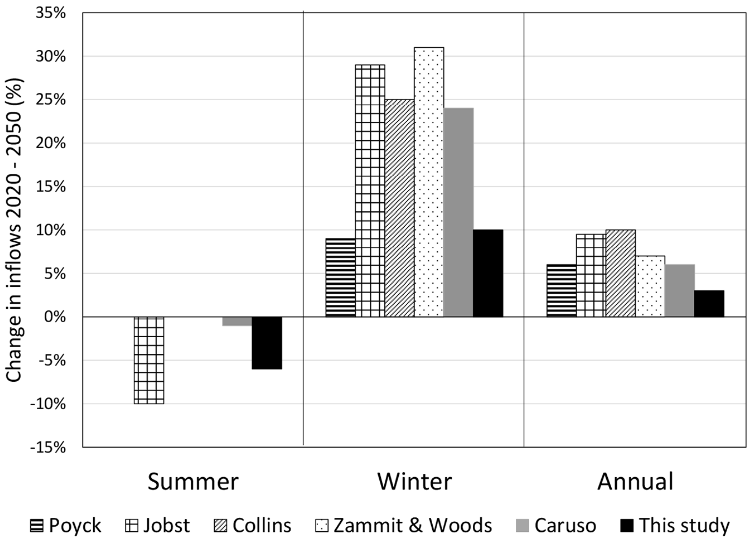

Figure 12 – Comparison of seasonal and annual changes to catchment inflows by 2040s or 2050 – various New Zealand studies. All studies are for a mid-range emissions scenario. Poyck et al. (2011) and Jobst et al. (2018) projections are for the Clutha catchment, Zammit and Woods (2011) projections are for the Waimakariri catchment, Caruso et al. (2017b) is based on the Waitaki catchment, Collins (2020) projections are for the Southern Alps snow-fed catchments, and this study shows results for the Waitaki (Pukaki and Tekapo), Clutha, and Waiau (Manapouri) catchments.

Hydropower lake storage and spill

Large increases in both hydropower lake storage levels and spill are projected between 2020 and 2050. Average storage is projected to increase by 37% at Lake Pukaki between 2020 and 2050, 35% at Lake Tekapo, 17% at Lake Hawea (Clutha), and 24% at Lake Manapouri. Percent time at empty is projected to decrease by 4% between 2020 and 2050, and percent time at full increase by 10%, averaged over the four lakes. The range of storage utilised at these lakes is predicted to decrease, as better correlation between supply and demand reduces the need for utilisation of hydropower storage.

Spill is predicted to more than double in the combined South Island hydropower catchments of Pukaki, Tekapo, Clutha, and Manapouri by 2050, and be equal to 3% of generation in 2020 and 6% of generation by 2050. In addition to greater volumes of spill, climate change will move spill away from summer and into the winter period, where currently little spill occurs (10%). Seventy-five percent of spill currently occurs in summer and autumn, and this is expected to reduce to 58% of spill. Winter and spring currently only see 25% of spill in these catchments, and this is projected to increase to 42% by 2050.

There are many likely explanations for increases in hydropower storage and spill in these catchments. The relatively small increase in total inflows would likely lead to moderate levels of increased spill. Increased volatility of inflows, with larger flood peaks, will lead to an inability of storage to capture all the water flowing into the lakes in a flood event. In addition to this, increasing levels of renewable energy in the New Zealand electricity system will lead to more intermittent calls on hydroelectric energy, which, in a highly renewable system is often employed as the 'battery bank' to soak up the intermittency of wind and solar generation. These findings are commensurate with international studies showing that increases to spill from hydropower reservoirs are a consequence of both increased extreme precipitation events and increased levels of intermittent renewable electricity generation in future (Mason *et al.*, 2010; Caruso *et al.*, 2017b; Tarroja *et al.*, 2016).

LPCon has penalties in its optimisation for running out of stored hydropower water, which would impact security of supply and wholesale electricity price. With increasing intermittency of the need for generation, and increasing flood peaks, hydropower lake managers will be incentivised to hold lakes higher in future, as the cost to the electricity system and the country of running out of water is far higher than the cost of spilling more.

With increasing inflows, changing seasonality of inflows, increasing volatility of inflows, and increasing volatility of generation, it is difficult to ascertain whether it is supply (water) or demand (electricity generation) that has the bigger impact on storage and spill. The thirty-year projected time series of annual inflows, electricity demand, and percent renewable at Lake Pukaki all show high cross-correlations with storage and spill (between 0.75 and 0.99), implying that they are all contributing to increased storage and spill. Causative relationships between these variables will be examined further in future work.

Combined modelled spill in the Pukaki, Tekapo, Hawea (Clutha) and Manapouri catchments is predicted to increase by 602 GWh by 2050. In comparison, the increase predicted in total annual hydropower inflows in these four catchments is 430 GWh by 2050, showing that increases in inflows will be negated by increases in spill. Globally, a large review of power system vulnerability to climate change examined 24,500 hydropower generation facilities and concluded that an average reduction in generation capability of 61–74% was likely by mid-century (van Vliet *et al.,* 2016). This study found that moderate increases to total inflows in these important hydropower catchments will be offset by increases in spill, but extensive changes to the seasonality of inflows will better match electricity demand.

Conclusions and future work

This study has shown that significant changes to river flows resulting from changes to rainfall and snow melt are expected between now and mid-century, particularly in the snow-fed hydropower catchments in the Southern Alps. These shifts, combined with changes to electricity demand and supply, will result in changes to hydropower catchment management which will result in significant changes to lake storage levels and hydroelectric scheme spill in coming decades. This study concludes that seasonal changes to inflows will better match electricity demand, but higher hydropower lake levels and increases to annual spill volumes are likely to offset any increases in projected annual inflows expected over the study period, particularly in the large snow-fed Southern Alps hydropower catchments.

This work portrays the results from a simple statistical model, using broad relationships to predict change in complex systems. It does not include representation of a large ensemble of GCM outputs and uses single trajectories for snowpack and flood peak changes. It uses an electricity system model that includes many opaque assumptions around the way the electricity system will operate in future. As such, the results have significant uncertainties, which are currently being addressed as part of ongoing work in this area and will be published in future. This work is part of an ongoing larger study into climate change impacts on New Zealand's electricity system, which includes using NIWA's wind speed and Topnet river flow projections out to 2050 as input to the electricity system model LPCon. More detailed nationwide results of this work will be published as this study progresses.

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