National hydrological and water resource impacts of climate change

Compilation of outputs

Prepared for the Deep South National Science Challenge

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Executive summary

This report brings together outputs from the Deep South National Science Challenge Phase 1 funded "Climate changes impacts on national water cycle" project. Five outputs from that work have been produced; the first, a paper titled 'New Zealand River Hydrology under Late 21st Century Climate Change' was published in *Water* journal in August 2020 (Collins 2020), another titled 'Hydrological sentinels and the relative emergence of climate change signals in New Zealand river flows' was published in the Hydrological Sciences Journal in November 2021 (Collins 2021). This report contains a compilation of data analysis and interpretation from the remaining three self-contained papers which were submitted as outputs for this project. The reader is referred to the published literature for potential published versions of these draft papers in the future. Each chapter (or paper), represents a research task within the Deep South project, the abstracts for which are as follows below. In addition to these draft papers, a key deliverable from this project were model output data which are available via the Deep South Data Knowledge Broker.

1. **Shifts in hydropower generation under climate change in relation to growing electricity demand**
   Authors: Daniel Collins[1], Roddy Henderson, and Laurence Fischer[2]

   Hydropower generation is projected to expand over the course of the 21st century to meet growing global electricity demand, in part driven by the need to mitigate climate change. At the same time, hydropower is sensitive to climate change, with shifts in annual supply and seasonal timing. In planning energy system development, it is therefore prudent to consider how the hydrological effects of climate change may influence the ability to meet growing electricity demand. To this end, climate projections are used to assess the effects on generation potential for six hydropower schemes across New Zealand's national grid, together accounting for half of the country's installed electricity generating capacity. Significant increases in winter precipitation in major hydropower catchments shift the timing of low hydropower supply from winter (the time of peak demand) to summer. By mid-century, an extra 1 TWh of annual generation potential is projected (a 5% increase), which equates to 3-16% of 2050 electricity demand. By late century, additional generation potential varies more with emissions scenario. These results highlight the need to consider changing hydropower generation potential, annually and seasonally, across national grids alongside projections of national electricity demand and expansion of renewable energy generation.

2. **Emergence of increasingly extreme floods within New Zealand under climate change**
   Author: Daniel Collins

   Evidence is mounting of non-stationary flood behaviour, which is projected to become more pronounced under 21st century climate change. One of the challenges this poses flood risk management is the question of when to adapt. To this end, a useful indicator of the growing significance of climate change effects is the Time of Emergence when a signal becomes detectable above background variability. Using a national climate-hydrology model cascade for New Zealand, the times and magnitudes of emergence of changes in the 100-year flood are assessed. Emergence varies with emissions scenario and location, with most locations showing no robust emergence this century. When changes in the 100-year flood do emerge, they tend to lie within the south and west of the South Island, with Times of Emergence towards the end of the century and practically none by

[1] We note that this work was completed whilst the primary author Daniel Collins was employed at NIWA, however he left NIWA in August 2020 and is now an independent consultant.
[2] Laurence Fischer was an intern at NIWA studying at the University of Neuchâtel when this work was completed, most recently she worked for Beca Consulting in NZ.

mid-century. These results have implications for both climate change mitigation and adaptation. Avoided emergence by the end of the century amounts to 20-37% of the country when comparing the high- and low-end emissions scenarios, depending on the stringency of the inter-model evaluation. And the low rates of emergence combined with the lag between effects and detectable emergence support a phased but flexible transition from stationary to non-stationary risk assessment in a patchwork manner across regions.

3. **Impacts of 21st century climate change on water stress and availability across New Zealand**
   Author: Daniel Collins

   Land-based primary industries depend on rainfall or irrigation to support crop and economic productivity. With the prospects of climate change this century altering the water cycle, there is a need to assess how these impacts translate to water stress and water availability. Using a climate-hydrology model cascade, impacts of 21st century climate change on water stress and river water availability for abstraction are projected across New Zealand and across four emissions scenarios. Results reveal a patchwork of increases and decreases in both metrics, typically with sub-catchments exhibiting either both beneficial or both detrimental effects. Higher water stress and longer restrictions in river abstraction are projected for the north and east of both main islands, as well as along them idle of the South Island. Conversely, lower water stress and fewer restriction on abstraction are generally projected for the west and south of both islands. Under the higher emissions scenarios, however, areas experiencing increased water stress and longer restrictions expands to cover most of the country.

1 Shifts in hydropower generation under climate change in relation to growing electricity demand

1.1 Introduction

Hydropower is currently the largest source of renewable electricity generation globally, with 1,292 GW of installed capacity as of 2018 providing 4,200 TWh of electricity, which amounts to 16% of total electricity generated internationally [1]. For several countries, hydropower provides the majority of the electricity generated. This capacity continues to grow to meet demand for electricity, and in coming decades will also be part of countries' climate change mitigation efforts as they move their energy systems away from carbon-intensive sources [2, 3]. While not without social and environmental costs [4-6], hydropower has a low carbon footprint [7].

At the same time, however, hydropower generation is itself particularly sensitive to climate change. Projected shifts in temperature and precipitation affect the frozen storage of water within catchments, inflows to hydropower stations, and evaporation from reservoirs [8]. These changes in turn affect the overall amount of electricity generated [9-12], the seasonality of generation potential [13-18], and the reliability of electricity supply [19]. Some of the changes are beneficial, some detrimental, and others too small to be of consequence, depending on the hydroclimatology of the region and the emissions scenario.

These potential changes in hydropower supply and its uncertainty must be factored into future hydropower planning, and into energy planning more broadly [20]. Several researchers have examined how to adapt hydropower design and operation under climate change, from station to network scale [20-23], and how climate change influences the generation potential of possible new developments [10, 24, 25]. Where large declines in generation potential occur, the financial viability of present or proposed schemes may become questionable [26, 27]. Tarroja et al. [28] considered effects of high-end climate change on a highly renewable regional electric grid and found that higher hydrological variability would require greater dispatchable power plant capacity across the grid. And using a cascade of global climate, hydrology, and hydropower models, Turner et al. [29] showed how increases and decreases in late-century hydropower generation potential affect power sector investments.

Casting the hydropower changes in terms of growing renewable power needs, an important question emerges: How will the direct effects of climate change on hydropower generation potential affect the ability to meet growing demands for electricity nationally?

To examine this question, we use New Zealand as a case study. Sixty percent of the country's 43,041 GWh of generated electricity currently comes from hydropower [30], distributed across a national grid with low levels of energy storage and no connection to another country's energy grid (Transpower 2018). High reliance on hydropower with low storage has left the country susceptible to hydroclimatic droughts, resulting in winter electricity shortages, when demand is highest [31]. Demand for electricity is projected to grow by 2050 by between 18% and 78% [32, 33], and with a shift to decarbonise the energy system, the new generating capacity will need to be largely or entirely renewable. At the same time, much of the present hydroelectricity generation lies within snow- and glacier-affected catchments that are projected to undergo increases in river flows and seasonal shifts over the course of the 21st century, while other schemes may experience declines in flows [35]. In terms of implications for hydropower, only one scheme has been studied to date. For the Waitaki River catchment, Caruso et al. [9] projected increasing annual and winter inflows and decreasing summer inflows, with an overall increase in generation and supply shortfalls shifting from the winter/spring period to summer/autumn. How climate change may affect other schemes and the national grid as a whole, however, are as yet unknown, nor how these effects compare to growth in electricity demand.

In this research we investigate the implications of projected climate change on generation potential for six hydropower schemes across New Zealand, together accounting for 83% of the country's installed hydropower capacity or 48% of total generation capacity. The hydropower projections are derived from catchment hydrological modelling based on climate information downscaled and bias-corrected from six General Circulation Models (GCMs) and four Representative Concentration Pathways (RCPs). Attention is given to the seasonality of generation potential, and to changes in mean annual, mean winter, and mean 3-month low generation potential. The projected changes in annual generation are then compared to published scenarios of electricity demand for 2050.

1.2 Data and methods

1.2.1 Study region: Climate, hydrology, and hydropower

New Zealand lies between 34° to 47°S in the Southwest Pacific within the prevailing westerlies of the mid-latitude Southern Hemisphere [36]. Topography is dominated by a volcanic plateau in the centre of the country's North Island and by the southwest/northeast-aligned Southern Alps in the South Island. Orographic effects combined with the prevailing westerly airflow produce high precipitation rates along the Southern Alps, in places over 10 m/year, with leeward areas dropping to 350 mm/year [37]. The North Island and the north of the South Island have seasonal precipitation and river flow patterns with winter (June, July, August) maxima and summer low flows, while west and alpine parts of the South Island have flatter seasonal cycles with either autumn maxima or bi-modal patterns (autumn/spring maxima and winter minima), and winter low flows [38, 39]. In the South Island, seasonal snow cover varies between 5% and 35% from summer to winter [40], and snowmelt over spring and summer contributes up to 17% of mean annual flows at the outlets of snow affected catchments [41].

Fed by abundant water resources, hydropower provides 60% of New Zealand's electricity as of 2018 with an installed capacity of 5381 MW [30] spread across 71 power stations [42, 43]. Water storage is dominated by 10 major lakes [44], and accounts for roughly 10% of the country's annual electricity consumption [45]. The South Island schemes, which generate most of the country's hydroelectricity, are largely fed by precipitation spilling over the Southern Alps during westerly storms [31]. Snow storage during winter is an important component of the seasonality of hydropower generation in these schemes; snow melt provides about 50% of the spring and summer inflow to the Waitaki scheme's upland lakes [46]. Glacier melt also contributes to southern scheme inflows [47]. Hydropower generation in the North Island is dominated by the Waikato River scheme, downstream of New Zealand's largest lake, Lake Taupo, and originating in the central volcanic plateau. Annual reservoir inflows in the South Island thus tend to be lowest during winter and highest during spring and summer, while inflows in the North Island tend to have summer lows and winter/spring highs. Aggregated hydropower generation nationally also produces minima during winter [48]. The two islands are also generally out of phase in the interannual timings of lows and highs.

For this study, eliminating those schemes and stations with insufficient data to inform hydropower modelling leaves six schemes with a total of 23 power stations (Figure 1-1, Table 1-1) [42, 49, 50]. Together they account for 83% of New Zealand's installed hydroelectricity generation capacity (48%

of total electricity generation capacity), on average generate 207 TWh annually, and represent a large range of New Zealand's hydroclimatic conditions where hydropower is generated.

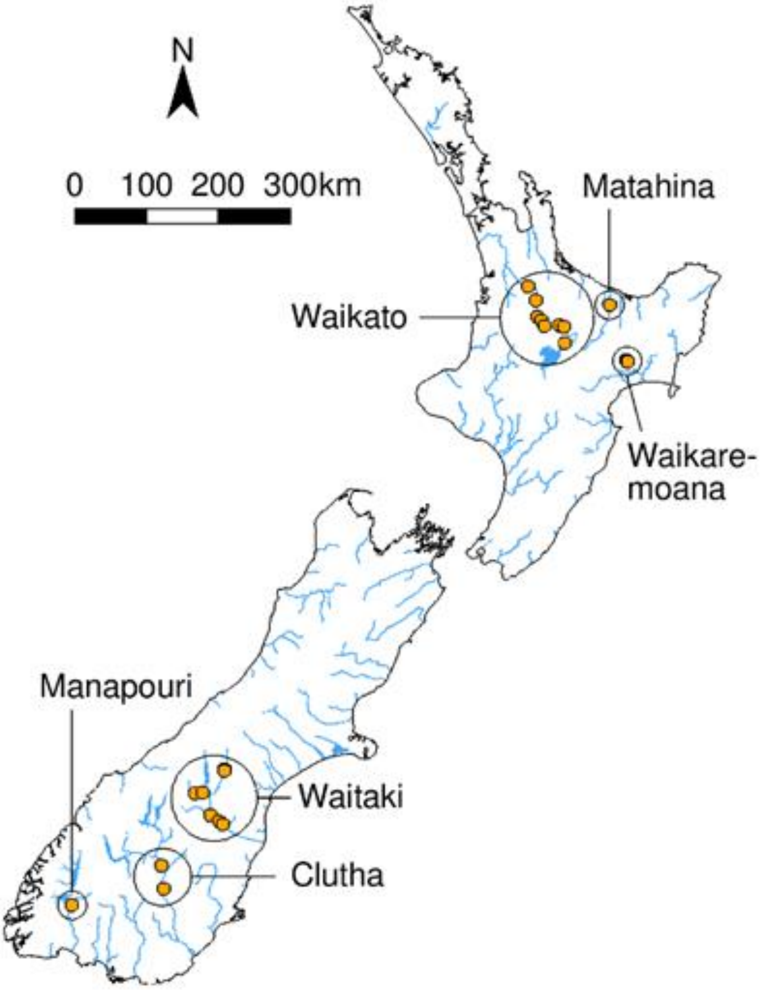

Figure 1-1: Locations of the six hydropower schemes and 23 stations considered in analysis. In the North Island, the Waikato River scheme uses 290 m of head along 180 km of the North Island's longest river, and the storage available upstream in Lake Taupo, New Zealand's largest lake. The scheme comprising eight dams and nine power stations is also augmented with flows diverted through the Tongariro Power Scheme around the central North Island volcanoes. Matahina, to the east of the Waikato valley, is a run-of-river scheme with 61 m of head on the Rangitaiki River. The Waikaremoana scheme still further east, consists of three power stations that use water from Lake Waikaremoana augmented by a river diversion and inflow from small tributaries downstream of the lake, with a total head of 450 m.

Table 1-1: Installed capacities and conversion efficiencies of the 23 stations analysed.

Scheme	Station	Installed capacity (MW)	Mean annual generation (TWh)	Conversion efficiency, k (MW s m^{-3})
Waikato	Aratiatia	84	0.34	0.268
	Ohakuri	112	0.41	0.278
	Atiamuri	84	0.29	0.204
	Whakamaru	100	0.49	0.315
	Maraetai 1 and 2	360	0.89	0.498
	Waipapa	51	0.24	0.143
	Arapuni	172	0.88	0.463
	Karapiro	96	0.51	0.265
Matahina	Matahina	72	0.26	0.546
Waikaremoana	Kaitawa	36	0.45	1.006
	Tuai	60		1.587
	Piripaua	42		0.942
Waitaki	Tekapo A	25	0.13	0.232
	Tekapo B	160	0.83	1.282
	Ohau A	264	1.11	0.501
	Ohau B	212	0.94	0.417
	Ohau C	212	0.93	0.417
	Benmore	540	2.22	0.818
	Aviemore	220	0.92	0.310
	Waitaki	105	0.49	0.162
Clutha	Clyde	432	2.04	0.518
	Roxburgh	320	1.62	0.394
Manapouri	Manapouri	710	4.70	1.531

In the South Island, the Waitaki scheme south and west of Christchurch comprises three lakes and eight stations using 480 m of head. The majority of the scheme's water comes from rivers draining the Southern Alps. Most of that water is stored in three large natural lakes, all of which are controlled for storage, before being extensively diverted with a series of canals that allow the upper catchment flows to pass through five power stations. Downstream the final three stations on the main stem are effectively run of river. Clyde Dam (102 m head) on the Clutha River (New Zealand's largest by mean flow and catchment area) also uses water from three large natural lakes the smallest of which has controlled storage. The Manapouri scheme in Fiordland comprises two lakes and one station that uses 177 m of head between the lake and the ocean through a tunnel and underground powerhouse.

In terms of electricity demand, the annual cycle peaks during winter, primarily due to demand for household heating [51]. With the period of high demand coinciding with the period of low generation, New Zealand experiences occasional electricity shortages during dry years [31, 52]. Effects of these shortages have included higher electricity prices, voluntary energy use reduction campaigns, and blackouts. The most severe drought duration, based on analysis up to and including the 1992 drought, is 2.5 months [53], although the dry conditions that led up to shortages were typically longer.

1.3 Climate and hydrological modelling

The hydrological simulations used in this study are described by Collins [35] and are based on climate projections described by Ministry for the Environment [54]. Summaries are provided below. The simulations were run from 1971-2005 for the 'historical' period, and from 2006-2099 under the climate change scenarios.

The climate data are derived from four Representative Concentration Pathways (RCPs) [55] and six Global Circulation Models (GCMs) as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) [56]: BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and NorESM1-M. GCM output was dynamically downscaled using the regional climate model HadRM3P over New Zealand [57], further downscaled using seasonal quartile and statistical mapping to an approximately 5 km grid at a daily time-step, and bias-corrected relative to 1980-1999 climatology [58]. Lastly, precipitation fields were adjusted following Woods et al. (2006), and stochastically disaggregated from daily to hourly following Clark et al. (2008).

Time-series of precipitation, temperature, relative humidity, short wave solar radiation, mean sea level pressure, and wind speed were then used to drive the semi-distributed, physically based catchment hydrological model TopNet [59, 60]. Abstractions, diversions, return flows, impoundments, and irrigation are not included. Natural river flows are simulated across the national digital river network partitioned into 43,862 reaches corresponding to sub-catchments with a mean area of 6 km^2. It is from these reaches that hydropower station inflows are obtained for the purpose of modelling hydropower generation potential in the present study. The hydrological model is uncalibrated but validation performed by Collins [35] shows good agreement between observed and modelled mean annual and seasonal flows.

1.4 Hydropower modelling and analysis

In this study our motivation is to focus on the effects of climate change on hydropower potential, as mediated by river flows. Isolating the supply side of energy production is complicated by the fact that electricity is generated to meet demand subject to the availability of stored water in the context of grid-wide generation. We are also limited by the availability of data describing hydropower operations. We thus average station conversion efficiencies, k ($MW\ s\ m^{-3}$) (Figure 1-1, Table 1-1) [44, 53], relating mean flows, Q ($m^3\ s^{-1}$), to hydroelectricity generation, P (MW), following $P = k\ Q$. This is applied monthly and conversion efficiencies are assumed stationary, and broadly describes how generation potential varies with hydrology. Total scheme generation is subsequently the contemporaneous sum across constituent stations, and what in this study we call 'national generation' is the sum across the six schemes.

The combined climate-hydrological-hydropower modelling thus gives us monthly time-series of generation potential from 1971-2005 and from 2006-2099 for six hydropower schemes and the national total under four RCPs and six GCMs. Model outputs are analysed in terms of their seasonal cycles, the mean annual generation potential, the mean winter generation potential (the time of greatest historical demand), and the mean annual 3-month low generation potential (the typical duration of historical electricity shortages). The water year is defined as October to September. Implications of climate change are inferred by comparing the reference period of 1986-2005 to two future periods: mid-century (2040-2059) and late century (2080-2099).

Statistical significance of any changes, relative to the modelled reference period for each RCP, is estimated using the t-test with a confidence limit of 5% [61], drawing from the 20-year time-series of the reference and future periods. The results of the test help us to isolate the effects of climate change from the combined effects of climate model uncertainty and internal variability.

1.5 Results and discussion

1.5.1 Seasonal generation potential

Changes in the annual cycles of generation potential vary with the scheme, RCP, and projection period (Figure 1-2). The three North Island schemes maintain their seasonal pattern, with the 3-month minimum in summer/autumn and the 3-month maximum in winter/spring. Differentiating them from one another, Matahina shows little change overall, Waikaremoana tends to show lower generation potential during winter and spring by late-century, while the generation potential for Waikato increases during winter/spring and decreases during summer. In contrast, the three South Island schemes exhibit distinct shifts in seasonal generation potential, with large increases in winter production shifting the timing of the month with the lower potential from August to February. The spring-time maxima also increase. Given the large capacity of the South Island schemes compared with the North Island's, shifts in national generation also show a significant increase in winter, and the period of low potential shifts from winter/spring to summer/autumn.

For mean winter (June, July, August) generation potential specifically, none of the North Island schemes exhibit significant changes, while all of the South Island and the national aggregate do (Figure 1-3). By mid-century there is a subtle increase in generation with increasing RCP, while by late-century this pattern is pronounced. National mid-century generation potential is projected to increase by 7.7% under RCP2.6 and 13.3% under RCP8.5, respectively, and by late-century the values are 8.0% and 37.1%, respectively.

For the 3-month minimum generation (Figure 1-4), all the South Island schemes and the national aggregate show significant increases under all RCPs and both time periods. There is little difference across RCPs mid-century, but by late-century there is a clear trend of increasing generation from RCP2.6 to RCP8.5. These South Island increases are not as large as the winter increases because, as described above, the timing of the 3-month minimum shifts from winter to summer/autumn, and the increases during the new minimum months are more subdued. For the North Island, there are no significant changes by mid-century, while Matahina and Waikaremoana show some significant decreases under the high RCPs by late-century. National mid-century generation is projected to increase by 7.5% under RCP2.6 and 7.9% under RCP8.5, respectively, and by late-century the values are 4.6% and 12.1%, respectively.

These seasonal shifts arise from the significantly greater precipitation and runoff during the winter months along the west and alpine areas of the South Island, and from higher alpine temperatures in both islands [35, 54]. The hydrological impacts of climate change are smaller in the North Island, and the location of the Waikato scheme's catchment in the middle of the island is nestled between the slight increases in precipitation to the west and the slight decreases to the east. Given that peak electricity demand occurs during winter, this seasonal shift would help to meet peak seasonal demand and reduce the chance and severity of hydropower droughts, increases in overall electricity demand notwithstanding.

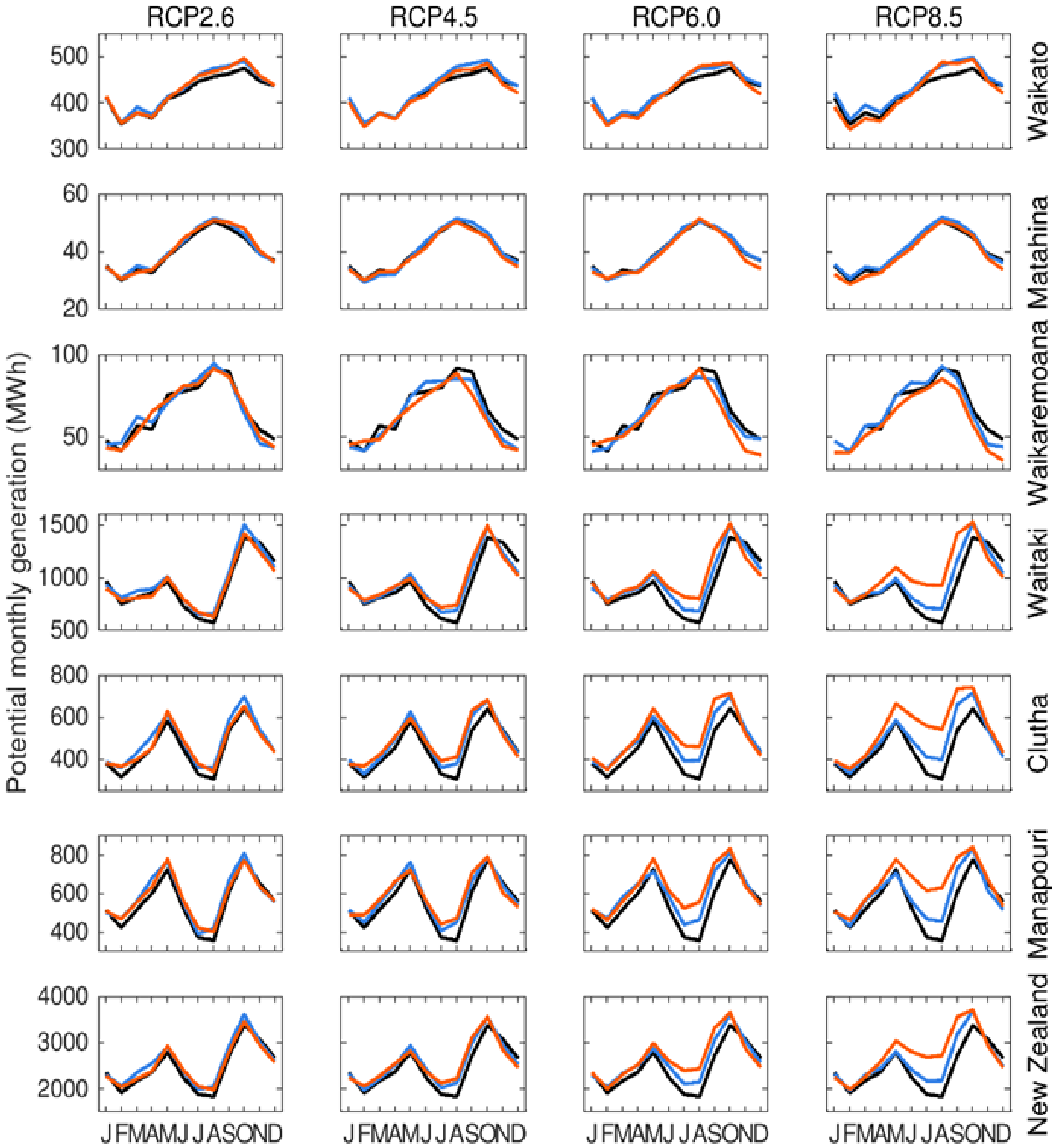

Figure 1-2: Multi-model mean potential monthly generation for each hydropower scheme and national aggregation, for each RCP, and for each time period:. reference period (black), mid-century (blue), and late century (orange).

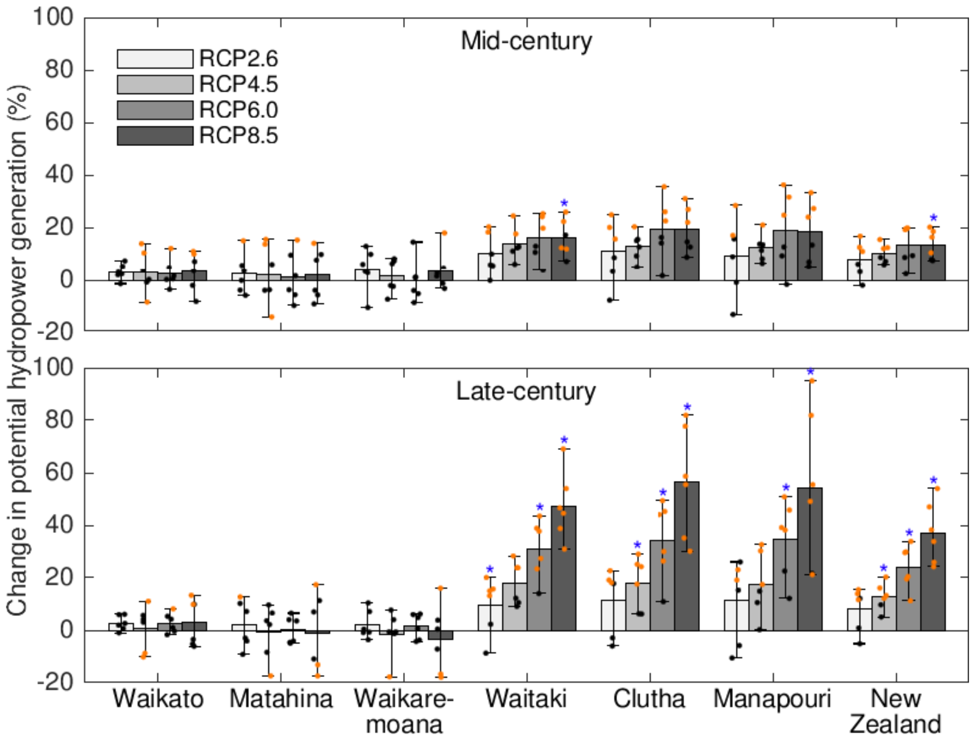

Figure 1-3: Change in mean winter (June, July, August) hydropower generation potential for all schemes. Bars represent multi-model means, upper and lower whiskers represent the maximum and minimum model means, and the stars indicate statistical significance.

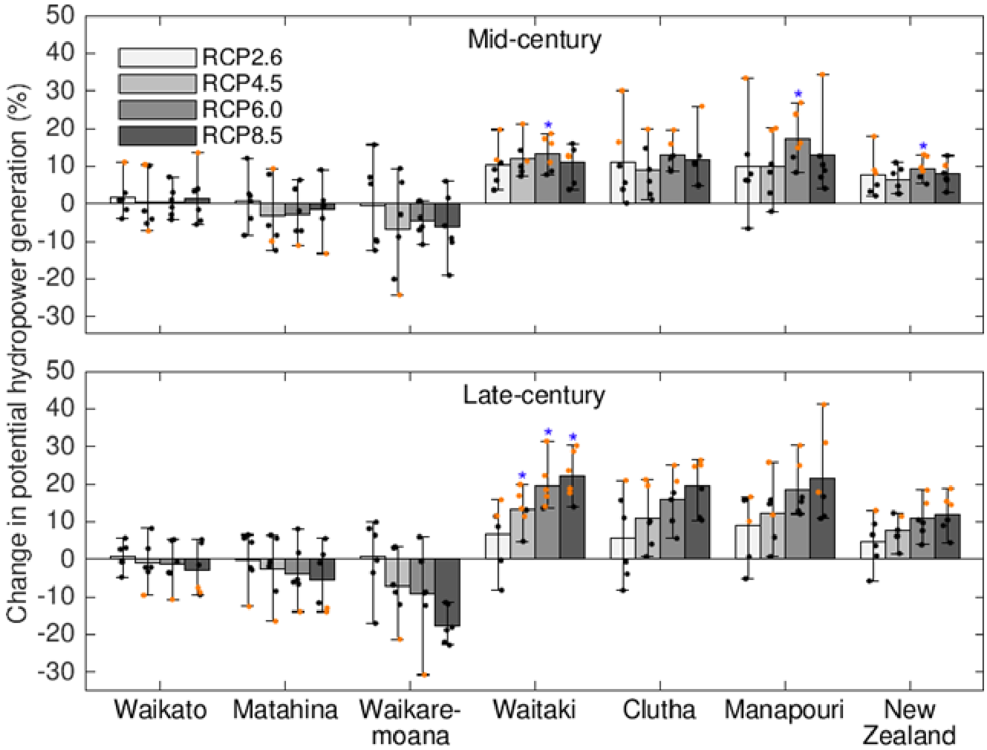

Figure 1-4: Change in mean annual 3-month low potential hydropower generation for all schemes. Refer to Figure 1-3. for the description.

These results show that even within a country the size of New Zealand the types of seasonal hydropower response to climate change can vary due to sub-national patterns in precipitation and runoff changes. For the Waikato scheme, the wet season gets wetter and the dry drier. For Waikaremoana, both wet and dry seasons get drier. For the three South Island schemes and the country as a whole both the wet and dry seasons get wetter. And for Matahina in the North Island, there is no appreciable difference. Such diverse behavioural responses is also seen within and among other countries [62] [63] [64]. Grid-wide increases in generation potential during the dry season or the season of greatest demand have also been projected elsewhere [65].

1.5.2 Annual generation potential

Aggregating monthly changes to annual totals allows us to see the overall change in generation more clearly (Figure 1-5). By mid-century all South Island schemes and the national aggregate show statistically significant increases under all RCPs, although there is little to distinguish the effects of one RCP from another during this time frame. The North Island schemes, meanwhile, show little change, and only Waikato under RCP8.5 shows a statistically significant change. By late-century, however, the differences among RCPs have diverged, with the increases becoming consistently smaller under RCP2.6, and increases becoming larger towards RCP8.5. The RCP2.6 increases are now only significant for Clutha and Manapouri, while three RCPs produce significant decreases for Waikaremoana. National mid-century generation is projected to increase by 4.6% under RCP2.6 and 5.1% under RCP8.5, respectively, and by late-century the values are 2.3% and 12.1%, respectively. This is primarily due to increases in winter inflows (Figure 1-2).

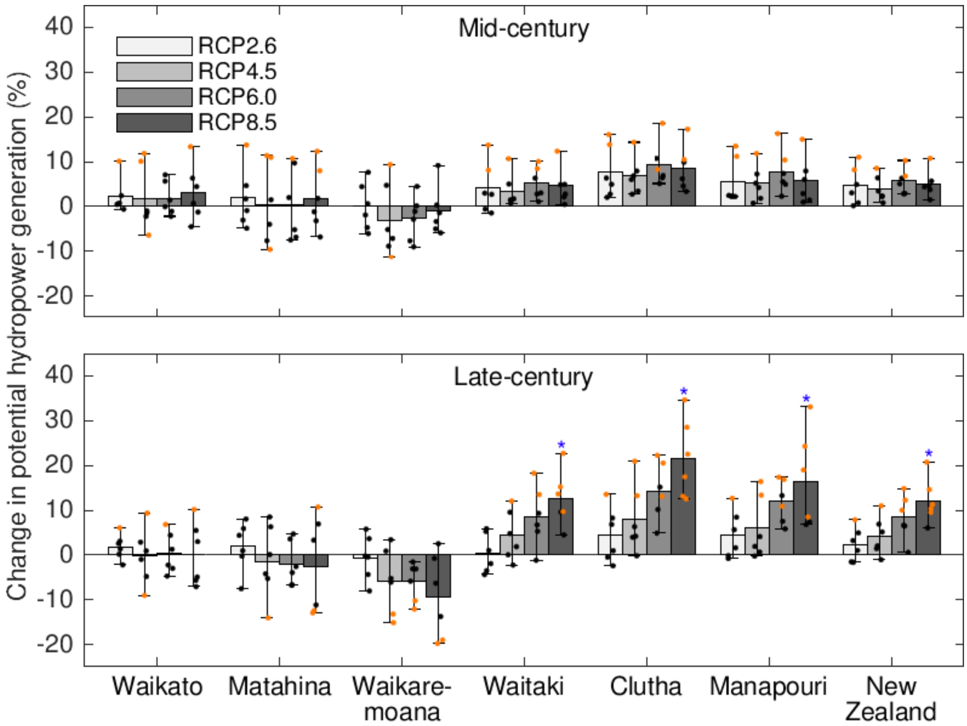

Figure 1-5: Change in mean annual potential hydropower generation for all schemes. Refer to Figure 1-3 for the description.

At the annual scale as at the seasonal scale, both increases and decreases in generation potential are projected within the country's national grid, which stems from the sub-national differences in the hydrological response to climate change [35]. The Waikato scheme's increases, specifically, are consistent with Caruso et al. [9]. And aggregated nationally, the increase in generation potential is a benefit of climate change, which has been reported in other studies [25, 66] despite the global tendency for a reduction in usable hydropower capacity [3]. Our results also contrast with many other studies of snow- and ice-affected hydropower systems [16, 17, 67, 68], which are projected to experience declines in generation potential. While the reduction in snow cover, glacial retreat, and earlier snow-melt are projected for New Zealand [69, 70], and would be a factor in future hydropower inflows, any negative effects are outweighed by the large increases in winter precipitation and runoff.

1.5.3 Hydroelectricity supply and demand

To put the projections of generation potential into context it is useful to compare the change in electricity generation to projections of electricity demand. MBIE [32] developed five scenarios of growth in electricity demand by 2050, ranging from 7 to 31 TWh above the present day 39.7 TWh (Table 1-2). The 'Reference' scenario sees demand growth continue under current policies and technologies with no major changes. The 'Growth' scenario sees an emphasis put on high technology with a larger commercial sector and higher income growth. In the 'Global' scenario, New Zealand's economy is hampered by international events, increasing the cost of wind and solar power. For the 'Environmental' scenario, a more ambitious emissions reduction goal is adopted, compared with the 'Reference' scenario, aiming to decarbonise the economy. Lastly, in the 'Disruptive' scenario, new and improved technologies enable rapid electrification. Transpower [33] also developed scenarios of future growth in electricity, with a wider spread of mid-century projections (40-125 TWh). The large difference in the high-demand scenarios between the two studies highlights the subjectivity involved in scenario planning, but for the purposes of the present study the MBIE [32] projections are used.

Table 1-2: Projected increase in electricity demand for New Zealand across five scenarios [32].

Electricity demand growth scenario	Demand (TWh)	
	2017	2050
Reference: Current trends continue	39.7	56.7
Growth: Accelerated economic growth	39.7	65.1
Global: International economic change	39.7	46.7
Environmental: Sustainable transition	39.7	66.5
Disruptive: Improved technologies developed	39.7	70.5

Focusing on the mid-century results from the present study, we take the mean annual increase in generation potential across the six hydropower schemes (Figure 1-5), and multiply the result by the annual mean electricity generation of all schemes combined (20.7 TWh). This gives an increase in hydropower generation potential due to the hydrological effects of climate change of 0.96, 0.82, 1.17, and 1.06 TWh for RCPs 2.6, 4.5, 6.0, and 8.5, respectively. Because there is little difference among the RCPs at this time we take the average of the four: 1.00 TWh. This would equate to over 114 MW of installed generating capacity, which is larger than most existing hydropower stations. For the 'Global' electricity demand scenario of MBIE [32], this would account for 14% of projected demand growth. For the 'Reference' scenario, this drops to 6%, and for the other scenarios the proportion drops below 5%. In all scenarios the increase in annual electricity demand outweighs the increase in annual supply, and in most scenarios significantly so.

Looking further ahead to the end of the century, the change in generation potentials across RCPs diverge. For RCP2.6 the additional national generation declines to 0.47 TWh, for RCP4.5 it remains roughly the same at 0.87 TWh, and for RCP6.0 and RCP8.5 generation increases to 1.75 and 2.50 TWh, respectively.

With the growth in demand and a shift to more renewable generation, however, hydropower generation may not be managed in the future in the same manner as it is currently [68]. Reticence for further largescale hydropower schemes in New Zealand [71] is likely to lead to growth of other renewable sources, such as wind and solar [32, 33], which are more variable and lack storage capacity. Hydropower schemes may thus move from providing the majority of the demand, which it does now, to primarily providing buffering capacity when wind and solar generation drop [2, 72], such as during calm winter nights. The increase in South Island lake inflows during winter would be particularly helpful in this regard and may in turn help to ameliorate the impacts of fuel poverty [73].

1.5.4 Uncertainties and limitations

The modelling presented here depicts a future of increasing hydropower generation potential for New Zealand as a whole, with regional differences and shifts in seasonal patterns. It is important to couch these results in terms of model uncertainties and limitations [74].

Uncertainties associated with the climate projections have been discussed in Ministry for the Environment [54], and both climate and hydrological uncertainties have been discussed by Collins [35]. In summary, using four RCPs offers good treatment of future emissions uncertainties, and the six GCMs that have validated well on New Zealand's observed climate support a robust interpretation of climate change impacts in the context of climate model uncertainty [75]. An important limitation, however, is the use of just a single downscaling model, bias-correction method, and hydrological model [76], particularly for the snow-affected schemes of Waikato, Waitaki, Clutha, and Manapouri [77].

There is appreciable variability in projections across the GCMs, represented by the uncertainty bars in Figure 1-3 to Figure 1-5, even though the six GCMs chosen validate well on observed climate. Differences between GCMs producing the highest and lowest changes are typically similar to or larger than the multi-model mean, and much larger than the differences among RCPs. This is emblematic of climate change impact studies [75]. Yet, according to the t-tests, most of the differences when pooling the GCMs together are statistically significant, indicating that the RCPs do have discernible effects in spite of combined GCM uncertainty and internal variability.

There are also sources of uncertainty arising from the hydropower modelling here. Firstly, only 83% of New Zealand's currently installed hydropower capacity is considered. There are many other schemes, albeit mostly with about 1% or less of total hydropower capacity each. The one notable exception is the Tongariro power scheme [42], which was excluded due to its complex series of diversions. That said, 83% should offer a good impression of the country's hydropower generation. Secondly, the station conversion efficiencies are more representations of the influence of hydrological variability on generation potential rather than of actual generation [44]. This is useful for modelling broad patterns of climate change impacts, although more thorough modelling of reservoir and station operation would improve the fidelity of the analysis [8]. An increase in spills, for example, may affect the validity of efficiency values into the future [28]. Thirdly, the research considers generation potential as influenced by monthly inflows, but what is generated in reality depends on electricity demand, the management of inter-seasonal water storages, and generation across the whole electric grid. Coupling electricity generation to electricity demand was outside the scope of the study and would require projections of the wind and solar energy resource under climate change as well as scenarios of generation expansion [28, 78].

In terms of the proximal drivers of the changes in generation potential, namely temperature, snow- or glacier melt, or precipitation, this study did not identify which causal pathway had the greatest influence. Both a change in precipitation and higher temperatures can be responsible for the changes in seasonality. And while glacier retreat has been identified as a threat to hydropower generation internationally [17], our results show that any such effect in New Zealand would be outweighed by the large increases in precipitation.

1.6 Conclusions

Using a climate-hydrology-hydropower model cascade based on four emissions scenarios and six GCMs, this study projects the mid- and late-century changes in hydropower generation potential across New Zealand's electric grid. While there are regional differences in the direction and magnitude of the changes, stemming from sub-national variations in hydrological effects of climate change, the net national results are an increase in both the wet and dry season generation potential, a shift in the timing of the dry season from winter to summer, and an overall annual increase in generation potential. In the context of interannual variability and GCM uncertainty, a majority of these changes are statistically significant. And while the shrinkage and earlier melt of snow and glaciers plays a part in the seasonal shifts, the primary driver for modelled changes is the increased westerly airflow during winter bringing additional water to the catchments of the major South Island hydropower schemes.

Added together, the additional scheme inflows are projected to generate an additional 1.00 TWh by mid-century, with no meaningful differences among emissions scenarios. This is 2.5% of current electricity demand and equates to between 3-16% of projected mid-century electricity demand, depending on the scenario of social and economic development. By late-century, the effect of the emissions scenarios emerges, with additional generation of between 0.47 to 2.50 TWh, for RCP2.6 and RCP8.5 respectively. Thus, while the additional annual generation potential would contribute to climate change mitigation efforts, it is small compared with growing electricity demand. Perhaps of more relative benefit is the increase in dry season (winter) inflows, which is when electricity demand peaks. This would support the transition of hydropower from the major electricity supplier, as it is currently, to the primary source of energy storage, buffering the more variable supplies from wind and solar power generation. However, it would be advisable to develop coupled projections of future renewable energy availability and grid-wide electricity demand to explore this more thoroughly.

These results have several implications for climate change impact studies and energy sector development more generally. Considering the direct effect of climate change on hydropower generation potential is important for future planning, not only in terms of net generation but also changes in seasonality. Doing so across the electric grid – whether national, sub-national, or transnational – allows the climate change impacts to be connected more directly to electricity demands. And while any change in potential may be small in comparison with future electricity demand, it could still be a significant factor when compared with power station capacities and timing of peak seasonal demand, necessitating or obviating the building of other power stations.

1.7 Acknowledgements

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2 Emergence of increasingly extreme floods under 21st century climate change

2.1 Introduction

Floods affect more people worldwide than all other natural disasters combined (CRED 2015), leading to loss of life and livelihood, displacement, and economic damage. Management of these flood risks is grounded, in part, on flood frequency analysis of historical events, typically treating flood generation as a stationary process. However, evidence is mounting of non-stationarity in flood hydrology, with changes in magnitude, frequency, and timing (Gudmundsson et al. 2019; Mallakpour and Villarini 2015; Berghuijs et al. 2017; Bloschl et al. 2017; Blöschl et al. 2019). These shifts will likely be compounded by 21st century climate change (IPCC 2014; Winsemius et al. 2016; Alfieri et al. 2017) with concomitant implications for society (Dottori et al. 2018). Effective flood risk management therefore needs to look both backwards and forwards (Milly et al. 2008; Stedinger and Griffis 2011), becoming a more continuous process (Thieken et al. 2016).

Adapting to changes in flood risk is a multi-faceted problem that necessarily involves a decision of when to act. A possible way to inform this decision is to estimate the Time of Emergence (ToE). ToE is the point in time when a climate change signal becomes statistically distinguishable from climate variability and remains so thereafter (Giorgi and Bi 2009). Knowing whether, where, and when climate change may lead to adverse impacts can help prioritise and stage the implementation of costly (both socially and economically) adaptive measures (Adger et al. 2005; Merz et al. 2010). Comparisons across socio-economic scenarios can also inform mitigation choices by quantifying effects of avoided or delayed emergence (Frame et al. 2017).

Although exact implementations differ, ToE has been assessed for a range of environmental variables, including temperature (Diffenbaugh and Scherer 2011; Harrington et al. 2016), precipitation (Giorgi and Bi 2009; Maraun 2013), river flow (Wilby 2006; Zhuan et al. 2018; Leng et al. 2016; Pohl et al. In review), sea-level (Lyu et al. 2014), and ocean biogeochemistry (Keller et al. 2014). By assessing the significance of a signal, ToE assessments echo trend detection from time-series, albeit simulated (Wilby 2006). ToE complements the typical climate change impact assessments of changes between an historical reference period and specified future periods (e.g., Collins 2020). It also complements attribution studies that use model ensembles to assess whether and how much climate change has affected observed climate variability (Viglione et al. 2016).

To be relevant to flood risk management, ToE assessments must focus on extreme events. Maraun (2013) used Extreme Value Analysis (EVA) to estimate the ToE of heavy precipitation across Europe, but the same has not been implemented for extreme floods. Many EVA approaches for floods under climate change are in use (Salas et al. 2018) although there is as yet no consensus on the most appropriate one, or even if it is necessary at all (Serinaldi et al. 2018; Silva and Portela 2018). One approach is to treat discrete time periods as quasi-stationary and carry out the analysis over moving windows (Mentaschi et al. 2016), much like many ToE analyses. This is simple but can produce high uncertainties for the more extreme events due to the small sample sizes. A more common approach is to fit extreme value distributions to the whole projection period using time-varying parameters (Salas et al., 2018). This has the benefit of incorporating more events together, but it requires the parameters to be simple functions of known environmental covariates.

To demonstrate the use of ToE in the context of extreme floods, the case study of New Zealand is chosen. New Zealand has warmed about 1°C over the past century (Mullan et al. 2010) and is projected to warm by a further 0.1-4.6°C by the end of the 21st century (Ministry for the Environment 2018), depending on future emissions trajectories. Caloiero (2015) has reported regional trends in precipitation, including increases in mean winter precipitation on the west of the South Island and decreases during summer on the east, as well as decreases in medium intensity storms. Over the 21st century, climate models project more precipitation in the west and south of the country and less in the north and east, as well as more intense rainfalls (Ministry for the Environment 2018; Carey-Smith et al. 2018). These climatic changes in turn affect river flows (Collins 2020) resulting in a patchwork of increases and decreases in mean and extreme flows across the country, including extensive areas of increasing Mean Annual Flood (MAF). While New Zealand's 1991) directs regional government to manage significant risks from natural hazards and account for climate change, and central government has provided some guidance in achieving this for flood hazard management (Ministry for the Environment, 2010), there remains a knowledge gap in terms of how and when flood hazard will change, and how to sequence any adaptation (Climate Change Adaptation Technical Working Group 2018).

The purpose of this research is thus to determine the spatially distributed Times of Emergence for the 100-year flood (Q100) across New Zealand and across scenarios of future emissions. A climate-hydrology model cascade is used to generate river flows at 43,862 locations across the country from 1971-2099, driven by downscaled and bias-corrected output of six General Circulation Models (GCMs). Time-varying estimates of Q100 in the future are considered in the context of internal and inter-model variability to estimate when and where climate change signals may emerge, and how this emergence is affected by mitigation pathways.

2.2 Data and Methods

2.2.1 Study region

The study region comprises New Zealand's two main islands, the North Island and South Island, lying predominantly between 34° to 47° S in the Southwest Pacific (Figure 1). The North Island is dominated by a central volcanic plateau and the South Island by the southwest/northeast-aligned Southern Alps (Pettinga 2001). The islands are situated within the prevailing westerlies of the mid-latitude Southern Hemisphere (Salinger et al. 2004), with a predominantly temperate maritime climate. Interannual to inter-decadal climate variability is influenced most strongly by El Nino-Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM) (Salinger et al. 2004; Ummenhofer et al. 2009). Orographic effects along the Southern Alps produce high precipitation rates, in places exceeding 10 m yr-1 (Macara 2018), and much of the South Island is affected by snow and ice (Owens and Fitzharris 2004).

Floods are a significant hazard across the country and are generated by high intensity or long duration storms and rapid snowmelt, and are influenced by antecedent soil moisture conditions (Pearson and Henderson 2004). Mean annual floods normalised by catchment area are highest in rivers draining mountainous regions, particularly the Southern Alps, and lowest in leeward areas and those in the North Island underlain by rock of volcanic origin, reflecting both precipitation and geological controls on flood generation (Henderson et al. 2018). Times of concentration are typically less than 12 hours (Griffiths and McKerchar 2012).

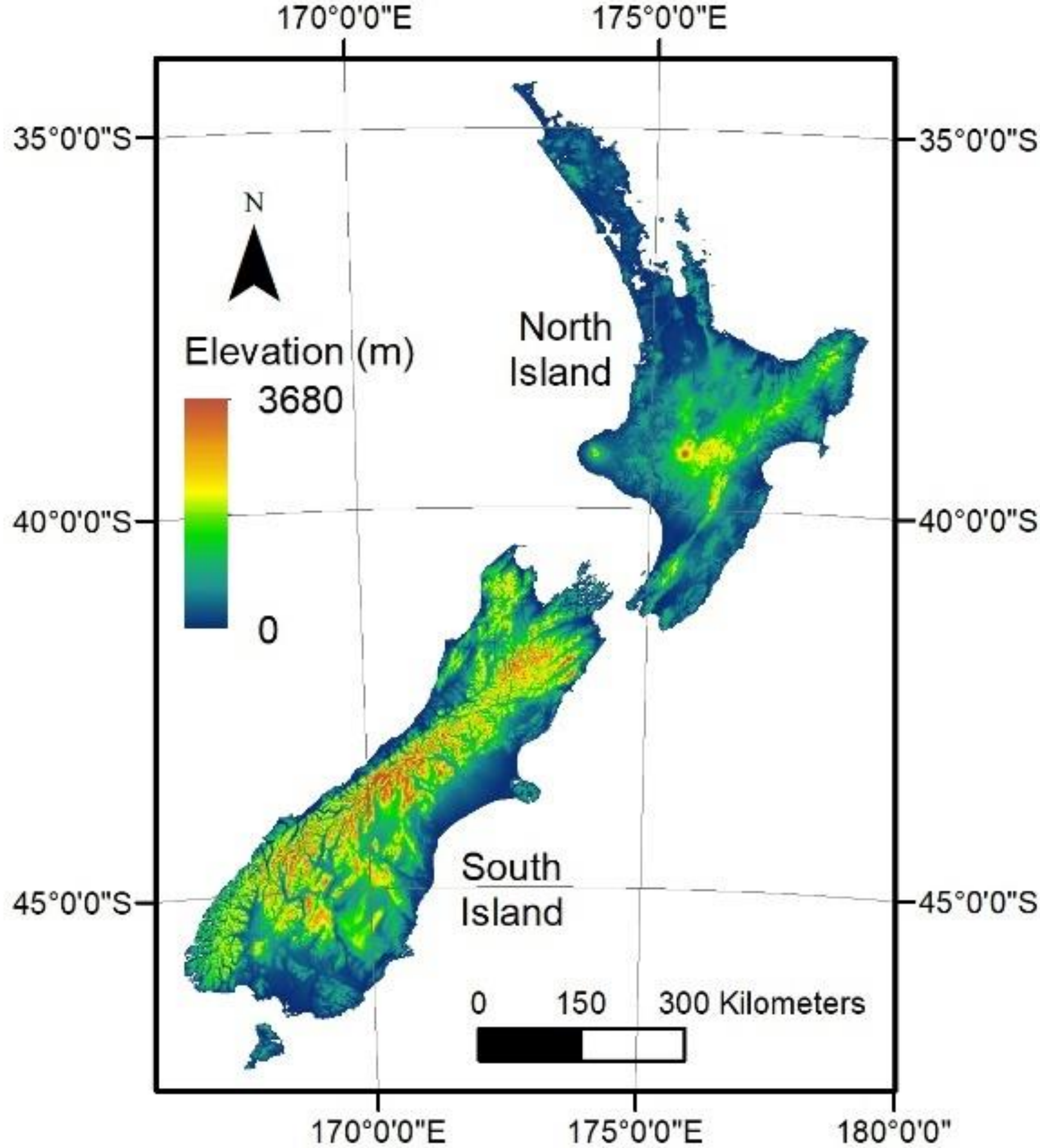

Figure 2-1: New Zealand topography (m).

2.2.2 Climate and hydrological modelling

The flood data used in this study were generated using the national climate-hydrology model cascade described by Collins (2020) and driven by climate projections described by Ministry for the Environment (2018). Future emissions scenarios were embodied by four Representative Concentration Pathways (RCPs) (Van Vuuren et al. 2011): RCP2.6, RCP4.5, RCP6.0, and RCP8.5, ranging from low- to high-emissions trajectories. Six Global Circulation Models (GCMs) were selected from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (IPCC, 2013) for validating well on New Zealand's historical climate: BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and NorESM1-M. Sea surface temperatures from these were bias-corrected and used to drive the global atmosphere model HadAM3P (Anagnostopoulou et al. 2008) and then the regional atmosphere model HadRM3P (Jones et al. 2012). The resultant precipitation fields were then adjusted following Woods et al. (2006) and stochastically disaggregated to hourly time steps following Clark et al. (2008).

The national hydrological model embedded within the model cascade is the semi-distributed and physically based TopNet model (Clark et al. 2008; McMillan et al. 2016). Downscaled climate fields are used to simulate natural river flows at hourly timesteps at 43,862 river locations across the country. The computational sub-catchments have a mean area of 6 km^2. Validation of TopNet based on the observed climate has been reported by Booker and Woods (2014) and McMillan et al. (2016), with Mean Annual Flood (MAF) exhibiting either positive or negative biases depending on the inclusion of a flow duration curve-based correction. Validation of the climate-hydrological model cascade used in the present study, driven by climate simulations rather than observations, shows MAF exhibits a moderate negative bias (-21%) across the country; the same annual flood maxima are used in this study. The simulations span two periods: 1971-2005 is driven by historical emissions forcing and 2006-2099 is driven by the RCPs.

2.2.3 Flood frequency analysis

Flood frequency analysis is carried out using the method of L-moments (Hosking 1990) to estimate at-site parameters of the Gumbel distribution based on the series of annual maximum flows, as has been applied by McKerchar and Pearson (1989) for New Zealand's observational records previously. The analysis treats the model data as quasi-stationary within the 30-year reference period (1976-2005) or within 20-year moving windows during the projection period. The projection period windows are incremented by one year from 2020-2039 to 2080-2099 producing 61 windows in total. The reference and projection period Gumbel parameters are then used to compute the 100-year flood, Q100, across the country and across the century. The 95% confidence intervals of Q100 for the reference period are estimated following Phien (1987).

The quasi-stationary method is chosen here to bypass the derivation of time-varying functions of the distribution parameters used in non-stationary EVA. The relative weakness of the quasi-stationary approach – that each analysis is carried out on short 20-year periods – is mollified here in two ways. Firstly, the reference period is not much longer (30 years) and would thus have comparable uncertainties for rarer floods. Secondly, a condition of the ToE described below – that emergence must be sustained, not a short-lived episode caused by a few extremes – essentially incorporates the whole time-series into the final ToE analysis.

2.2.4 Time of emergence

The Time of Emergence (ToE), is the point in time when a climate change signal becomes distinguishable from the combined internal and inter-model variability of climate change projections and remains so for the foreseeable future (Giorgi and Bi 2009). Accounting for inter-model variability achieves an important degree of robustness in the results considering climatic response uncertainty. The signal and variabilities may be estimated in different ways. Giorgi and Bi (2009) estimated the signal of changing sub-continental precipitation as the magnitude of the ensemble mean over 20-year periods, the internal variability from the difference between the change for individual realisations and the ensemble, and inter-model variability from the models' changes. Diffenbaugh and Scherer (2011) adopt a similar approach for extreme temperatures over 10-year periods and characterise internal variability based on the maximum seasonal temperature modelled during the reference period. Mahlstein et al. (2012) account for internal variability by using the Kolmogorov-

Smirnov test at a 5% significance level to distinguish between 30-year periods of precipitation from the reference and projection simulations, and inter-model variability by only accepting emergence once a majority of models agree; they considered both 66% and 90% model agreement. And Keller et al. (2014), Leng et al. (2016), and Zhuan et al. (2018) estimate ToE using still different variables, statistical tests, and significance thresholds, each tailored to the research question and model availability.

For the present study, the climate change signal is quantified by changes in the Q100 between 20-year moving windows for the future and the 30-year window over the reference period, where Q100 is calculated by fitting a Gumbel distribution to the annual flood series over these periods. Internal variability is quantified by the 95% confidence interval of the Q100 estimate from the reference period, and inter-model variability is accounted for by only deeming a location as emerging if a majority of GCMs agree in both emergence and direction of change. With hydrological impacts of only six GCM available, and with one realisation each, constraining the inter-model variability is limited, although using models that validate well offsets this somewhat. Within the limitation two criteria are used for emergence: the more permissive criterion requires four of the six models to agree, and the more stringent requires agreement across at least five.

2.3 Results

The threshold change in Q100 ($\triangle$Q100,E), separating non-emergence from emergence, depends on the at-site variability of the annual flood series during the reference period. This at-site variability itself varies among GCMs and, as represented by the median values across the GCMs, spatially (Figure 2-2). All values of the GCM-median $\triangle$Q100,E across New Zealand lie between 10-35%, and most between 20-30%. In the central part of the North Island there is a conspicuous area of lower values (10-15%) reflecting the dampening effect local high-porosity, volcanically derived soils and geology play on hydroclimatic variability. Elsewhere, gradients in $\triangle$Q100,E are dominated by patterns of climatic variability (McKerchar and Pearson, 1989). The lower values of $\triangle$Q100,E would make detection of a climate change signal easier, all else being equal.

All else is not equal, however. Spatial variations in the climate signal and model agreement combine to produce patterns of emergence that differ substantially from those of low $\triangle$Q100,E (Figure 2-3). Few rivers exhibit emergence across the North Island's volcanic soils or in central, inland South Island where $\triangle$Q100,E is also lower than average. Instead, emergence occurs primarily in pockets in the south of the South Island, expanding under higher emissions scenarios to include the west of the South Island and the north of both islands. This pattern of expansion is the same whether the criterion for emergence is the agreement of four GCMs or five, although the areal extent of emerged sites is much smaller for the more stringent of the two. This pattern resembles the projected changes in MAF reported by Collins (2020), as would be expected given that both analyses use the same simulated annual flood series. However, caution is advised against interpreting the results at individual river scales, due to the limited ensemble and model cascade uncertainty, but rather at region or sub-regional scales.

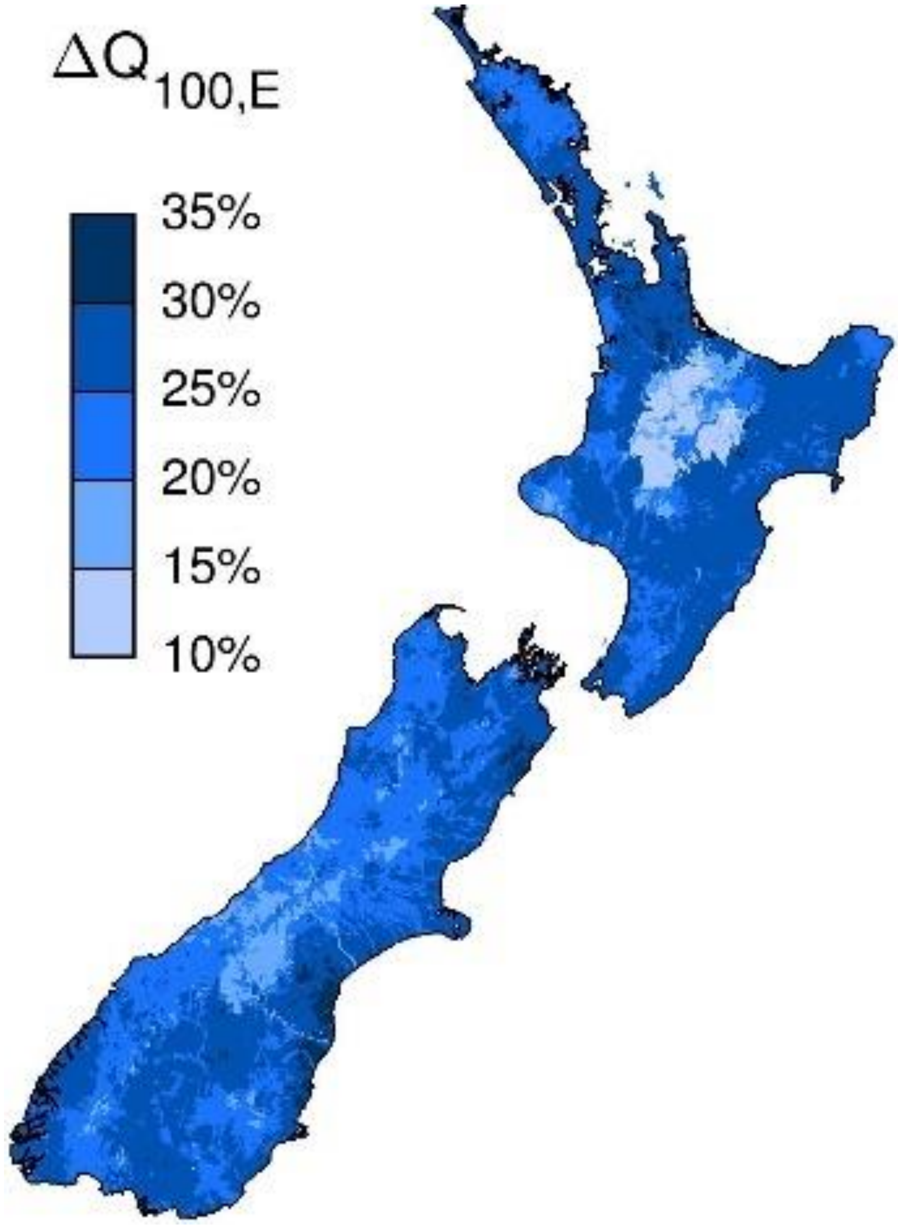

Figure 2-2: Median multi-GCM threshold change in Q100 (%) required for emergence, △ Q100,E.

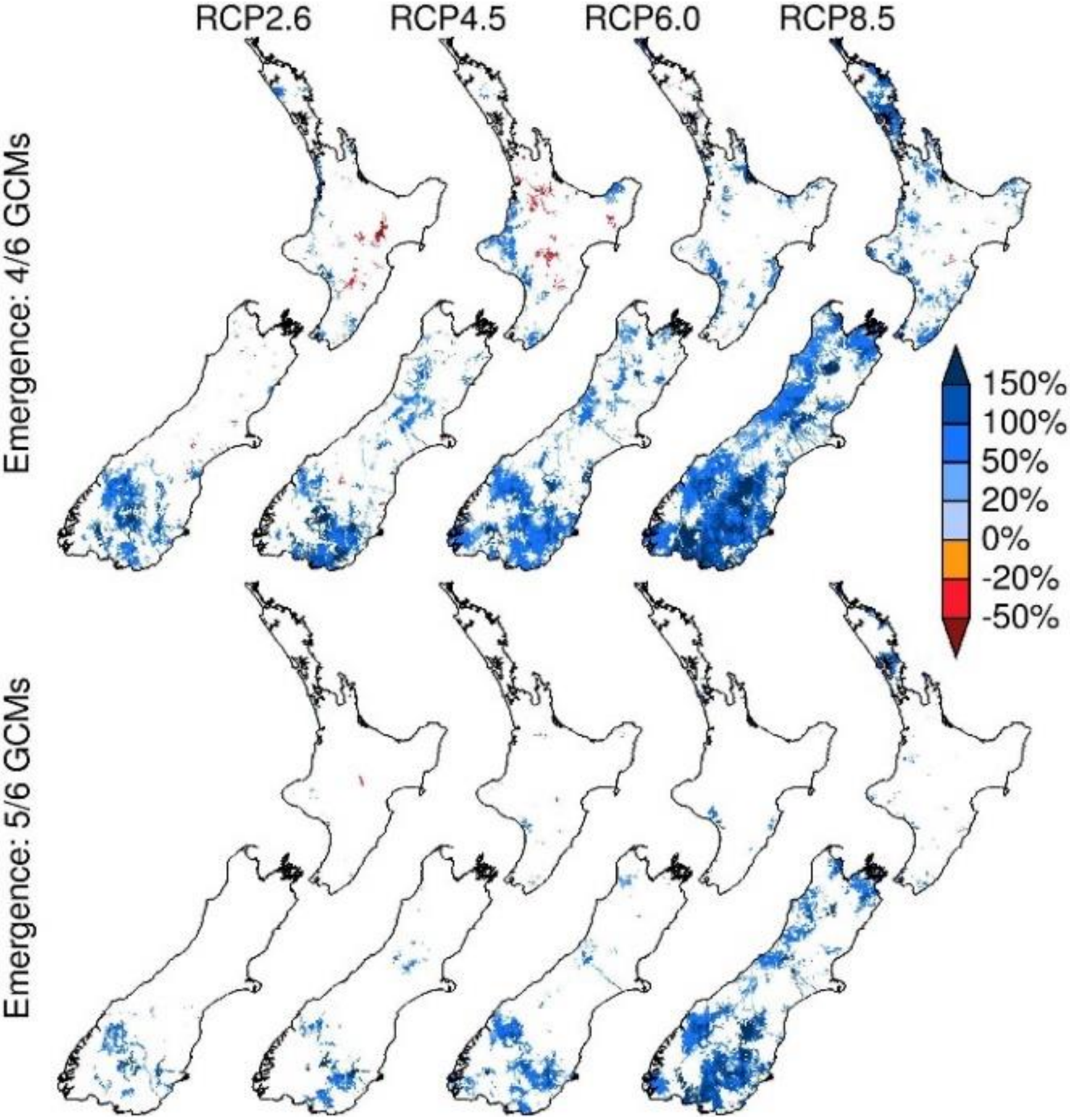

Figure 2-3: Mean △Q100 by the end of the century averaged over emerged GCMs. where emergence requires either the agreement of (top) four or (bottom) five of the six GCMs. White indicates no robust emergence by the end of the century.

In terms of the magnitudes of △Q100 by late century, most emerged changes are positive with many over 50% and some over 150%. There are also small areas of negative changes predominantly in the North Island, although they dwindle under the higher two emissions scenarios. The values of △Q100 are all larger than the emergence threshold, △Q100,E, as is expected, and generally much larger. This implies that detection of sustained changes in extreme flood risk using local river flow observations would lag substantially behind any climate change effect taking place, if detection is even possible in light of natural variability (Wilby 2006).

As with △Q100, ToE also varies with RCP and location (Figure 2-4). Most of the country does not exhibit emergence by late century, even under RCP8.5 and the more permissive emergence criterion.

However, emergence occurs preferentially and earlier in the south of the South Island, expanding to include the west under higher emissions scenarios.

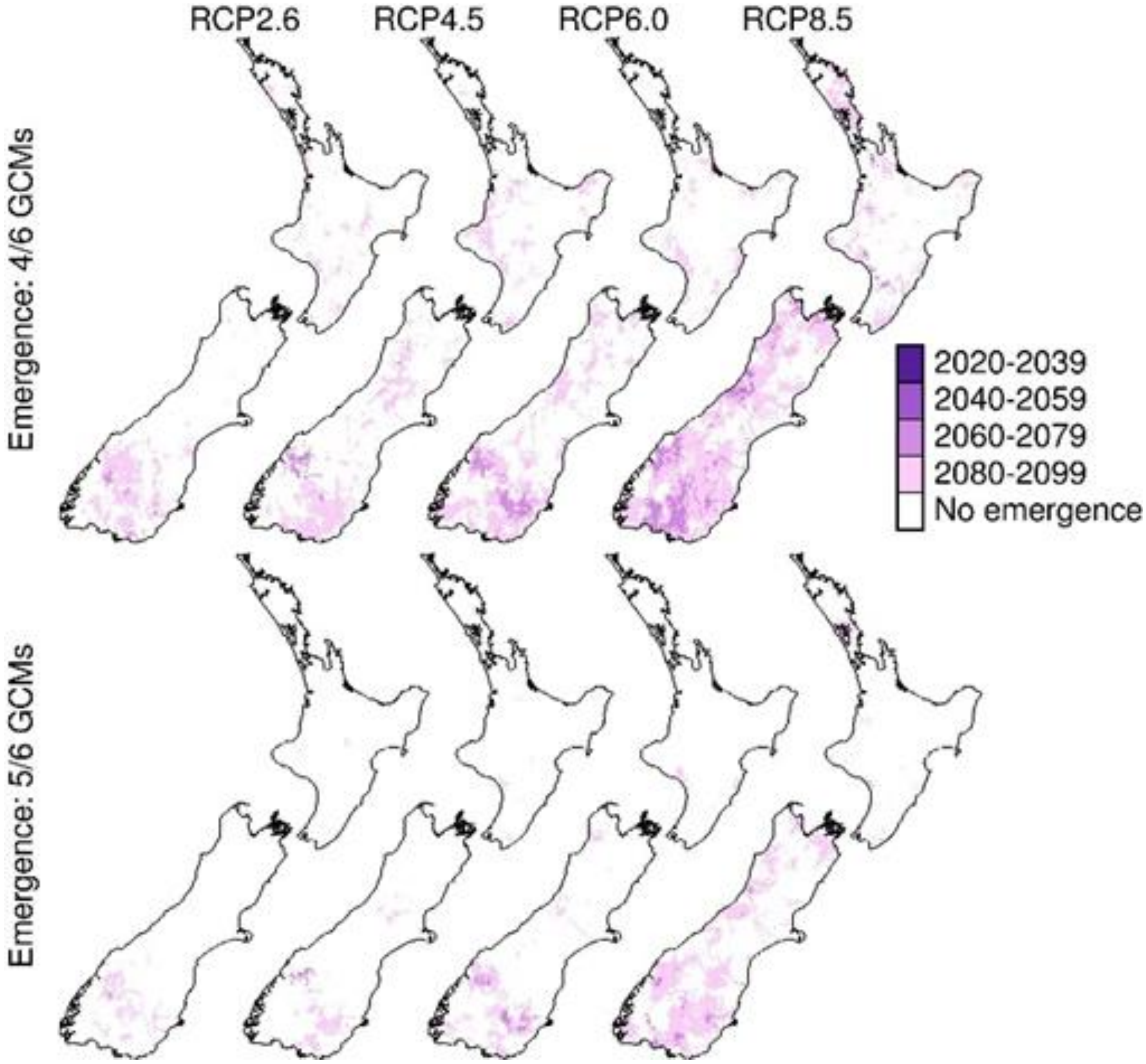

Figure 2-4: ToE of changes in Q100, both positive and negative . As indicated by the agreement of either (top) four of six GCMs, or (bottom) five of six GCMs. White indicates no robust emergence by the end of the century.

Examining the time-series of the national extent of emergence of larger floods (Figure 5(a) and (b)) more clearly shows the pace of the expansion. For RCP2.6, 10% of locations show emergence of larger floods based on four agreeing GCMs, and 3% based on five. This emergence occurs predominantly towards the end of the century. For RCP4.5, the value increases to 14% for the 4-GCM criterion but remains steady for the 5-GCM criterion. Again, emergence occurs more so later in the century. There is little difference between RCP2.6 and RCP4.5 in terms of the extent of emergence for most of the century, although the precise locations are not entirely congruous. For RCP6.0, Q100 emerges earlier and at substantially more locations across both islands than for the lower-emissions scenarios, reaching 25% and 8% emergence under the 4-GCM and 5-GCM criteria, respectively. The emergent fraction for RCP6.0 diverges from the two lower emissions scenarios only after 2060. The extent of emergence climbs further under RCP8.5 to 47% and 23% by the end of the century, for the 4-GCM and 5-GCM criteria, respectively. However, even under this extreme scenario the extent of mid-century emergence remains under 1%. This suggests that changes in extreme flood hazard across New Zealand are unlikely to be detectable from river flow observations alone until the second half of the century.

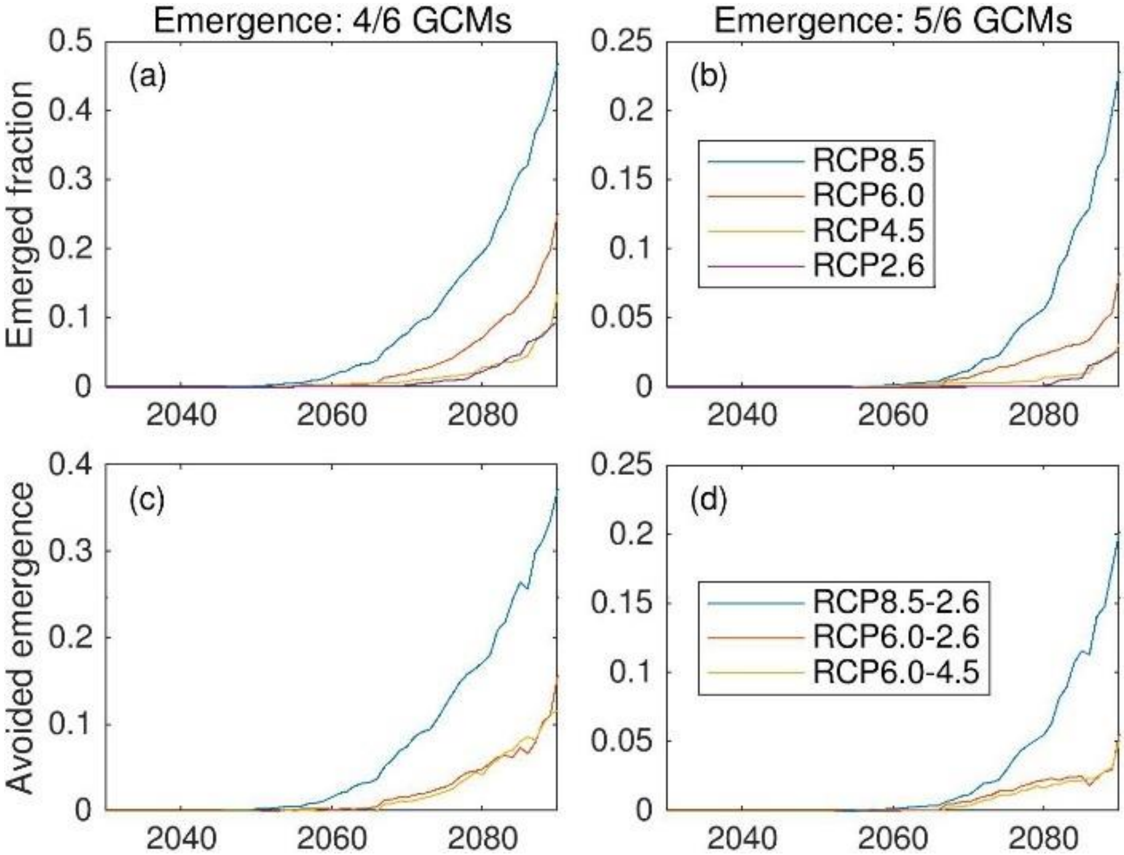

Figure 2-5: Fraction of New Zealand river sites exhibiting emergence of larger Q100 across four RCPs. Based on agreement of (a) four of six GCMs, and (b) five of six GCMs. Fraction of river sites that avoid emergence of larger Q100 due to lower emissions based on agreement of (c) four of six GCMs, and (d) five of six GCMs. Years are the mid-points of the 20-year analysis windows.

Comparing the emerged fractions across the RCPs finally allows us to estimate the avoided emergence due to lower emissions scenarios (Figure 2-5) (c) and (d)). By the end of the century there is a stark contrast between RCP8.5 and RCP2.6, with 37% of the country's river locations avoiding significant change in Q_{100} under the low-emissions scenario and using the more permissive emergence criterion. Requiring the agreement of five GCMs drops this avoided extent to 20%. Comparing scenarios to RCP6.0 instead, which is possibly a more realistic business-as-usual course than RCP8.5 (Hausfather and Peters 2020), RCP4.5 results in 12% fewer locations exhibiting emergence by the end of the century for four agreeing GCMs (5% for five), and RCP2.6 results in 16% fewer (6% for 5). In terms of the areal extent of detectable emergence of large extreme floods, there are clear benefits in choosing a lower emissions scenario over a higher, although there is no practical difference in this metric between RCP2.6 and RCP4.5.

2.4 Discussion

Using a climate-hydrology model cascade projected to 2099, emergence of a climate change signal in the 100-year flood from background climate variability has been assessed across New Zealand. Most of the country shows no signs of emergence this century, although the extent of emergence increases, and the timing of emergence is earlier for both higher emissions scenarios and more permissive treatment of inter-model variability. When a signal does emerge, it is principally located in the south and west of the country, with many of the emerged signals exceeding a 50% increase in flood magnitude. The same regional focus was seen for less extreme river flow metrics (annual and seasonal mean flows, and the annual flood), and while methods differ somewhat, emergence of a climate change signal in the annual flood across New Zealand is both later and less extensive (see Chapter 4 of this report) than for Q100 reported here.

A lack of emergence of a signal in the 100-year flood in many places is not unexpected. Due to a combination of high internal model variability, high inter-model variability, and low climate change signal strength, non-emergence this century has been identified in various regions for mean and extreme precipitation, and mean river flows (Giorgi and Bi 2009; Maraun 2013; Zhuan et al. 2018), including New Zealand (see Chapter 4 of this report). Zhuan et al. (2018) also note that river flow emergence may lag precipitation emergence, which could in places tip hydrological emergence past the end of the century. High model uncertainty for extreme rainfall, in particular, would impede detection of a climate change signal if there is one. Where emergence does occur, according to the current results, the ToE in the second half of the century again falls well within expectations based on other hydrological emergence studies (Leng et al. 2016).

The earlier and more extensive emergence of a climate change signal under higher emissions scenarios is also consistent with other studies (Leng et al. 2016). Emergence is more likely with a stronger warming signal. But results also show that some emergence is unavoidable even under the low emissions scenario, RCP2.6, due to committed warming. Emergence is also identified earlier and more extensively if the signal is compared to a less stringent level of internal or inter-model variability (Hawkins et al. 2014; Mahlstein et al. 2012).

As with all modelling, however, there are uncertainties and limitations that must temper the conclusions. Many have been discussed by Ministry for the Environment (2018) and Collins (2020) for the climate and hydrological modelling used here. The use of six GCMs that validate well on observed regional climate provides a firm basis on which to conduct climate change projections, although the limited size of the ensemble constrains our ability to define inter-model variability. The lack of ensemble modelling for the downscaling, bias correction, and river flows contribute additional uncertainties (Hakala et al. 2020), and importantly the bias-correction was not able to account for the more extreme events (Sood 2014). And so, along with the other uncertainties inherent with climate change, emissions mitigation, and model processes, these uncertainties put flood adaptation under climate change into the category of decision-making under deep uncertainty (Walker et al. 2013).

Despite and because of the uncertainties, the results presented here offer several important implications for flood risk management under climate change. This is stressed by the increases in Q100 in some regions of over 100%. The first implication is that the absence of emergence of a climate change signal in Q100 this century for most areas implies that the stationary assumption for flood events may be sufficient (Stedinger and Griffis 2011; Leng et al. 2016). Tempering this conclusion, however, is the fact that emergence will not be detected until after the climate change effect starts (Wilby 2006). In a way, this introduces a trade-off between Ockham's Razor, where the simpler stationary model is preferred against a more complex one, and the Precautionary Principle, where non-stationary decisions are taken despite no immediate or definitive evidence to do so. Implementing this within flood risk management may entail using the stationary assumption initially and transitioning flexibly to a non-stationary approach as the ToE approaches.

There is robust evidence, however, of emergence in some parts of New Zealand, particularly the south of the South Island, and to a lesser degree the west of the island. This signal may prompt regional flood managers to more frequently consider increases in flood hazard within the planning of long timeframe policies or infrastructure as a precautionary measure now. Were adaptation planning to follow Dynamic Adaptive Policy Pathways (Haasnoot et al. 2013) or another method that involves decision triggers (preceded by early signals), then it would be important that these triggers be set regionally but not so low as to be statistically undetectable. A signal much below a 50% increase in Q100, for example, may be of little use.

2.5 Conclusions

This study estimates, for the first time, the Time of Emergence of global warming-induced changes in the 100-year flood, using New Zealand as a case study. It also presents the magnitude of the emerged changes and the national extent. Based on quasi-stationary analysis using L-moments of annual flood series produced by a national climate-hydrology model cascade, results show that the extent of emergence increases over the course of the century, with little detectable difference before mid-century, and does so at a faster rate for the more extreme emissions scenarios. Most river locations exhibit no detectable emergence of a climate change signal at all. Those that do tend to be in the south and west of the country.

The results have several implications for flood risk management under climate change. Firstly, a stationary treatment of flood series may still be adequate in many cases, at least initially. Secondly, the south and west of the South Island are hotspots of increasing Q100, with some changes in Q100 exceeding 100% of reference period value, suggesting a staged regional focus for adaptation. Thirdly, bolder mitigation efforts can translate into substantial areas of avoided and delayed emergence. And, lastly, while the climate-hydrology model cascade and subsequent analysis can shed light on changes in extreme floods, uncertainties are too substantial to allow the model results to be used in a quantitative engineering context. Instead, decision making under deep uncertainty is more appropriate. Taken together, the study's results shed light on the effects of climate change on flood extremes across New Zealand, and more generally how Time of Emergence analysis can be used in flood risk management in a changing climate.

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2.8 Feedback received

The following feedback was received on the submitted paper and is included here for completeness.

The described research assesses the influence of climate change on extreme floods in New Zealand by estimating the time and magnitudes of emergence of changes in 100-year flood across the country. It was found that there is currently little or no emergence of changes in extreme floods due to climate change in most parts of the country; however, some regions of the South Island show emergence of climate change signal by the end of the 21st century.

Whilst the research has focussed mainly on the influence of climate change, some analysis and discussion related to the role of catchment characteristics and flood generation mechanisms would make the study more scientifically rigorous and useful for decision makers. In particular, the following areas of improvement are identified:

2.8.1 *Catchment properties*

It is noted that catchment properties are significantly different in northern and southern parts of the country. For example, the North Island has porous volcanic rocks and South Island has mountainous terrain. It would be interesting therefore to explore how the climate change signal in precipitation is transformed into change in flood magnitude in regions with different catchment properties. A figure showing the spatial pattern of emergence for precipitation and a comparison of spatial patterns of emergence for precipitation and floods could reveal important insights into the role of catchment properties. Such analysis could also be useful for understanding how climate change may affect floods in other parts of the world with varying catchment properties.

2.8.2 *Flood generation mechanisms*

While the study focussed on analysing the changes in magnitude of extreme floods, it could also important to investigate how the flood generation mechanisms maybe affected by climate change. For example, in the South Island, where snowmelt is involved in flood generation, climate change may impact floods more through changes in temperature and snowmelt rates, which can affect the timing of floods. While in this case, the magnitudes may not change, a change in the timing of floods could have important implications for reservoir operations. Future discussion and analysis of the changes in the flood generation mechanisms will be of interest in the future.

2.8.3 *Land-use changes*

Climate change is only one of the contributors to the non-stationarity of floods. Land use and land cover changes can also have significant impact on the non-stationarity of floods. Whilst it has not been possible to address the issue of land-use change in this study, it will be important to address the role of land-use change in the future. For example, studies which have analysed the trends in observed extreme floods in New Zealand and in which regions the influence of land-use changes has been identified as significant would be of interest.

3 Impacts of 21st century climate change on water stress and availability across New Zealand

3.1 Introduction

Water is essential for New Zealand's land-based primary industries, whether from rain, rivers, or aquifers, and whether for crop growth, frost protection, or stock water (Robb and Bright 2004). Irrigation itself accounts for 7,500 million m3 of consumptive water allocation per year (Booker and Henderson 2019). Water resources in turn support economic productivity, with irrigation directly and indirectly contributing to 2.4% of the country's GDP (NZIER and AgFirst Consultants NZ 2014) and dairy exports amounting to $15 billion (Statistics NZ 2019). The difference between a surfeit and deficit of water is further highlighted by droughts when both primary productivity and economic output drop (Kamber et al. 2013; Pourzand et al. 2019).

The primary sector has adapted to New Zealand's variable climate in many ways, including the use of irrigation and water storage, inter-basin water transfers, precision irrigation, and systems of water governance that seek to manage economic expectations based on environmental limitations. However, the climate is also changing. New Zealand's mean air temperature has increased by about 1°C over the past century (Mullan et al. 2010) in concert with global rises caused by long-term and growing emissions of greenhouse gases (IPCC 2013). This has been accompanied by global changes in precipitation (Trenberth 2011) and drought (Dai 2013), and changes in the water cycle are projected to continue over the 21st century (Leng et al. 2016; Donnelly et al. 2017), depending on the pace of emissions. For New Zealand, air temperatures are projected to increase by 0.1-4.6°C by the end of the century (Ministry for the Environment 2018) alongside a regional pattern of increases and decreases in precipitation. These, in turn, translate to a patchwork of increases and decreases in river flow across the country, affecting seasonal and annual mean flows, low flows, and floods (Collins, 2020). More pertinent to agriculture, Srinivasan et al. (2011) reported potential declines in water supply reliability for an irrigation scheme in Canterbury, Collins and Zammit (2016) projected changes in water supply reliability broadly across agricultural land, and Collins et al. (2019) assessed implications for irrigation on currently irrigated land. With the prospects of changes in water supply and demand, water governance in New Zealand requires that reasonably foreseeable effects of climate change be considered in water allocation deliberations (National Policy Statement for Freshwater Management 2014) in order to inform climate change adaptation. However, there remains a need for complete national coverage of water resource impact assessments for the whole land-based primary sector and to assess how primary productivity may be affected by changing drought conditions.

The purpose of this research is to model the potential effects of climate change on water stress and water availability across New Zealand. Soil moisture and river flows are simulated using a climate-hydrology model cascade driven by future scenarios of greenhouse gas emissions. Water stress is considered in terms of the water stress coefficient influencing crop growth, and water availability by the number of days abstraction from rivers is restricted.

3.2 Data and methods

3.2.1 Climate and hydrological modelling

This study uses soil moisture and river flows simulated by a national climate-hydrology model cascade described Collins (2020), driven by climate projections described by Ministry for the

Environment (2018). Trajectories of future emissions are encapsulated by four Representative Concentration Pathways (RCPs) (Van Vuuren et al. 2011) – RCP2.6, RCP4.5, RCP6.0, and RCP8.5 – ranging from low- to high-emissions scenarios. Six Global Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (IPCC, 2013) were selected for performing well on New Zealand's historical climate. The GCMs are BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES, and NorESM1-M. GCM output are then downscaled using a combination of dynamic modelling (Ackerley et al. 2012) and seasonal quartile and statistical mapping (Sood 2014). Precipitation fields are subsequently adjusted following Woods et al. (2006) and stochastically disaggregated from to hourly time steps following Clark et al. (2008).

The hydrological model is the semi-distributed and physically based TopNet (Clark et al. 2008; McMillan et al. 2016). Downscaled climate model output is used to simulate soil moisture and natural river flows at hourly timesteps at 43,862 sub-catchments across the country. The sub-catchments have an average area of 6 km^2. Validation of TopNet based on the observed climate has been reported by Booker and Woods (2014) and McMillan et al. (2016). River flows of the climate-hydrology model cascade have also been validated in the context of climate change, with generally good agreement for mean annual and seasonal flows, although a substantial systematic bias for MALF (Collins 2020). The same modelling approach is used in this study to focus more closely on agricultural-relevant indicators. The simulations span two periods: 1971-2005 is driven by historical emissions and 2006-2099 is driven by the RCPs.

3.3 Water stress and availability

The soil moisture (θ) and river flow (Q) output of the climate-hydrology model cascade are analysed to shed light of quantitates specifically relevant to land-based primary industries. The two variables considered are (1) the water stress coefficient, K_s, and (2) the number of days abstraction from a river is restricted, T_R.

K_s represents the influence soil moisture conditions have on crop growth and yield (Allen et al. 1998). It is a measure of the soil moisture conditions, here averaged over the September-April irrigation season, between wilting point and the point of stomatal closure, which is approximated as half the soil moisture at field capacity (θ_{fc}):

$$K_s = \begin{cases} 1, \theta \geq \frac{1}{2}\theta_{fc} \\ \theta / \frac{1}{2}\theta_{fc}, \theta < \frac{1}{2}\theta_{fc} \end{cases} \qquad \text{Equation 1}$$

For $K_s = 1$, crop growth is uninhibited by water and proceeds at the otherwise maximum rate. For $K_s < 1$, crop growth and yield are limited by water-stress. This representation may be refined for different crops but in order to provide a first order indication of climate change effects across New Zealand's land-based primary industries this equation offers an informative compromise. It is also informative for other plants and plant communities (Porporato et al. 2001).

T_R is the number of days during the September-April irrigation season that river flow drops below a minimum level, Q_{min}, whereupon abstraction is prohibited. Q_{min} is typically set locally based on competing social, cultural, environmental, and economic values (Norton et al. 2010). For the sake of coherency, this national study uses a uniform approach to set Qmin based on Ministry for the Environment (2008):

$$Q_{min} = \begin{cases} 0.9 \times MALF, \bar{Q} \le 5m^3/s \\ 0.8 \times MALF, \bar{Q} > 5m^3/s \end{cases} \qquad \text{Equation 2}$$

where MALF is the Mean Annual 7-day Low Flow, and $\bar{Q}$ is the mean river flow. MALF and $\bar{Q}$ are calculated over the reference period from simulated flows.

The focus of T_R is thus on water availability from rivers. The hydrological model does not have an explicit deep aquifer system and only simulates shallow groundwater flow. As such, availability of groundwater for abstraction cannot be formally calculated in this study. No national modelling system for New Zealand currently includes groundwater in a necessary way, although the capability is being developed (Yang et al. 2017).

Changes in K_s and T_R are assessed between the reference period (1986-2005) and two projection periods: mid-century (2040-2059) and late century (2080-2099). Because the irrigation season straddles calendar years and the simulations end on December 2099, the period of analysis includes the four months of the preceding year. For each metric, interannual means are calculated across the 20 irrigation seasons for each period, and then medians across the six GCMs. RCPs are kept distinct. Changes are represented in absolute terms, i.e., average future values minus average reference values.

3.4 Results and discussion

Changes in K_s across New Zealand reveal patterns of increases and decreases across the country, century, and RCPs (Figure 3-1). Most changes lie within +/- 0.02. That is, a change in yield for rain-fed conditions equal to 2% of the maximum unstressed yield. Increases tend to lie along western portions of both islands, in the south of the South Island, and along the Canterbury Plains, while decreases tend to lie in the north and east of both islands, and along the middle of the South Island. Patterns of change across RCPs are broadly similar mid-century, reflecting the committed climate change impacts relative to the reference period before the effects of the RCPs diverge. By late century there is a rough gradient of national change, from smaller changes under RCP2.6 to larger under RCP8.5, and there are fewer areas of increases than at mid-century. Both increases and decreases in K_s grow with RCP. The north and east of the North Island at this time is dominated by decreases for all but RCP2.6, and increasingly those greater than 0.02, with some greater than 0.06. The north and central spine of the South Island similarly sees an expansion of areas with decreases greater than 0.02 under RCP8.5.

Changes in T_R across New Zealand reveal similar patterns of increases and decreases across the country, century, and RCPs as K_s, albeit patchier (Figure 3-2). Most changes lie within +/- 5 days. As with K_s, increases tend to lie along western portions of both islands, in the south of the South Island, and somewhat along the Canterbury Plains, while decreases tend to lie in the north and east of both islands, and along the middle of the South Island. Patterns of change across RCPs are slightly more distinct at mid-century than for K_s, with slightly different magnitudes between RCP2.6 and RCP6.0 on the one hand and RCP4.5 and RCP8.6 on the other. This non-linear dependence on RCP may relate to under-sampled interannual variability, with only one simulation for each GCM-RCP combination, or to subtleties in RCP differences. By late century there is again a rough gradient of national change, from smaller changes under RCP2.6 to larger under RCP8.5, and there are fewer areas of increases than at mid-century. In the North Island, the increases in T_r contract with higher RCP, while in both islands the decreases in T_r become more extreme, with some rivers experiencing abstraction restrictions for an additional 20 days. This is almost 10% of the irrigation season.

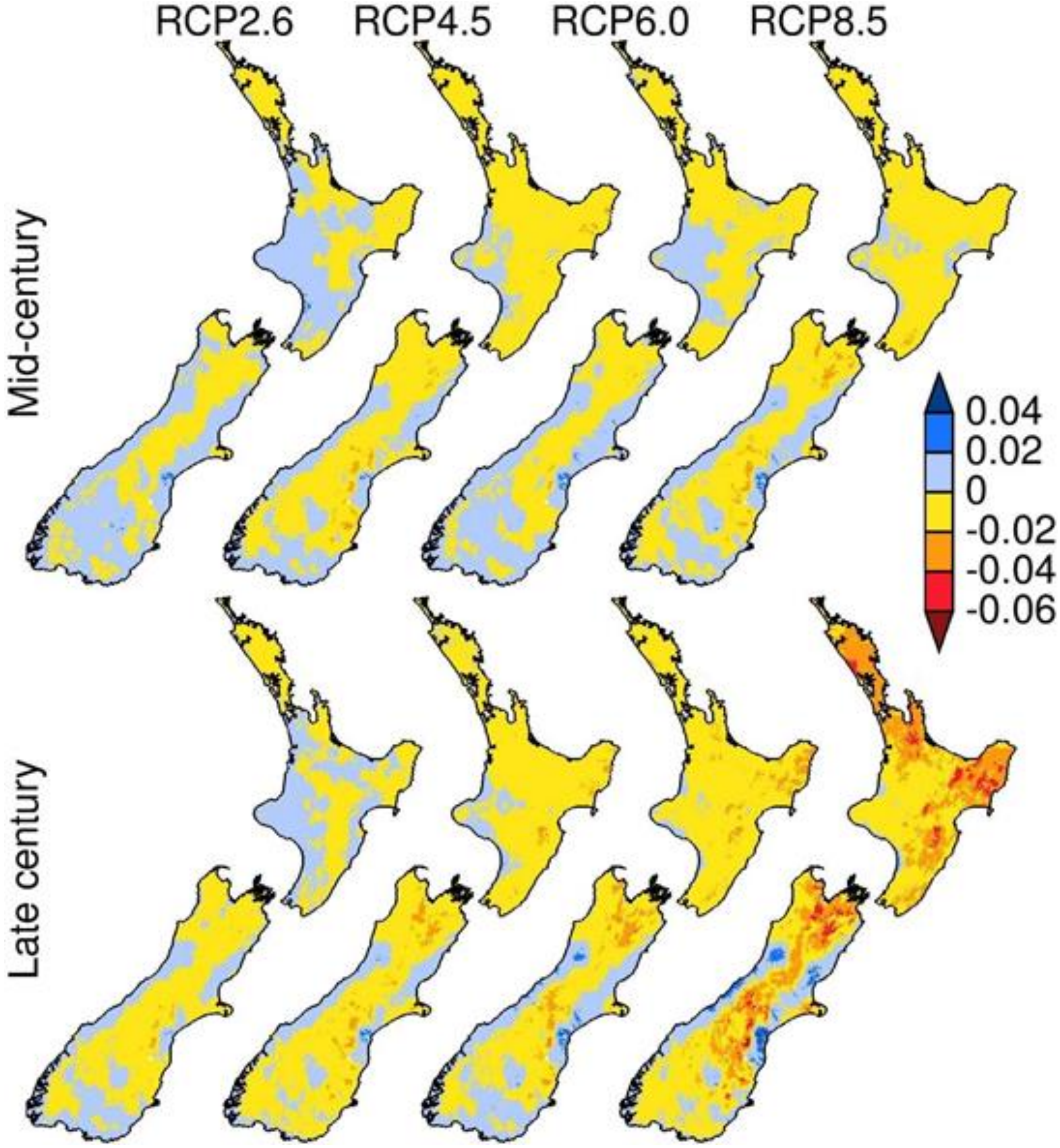

Figure 3-1: Changes in water stress coefficient, Ks, between the reference and projection periods. Values are GCM medians of multi-year means.

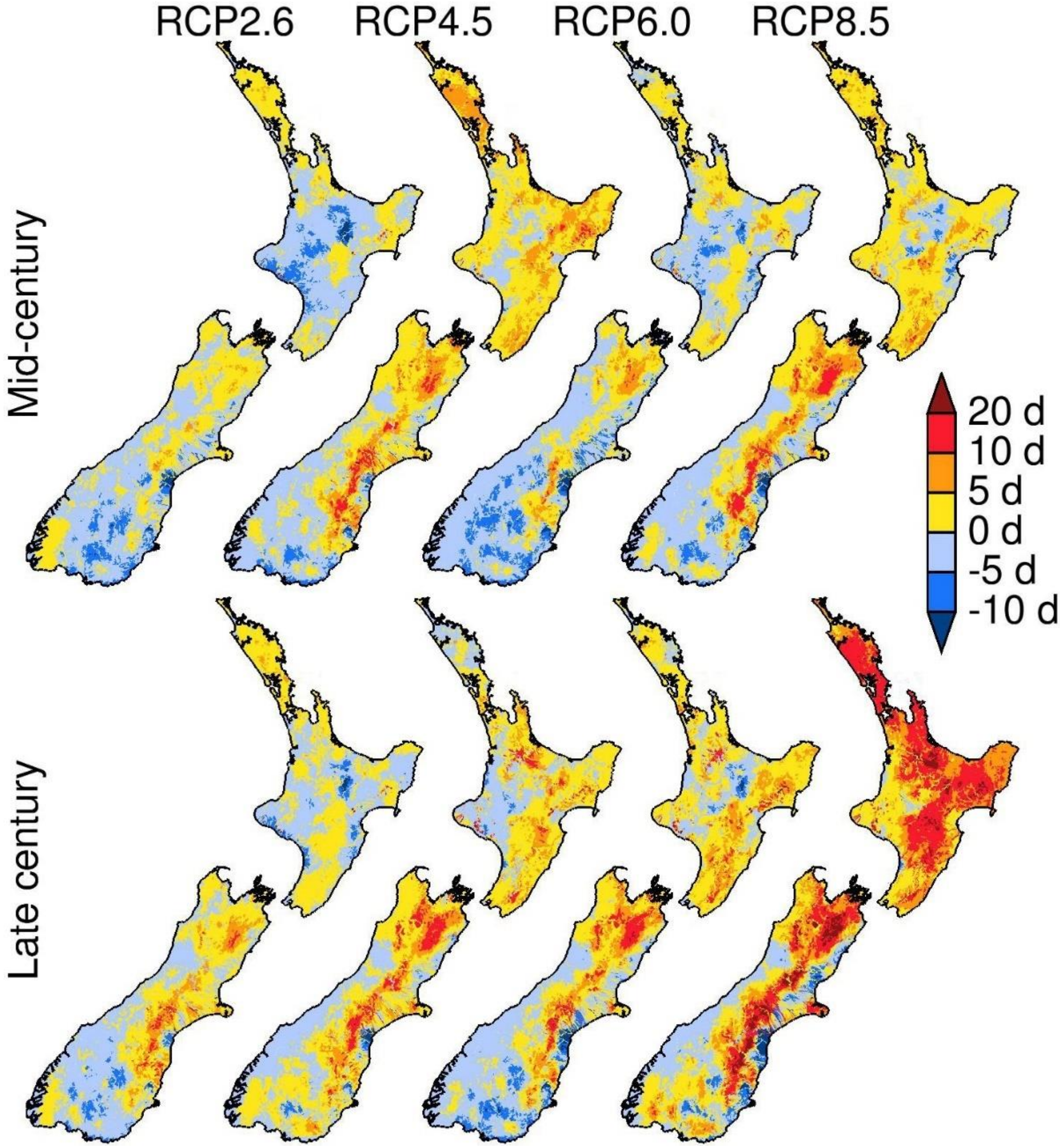

Figure 3-2: Changes in the number of days, Tr, rivers are below the minimum flow, Qmin, between the reference and projection periods. Values are GCM medians of multi-year means.

The similarities and differences in the Ks and TR effects are considered more closely for RCP8.5 late century for north Canterbury (Figure 3-3). The general pattern is for increases in Ks to be associated with decreases in TR, and vice versa. But the results for TR are patchier not just because of the discretised colour scale chosen to map the results but also because rivers have the effect of accumulating hydrological changes downstream, whereas Ks is always local. This means that for smaller rivers, there will be good correspondence between changes in the two metrics, but as rivers become larger, such as the Waimakariri River indicated, changes in low flow extremes reflect headwater effects, where most of the water for the river comes from. The result is that large rivers may decline in TR while their immediately neighbouring sub-catchments experience increases in K_s, and vice versa.

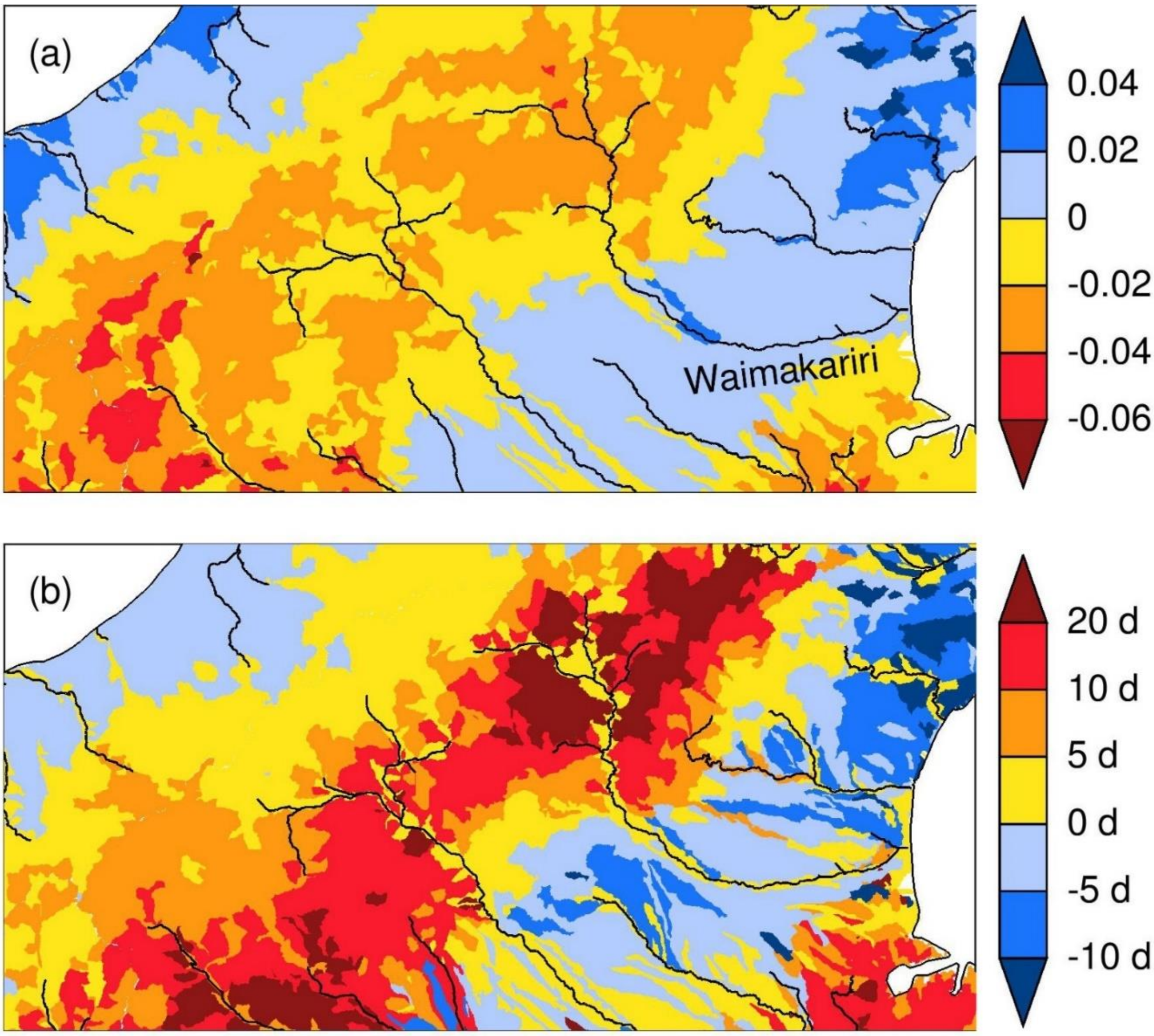

Figure 3-3: Changes in (a) Ks and (b) TR for RCP8.5 by late century, focussing on north Canterbury. Larger rivers are marked as black lines.

Comparing changes in K_s and TR directly, again for RCP8.5 late century, highlights the negative relationship between the two metrics (Figure 3-4), which emphasises the overwhelming tendency for areas to experience parallel changes in the two metrics: either both beneficial or both detrimental. The correlation coefficient is -0.55. The central tendency passing through the origin suggests a near linear relationship, although there is a lot of scatter, and there are more declines in K_s and increases in TR than the converse. For other RCPs, and RCP8.5 mid-century, the correlations between the two metrics are weaker, although consistently negative, ranging from -0.25 (RCP2.6 mid-century) to -0.41 (RCP8.5 mid-century).

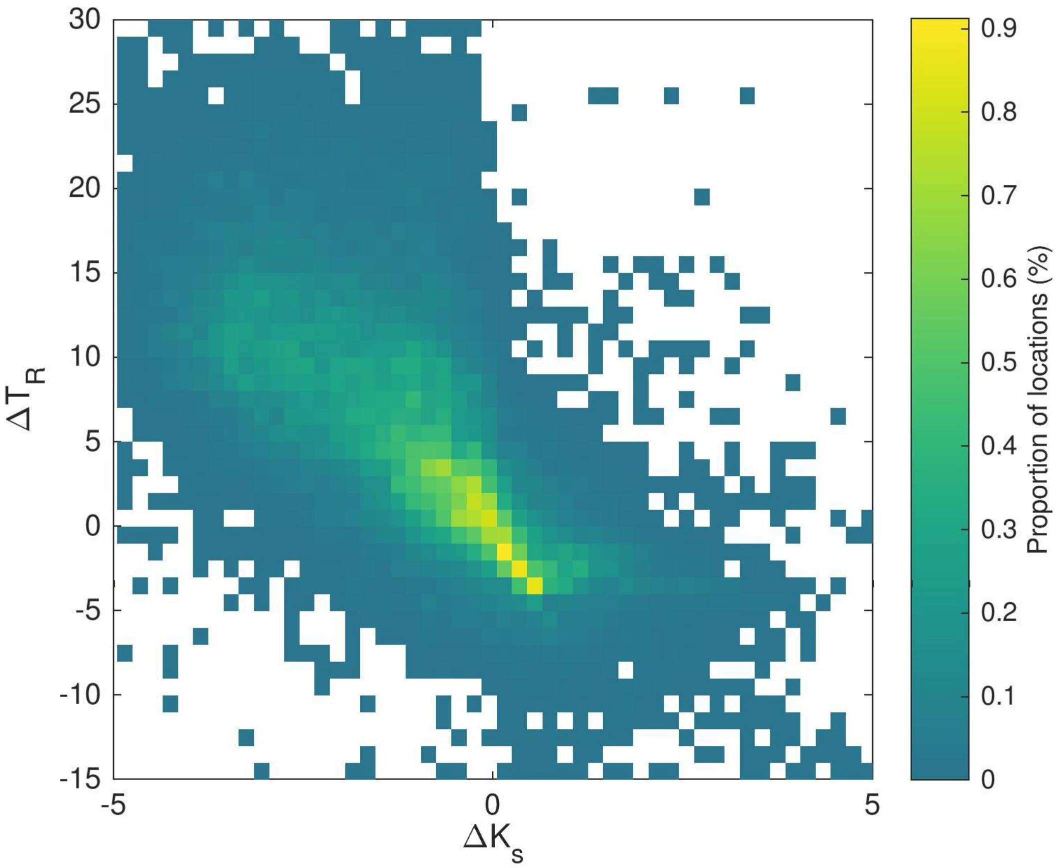

Figure 3-4: Density plot of changes in Ks compared with changes in TR for the same sub-catchment for RCP8.5 late century.

3.5 Discussion

The results presented here describe potential changes in rain-fed plant water stress coefficients and in durations of river abstraction restrictions across New Zealand during the irrigation season under four scenarios of 21st century global warming. While some parts of the country are projected to experience beneficial changes in both metrics, changes in much of the country are detrimental. This poses a challenge to the land-based primary sector which depends on rainfall or supplemental irrigation to support crop yield and economic productivity. Where water stress increases, more irrigation would be required to maintain status quo agricultural production. However, changes in water stress and river water availability tend to be either both beneficial or both detrimental, indicating that areas with higher water demand are less likely to meet any demand from river abstraction during the irrigation season, compounding the effects of drought.

These results have implications for both mitigation and adaptation decisions. The range of impacts across the RCPs reveal, to some degree, the benefits of following lower global emissions trajectories. Any mitigation translates to a reduction the detrimental impacts of climate change on water stress and availability, particularly any avoidance of a trajectory similar to RCP8.5. The spatial patterns and decadal timing of the changes in water stress and availability also shed light on adaptation options. The most important result is that not all regions are exposed to climate change impacts to same degree, nor in the same direction. This helps to highlight regions where adaptation is likely to be more important. The exact nature of the adaptation interventions is outside the scope of the present study, but the spatial results do indicate that large rivers help to buffer the effects of climate change in some regions. Furthermore, seasonal changes in river flow reported by Collins (2020) suggest that water storage accumulated over winter is one of many options.

While the results provide compelling motivations for adaptation or mitigation, they must be couched in terms of model uncertainties and limitations, which Collins (2020) outlined previously for river flows. In particular, validation of MALF has shown it to exhibit substantial biases. This directly impacts the validity of any metric derived from MALF, such the TR. Furthermore, the paucity of soil moisture data and the disconnect between modelled soil moisture and measurable quantities mean that the soil moisture component of the model cascade cannot be directly validated nationally. Taken together, these reduce the confidence we can have in the quantitative results, although qualitative patterns that reflect changes in temperature and precipitation are still likely to hold in so much as the climate projections are informative.

In terms of limitations, the absence of aquifers from the modelling system restricts consideration of water availability to rivers, despite groundwater abstraction playing a significant role in irrigation across New Zealand (Booker and Henderson 2019). The simplicity of the water stress calculation also means that only broad conclusions for crop productivity can be made. To target agricultural, horticultural, forestry, and viticultural productivity more specifically would require closer coupling of crop-water relationships and the inclusion of irrigation from river, aquifer, and storage sources.

These uncertainties and limitations thus imply that while physical modelling of climate change impacts on water stress and availability may be qualitatively informative, their use in informing quantitative decisions is questionable. Successful adaptation would thus require bottom-up vulnerability assessments constrained by adaptive capacity (Wilby and Dessai 2010). Decision-making under deep uncertainty lends itself well to supporting this challenge (Kwakkel et al. 2016).

3.6 Conclusions

Using a climate-hydrology model cascade, impacts of 21st century climate change for crop water stress and river water availability are modelled across New Zealand. While both increases and decreases in water stress are projected in different regions, increases in stress increasingly outnumber decreases, and become more extreme. The same broad pattern is seen with changes in the number of days where abstraction from rivers is restricted, with the partial exception of large rivers that reflect hydroclimatic changes in their headwaters. Increasing water stress would impact rain-fed crop yield directly, including forestry. Furthermore, increasing water demand will tend to coincide with decreasing water availability during the irrigation season, compromising the ability for irrigation to offset the effects of climate change. These impacts are heightened under more extreme emissions scenarios. These results have implications for both mitigation and adaptation decisions in order to avoid or reduce the potential negative impacts of climate change.

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