QUANTIFYING THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON AUCKLAND'S WATER RESOURCES

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ABSTRACT (500 WORDS MAXIMUM)

Watercare is responsible for supplying high quality drinking water to more than 1.7 million people with more than 400 million litres supplied every day. Following Auckland's 2019/2020 drought, the security of the city's water supply both today and into the future has been brought into sharp focus.

Over the past twenty years Watercare has used an Integrated Source Management Model (ISMM) to assist operational and planning decisions. For example, it is used to help identify when new water sources may be needed. One of the functions of the model is to determine the current system yield.

Climate change is expected to impact the pattern and reliability of precipitation as well as to increase potential evapotranspiration (PET). ISMM has recently been updated to consider multiple potential climate futures and assess how the system yield might be expected to change in the future.

In alignment with Watercare's 2019 Climate Change Strategy, the analysis presented here considered two time horizons (2040 and 2090) and two Representative Concentration Pathways (RCP 4.5 and 8.5). Six Global Climate Models (GCMs) (selected for dynamical downscaling based on past performance and model diversity) have been used to simulate each combination of time horizon and RCP, resulting in a total of 24 modelled future scenarios.

The project team applied the changes predicted by the GCMs to an existing rainfall record to create synthetic future records. This approach was selected to preserve natural variability captured in the long-term historical rainfall record, as was necessary for modelling the future performance of an operational water supply system. Rainfall perturbations were applied to the historical data set using a method based on gamma distributions, and a stochastic weather generator was then used to extend the datasets for each scenario.

The impacts of climate change have been modelled and quantified by estimating the yield of the system under the historical baseline climate and then each future climate scenario. Yield, as it is discussed here, represents the annual average daily demand that can reliably be provided by a water supply system, while meeting the required security of supply standard. Preliminary conjunctive-use yields have been estimated using the ISMM model to consider the performance of the integrated system. Stand-alone yields for each of the ten reservoir sources have

also been modelled to better understand the possible impacts on the stored-water sources.

The outcomes of this work will be used to inform Watercare's long term strategic planning to ensure security of supply to Auckland under a changing and uncertain climate. This paper details the work done and provides a valuable example of climate change impact modelling for the New Zealand water industry.

KEYWORDS

Water supply, climate change, dams, sustainable yield, conjunctive use model, impact modelling, rainfall distributions, stochastics

PRESENTER PROFILE

Lucy is a Water Resources Engineer with an undergraduate degree grounded in operations research and numerical modelling. Her technical experience has included water resource management and optimisation, hydrological analysis, and climate change impact modelling. Lucy's work currently focuses on studying the sources and optimising the use of Auckland's water supply.

Sarah is a Water Resources Engineer with a background in civil and environmental engineering. She has experience in integrated water management, hydrology, climate change analysis and drought resilience. Sarah has been involved in modelling Auckland's metropolitan water supply over the past few years, focusing on forecasting potential climate change impacts.

1. INTRODUCTION

Auckland's bulk water supply across the metropolitan system services the majority of the Auckland Region (covering communities from Whangaparaoa towards the north to Pukekohe towards the south) and is derived mainly from surface water sources with a relatively minor contribution from groundwater. The current integrated system includes:

- Ten storage dams (five in the Hunua Ranges and five in Waitakere Ranges)
- Two Groundwater sources (the Onehunga and Pukekohe aquifers)
- One run-of-river source (Waikato River intake, although technically this source includes multiple points of abstraction).

The primary function of the dams in the Hunua and Waitakere Ranges is to capture and store water from catchment runoff to meet demand. The run-of-river and aquifer sources do not rely on storage and instead draw water for supply from the flow passing the intakes on these sources. Each of these sources has a minimum operational flow requirement for plant and equipment, thus providing at least some water for supply throughout the year.

Approximately 55% of the region's water supply is sourced from the Hunua Dams, 20% from the Waitakere dams, 20% from the Waikato River and 5% from the Onehunga and Pukekohe aquifers combined. In drought conditions, the proportion sourced from the Waikato River can increase significantly. For example, at times during the 2013 and 2020 drought periods, abstraction from the Waikato River provided up to 50% of Auckland's water (noting however, that this represented less than 1% of the river flow).

Tonkin & Taylor Ltd (T+T) was engaged by Watercare Services Ltd (Watercare) to investigate the impacts of climate change on Auckland's metropolitan water supply. This included the creation of hydrological datasets for a range of climate change scenarios. The overall project aim was to enable their source allocation model to simulate future climate scenarios and thus to assess the yield of Auckland's metropolitan water supply system under a range of possible future climates.

This project links directly to Watercare's Climate Change Strategy which includes an adaptation work plan with nine short term portfolios for delivery by 2025. Portfolio 3 ("Understanding water source resilience") states that:

"Modelling platforms that utilise past rain data are to be updated to include changes in current and future rain patterns. This includes the Integrated Water Source Management Model (ISMM) which is currently used to manage raw water supply. The rainfall runoff model of the ISMM will require regular calibration as the climate changes". (Watercare 2019).

The Integrated Source Management Model (ISMM) is a decision support system for managing Auckland's bulk water supply. It provides the facility to optimise conjunctive source abstractions and, among other things, is used to estimate the yield of the system. It reads in a long (1,000+ years) rainfall record and simulates optimal daily abstraction from each water source by balancing the cost of operation against the risk-cost consequences of running out of water.

2. METHODOLOGY

The task of confirming a methodology for impact modelling began with a literature review to establish other similar practices around the globe, which built on a similar review completed by T+T for Watercare in 2014. T+T and Watercare then met with NIWA at the onset of this project, as well as several times throughout, to agree on and refine the methodology, assumptions, and preliminary conclusions. Under this collaborative arrangement, NIWA experts[1] acted as a technical challenge team at each key stage of the project.

Furthermore, at each stage of the development of the methodology the data were analysed in detail by T+T to validate methodological decisions. By design, the methodology adopted aligns with international climate impact modelling practices.

The following is a summary of the methodology applied in this assessment, with further details provided in subsequent sections:

- Projections of rainfall, potential evapotranspiration (PET) and maximum temperature were provided by NIWA at a daily scale extending out to at least 2100. The projections covered 16 sites within the Hunua Ranges, six sites across the Waitakere Ranges, two sites near Onehunga, and three sites in the Waikato region.

[1] Dr Abha Sood (Climate Scientist) and Dr Andrew Tait (Chief Scientist - Climate, Atmosphere and Hazards).

- Two-time horizons, 2040 and 2090, were considered in alignment with Watercare's 2019 Climate Change Strategy. Quasi-stationarity was assumed over 31-year windows of data used to represent each time horizon.
- Future climate rainfall datasets were produced using a version of the so-called "delta change" method, which involves applying "change factors" or "deltas" derived from climate model projections onto historical climate observations. This approach was selected to preserve the natural variability of the long-term historical rainfall record.
- The perturbed rainfall datasets were then extended using a stochastic weather generator to each cover more than 1,000 years.
- Conjunctive-use yields were estimated (using ISMM) to consider the performance of the integrated system – where conjunctive-use refers to the integrated operation of a range of surface water and groundwater sources (e.g., reservoirs, aquifers, run-of-river intakes, etc.) to maximise the yield of the overall supply system.
- Stand-alone yields for each of the ten reservoir sources were also modelled to better understand the possible impacts on each of the supply system's stored-water sources.

3. CLIMATE CHANGE PROJECTION DATA

Climate change projections were obtained from NIWA. The projections currently available are based on Global Circulation Model (GCM) simulations forced by future "low" to "high" emissions scenarios and used to inform the IPCC Fifth Assessment Report. As described in its 2018 report (MfE 2018), NIWA dynamically downscaled six GCMs across a nation-wide 30 km horizontal grid resolution.

Dynamical downscaling refers to the use of higher-resolution physics-based climate models to bridge the gap between large-scale climate processes and regional or local impacts. The regional model outputs (at 30 km grid resolution) are then bias corrected guided by Virtual Climate Station Network (VCSN) data. The climate data are further refined on 5 km grid using a simple physics-based semi-empirical model. They were provided as daily time series of rainfall, potential evapotranspiration (PET[2]), and maximum daily temperature for all grid cells covering the Watercare catchments. The time series spanned the "past" period from 1971 through to 2005 reflecting the impact of the historic emissions, and from 2006 to at least 2100 for the set of projected emissions.

4. MODELLED SCENARIOS

The specific climate change scenarios modelled (in terms of the time horizons and emissions scenarios considered) were chosen to align with Watercare's Climate Change Strategy (Watercare 2019).

Although, while Watercare's Climate Change Strategy (ibid.) considers horizons out to 2110 the modelling in this study was limited to the horizons of 2040 and 2090.

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[2] Specifically, Penman-Monteith PET which is calculated based on the downscaled predictions of temperature, wind, solar radiation and relative humidity.

The two emissions scenarios (so-called Representative Concentration Pathways or RCPs) identified in Watercare's Climate Change Strategy (ibid.) have been modelled, being RCP 4.5 and RCP 8.5. RCP 4.5 is a stabilisation scenario in which total radiative forcing is stabilized shortly after 2100, while RCP 8.5 is a very high baseline emission scenario characterised by increasing greenhouse gas emissions over time.

5. RAINFALL PERTURBATION

5.1 BACKGROUND

To model the impacts of projected changes in rainfall, two general approaches were considered:

- Using the raw downscaled GCM projections (as received from NIWA) as inputs and then comparing the modelled responses to their respective baselines (simulated pasts). This would only allow the relative impacts to be quantified, rather than being able to estimate outright the yield at any given time horizon.
- The alternative involves calculating the changes (or "deltas") in the downscaled GCM projections (compared to their respective baselines), imparting them onto the historical baseline (observed past), and then using the perturbed series as inputs. This approach seeks to preserve the natural variability of the long-term (168-year) historical rainfall record and allows for the direct estimation of impacts (i.e. avoiding assessing changes in relative terms).

A version of the latter approach, referred to as the "delta method", has been employed in this assessment.

The "delta method", as it is typically applied, *"is conceptually very simple and has been widely applied in water planning studies, particularly in earlier studies (prior to about 2000) when GCM resolution was typically very coarse"* (Hamlet et al. 2010), meaning the GCMs were limited in their capacity to simulate regional-scale changes in both temperature and rainfall (Lettenmaier et al. 1999).

For example, free-running GCMs are known to poorly capture the frequency of blocking events observed in climate records (Patterson et al. 2019). Atmospheric blocking is an important weather system in the midlatitudes (over New Zealand) and is frequently linked to extreme weather (Gibson et al. 2017; Perkins-Kirkpatrick et al. 2016; Sillmann et al. 2011; Woollings et al. 2018). With GCMs often failing to accurately simulate blocking events under present day conditions, the confidence in their future projections of blocking frequency is undermined (Patterson et al. 2019). Hence, the natural variability captured in a long-term observed record becomes increasingly important.

Furthermore, there are random phenomena that can have a significant effect on rainfall patterns that are captured in historic records but are not represented in the GCM projections. For example, the injection of sulphate aerosols into the upper atmosphere from massive volcanic eruptions have been found to alter precipitation patterns. Zhuo et al. (2014) modelled the effect of volcanic aerosols on China's monsoon precipitation and found that drying trends (spanning multiple years) over mainland China could be linked to eruptions in the Northern Hemisphere.

5.2 MODIFIED "DELTA METHOD"

For rainfall specifically, "deltas" are usually calculated as percentage changes (i.e., capturing changes in the means). In this application, the "deltas" have been calculated based on fitted gamma distributions and their two-parameter descriptions (i.e. the shape, α, and rate, β). This involved fitting gamma distributions to monthly rainfall series, calculating the changes in shape and rate parameters expected in the future distributions (compared to the simulated pasts), and imparting those changes on the observed rainfall distributions to create perturbed historical datasets representative of future scenarios.

This approach (of matching series based on assumed distribution functions) is sometimes referred to as the "Distribution Mapping" method. It allows for the adjustment of both the mean and variance of a series and, furthermore, preserves the extremes (Themeßl et al. 2012). Fitting theoretical distributions (as opposed to, say, fitting empirical distributions) may potentially introduce biases (Fang et al. 2015) however, the gamma distribution is widely used for representing rainfall *"due to its flexibility of fitting all patterns of rainfall from an exponential to normal distribution"* (Ahamed et al. 2013:2508).

This perturbation method has been developed to also capture and impart changes in the proportion of dry days seen in the climate change projections. Although, it is worth noting that an explicit assessment of the changes in dry day proportion was not considered critical for this assessment because it is modelling a storage system that can, to a large extent, attenuate the effects of increased no-rain days. Thus, capturing the changes in cumulative rainfall was considered more material.

6. STOCHASTIC RAINFALL GENERATION

After the deltas were applied, each resulting series was 168 years long, which is the length of the observed record. To robustly model the water supply system, a longer dataset was required. This was achieved through a stochastic extension. The Stochastic Climate Library (SCL) tool from eWater was used to generate six replicates of each of the series, thus creating combined synthetic datasets of 1,176 years each.

Corresponding PET datasets were calculated as annually repeating functions based on the downscaled GCM predictions. This simplified approach (compared to the handling of rainfall projections) was employed because the use of PET data was limited by the stochastic weather generator utilised. Limitations within the SCL meant that co-variant rainfall and PET could not be generated across multiple sites. Priority, in this case, was given to co-variant rainfall across the different locations, thus requiring an alternative (and simplified) approach for PET.

7. YIELD IMPACT MODELLING METHODOLOGY

7.1 INTRODUCTION

While the focus of this project has been on updating the ISMM model to enable modelling of future climate scenarios, preliminary results have been produced as part of the model update process and are reported here to indicate the expected future trends. It is recommended that more detailed analyses and testing be carried out to better understand the sensitivity of the system to climate change.

The impacts of climate change have been modelled and quantified by estimating the yield of the system under the historical baseline and then each future climate scenario. Yield, as it is discussed here, represents the annual average daily demand that can reliably be provided by a water supply system, while meeting the required security of supply standard.

Firstly, preliminary conjunctive-use yields have been estimated to understand the performance of the integrated system. Conjunctive-use refers to the integrated operation of a range of surface water and groundwater sources (e.g., reservoirs, aquifers, run-of-river intakes, etc.) to maximise the yield of the overall supply system.

Secondly, stand-alone yields for each of the ten reservoir sources have been determined to understand better the impact of climate change on each of the supply system's stored-water sources. Stand-alone reservoir operations were simulated using bespoke water balance models with flow data from the ISMM rainfall runoff models as reservoir flow input data.

7.1.1 SUSTAINABLE YIELD

In order to estimate the amount of water that can be reliably supplied from a system, a long-term series of inflows needs to be obtained (whether through observation or derivation based on hydrological conditions) and this series needs to be a realistic expectation of what is likely to occur in the climate you are planning for. If a sequence of low inflows occurs, especially over an extended period of time, and those inflows are less than the demand for water placed on the system, the stored water sources will become depleted. If this depletion results in the sources emptying completely or falling below a specified threshold (and as a result demand cannot be met), 'system failure' has occurred from a water supply perspective.

The average frequency at which such failure occurs determines the probability of failure. For example, if there were 1,000 years of inflow data and for a given level of demand the system failed five times, then the annual probability of failure would be five over 1,000 or 0.5% or 1 in 200. Hence, that level of demand corresponds to the 'sustainable yield' for the 1-in-200-year event.

For the work presented here, yield has been assessed along these lines. ISMM and the stand-alone reservoir water balance models have been used to simulate system operations through a range of demand steps for each of the climate scenario sequences produced, with the aim of producing a set of curves of demand versus 'system failure' probability.

7.1.2 SYSTEM DESIGN STANDARD

For Auckland's water supply, yields are presented in mega litres per day (ML/d) and can be defined within ISMM in terms of two failure modes:

- Supply shortfall: failing to supply unrestricted demand on any given day
- Volume shortfall: storage in the reservoirs dropping below a set threshold.

Watercare’s current drought security standard is defined as follows:

“The metropolitan water supply will be operated to a 1-in-100-year event with a 15% residual storage at the end of the drought event.” (Watercare 2021)

Yields have been modelled for a range of event frequencies (for example, see Figures 4 and 5 in Section 8.1 below), but key conclusions are primarily discussed in relation to 1% annual exceedance probability (AEP) (i.e., 1-in-100-year) volume shortfall events in order to align with this drought standard.

7.2 ASSESSMENT OF CONJUNCTIVE-USE YIELDS

Conjunctive-use has been modelled for two supply system configurations, one approximating the current system configuration (hereby referred to as the ‘2021/2022’ system) and the other representing a future configuration accounting for anticipated resource consent changes and infrastructure upgrades. More specifically:

- The ‘2021/2022’ system includes Watercare’s presently operational Waikato River water treatment plants (WTPs) and assumes the Board of Inquiry (BOI) consent (to take an additional 150 ML/d from the river) is not yet operational. A treated water pipeline limit for the combined Waikato WTPs of 225 ML/d is then applied to represent the current conveyance capacity between the river intake and its connection into the Auckland system (at the Redoubt Road Reservoir).
- The ‘future’ system assumes the Waikato A treatment plant has replaced Waikato 50 WTP and the BOI consent has replaced the 100 ML/d seasonal consent. It also assumes the treated water pipe conveyance limit has increased to 300 ML/d, and that the Huia water treatment plant has been upgraded to a 140 ML/d capacity.

The yield analyses are based on a demand profile that is representative of the long-term demand for water in Auckland’s metropolitan system. The prediction of changes to the demand profile in response to climate change is beyond the scope of this study. More work is required to model and assess how the pattern of demand may be expected to change under warmer climates and the impact of this on the system capability.

The system was simulated assuming an operational regime that prioritises the conservation of stored water in the reservoir systems. This was achieved by setting the ‘Risk Cost Rate’ in ISMM to a very high value (of 5,000), which increases the value assigned to stored water. In effect, this prioritises the use of higher-cost run-of-river sources (e.g., the Waikato River) over reservoir sources, particularly when total system storage is low. This is how Watercare proactively manages risks to water supply during periods of water stress.

7.3 ASSESSMENT OF STAND-ALONE RESERVOIR YIELDS

The stand-alone yields for each of the ten reservoirs have been assessed using water balance models for each reservoir operating independently of the other sources.

The individual reservoir operations were modelled over the 1,176-year synthetic rainfall datasets, with an annual average daily demand varied according to month (i.e., a simplification of the higher resolution weekly pattern modelled within ISMM). Input datasets were based on the historical baseline, and on each of the six GCMS for the RCP 4.5 and RCP 8.5 emissions scenarios at both 2040 and 2090.

The stand-alone reservoir models account for reservoir inflows (i.e., direct catchment runoff, direct rainfall on the reservoir, and as appropriate upstream dam releases) and outflows (i.e., water supply abstractions, reservoir evaporation, compensation releases, and dam spill). Catchment runoff time series were provided for each dataset from ISMM rainfall runoff modelling results. Inflows to Lower Huia and Lower Nihotupu reservoirs included the spill and compensation releases from the respective upper dams for the corresponding scenario. Direct rainfall and evaporation were determined from the reservoir surface area which varies depending on storage level. Compensation releases were calculated in accordance with the resource consent conditions for each dam.

For each dataset, the objective of the analysis was to determine the number of failures over the 1,176 years that corresponded to the target drought security of supply standard. That is, the 0.1 % AEP standard corresponds to between 1 and 2 failures in that period; the 0.5 % AEP standard corresponds to between 5 and 6 failures; and so on. Annual average daily demand was adjusted, and reservoir operation modelled, until the failure count corresponded to the target standard, and this was determined as the stand-alone yield of the reservoir for that climate dataset. Failure was defined by both the supply and volume modes discussed above.

8. PRELIMINARY YIELD MODELLING RESULTS

This section presents preliminary modelling results for assessing the impact of climate change on both the conjunctive system yield and stand-alone reservoir yields.

8.1 SUMMARY OF CONJUNCTIVE-USE YIELD RESULTS

Using the ISMM tool to model future system yield suggests that, at or around Watercare's drought level of service, the conjunctive system yield by 2040 is likely to reduce for both RCPs and all GCM scenarios considered:

- For the 2021/2022 system configuration, modelling indicates this change could range from -1 ML/d to −57 ML/d (or -0.2% to −11%), with a mean decrease of 32 ML/d.
- For the future system configuration, the change could range from +3 ML/d to −60 ML/d (or <1% to −10%), with a mean decrease of 30 ML/d.

By 2090, the conjunctive system yield is likely to reduce for both RCPs and all but one of the GCM scenarios considered:

- For the 2021/2022 system configuration, modelling indicates this change could range from +9 ML/d to −69 ML/d (or +2% to -13%), with a mean decrease of 38 ML/d.
- For the future system configuration, the change could range from +6 ML/d to −68 ML/d (or +1% to -11%), with a mean decrease of 38 ML/d.

Figure 1 presents a summary of the changes outlined above but drilling into both time horizons and emissions scenarios.

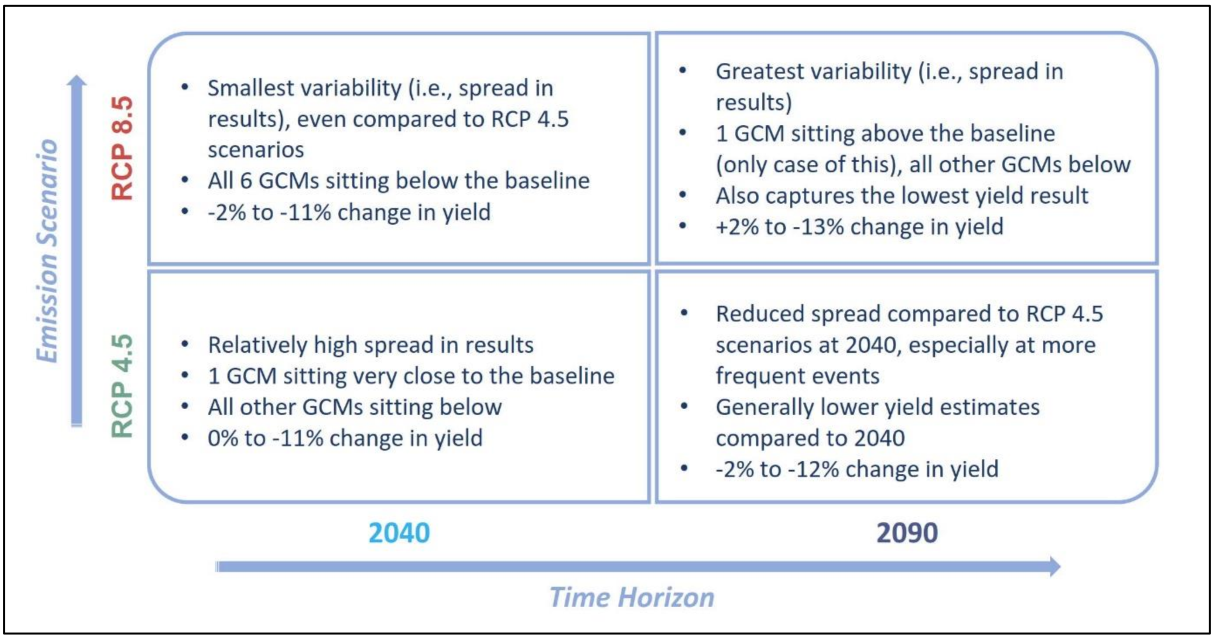

Figure 1: Summary of conjunctive-use yield result characteristics by time horizon and emission scenarios

Figure 2 presents the range of conjunctive-use yield estimates at Watercare's drought level of service across each of the time horizons modelled. These highlight how the yield is expected to generally reduce over time, and how the range of results (i.e., the uncertainty) also increases. This latter observation aligns with the emissions scenario projections more generally which fan out considerably about the 2090 horizon (see Figure 3 as an example of this).

Table 1 and Table 2 summarise the projected changes in yield estimates for selected event frequencies (in absolute and relative terms, respectively).

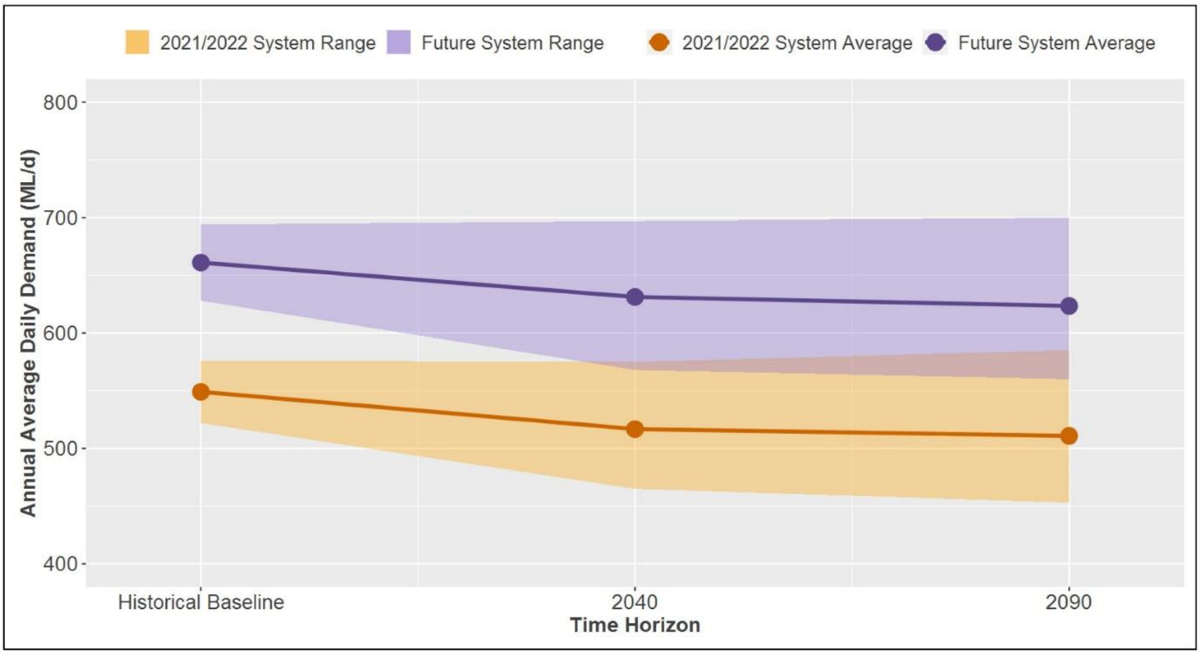

Figure 2: Conjunctive-use yield estimates[3] under all climate scenarios for two system configurations at Watercare's drought level of service[4]

Table 1: Changes in conjunctive-use yield estimates (in ML/d) (compared to the historical baseline climate) at Watercare's drought level of service

System Configuration	2040 Time Horizon			2090 Time Horizon		
	Minimum	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
'2021/2022'	-57	-32	-1	-69	-38	+9
Future	-60	-30	+3	-68	-38	+6

Table 2: Relative changes in conjunctive-use yield estimates (compared to the historical baseline climate) at Watercare's drought level of service

System Configuration	2040 Time Horizon			2090 Time Horizon		
	Minimum	**Average**	**Maximum**	**Minimum**	**Average**	**Maximum**
'2021/2022'	-11 %	-6 %	- <1 %	-13 %	-7 %	+2 %
Future	-10 %	-5 %	+ <1 %	-11 %	-6 %	+1 %

[3] Note: ±5% has been added to the conjunctive-use yield results to represent the uncertainty associated with data and model inaccuracy. This aligns with Watercare's adopted methodology for assessing headroom.
[4] Volume shortfall (15% residual storage) yield for a 1% AEP (1-in-100-year) event

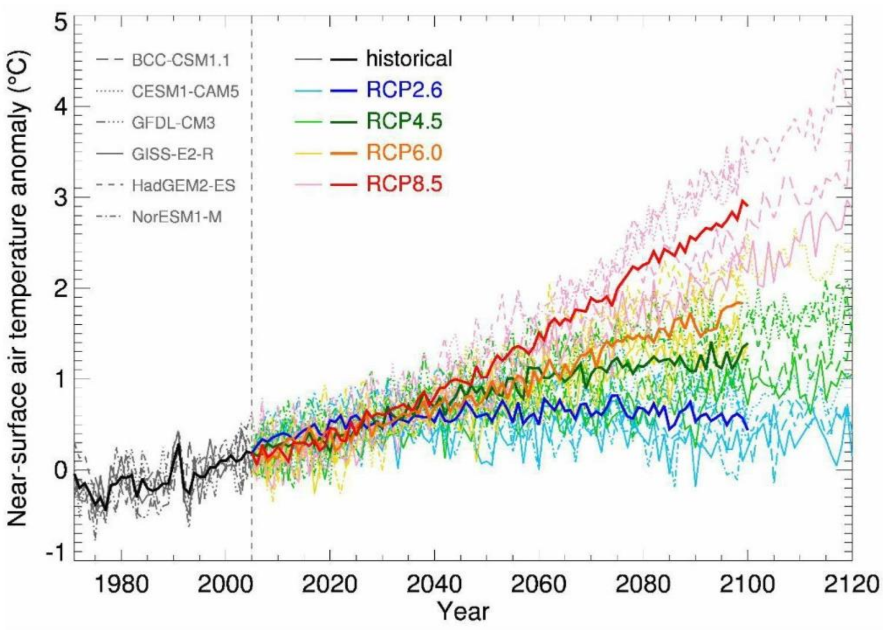

Figure 3: Projected New Zealand-average temperatures relative to 1986-2005, for the six downscaled CMIP5 GCMs, and for the historical simulations (1971-2005) and four future emissions scenarios (RCPs 2.6, 4.5, 6.0 and 8.5) (MfE 2018)

Figure 4 and Figure 5 present the range of conjunctive-use yield estimates (for the 2021/22 and future system configurations, respectively) across the various event frequencies (i.e., exceedance probabilities) modelled. These show that the conclusions discussed above apply to most event frequencies. However, at the more extreme frequencies (less than or equal to 0.2% annual probability) the baseline yield range starts to shift closer to the average future yields. The reason for this shift needs exploring further, although it is worth noting that model uncertainty is greater at this extreme end. This is because, statistically, uncertainty (the confidence interval around an estimate) increases as the recurrence interval being estimated approaches the length of the record used to inform it. For example, Dalrymple (1960) found that the length of record required to estimate floods of various probabilities increases as one's target confidence interval increases. This relationship is illustrated in Table 3.

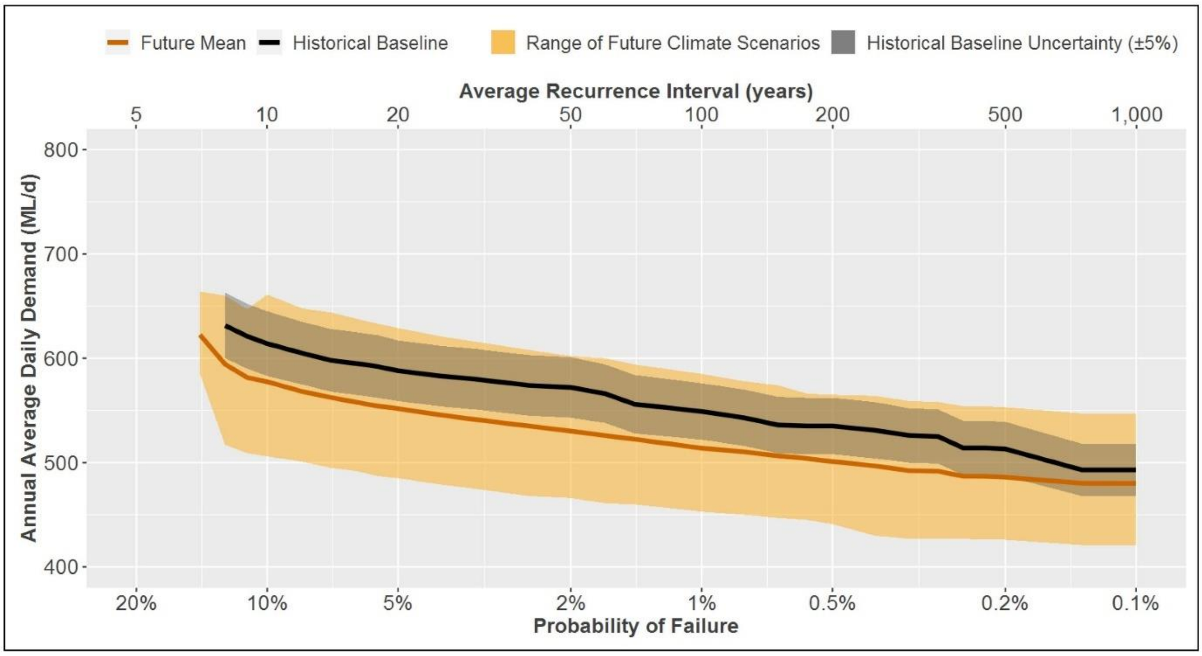

Figure 4: Conjunctive-use yield modelling range of scenario results for various event frequencies for the 2021/22 system configuration

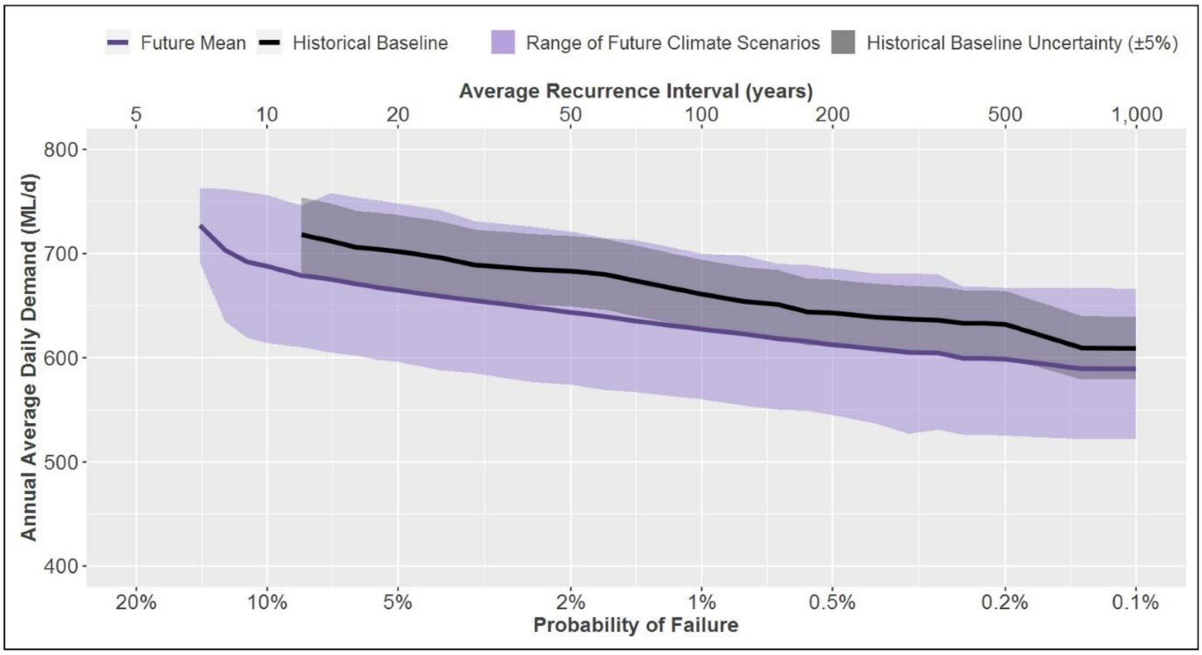

Figure 5: Conjunctive-use yield modelling range of scenario results for various event frequencies for the future system configuration

Table 3: Length of record required to estimate floods of various probabilities within 10 percent of the correct value 80 or 95 percent of the time (Dalrymple 1960)

Design Probability (AEP)	Recurrence Interval (years)	Length of Record in Years	
		80 Percent of the Time	95 Percent of the Time
10%	10	38	90
4%	25	75	105
2%	50	90	110
1%	100	100	115

8.2 SUMMARY OF STAND-ALONE RESERVOIR YIELD RESULTS

Separate modelling of the potential impact of climate change on each of the ten storage reservoirs suggests that, at or around Watercare's Level of Service, the impact of climate change on the reservoirs in the Hunua Ranges is likely to be slightly greater in percentage terms than the impact on those in the Waitakere Ranges. This can be seen in the following charts (Figure 6 and Figure 7) which show the consolidated outputs of the RCP and GCM scenario modelling, to indicate the minimum, average and maximum changes to yield that could be expected.

Inspection of the relative changes indicates that they are the same order of magnitude as the changes predicted in the conjunctive yield (refer Table 2). However, the range of changes in stand-alone reservoir yields is slightly greater (+6% to -21% versus +2% to -13%). This could suggest that the reservoirs are more susceptible to the effects of climate change compared to the Waikato River and aquifer sources. Alternatively, it may indicate that conjunctive-use (managing the various sources in an integrated way) is inherently able to buffer some of the effects of climate change.

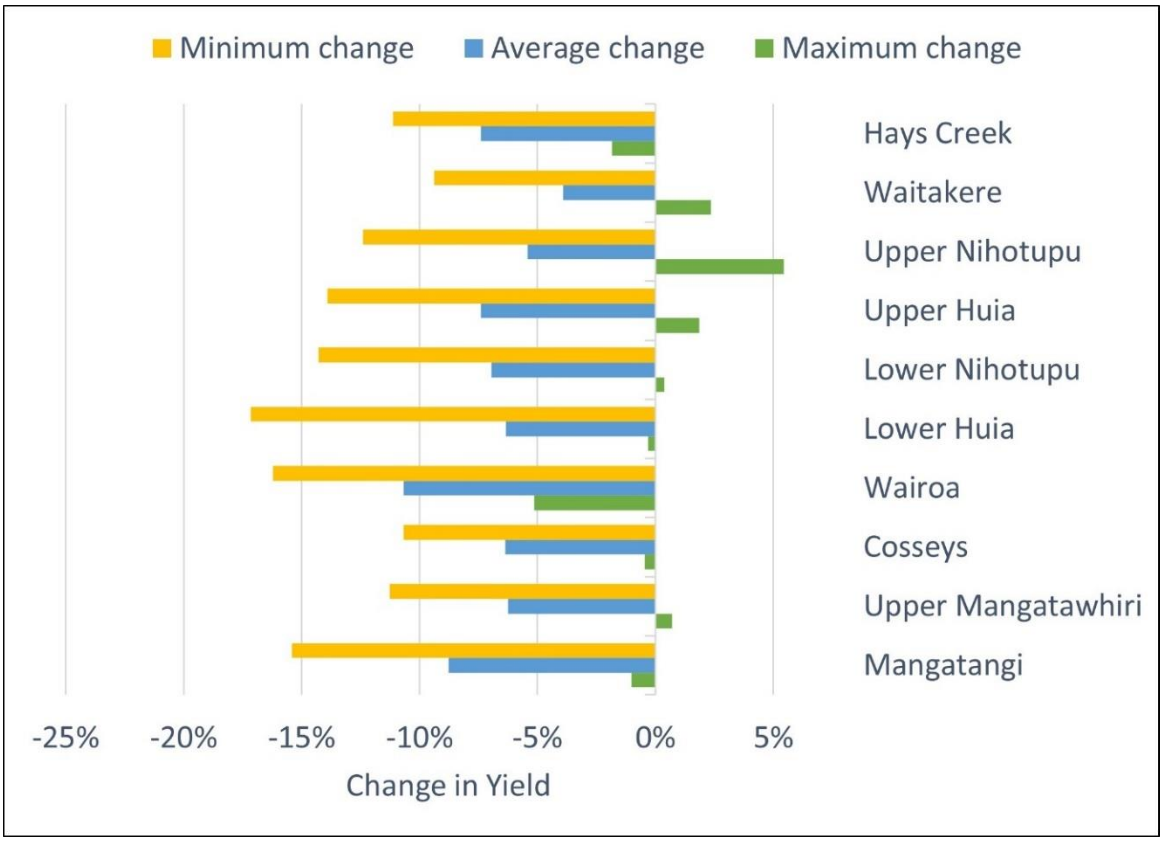

Figure 6: Relative changes in stand-alone reservoir yield estimates by 2040 (compared to the historical baseline) at Watercare's drought level of service

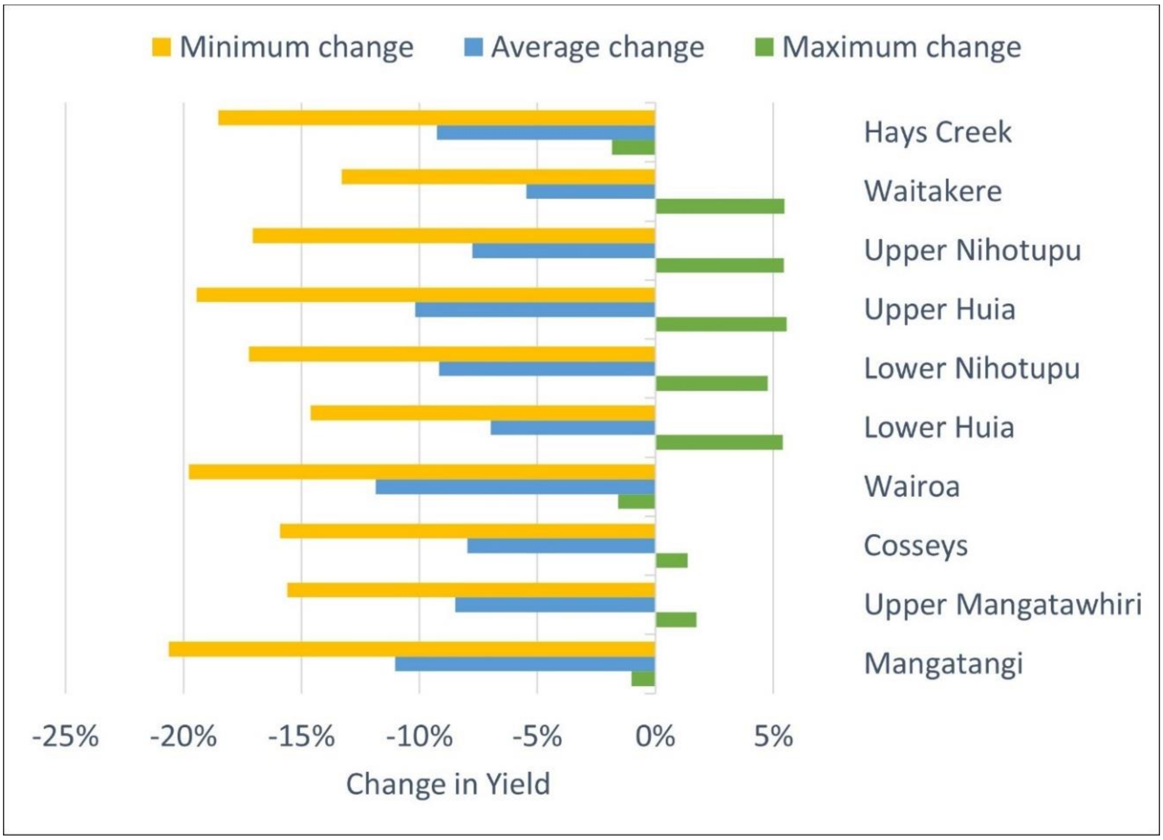

Figure 7: Relative changes in stand-alone reservoir yield estimates by 2090 (compared to the historical baseline) at Watercare's drought level of service

9. CONCLUSIONS AND RECCOMENDATIONS

As discussed in Section 8.1 (refer Table 1) above, the conjunctive system could expect to see an average reduction in yield of 32 ML/d by 2040 and 38 ML/d by 2090. To put that into context, such a reduction would be analogous to losing much of Cosseys reservoir in the Hunua Ranges – this being the third largest reservoir in the system with a current baseline yield estimate of 44 ML/d. Furthermore, the maximum reduction in conjunctive yield could be up to 60 ML/d by 2040 and 69 ML/d by 2090. This 2090 projection would be equivalent to losing four of the five reservoirs in the Waitakere Ranges – these being the Waitakere, Upper Nihotupu, Upper Huia, and Lower Huia reservoirs which have a combined baseline yield of 68 ML/d.

With these results in mind, it is recommended that Watercare:

- Consider how to maximise the yield of existing sources into the future,
- Consider the impact of climate change when investing in new or upgraded source and treatment infrastructure,
- Update its assessment of headroom to incorporate climate change,
- Update its supply demand balance to incorporate these findings, and
- Develop an adaptive pathway, including thresholds and trigger points, to respond to the expected reduction in yield over the planning period.

It is also worth mentioning some of the key limitations of this assessment, which can all be attributed to simplifications made regarding the type of climate change effects considered. This assessment focused primarily on the impact of changes hydrological conditions on the system's surface water catchments, with a particular focus on changes in rainfall and PET. Whereas, in reality, there are many more moving parts to consider. The following aspects have not been integrated in this assessment but would be worth exploring in the future, especially as they may compound with the aforementioned hydrological impacts:

- Impacts of sea level rise on the aquifer sources,
- Projected changes to water demand, both in terms of population growth and changing water-use patterns
- Possible changes to the Waikato River flow regime upstream of Watercare's intake site, for example, looking at upstream water abstractions and hydro-power scheme operations,
- Potential effects on water quality, noting however that this is more of an operational issue and less of a concern from a yield perspective.

Given the findings of this preliminary modelling, the following next steps are proposed:

- Carry out further modelling and analyses to better understand the sensitivities of the system to climate change and where the uncertainties lie
- Further interrogate the results to understand the driving climatic forces behind the projected changes in yield. For example, to investigate if yield reductions are a result of increasing PET and/or changing rainfall patterns
- Carry out further analyses to confirm the impact of climate change on peak deployable outputs

- Model the impact of climate change on water demand and update this analysis for an integrated supply-demand assessment
- Update this assessment once downscaled projections from IPCC's Sixth Assessment Report are made available.

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