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Modelling the supply–demand balance of New Zealand's largest water supply system

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Abstract

Watercare provides water and wastewater services to the Auckland region, with its metropolitan water system supplied by a complex conjunctive-use system, comprising dams, groundwater and run-of-river takes. With a responsibility to provide safe, reliable drinking water to the people of Auckland at an agreed Level of Service, understanding the supply–demand balance of this system and how it changes over time is crucial to a focused investment programme. Recent supply and demand data are heavily influenced by multiple notable climate events and a global pandemic affecting socio-economic activity and population growth; this means that capturing trends to forecast demand and assess supply availability has its challenges.

Forecasting into an ever-changing future means that there are a lot of uncertainties to capture. The compounding effect of taking a conservative approach to capture the worst-case outcome of any scenario would lead to an over-engineered, unfeasible outcome. A Monte Carlo approach was utilised, assessing the likelihood and consequence of these uncertainties, to represent a realistic impact on the system to inform investment. This was represented by an additional allowance applied to demand as headroom and an allowance for unplanned outages.

The key drivers influencing demand are weather and population growth. Baseline years were established by measuring the dynamic relationship between demand drivers and patterns to uncover underlying trends. Various population forecasts were compared, by assessing how well they have previously captured growth, and consideration was given to the spatial distribution of growth across the Auckland region, accounting for plan changes and new developments.

Forecasting supply involved modelling both the peak and long-term yield potential from the supply system, i.e., at the agreed Levels of Service. Auckland's dams provide around 80% of Auckland's water supply under current conditions. Peak capacity from these dams makes up a large component of Auckland's available supply, but the capacity of the dams as a percentage of the mean annual inflow is low for most of the dams, meaning they are susceptible to failure of supply under drought conditions, especially during multi-year drought events.

In the past, Watercare's system has typically been constrained by time constraints from the supply–demand balance representing peak summer demand and supply of one to three days duration, encouraging investment in increasing the capacity of the water treatment plants servicing the dams. However, Watercare recently carried out

a study to quantify the impacts of climate change on supply, which found a notable reduction in potential yield under drought conditions – which does not have the same effect at the peak Level of Service.

Accounting for this impact of climate change shifted the focus from investing to meet yield under peak conditions to meeting longer term yield under drought conditions. The results confirmed the need to invest in additional drought-resilient sources and sources that are less vulnerable to climate change. In the short to medium term, increasing the capacity of the water abstraction from run-of-river and groundwater sources, which are less vulnerable to climate change than the dams, is likely to be required. However, the supply from these sources is still finite and is typically consent constrained. This highlights the importance of forecasting timeframes whereby Watercare will need new additional water supply sources, such as purified recycled water or desalination, once traditional water sources are not able to be sustainably recharged in a drought. Implementing these sources will be very complex, requiring a lot of research and development. These sources would be the first of their kind in New Zealand and are likely to require Watercare to lead the way, navigating potential complex community engagement, changes to drinking water regulations, resource management and funding strategies (Beca and Tonkin + Taylor, 2020b, 2020d; Beca, 2020).

Modelling the supply and demand balance over time emphasises the importance of Watercare's early investment into research, development and design of sources to improve both long-term yield and ability to meet peak demand. This work has shown that despite the inherent increase in uncertainty as projected timeframes increase, early planning and investment is crucial.

Keywords

supply–demand balance; level of service; drought management; climate change; water supply planning

Introduction

Watercare has responsibility to provide safe and reliable water and wastewater services to around 1.7 million people across the Auckland region, New Zealand. Watercare's Drought Management Plan (Watercare Services Limited, 2023) states that the first water supply Level of Service (LoS) (the drought standard) requires that "unrestricted demand is to be met while keeping the volume in Auckland's storage lakes above 15%". A severe drought is considered by Watercare to have a 1% annual exceedance probability (AEP). Water restrictions are utilised to extend the actual operational return period of such events.

The second LoS states that there should be "no more than a 5% chance of restrictions being needed in any given year". This is in relation to summer peak demand, where very hot and dry weather drives high demand which can be curbed using restrictions, but restrictions should not be applied more frequently than 5% of the time. This informs the peak capacity of Watercare's system.

The demand and supply balances for these two LoS are different. The critical path to balancing supply and demand informs the priorities for future investment. The upgrade or development of different sources contributes to improving peak supply, and/or increasing long-term yield – not necessarily both.

Auckland's metropolitan water supply is a complex, conjunctive-use system. It comprises ten dams (in and around the Waitākere and Hunua Ranges), two groundwater sources (in Onehunga and Pukekohe, when operational), and one run-of-river supply (the Waikato River). The balance of abstractions from these sources is dynamic, depending on storage levels, weather conditions, time of year, system constraints and costs. The supply system is optimised to ensure ongoing security of supply at an agreed level of risk, for the lowest possible cost.

Managing a conjunctive-use system supports drought resilience by being able to utilise more water from storage-based sources (the dams) when levels are full and the risk of spill from the dams is high, then favouring abstraction from non-storage-based supplies (run-of-river or groundwater supplies) during drier conditions. Whilst having multiple sources provides resilience and redundancy for meeting peak demands, this conjunctive-use system does not increase peak capacity, which is limited by treatment plant capacity and consent limits.

Scope

Two key step-changes in the demand and supply balance have been evident, driven by the uncertainty of future planning. On the demand side, events over the past few years (namely the drought, 2023 storm events and the COVID-19 pandemic affecting socio-economic activity and population growth) have distorted and suppressed demand patterns. The 2024 year was the first time since the COVID-19 pandemic that weather patterns were typically normal. This resulted in a sharp return to expected 'normal' demands, which were consistently elevated above the previous few years, where the underlying growth was previously masked by these events. On the supply side, recent climate change work (particularly around the effects of climate change on the applicability of the historical record for future forecasting) has impacted the modelled annual drought yield of the system. Driven by these recent updates to the supply–demand balance, Watercare has had to reassess its investment strategy.

To manage this system and inform future investment, there needs to be a clear understanding of the supply–demand balance, both now and into the future. This must consider both peak and long-term water demands and supplies. Auckland's water supply faces the common challenges of population growth, ageing infrastructure and the new, more uncertain, challenge of a changing climate. To continue providing the agreed LoS, Watercare must have a focused investment plan to continue meeting demand in a timely manner, particularly given the lead times for the development of new water sources.

Investment decisions are informed by the difference in Water Available For Use (WAFU) and the demand forecast within the system. WAFU is the deployable output, less a factor applied to capture an allowance for outage across the system. Demand comes from a demand forecast, with headroom applied to represent an allowance for uncertainty in the supply–demand balance (Figure 1). The difference between demand (including headroom) and WAFU represents the headspace within the system, and the point where these lines meet (line A-A on Figure 1) represents the timeframe by which further investment should prudently be expected to be in place.

The purpose of this work was to update the supply–demand balance (aligning with the methodology detailed in the 2020 assessment; Beca and Tonkin + Taylor, 2020c), to reassess priority timeframes and projects to ensure Watercare can continue to maintain its agreed water supply LoS for Auckland.

Demand

The overarching approach taken for the demand assessment followed the robust methodology that was implemented to support a consent application in 2020 (Beca and Tonkin + Taylor, 2020a).

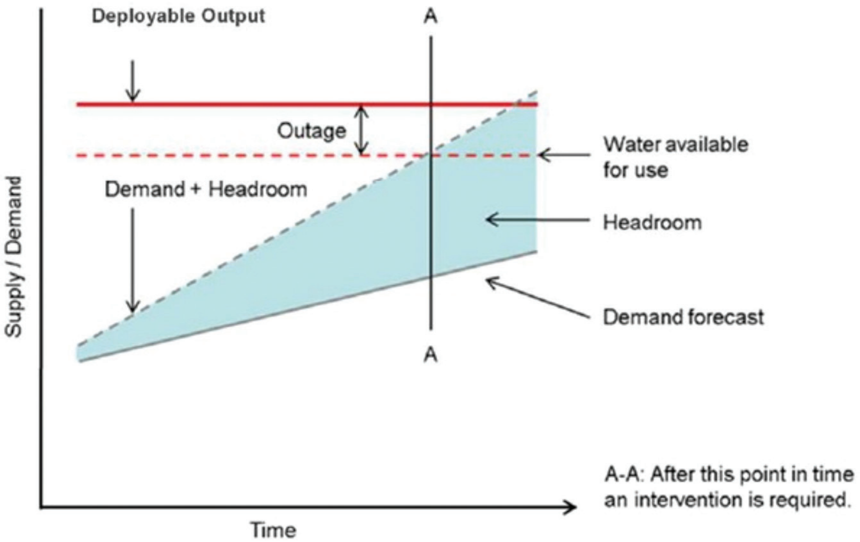

Figure 1 – Supply–demand balance (Reed et al., 2018).

Since the last update to the demand forecast in 2020, Auckland has experienced multiple notable events (as shown in the shading in Figure 2), making it difficult to revise the baseline and trends in demand from the past five years. Firstly, Auckland experienced a drought in 2020 (continuing through to 2021), coinciding with the COVID-19 pandemic in 2020/2021. The dry weather increased demand, leading to record-high demands before the first March 2020 COVID-19 lockdown and the implementation of water restrictions across Auckland in May 2020. The combination of decreased economic activity from the COVID-19 pandemic and water restrictions resulted in a sharp decline in Auckland's demand, followed by ongoing reduced demand. Closed borders reduced net migration to New Zealand, particularly reducing the presence of short-term visitors, dampening the seasonal fluctuations that are typically seen in Auckland's demand. With the drought easing in 2021, the combination of these factors also led to lower demands in 2021.

In 2023, several large storms occurred – such as those of Auckland Anniversary (January) and Cyclone Gabrielle (February) – significantly reducing summer demand. The magnitude of these events also had prolonged effects on soil moisture content, with reduced demand through autumn.

Finally, the end of border restrictions and the Women's FIFA World Cup in 2023 (the start of the 2024 financial year (FY2024)) resulted in a sudden change in net migration, bringing a lot of short-term visitors to New Zealand in the winter. This had a prolonged effect on 2023 winter demand, resulting in an abnormally high baseline winter demand. These trends can also be seen in Figure 3, which shows the peak of 2020, followed by three abnormally low-demand years before returning to a more expected 'normal' profile during FY2024.

Demand modelling

The demand forecast model developed in 2020 was updated by incorporating the changes in demand patterns that are described above. The model update had a

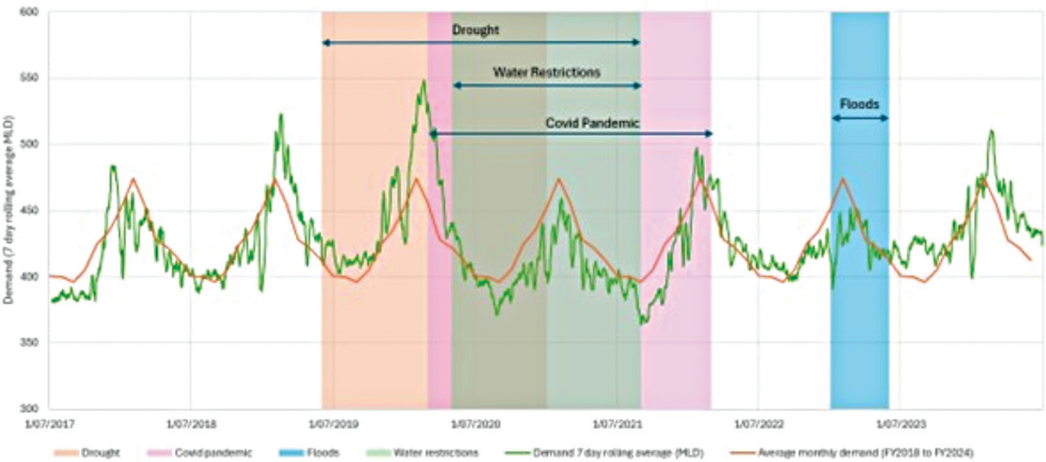

Figure 2 – Auckland's 7-day rolling average water supply demand from FY2017 to FY2024.

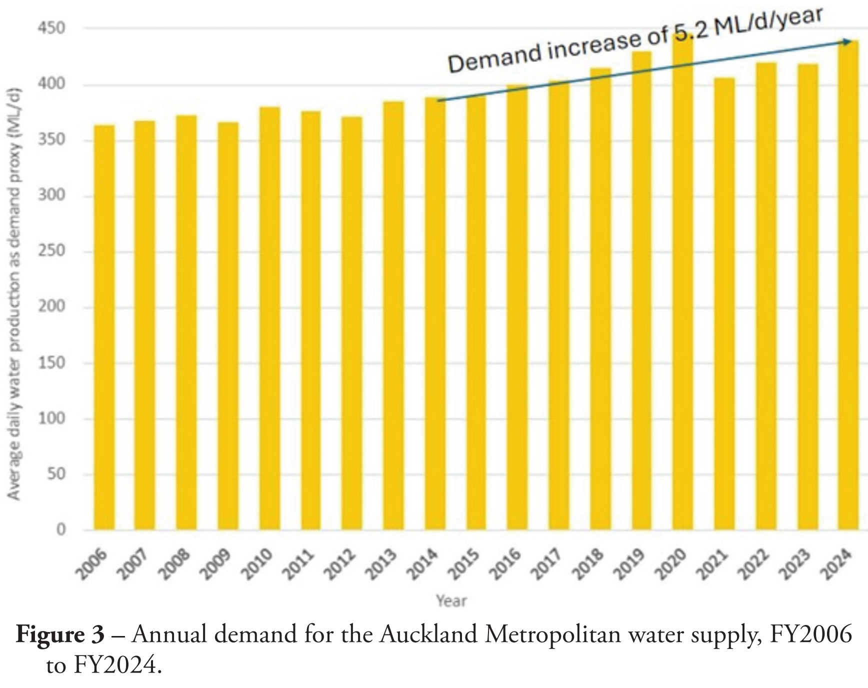

Figure 3 – Annual demand for the Auckland Metropolitan water supply, FY2006 to FY2024.

particular focus on the impact of demand driver changes on demand characteristics represented by per capita consumption (domestic PCC), water losses, and the benefit of water efficiency programmes. A headroom allowance was also included in the forecast, to allow for uncertainties that are inherent in forecasting the supply–demand balance. Below we set out the changes to demand drivers that were incorporated into the demand forecast. Demand forecast scenarios (incorporating headroom) were compared against the WAFU in the supply–demand balance to predict the timing of intervention and investments.

FY2024 demand characteristics were set as a new baseline for supply–demand balance forecasts for normal year, dry year, and dry year with drought management. FY2024 exhibited near-normal temperatures and rainfall, with rainfall at representative rain gauges at around 93% of the annual average[1]. In comparison, representative rainfall during summer months of the 2020 drought was around 44% of normal[1] but during the summer months of 2023 it was around 360% of normal[1]. In addition, there were fewer notable political, social, and economic events affecting demand than in previous years. This resulted in the first reliable baseline year in a while. It revealed a sharp return to higher demands, proving that underlying growth in Auckland has been occurring but had been masked by other events over recent years.

The COVID-19 pandemic has significantly altered water consumption patterns, leading to a demand shift from commercial[2] to domestic sectors (Figures 4 and 5). This transformation is primarily attributed to increased remote work and economic downturns, resulting in higher residential water usage and reduced commercial demand. In Auckland, the adoption of remote work-from-home practices has led to an estimated 14% increase in daily domestic water consumption, equivalent to approximately +30 ML/d, compared to pre-lockdown averages.

Conversely, the economic downturn, restrictions on business activities and associated behaviour changes have resulted in a decline in commercial water consumption. In Auckland, this reduction is estimated at -9%, or approximately -9 ML/d, compared to pre-lockdown averages. Many businesses, including offices, restaurants and hotels, experienced reduced operations or temporary/permanent closures.

Population

The medium and high Statistics NZ (StatsNZ) population forecasts, Auckland Council i11v6 (2020) and post-COVID population forecasts (Figure 6) were all considered. i11v6 was chosen to replace i11v3 as the best estimate of population to update connected population as one of the core factors in demand forecast. i11v6 (2020) is the growth scenario developed using policy, Auckland Unitary Plan Operative in Part (AUPOIP) intensification rules and development sequence input from Auckland Council, Auckland Transport and the New Zealand Transport Agency Waka Kotahi. It forms the foundation of Auckland Council's 10-year budget plan and reflects 30 years of land development priorities for asset planning, financial forecasting and funding prioritisation decisions. The AUPOIP and the Future Development Strategy support further intensification within existing AUPOIP's urban zones, which consist of over 90% of the population serviced by the metropolitan supply system.

The i11v6 revision has also rectified overcounted net migration from 2018 to 2020 by StatsNZ. The overcount is a combined effect from overstated estimated usual population in the 2018 StatsNZ Census and the effect of border closures during the COVID-19 pandemic from 2020 to 2022. However, i11v6 did not account for the higher-than-expected short-term visitor influx following the border reopening in 2023.

Demand behaviour

The general methodology for calculating all types of per capita consumption – Gross PCC, Residential PCC and Commercial

1 Average of Lower Huia, Upper Mangatawhiri and Auckland Airport rain gauges compared to their historical baselines (1991–2020).

2 Commercial refers to all categories of non-residential water use, including public services, education, businesses, and similar sectors.

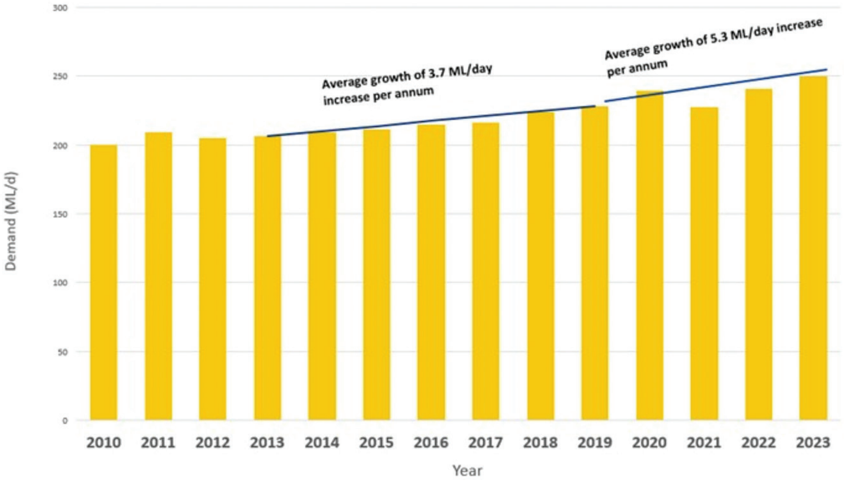

Figure 4 – Metropolitan Auckland domestic water consumption between FY2010 and FY2023.

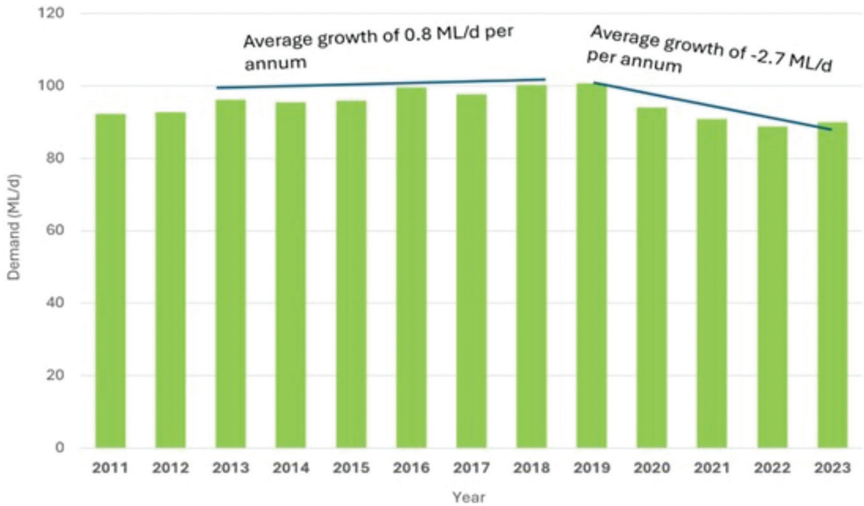

Figure 5 – Metropolitan Auckland commercial consumption FY2011 to FY2023.

PCC – involves dividing the total demand for each category by the population specific to that category connected to the metropolitan supply. Thus, PCC is highly sensitive to population data. An undercount of population can lead to an overestimation of PCC and vice-versa.

A new baseline PCC was established from the reassessment of PCC for this analysis, and included further examination of the relationship between intra-annual and inter-annual variability of baseline demand and net migration. This analysis identified approximately 40,000 undercounted individuals based on net migration data sourced from the Ministry of Business, Innovation, and Employment (MBIE) due to the borders opening in 2023. The estimation

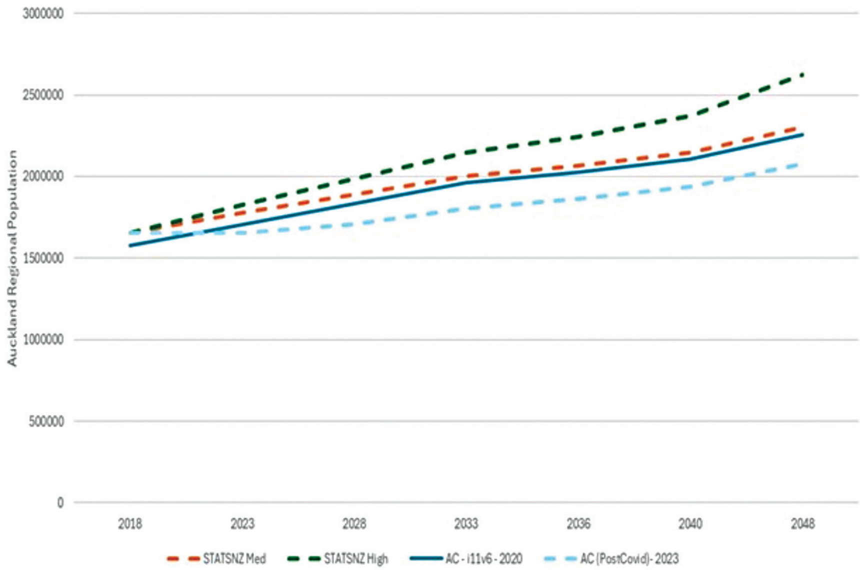

Figure 6 – Population projections for the Auckland region.

of PCC was adjusted accordingly within the modelling work and resulted in a slight reduction in PCC due to the abnormally high population count.

Demand management

Demand management and water efficiency targets were applied within the demand forecast. This is consistent with the approach taken in 2020 and included the benefit of the following programmes of work:

- Demand management Option A – Smart metering and pressure management
- Network renewals; and
- Reducing real losses.

Demand forecast scenarios

The demand forecast model projects various scenarios for dry year average daily demand (i.e., forecast average daily demand at the drought Level of Service) and unrestricted 5% AEP peak day demand, as illustrated in the supply–demand balance in Figure 7 and Figure 8 to determine when demand is expected to surpass annual drought and peak capacity under the following scenarios:

1. Dry year average daily demand including demand management Option A;
2. Dry year average daily demand at 5 ML/d increase per annum + 75% headroom[3];
3. Dry year peak day demand including demand management Option A; and
4. Dry year peak day demand including demand management + 75% headroom[3] allowance.

Supply

In the past, peak capacity of Watercare's system has typically driven investment, whereby

3 The '+75% headroom' accounts for 75% of the risks and uncertainties in the supply-demand balance for both dry year average daily demand and peak day demand forecasts. These uncertainties will increase over time, reflecting growing levels of risk.
75% headroom in dry year, peak day demand increases from 7.5 ML/d in 2025 to 18.4 ML/d by 2040.
75% headroom in dry year, average daily demand increases from 2.1 ML/d in 2025 to 14.2 ML/d by 2040.

some of this investment has also contributed towards improving the annual drought yield of the system. The assessment of both peak and drought capacity of the metropolitan supply is described below. For Watercare's sources under normal operating conditions, treatment plant capacities typically limit the peak supply before abstraction or network constraints are reached. This is not the case for drought yield, whereby yield from the stored water sources is reduced due to water supply availability.

Peak capacity

To update this assessment for peak conditions, both the 3-day and the 1-month peak supply–demand balances were considered. From the supply side, peak deployable output was assessed as the sum of the individual peak 3-day operational treatment plant capacities.

Peak outage was updated for this system by reassessing possible risks to the supply–demand balance during peak demand periods. Collaboration with key Watercare staff updated possible outage events, and their magnitude, duration and return periods, that may occur within the sources or Water Treatment Plants (WTPs). This was modelled using a Monte Carlo simulation approach (UKWIR, 1995) to assess mean peak outage, which was applied to the deployable output to determine WAFU under peak conditions.

This assessment found minimal difference in the WAFU for the 3-day and the 1-month peak. Since the 3-day peak demand was notably higher than the 1-month peak demand, the 1-month supply–demand balance was not as critical as the 3-day. Therefore, the 1-month period was not considered further.

Drought capacity

The annual drought yield of the system includes the conjunctive-use benefit from the multi-source dynamic system that supplies Auckland. Watercare used the bespoke Integrated Source Management Model (ISMM) to assess the yield (Corneby *et al.,* 2016). This model balances cost of operation against the risk of running out of water to optimise water allocation from Watercare's system at a daily level and can also be used for long-term planning. It has a synthetic rainfall record of over 1,000 years, based on a composite observed rainfall record of around 170 years that was stochastically extended. The synthetic rainfall record feeds into an embedded rainfall-runoff model, calibrated to Watercare's catchments. The system configuration, constraints, costings, and risk profiles are all defined within the model.

To determine system yield, the model runs through a risk-cost decision making framework at a daily timestep under these simulated conditions for the 1000-year record. The model records the number of failure events whereby (without any demand restrictions) Watercare would be unable to maintain the LoS by either failing to supply water on any given day (supply failure) or dropping below 15% total system storage across the dams (volume failure). From this modelling, the annual average supply that can be provided without failing more than 1% of the time (Watercare's drought standard) defines the annual drought deployable output under drought conditions.

The outage factor applied to the drought deployable output is different from that applied to the peak deployable output. To determine the drought outage factor for this assessment, the correlation between the outage factors from the peak analysis and drought analysis carried out in previous work (Beca and Tonkin + Taylor, 2020c) was applied to the 2024 revised peak outage factor described earlier.

Unlike peak WAFU, the annual drought WAFU is particularly susceptible to climate change. One of the key updates to Watercare's previous supply–demand balance was the inclusion of climate change impacts on drought WAFU. An internal investigation in 2021 to model climate change impacts using ISMM found a mean reduction of 29 ML/d in yield between the historical baseline and downscaled Global Climate Model (GCM) data[4] representing the present climate. This equates to approximately 6% of drought WAFU. There was also an additional mean reduction of 3 ML/d and a further 6 ML/d in yield due to climate conditions out to 2040 and 2090, respectively, which was linearly integrated into this analysis going forward.

Results

System

Watercare's two groundwater sources, Pukekohe and Onehunga, were non-operational in 2024. Pukekohe was damaged in the 2023 floods, returning to service at the end of 2024. Onehunga is out of service due to PFAS (per- and polyfluoroalkyl substances) contamination of the aquifer and at the time of writing is undergoing feasibility studies and optioneering to determine the return to service date and capacity of the upgraded WTP required. The scheduled return to service of Pukekohe and the proposed return to service of Onehunga are shown in the supply–demand graphs.

Previous work carried out as part of the 2020 drought response (Beca and Tonkin + Taylor, 2020e) resulted in an increase in Watercare's consented take from the Waikato River to 300 ML/d (unless restricted by low flow conditions). However, both the WTP and current pipeline capacity constrain this system to a lower abstraction rate. Investing in infrastructure to support the Waikato River abstraction, treatment and delivery will increase both peak and drought capacity of the system.

Peak capacity

Figure 7 shows the current and proposed peak supply–demand balance for the Auckland metropolitan supply. Under the modelled conditions, Watercare currently has sufficient headroom and is likely to be able to meet peak demand until early 2040 (assuming Pukekohe and Onehunga are in service). Increasing the capacity of the Waikato WTP would provide additional peak capacity and source yield. Drought capacity

Drought capacity

Figure 8 shows the current and proposed annual drought supply–demand balance for the Auckland metropolitan supply. Like the peak supply–demand balance (Figure 7), this graph shows an increase in capacity with the return to service of the Pukekohe and Onehunga WTPs. The red shading indicates the potential reduction in WAFU due to climate change. Thus, under current modelled conditions and without additional investment, applying the mean expected reduction in yield due to climate change could result in a deficit in the drought supply–demand balance by the mid-2030s.

Implications for Watercare's investment plan

This work shows that incorporating the reduction in WAFU due to climate change introduces uncertainty into the water supply–demand balance for Auckland, suggesting that Watercare needs to reinstate the Onehunga groundwater supply (back to its full capacity) by the early 2030s and needs to bring forward already planned capacity by around the mid-2030s to provide additional drought deployable output. This finding is different to findings of previous assessments, where investment was driven by a requirement to meet peak demand.

4 As per the Intergovernmental Panel on Climate Change Fifth Assessment Report, averaging results from two Representative Concentration Pathways (RCP4.5 and RCP8.5) and six GCMs (BCC-CSM1.1, CESM1-CAM5, GFDL-CM3, GISS-E2-R, HadGEM2-ES and NorESM1-M).

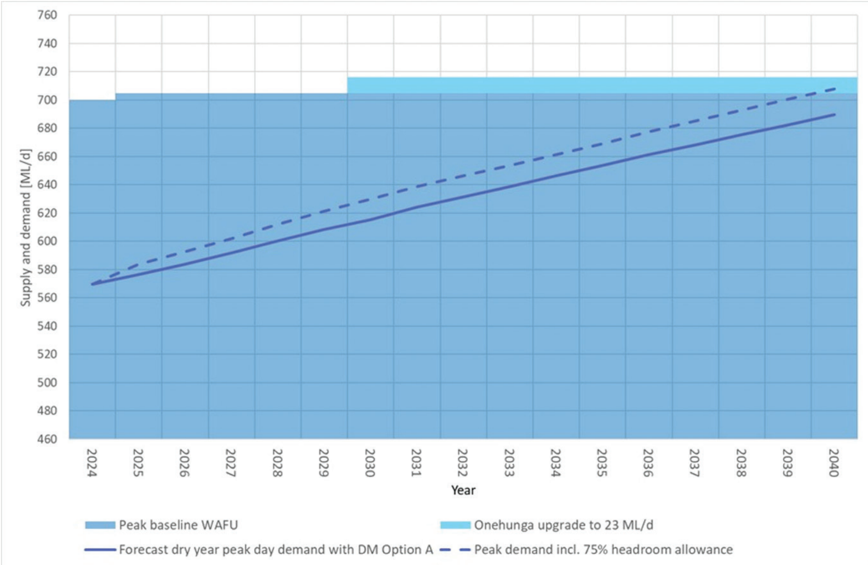

Figure 7 – Baseline peak supply–demand balance for the Auckland metropolitan water supply, 2024 to 2040.

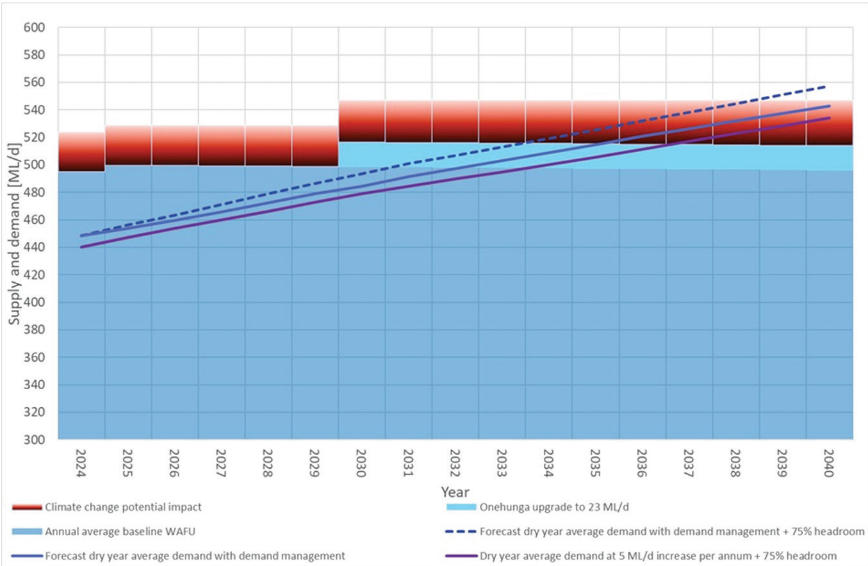

Figure 8 – Baseline annual drought supply–demand balance for the Auckland metropolitan water supply, 2024 to 2040.

Whilst the available headroom does not require the reinstatement of Pukekohe WTP yet, this groundwater source would provide increased resilience. Having more headroom in the system also allows for more flexibility in the way the system is operated, enabling Watercare to better optimise the balance of these sources.

The drought supply–demand balance shows the importance of reintroducing

Onehunga back into service. With the current ambiguity around solutions to manage PFAS, it is important that this work is continually progressed, to make sure that this WTP can be operational prior to the early 2030s. Like Pukekohe, this source is a standalone WTP, so bringing this back into service also provides resilience to the system.

This assessment changes the narrative from the system being constrained at the peak LoS to one of being constrained by annual drought yield. This in turn changes the investment priorities, as some of the projects in the investment plan only increase peak capacity, not drought yield.

Watercare's Asset Management Plan 2021-2041 (AMP) (Watercare Services Limited, 2021) identifies the replacement of the existing Huia WTP with a new plant, with the dual aims of increasing peak capacity and improving the resilience of the current system. This work is scheduled to begin within the 2021–31 timeframe and be completed within the 2031–41 window. The AMP also outlines plans to increase the capacity of the take from the Waikato River to utilise the full 300 ML/d consent limit. This is scheduled to begin in the 2031–41 investment window.

These investigations have highlighted the need to consider reprioritising these works. The replacement Huia WTP would have negligible impact on drought yield, whereas increasing capacity of the Waikato WTP and network (within our current consented limits) would increase both peak and drought capacity.

Irrespective of the increased capacity at the Waikato WTP, Watercare is going to need completely new sources in the future. At the scale that Auckland is considering, the most likely sources are purified recycled water and desalination. These processes are costly, require substantial investment and are novel in New Zealand. With the current state of the supply–demand balance, research and development of these next sources need to continue, and related planning and investment is critical.

Gaining relevant approvals and constructing assets at this scale is complex and time consuming. The planning for these types of assets needs to be carried out well in advance of when they are needed within the supply and demand balance. Watercare recognises the associated uncertainty with these projects, but with the extensive lead times required, work is being done to balance this uncertainty with the need for early investment in order to maintain the agreed water supply levels of service for Aucklanders.

References

Beca; Tonkin + Taylor. 2020a. Demand forecast. *Water Source Alternative Options Assessment for the Metropolitan Supply.* Prepared for Watercare Services Ltd. Published by the Environmental Protection Authority. https://www.epa.govt.nz/public-consultations/completed/watercare-application/watercares-application/

Beca; Tonkin + Taylor. 2020b. Desalination Scheme Concept Report. *Water Source Alternative Options Assessment for the Metropolitan Supply.* Prepared for Watercare Services Ltd. Published by the Environmental Protection Authority. https://www.epa.govt.nz/public-consultations/completed/watercare-application/watercares-application/

Beca; Tonkin + Taylor. 2020c. Outage, headroom and the supply / demand balance. *Water Source Alternative Options Assessment for the Metropolitan Supply.* Prepared for Watercare Services Ltd. Published by the Environmental Protection Authority. https://www.epa.govt.nz/public-consultations/completed/watercare-application/watercares-application/

Beca; Tonkin + Taylor. 2020d. Purified Recycled Water Scheme Concept Report. *Water Source Alternative Options Assessment for the Metropolitan Supply.* Prepared for Watercare Services Ltd. Published by the Environmental Protection Authority. https://www.epa.govt.nz/public-consultations/completed/watercare-application/watercares-application/

Beca; Tonkin + Taylor. 2020e. Waikato A WTP Concept Report. *Water Source Alternative Options Assessment for the Metropolitan Supply.* Prepared for Watercare Services Ltd. Published by the Environmental Protection Authority. https://www.epa.govt.nz/public-consultations/completed/watercare-application/watercares-application/

Beca. 2020. Waikato River Refresh Application. *Water Source Alternative Options Assessment for the Metropolitan Supply.* Prepared for Watercare Services Ltd. Published by the Environmental Protection Authority. https://www.epa.govt.nz/public-consultations/completed/watercare-application/watercares-application/

Beca. 2024. Updated Short Term Supply / Demand Balance. Prepared for Watercare Services Ltd. Unpublished internal report.

Corneby, D.; Bassett, T.; Byrne, M. 2016. Integrated Water Source Management Modelling: A Risk Based Approach. Paper presented at the Annual Water New Zealand Conference.

Reed, C.; Reed, J.; Green, C. 2018. Calculating Uncertainty in the Supply Demand Balance. Paper presented at the Annual Water New Zealand Conference.

Tamaki – Whenua Taurikura. 2024. *Auckland Future Development Strategy 2023-2053*. Available online at https://infocouncil.aucklandcouncil.govt.nz/Open/2023/08/20230824_AE_AGN_11660_AT_files/20230824_AE_AGN_11660_AT_Attachment_94539_1.PDF

Tamaki – Whenua Taurikura. 2017. Auckland Future Urban Land Supply Strategy 2017. Available online at https://www.aucklandcouncil.govt.nz/plans-projects-policies-reports-bylaws/our-plans-strategies/topic-based-plans-strategies/housing-plans/Documents/future-urban-land-supply-strategy.pdf

Watercare Services Limited. 2023. Auckland Drought Management Plan. Available online at https://assets.watercare.co.nz/media/drought_management_plan_2023_29bdee8a65.pdf

UK Water Industry Research (UKWIR). 1995. WRP-0001/B Outage allowances for water resource planning.

Watercare Service Limited. 2021. Asset Management Plan 2021 – 2041. Available online at https://assets.watercare.co.nz/media/watercare_asset_management_plan_2021_2041_1bd633e66d.pdf

Manuscript received 22 November 2024; accepted for publication 12 June 2025