DYNAMIC ADAPTIVE PATHWAYS PLANNING FOR A WATER RESOURCES INVESTMENT STRATEGY

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ABSTRACT

Water utilities around the world are facing long-term challenges to the supply / demand balance from future uncertainties such as climate change, technology change, population growth and reduced abstractions, in order to protect or enhance environmental values. Water utilities, such as Wellington Water Ltd (WWL), have started on the journey to develop long-term investment strategies and inform key decisions in a dynamic and adaptive way.

The Wellington metropolitan water supply currently operates to a 1 in 50-year Level of Service for drought and is facing challenges including high water loss, future population growth and the requirement to integrate Te Mana o te Wai, to increase cultural and environmental flows. The current 1 in 50-year Level of Service is not being met and there is elevated risk of supply shortfall. This paper sets out and discusses the process undertaken by Wellington Water to address these issues. A Dynamic Adaptive Pathways Planning (DAPP) approach was developed to investigate and address these issues over a 30-to-100-year timescale. This paper discusses the challenges of:

- Understanding the implications of uncertainty in variables such as climate change impacts on rainfall, sea level rise, population growth and environmental regulation on investment decisions within the context of NZ water resource planning,
- How these uncertainties can lead to outcomes where planning strategies fail to meet the target objectives, and
- The impact of changing fundamental assumptions, such as the drought Level of Service or achieving water quantity objectives set out in Te Mahere Wai o Te Kāhui Taiao (Te Kāhui Taiao, 2021) on the investment plan and the subsequent timing of actions.

We also compare the approach taken by Wellington Water with those taken by water utilities within the UK regulated water industry for example Anglian Water – which has adopted a Multi-Objective Robust Decision-Making (RDM) approach to water resources planning.

We show how a dynamic adaptive pathway can be clearly communicated to stakeholders, how it can be used for investment planning and how monitoring can be integrated to track achievement of strategic objectives.

KEYWORDS

Water resource planning, dynamic adaptive pathways planning, robust decision making, long-term strategy.

PRESENTER PROFILE

Geoff Williams is Senior Advisor Strategy at Wellington Water. Geoff has worked for over 25 years in the water sector. Areas of expertise and special interest includes water supply security and working collaboratively with science providers to integrate the best scientific advice into our strategic planning.

Jon Reed is Operations Manager of Beca’s Water Business in NZ. After a decade of water resource planning in the UK, he worked for many NZ Local Authorities developing water resource plans. He chaired Water NZ’s Climate Change group and was a lead author of Navigating to Net Zero: Aotearoa's low carbon journey.

1 INTRODUCTION

Many factors affect a water utility's ability to provide an appropriate standard of water security. These include, but are not limited to, population growth, customer consumption patterns, leakage, cultural context, environmental regulations (e.g., minimum flow requirements), climate change, changes in the Level of Service, network constraints and ever-evolving technological advancements. There is significant future uncertainty associated with each of these factors for the supply/demand balance and which is not typically considered as part of water resource planning in Aotearoa New Zealand.

Traditional water resource planning outlines a preferred sequence of investment decisions, which might then be deferred or brought forward in response to changing conditions. However, the future uncertainties may require investment options to be implemented at different timescales, in a different order or with a suite of different options. An iterative and adaptive approach can be applied in order for investment decisions to be responsive as conditions change and risks increase.

In 2017 the Ministry for the Environment (MfE) published updated guidance for local government to assist with planning for coastal hazards and the effects of climate change (Ministry for the Environment, 2017) and an update is expected in 2023. This guidance presents a 10-step decision cycle; starting with defining ‘what is happening’ and ‘what matters most’, then the process moves on to identifying adaptation options and developing pathways that are evaluated against a range of climate change scenarios for robustness and flexibility to address uncertainty. Combinations of short-term actions and long-term options are formulated into an adaptive strategy and signals and triggers identified for monitoring to enable timely responses that avoid critical thresholds.

This paper demonstrates how this adaptive approach can be applied to a strategic water resource planning context to enable a dynamic and adaptive water resources strategy to be developed that informs key investment decisions.

2 BACKGROUND

2.1 WELLINGTON WATER CONTEXT

Wellington Water currently supplies approximately 175 million litres of drinking water per day (“ML/d”) on average via the Wellington metropolitan supply to residents and businesses within Upper Hutt, Lower Hutt, Porirua and Wellington council areas. Demand for water has increased by around 30% over the last 10 years and continues to grow. The water supplied comes from the Te Awa Kairangi/Hutt River, supplemented by the Macaskill bankside storage lakes, the Waiwhetū aquifer, and the Wainuiomata and Ōrongorongo rivers.

Water availability reduces during periods of drought. Environmental limits restrict the volume that can be abstracted from the rivers during periods of low flow, and aquifer levels must be managed to prevent seawater intrusion. Water is stored in the Macaskill lakes to compensate for reduced summer flows, but the storage available is small (3 GL) which can only supply water for 2-3 months. This is limited in comparison to other major cities in New Zealand (e.g., Auckland, Watercare’s reservoirs total approximately 95 GL (Watercare Services Limited, 2023)) and internationally.

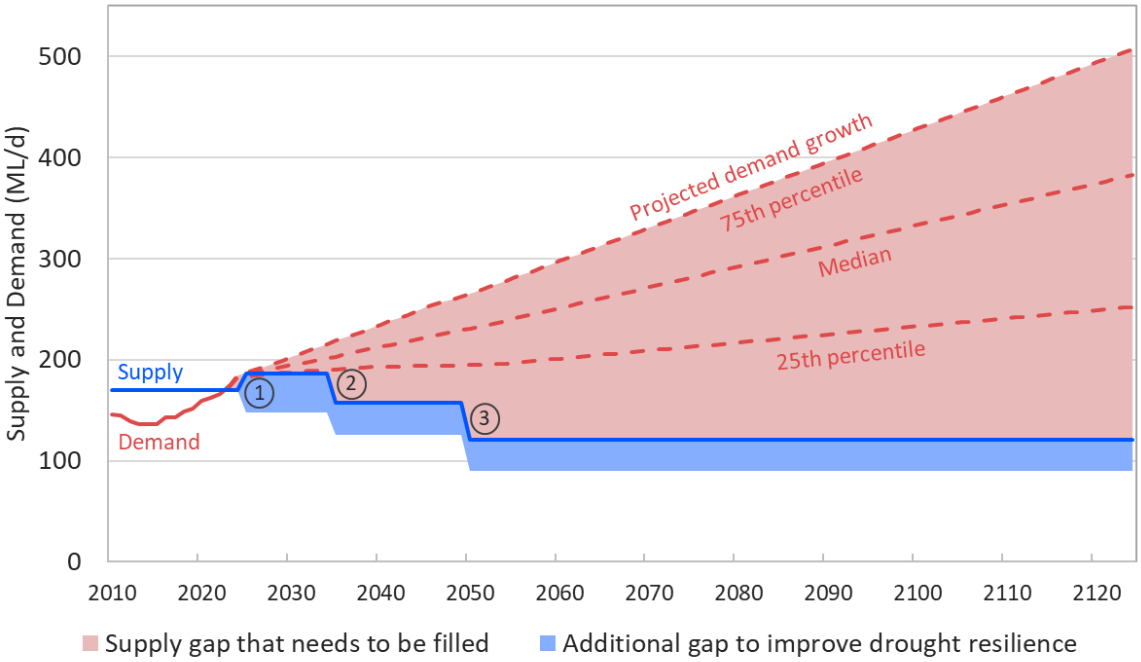
Wellington Water is currently reviewing its Level of Service (LoS) for drought resilience due to concerns that the standard may not appropriately reflect the high consequences of water shortage. There are currently no water supply drought standards in New Zealand. The following three options are being considered by Wellington Water:

- 1 in 50-year (2%) drought LoS (existing),
- 1 in 200-year (0.5%) drought LoS, or
- 1 in 500-year (0.2%) drought LoS.

These LoS have been recommended to bring the drought LoS into line with other water industry standards in Aotearoa New Zealand, Australia and the UK. For example, UK guidance recommends planning to a 1 in 500-year drought standard (UK Environment Agency, 2022) and Queensland planning guidance suggests a minimum level of supply should be available during a 1 in 10,000-year drought (Department of Natural Resources, Mines and Energy, 2018). In Auckland, Watercare plans investment to a 1 in 200-year drought standard (Beca, 2020).

The baseline supply / demand balance for the Wellington metropolitan water supply is shown in **Figure 1**. This illustrates the gap between supply and demand that is expected to occur with the forecast population growth if no action is taken to increase supply and/or reduce demand. Also shown is the reduction in supply needed to give effect to Te Mana o te Wai by increasing minimum environmental flows, and to increase the drought LoS.

Figure 1: Baseline supply/demand balance for Wellington metropolitan water supply.



Note: Without intervention a growing gap is expected between supply and demand (pink shaded area). The maximum sustainable supply at the current 1 in 50-year drought standard (solid blue line) reduces further to achieve a 1 in 500-year standard (blue shaded area). Notes: (1) Increase in supply from the Te Marua Optimisation Project, (2) and (3) Whaitua Te Whanganui-a-Tara implementation is expected to reduce supply available in two stages to enhance Te Mana o te Wai.

Looking ahead there are significant challenges that will affect supply and demand, and impact Wellington Water's ability to provide an appropriate standard of water security. These include:

- **Population growth** – an additional 130,000 people over the next 30 years is expected to drive up the demand for water;
- **Environmental enhancements** – less water available during summer in response to recommendations from the Whaitua Te Whanganui-a-Tara Committee to give effect to Te Mana o te Wai (Whaitua Te Whanganui-a-Tara Committee, 2021). It is expected that changes to water take requirements will be incorporated into the Natural Resources Plan and will come into effect for Wellington Water at consent renewal in the mid-2030s;
- **Water loss** – which has increased over recent years and is currently a substantial component of the overall demand for water. Water loss will also

need to be reduced to meet water efficiency requirements in the Natural Resources Plan;
- **Climate change and sea level rise** – expected to impact demand and water availability from river and aquifer sources; and
- **Drought resilience** – the current Level of Service (LoS) is low by national and international standards.

There is uncertainty and variability in how and when these challenges might impact the supply / demand balance. They largely depend on external factors that are outside of Wellington Water's direct control. This paper describes how this was addressed by developing different assumptions about these challenges to create a wide range of potential futures. Instead of creating a single plan for the future, Wellington Water developed an adaptive plan that responds to these challenges and their effects as they change over time.

2.2 THE OPTIONS ASSESSMENT PROCESS

An options assessment process was developed to guide the identification of a shortlist of supply- and demand-side options to be implemented as 'actions' within the adaptive strategy. The overall approach follows international water resource planning best practice. As an example, the UK Water Resources Planning Guidance (UK Environment Agency, 2020) recommends the following options assessment process:

- Development of an unconstrained list (i.e., all reasonable options);
- Removal of options to create a feasible list (i.e., removal of options that have unacceptable environmental impacts);
- Further screening to produce a manageable number of options, but to maintain real choice when assessing the preferred programme;
- For the feasible options, the environmental considerations, economic cost, and carbon impact of each option should be assessed; and
- Selection of the best value plan to ensure a secure supply of water and to protect and enhance the environment.

The assessment of the options has adapted best practice to bring in areas specific to New Zealand, such as giving effect to Te Mana o te Wai and engagement with mana whenua as part of the options appraisal. This was guided by a Project Objective and a series of principles unique to Wellington Water. The objective "*to develop a plan to balance supply and demand while meeting reasonable community expectations of water availability and supporting Te Mana o te Wai*", is underlain by a series of eight principles that guided the options assessment process.

2.3. SHORTLISTED OPTIONS

The shortlisted options are outlined in **Table 1**. A design basis was prepared for each of the shortlisted supply-side options which enabled an element of quantification to be brought into the options assessment process. This enabled the different supply-side options to be compared in terms of:

- An assessment against the eight Project Principles;
- A comparative (whole of life) cost assessment; and
- A comparative (whole of life) carbon assessment.

These comparative assessments were key inputs into the development of the adaptive strategy.

Table 1: Shortlisted supply- and demand-side options

Supply side options	• Managed Aquifer Recharge • Wainuiomata Storage • Pākuratahi Storage; Stage 1 – Lake 1 and 2 (combined volume of 3 GL), Stage 2 – Lake 3 (volume of 4 GL) • Desalination Plant; Stage 1 – 25 ML/d, Stage 2 – additional 25 ML/d • Purified Recycled Wastewater
Demand-side options	• Universal water metering including volumetric charging of residential customers and a demand management programme. • Reduction of leakage including a wider demand management programme. o Low, medium and high investment scenarios were considered.

3 DECISION MAKING UNDER UNCERTAINTY USING DYNAMIC ADAPTIVE PATHWAYS PLANNING (DAPP) AND ROBUST DECISION MAKING (RDM)

Two decision tools were used to address the uncertainties and changing climate risk conditions relevant to the long-term strategy: Dynamic Adaptive Pathways Planning (DAPP) and Robust Decision-Making (RDM).

DAPP is an adaptive planning approach that enables decision-making over time as operating conditions change (Haasnoot et al., 2019, Lawrence et al., 2019a). The output is an adaptive plan that sets out alternative sequences of actions in pathways comprising short and long-term options. Having proactive pathways reduces the potential for maladaptation and enables flexibility for the implementation of actions in the future that are stress tested for their sensitivity to future possible conditions using a range of plausible scenarios. The plan is monitored for defined signals and triggers which warn of changes and identify decision points for implementing the next action in the pathway or shifting to an alternative pathway to avoid the impacts of reaching a critical threshold.

We also used RDM to perform multiple iterations with scenarios of the future to seek robust, rather than optimal strategies – that is, strategies that can perform across many conditions as they change (Groves et al., 2019, Kwakkel et al., 2016, Lempert, 2019). This approach highlights the different vulnerabilities of the individual pathways. The two approaches together enabled:

- Actions and pathways to be developed and explored for robustness (i.e. that can perform under a range of conditions under changing circumstances).

- The individual pathways to be tested for their performance by stress testing the pathways under a range of scenarios (e.g., the effect of higher minimum residual flows at surface water abstractions) and under all future scenarios (*unknown future).*
- A robust investment plan to be developed that meets the future water demand at a given Level of Service (LoS).
- The identification of variables for monitoring (i.e., indicators) that might affect the timing of particular actions and the trigger points at which decisions must be made in time before thresholds are reached.

The shortlisted options were assessed and used to develop different potential pathways for analysis using a DAPP approach. The pathways were developed based on different strategies. These included the implementation of all actions, no universal water metering, fast track to desalination, the most easily implemented options first. Subsequent pathways were developed in an iterative process based on the improved understanding resulting in a total of 13 pathways.

3.1 EXTERNAL VARIABLES

This DAPP analysis considered a wide range of different plausible futures, summarised in **Table 2**. All possible external factors, including demand- and supply-side factors, were assessed to identify which factors had the greatest benefit to the supply / demand balance and to determine which external factors should be considered in the stress-testing.

All 64 external factors were simulated for every action on the 13 pathways at incrementally increasing populations leading to over 60,000 scenarios. During these scenario simulations, the external factors were held constant throughout the simulation (i.e., there was no time component applied to these factors). This means that the timing does not need to be defined and the impacts of changing from one external factor scenario to another, such as an increase in the minimum residual flow from 40% of MALF to 80% of MALF, can be evaluated by comparing the results of different scenario runs.

Table 2: Summary of the external factors considered in this assessment

EXTERNAL FACTOR	SCENARIO CONSIDERED
Environmental regulation	Minimum residual flow set at X% of MALF: 40%, 60%, 80% and 100%. Note that current indications from Greater Wellington Regional Council include transitioning to 60%MALF by 2035 and 80%MALF by 2050.
Climate change impacts on supply and demand	Stochastic datasets based on: Historic record (1890 – 2021), RCP 4.5, RCP 6.0 and RCP 8.5.
Sea level rise (SLR)	0m and 1.5m.
Residential per capita demand (PCD)	Existing and 10% reduction.

3.2 MODEL

Wellington Water developed a stochastic water resources model that simulates the availability of water from existing sources, treatment and distribution constraints and modelled demand at a bulk water network level (Singh & Ibbitt, 2018). Recently Sustainable Yield Model (SYM) demand modelling has been upgraded to utilize a hybrid, modelling approach by integrating statistical and machine learning approaches (Singh, 2023). A new process has also been established in the updated SYM to cope with the significant increase in the number of future scenarios – including running the SYM on the New Zealand eScience Infrastructure high-performance computing facility due to the 20 billion days of data.

There is a hierarchy of objectives and numerous complex operational and environmental controls and constraints that are built into the SYM to model the water supply system. Daily residential per capita water demand is calculated within the SYM based on climate variables (rainfall, sunshine hours, temperature and evaporation) and the time of year (e.g. lower demand over the Christmas period). Other elements in the SYM that are dependent on the climate variables are river flows, water loss from storage reservoirs through evaporation and the soil-moisture balance which affects rainfall recharge of the aquifer system.

The SYM performs a Monte Carlo simulation that evaluates the water balance of the system over 10,000 years of daily stochastic hydro-climate replications. The model bases the simulation on both historic datasets and climate-adjusted hydro-climate data. The performance of the network is determined by the number of failures observed in the Monte Carlo simulation expressed as the Annual Shortfall Probability (ASP).

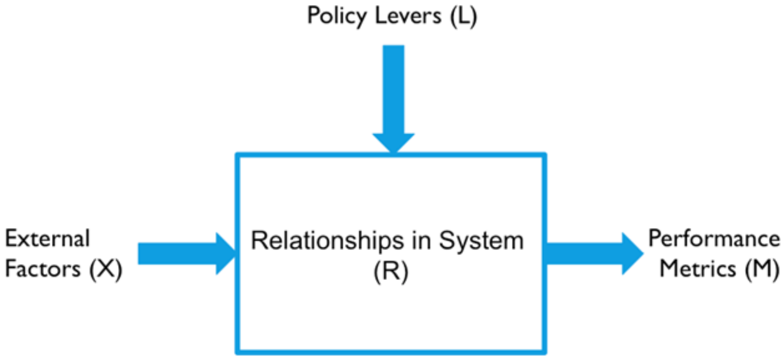
The actions within a pathway were modelled in a cumulative way using the defined order of actions for each pathway. This means the output yield benefit and population supported by ‘action x’ on ‘pathway y’ is the cumulative benefit of ‘action x’ and all the previously implemented actions on ‘pathway y’.

The key ‘Performance Metric’ (*M*) output from the model interactions is the supported population across all future scenarios and three Levels of Service (2% current, 0.5% and 0.2%). The supported population has been used to define the timing for each action (i.e., year of implementation completed) within each pathway, using three population projections for the region.

Figure 2 shows the RDM framework that was applied to this assessment for iteratively testing the 13 pathways across the future scenarios. Each future scenario was considered as equally probable and is considered as one observation from a uniform distribution of plausible futures.

The simulation of 64 external factor scenarios results in 64 different supported populations and therefore 64 different timings. The consequence of this is that a change of external variables can lead to more than 40 years of timing difference which highlights the importance of ongoing monitoring to enable reviews at trigger points, to assess the performance of the options and pathways in meeting objectives, against future uncertainties (Lawrence et al., 2019b).

Figure 2: Robust Decision Making XLRM Framework (Kwakkel, 2017).



3.3 SCENARIO ASSESSMENT

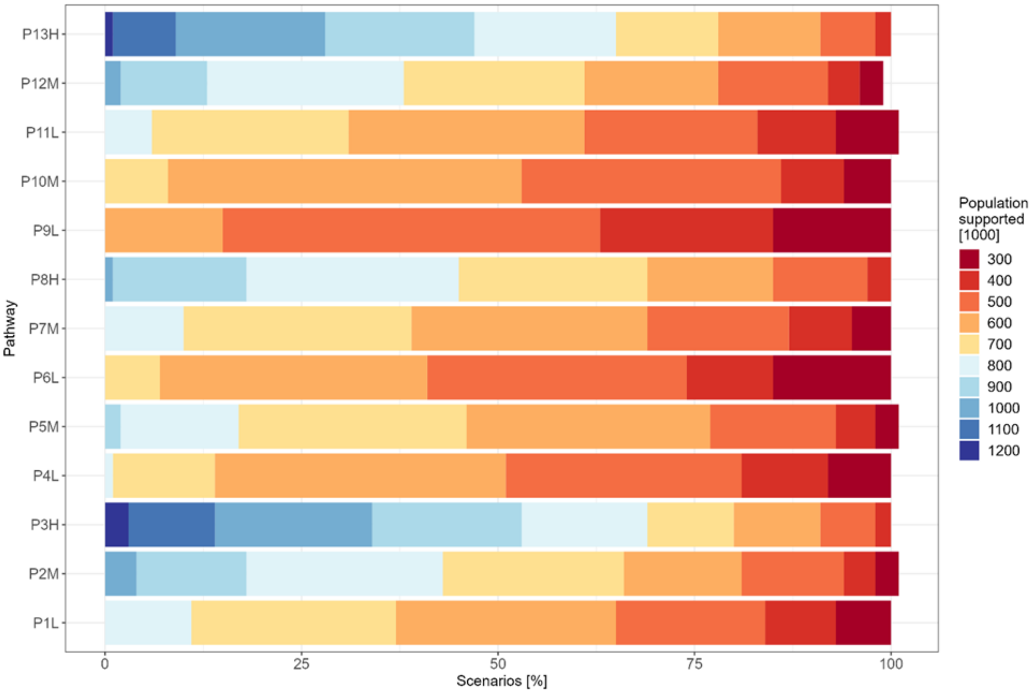
The initial analysis of the results considered different perspectives, in particular the supported population and the impact of external factors. The results indicate that of the 13 pathways only five pathways could support a population >800,000 (based on the mean). The commonalities of these five pathways are as follows:

- They all require the implementation of most of the available actions (excluding Pathway 8), and
- They all include either medium or high investment in water loss management.

The median population growth projection shows that a population of 800,000 will be reached at 2097 (and 2063 at based on the 75th percentile projection). The results in **Figure 3** are a key indication that the water loss investment action is critical and that all available actions to achieve the supply / demand balance in the future may need to be implemented.

The simulated supported population between the future scenarios (of the same action and pathway) varies by up to 200,000 people. To understand the influence of the external factors on the model results, each of the external factor’s effect on reducing the variance of the supported population range was measured. The result of this variance analysis (ANOVA) is shown in **Table 3**. This indicates that the majority (83%) of the supported population variance is attributed to the external factor variables, with 60% of this variance coming from the environmental regulation scenarios.

Figure 3: The supported population of all 13 pathways after all actions have been put in place.



Note: The suffix describes which water loss investment scenario is applied (L: Low, M: Medium; H: High).

Table 3: The influence of external factors. Variation explained is the result of an ANOVA, showing the impact of the external factor on the amount of supported population. The population effect shows the mean effect of this variable.

EXTERNAL FACTOR	**VARIATION EXPLAINED**	**MEAN POPULATION EFFECT**
Environmental regulation	60%	133,000
Sea level rise	10%	41,000
Residential PCD	9%	38,000
Climate change	4%	38,000
Other	17%	

3.4 STRESS TESTING THE PATHWAYS

The second step in the analysis was to stress-test the pathways to reveal the conditions under which the pathways perform poorly (‘*failure conditions*’). The stress testing of the pathways was undertaken in a two-step process:

- Step one – stress testing of the pathways against a range of external factors to identify the conditions under which the pathways do not meet the supply / demand balance (i.e., ‘fail’),
- Step two –identify which were the most robust pathways which supplied sufficient yield to meet the supply / demand balance.

In this RDM assessment we used ‘poorly performing’ scenarios to determine under which future conditions the pathways’ performance is lower than expected. This threshold that defines the failure conditions was iteratively calculated and set to the 40th percentile of the performance metric (supported population). These poorly performing pathways can be characterised by:

- 79% are caused by environmental regulation of minimum residual flow at 80% or 100% of MALF.
- 70% are caused by a residential PCD scenario of 100% (i.e., no change in current residential PCD of 195 L/p/d).
- 74% are caused by a 1.5 m sea level rise.
- 37% are caused by the historic climate series.

All pathways' performance were analysed under all conditions and ranked in order of their performance. This enabled us to recommend the pathway that not only performs best under specific conditions but also under all conditions. It also enabled us to quantify and understand the following under a wide range of future scenarios:

- The variable benefit of supply and demand interventions on system performance.
- The pathways that maximise the likelihood of success without overinvestment.
- The potential for option benefits to be affected by the chosen sequence or to develop unintended negative consequences.
- The effect of external factors on system performance.
- The actions required now, and the investigations needed to reduce uncertainty and lead time for 'do next' options.
- Identify inputs to the monitoring plan.

4 DAPP OUTPUTS

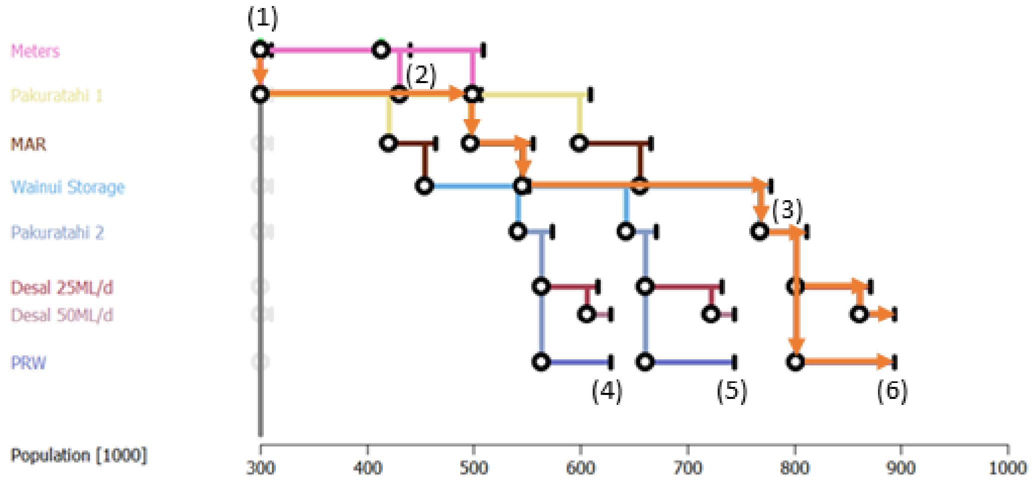
The DAPP approach is powerful, particularly when there are many uncertainties ahead. The results of the DAPP analysis identify the options that should be implemented now to maintain the supply/demand balance over the next ten years. The timing of future investment can then be assessed as future uncertainties are better understood, particularly how population growth will drive an increase in demand and the extent to which water loss reduction can be used to offset this.

The output of this analysis for Wellington Water was a range of Pathways (11 – 13). The order of implementation of interventions in these Pathways is the same, however there is a different allowance for water loss investment (low, medium, high) which affects the timing of subsequent actions. For example, achieving low water loss investment will result in all other actions within the pathway needing to be implemented in a shorter timeframe.

These pathways were identified as the most 'robust' and all have a sequence of actions that can be most realistically implemented in the short term. These pathways were defined as 'robust' as they have the longest duration before failure (based on all future scenarios), the lowest whole of life carbon and cost.

The output, shown in **Figure 4** has enabled Wellington Water to understand the range in timing of the actions as a result of the water loss investment achieved. It also provides an evidence-based strategy which can be used to communicate the impact of operating under the different water loss reduction situations to stakeholders. Similarly, the output of this analysis has enabled a greater understanding of the effect that fundamental changes, such as changes to LoS and/or minimum residual flows, have on water utilities investment planning.

Figure 4: Metromap of the 'most robust' sequence of options and remaining at the current 1 in 50-year drought resilience LoS.



Population [1000]	300	400	500	600	700	800	900	1000
25%ile growth scenario		2023	2042	NA	NA	NA	NA	NA
50%ile growth scenario		2023	2031	2052	2075	2097	2120	NA
75%ile growth scenario		2023	2027	2035	2043	2051	2060	2068

Note: The circles represent the timing when each option must be implemented, and the bars show when failure will occur without additional action. The population growth scenarios show the year when this population is reached. Graphic produced with Pathway Generator (Deltares and Carthago Consultancy, 2015), population projections from data provided by Wellington Water.

4.1 IMPACT OF CHANGING ASSUMPTIONS

Two external influences that have a fundamental impact on investment decisions are the drought Level of Service and the environmental enhancements to increase the minimum residual flows for Wellington Water's surface water sources. Defining potential future drought Levels of Service and minimal residual flow scenarios in the DAPP analysis, has enabled Wellington Water to quantify the impact of these decisions on pathway performance. **Figure 5** shows the timing based on the median population growth scenario for one Pathway. The vertical red line indicates the year 2024 as the starting point of the next financial year, thus showing which actions would need to be completed already. This illustrates that increasing the drought Level of Service and/or providing environmental enhancements has a significant influence on the timing of the interventions within a pathway. This will be used to inform discussions with stakeholders including regulators, councils and the community on the impact changing the assumptions.

Figure 5: The influence of environmental regulation [MRF as % of MALF] and the Level of Service on the timing of the actions (when it has to be completed + the line shows the respective lead time).

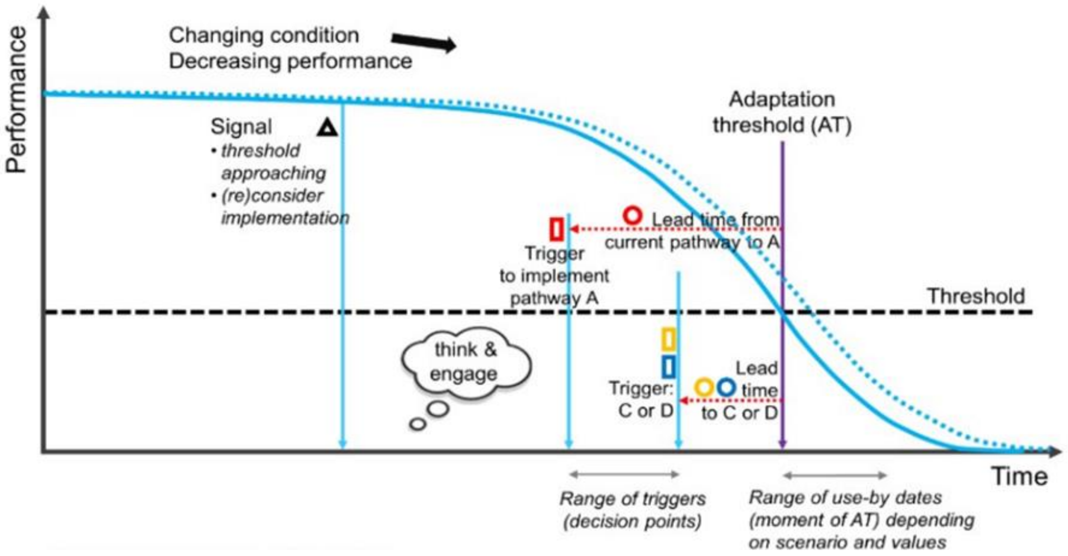
4.2 MONITORING AND TRIGGERS

Monitoring the DAPP strategy is essential to enable timely decisions to be made. A monitoring plan was developed for Wellington Water which identifies a number of backwards and forward-looking variables to guide future decision making. Given the number of variables involved, review of these together with the lead time of the next action, is necessary to determine when the next intervention should be made. A dedicated resource is required to carry out the monitoring and its analysis.

A systematic assessment of demand and yield within the hydrological context, that assesses the water security at the Level of Service is integral to this review. Once the review has been completed, trends can be used to understand the current position, compared to the robust pathway identified originally. Trends can also be used to identify when triggers are likely to be reached and enable communication to decision makers of any changes or actions that should be taken or provided for in future budgets.

The timing of actions depends on multiple *signals (warnings)* expressed as indicator variables for monitoring on an ongoing basis. When these reach the *trigger point* (*decision point*) actions must be reviewed and decisions taken on the next action/pathway and implemented before the adaptation *threshold is reached*. Triggers are pre-defined points on the pathway where actions must start to avoid failure and account for the expected delivery lead time. **Figure 6** presents an illustration (Lawrence et al., 2020) showing how monitoring is used to review triggers and lead time, and how these could affect when adaptation actions need to be taken.

Figure 6: Monitoring of signpost variables, reaching the predefined threshold and the implementation process in a DAPP context. Source: Lawrence et al. (2020).



5 COMPARISON TO THE UK

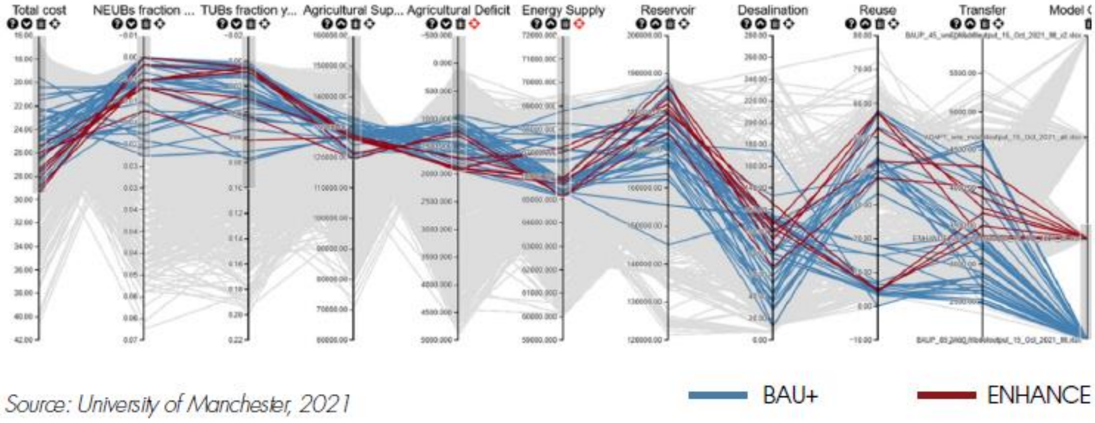
Water resources planning in England and Wales is long-established, and under the Water Industry Act 1991 (UK Government, 2023a) water companies have to prepare and maintain a Water Resources Management Plan. These Plans set out available supplies and expected demands over at least 25 years. Where there is a supply / demand deficit, companies must identify how this will be addressed, which has traditionally involved a 'twin-track' approach of demand management and the development of new supplies.

WRMPs have traditionally followed an 'aggregated' approach where a best-estimate supply forecast is compared with a best-estimate demand forecast, with uncertainties – both baseline measurement and forecast uncertainties – represented in 'target headroom', a minimum buffer between supply and demand. The forecasts – and headroom – consider factors including population growth, climate change, drought resilience and environmental protection. These forecasts are however subject to considerable uncertainties over the coming decades – extending to aleatory (e.g. drought) and epistemic (e.g. hydroecological requirements) uncertainties – meaning that planning for water resources has become an increasingly complex issue. In recognition of this, the latest guideline (UK Government, 2023b) asks companies to consider producing an adaptive plan, if there is significant uncertainty or where a strategic investment decision is required.

In the East of England, water resources planning is particularly complex, with four different water companies, significant agricultural demand as well as existing and potential new (net zero) energy installations (agriculture and existing energy facilities having some of their own supplies). In addition, the East of England is home to globally rare chalk streams, wetlands and The Broads National Park, with more water required to restore nature in the future. Water Resources East (WRE) is one of five regional water resources planning groups that have been mandated by the National Framework for Water Resources (UK Government, 2020) to coordinate multi-sectoral water resources planning.

WRE has produced a regional water resources management plan, using multi-objective robust decision making (MO-RDM) to identify low-regret strategic options to manage significant (so-called deep) future uncertainties. The decision-making framework involved problem formulation (using the XLRM framework (Lempert et al., 2003), baseline vulnerability analysis, robust search and trade-off analysis. Using a regional water resources model, coupled with a computation search algorithm, hundreds of options were tested against thousands of scenarios to identify pareto-optimal portfolios of options (Water Resources East, 2020). Decision makers then participated in workshops where performance criteria were traded-off to identify a preferred set of options. An example parallel-axis plot is shown in **Figure 7** (Water Resources East, 2022).

Figure 7: Parallel-axis plot showing performance metrics are on the vertical axes and portfolios are illustrated with horizonal lines, many of which have been greyed out as not meeting performance criteria selected by decision makers.



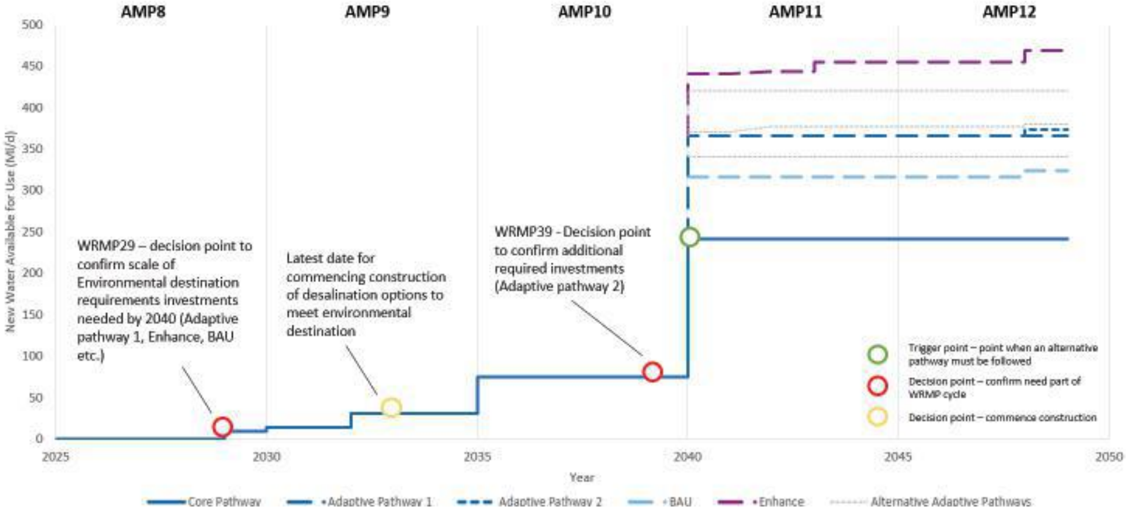
Source: University of Manchester, 2021

The WRE MO-RDM process identified low-regret strategic options, but the refinement and sequencing of options is the responsibility of WRMPs. Anglian Water is the largest water company in the East of England (and in England & Wales by area), supplying c.1.2 billion litres of water per day to c. 5 million people and c.100,000 non-household customers. In its draft 2024 WRMP (Anglian Water, 2024), Anglian Water independently verified the selection of two major new reservoirs (dams) as low-regret options, by running a large number of investment model simulations under a wide range of alternative future scenarios.

For Anglian Water's WRMP, low-regret options that need to be commenced in the next price review period (2025-30) were included in the WRMP's *core pathway*. Options that did not require immediate implementation, or which were only selected in particular future scenarios, were included in *adaptive pathways*. The most significant uncertainty in Anglian Water's WRMP is the potential quantity of water required to meet the 2050 'environmental destination' i.e. the amount of water that should be left (not abstracted) to facilitate the restoration of habitats. This is both an epistemic uncertainty (lack of knowledge about what habitats require, especially under climate change) as well as a policy uncertainty (requiring future decisions based on the costs and benefits of reducing abstraction and replacing this water). The scenarios considered range from a reduction of 168 ML/d to 384 ML/d.

The WRMP process is inherently adaptive, in that WRMPs are reproduced every 5 years as part of a continual cycle of monitoring, forecasting, optioneering and refinement. With regards to environmental destination, a significant set of investigations are planned in the next three years to better understand the quantity and location of required abstraction changes. This – along with policy direction for the 2029 WRMPs – will mean that Anglian Water can implement an adaptive pathway which will contain more or less desalination, itself a flexible option in terms of capacity, ahead of the 2040s (see **Figure 8**). A detailed monitoring programme covering all uncertainties relating to forecast and option performance will be implemented to inform the decisions at the next WRMP.

Figure 8: Anglian Water's adaptive plan output.



In summary, the Anglian Water approach is not a DAPP but instead uses RDM to identify robust portfolios. The process then looks for low regret options which are included in the core pathway. Alternative scenarios were developed by defining combinations of options that perform well in specific circumstances. These can be followed in the future, should monitoring identify that they are required.

6 APPLICATION OF DAPP TO THE WATER INDUSTRY

This paper sets out how DAPP can be successfully applied to water resource planning in Aotearoa New Zealand. Currently, there is no nationally prescribed approach for water resource planning, nor a required Level of Service. Within other jurisdictions, such as the UK, there is a long-established water resource planning framework upon which an adaptive planningapproach has been superimposed. As part of the reform of the water industry, in Aotearoa New Zealand, a water resource planning framework may be developed. If so, this should draw on good international practice and we suggest that it adopts a DAPP approach at its centre, as DAPP is increasingly being used in Aotearoa New Zealand and embedded in practice (Lawrence, 2023) to enable decisions under uncertain and changing conditions such as climate and environmental regulation.

The case study from the UK identifies several important points that could be adopted in Aoteraroa New Zealand. These include taking a high-level regional view across several water company areas to aggregate the needs of the environment and people. The quinquennial review process could be used to enhance an adaptive approach, to require a formal plan to be reviewed and updated, taking into account any new uncertainties.

A key part of the assessment process was the iteration and testing carried out to fully understand the results, before testing alternatives. DAPP coupled with RDM provides an opportunity for a robust assessment under uncertainty and provides a strong evidence base for decision making. This does not provide an 'optimum' solution that meets certain criteria, but the most 'robust' solution across a range of plausible and extreme conditions.

The outputs give a set of triggers and monitoring requirements that can be seen as a sliding window of reassessment, leading to dynamic robustness (Beh et al., 2015). The ongoing monitoring is likely to require an increase in operational expenditure in order that decisions can be made at the right time and thus avoid performance failure. This additional cost will enable short-term decisions to be made, without locking in decisions that could be more expensive in the future to address.

The development of financial forecasts may be enhanced when using a DAPP approach. Currently, budgets reflect fixed assumptions about the future that are updated every three years, but do not properly consider uncertainty. This can lead to affordability challenges when costs arise 'unexpectedly'. An approach that integrates RDM and DAPP enables the potential range of future costs to be defined.

This can also support better governance, as organisations should be able to describe several alternative futures and the monitoring that will be carried out to determine when investment is required. Boards and others in governance roles should require monitoring against established triggers to support robust planning with a long-term focus and understanding of lead times, thereby avoiding decision making under crisis conditions. This will also require decision makers to change their approach to a more anticipatory and flexible approach based on triggers, rather than acting on a single set of pre-defined actions that are insensitive to the changing conditions.

7 LIMITATIONS AND NEXT STEPS

Addressing changing climate conditions under uncertainty requires a shift from a professional practice culture of optimising over short-term timeframes using static decision tools, to a culture of robustness using dynamic decision tools. This shift means the use of scenarios to stress test options and pathways for their sensitivity to a range of future conditions, supported by a transparent monitoring system and accountability mechanisms that are actively managed to alert decision makers to review and change direction if necessary. This will require ongoing monitoring and assessment and a water resources planning process which incorporates regular updates and reporting may be one way to achieve this in the future.

The use of DAPP over the last ten years in Aotearoa New Zealand has seen increasing uptake across a wide range of decision settings. This has resulted in productive relationships with communities and stakeholders and better understanding of the climate changes affecting their lives and the ability to advance decision making on climate impacts when the future is uncertain. It has built flexible options and pathways to avoid lock-in of investment that makes addressing the mounting challenges from extreme events and progressive climate stressors more costly and difficult to adjust in time. Using the stepwise DAPP analysis outlined in this paper can also generate a better understanding of asset condition and attract finance and reinsurance as risk exposure increases. This in turn can improve preparedness through timely investments before unmanageable thresholds are reached.

The simulated climate series used in the SYM are either derived from historic data or future RCP scenarios. It is important to note that these series represent approximations of how future climactic conditions are likely to develop, but are not projections of the future. The version of the series utilised by the model is based on the most up-to-date information as provided by NIWA and consistent with the IPCC Fifth Assessment Report. As new information becomes available through downscaling of the IPCC Sixth Assessment and subsequent IPCC reports there will be a need to update the scenarios to stay current. Going forward, it is important that the most recent version of the IPCC climate scenarios is used in any future simulations of the SYM.

Failure of a water supply due to drought can have significant consequences for a community, in terms of both health and financial impacts. Drought standards are commonly adopted in many parts of the world which set out clearly the frequency and severity of water restrictions. Adoption of a drought standard and engagement with the community about this should be central to any future water resource planning guidelines in Aotearoa New Zealand.

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