# 5 Adapting to coastal change in urban and built environments

*New Brighton Pier, Christchurch (Photo: Public domain)*

## Adaptive tools for decisions on water infrastructure affected by compounding climate change impacts

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### Introduction

Multiple interacting hazards at the coast pose a challenging problem for local government and decision makers with critical water infrastructure assets located in at-risk locations. Of particular importance is navigating the uncertainty around the timing, frequency, and magnitude of coastal hazards such as relative sea-level rise (RSLR), coastal inundation, erosion, rising groundwater and rainfall-runoff events, while providing an agreed level of service for three waters systems and constraining costs.

We outline ongoing research that seeks to address the impacts of compounding climate change and flood hazards on water infrastructure in Aotearoa New Zealand and support the navigation of uncertainties (Hughes et al., 2021). This is essential because traditional approaches have fallen short in identifying the most robust[1] suite of adaptation actions under deeply uncertain climate, hazard and socio-economic futures. Examples from overseas (e.g., Hummel et al., 2018) and in New Zealand (e.g., Kool et al., 2020) have shown that many existing wastewater treatment plants (WWTPs) are susceptible to flooding after 25-30 cm of RSLR. Failure of WWTPs to reach their operational objectives and expected Levels of Service can have widespread biological impacts (Jaskulak et al., 2022) and social and political ramifications. New approaches are required that can evaluate which suites and sequencing of adaptation actions would provide infrastructure operators with the most leeway for effective adaptive actions as conditions and performance approach inoperable thresholds (Kool et al., 2020). These actions need to be able to create ongoing flexibility to move between different options and pathways rather than producing stranded assets. The framework we outline is not restricted to use in Aotearoa New Zealand, or for water infrastructure, and can be adopted elsewhere.

We are applying Multi-Objective Robust Decision-Making (MORDM) within a Dynamic Adaptive Pathways Planning (DAPP) process to assist the adaptation of two wastewater treatment plants on low elevation coastal plains. Using a MORDM approach in conjunction with DAPP enables identification of adaptation thresholds (a state after which adaptation strategies no longer meet objectives) and facilitates timely decision making on adaptation actions with sufficient lead time for implementation. Subsequent discussion details the approaches used and how they were applied.

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[1] Robust strategies are those that work well across a wide range of plausible scenarios, compared with optimal strategies that provide a best outcome within a single scenario and thus do not address deep uncertainty.

## Deeply uncertain futures

Deep uncertainty is where the external context of the system, system function, and the outcomes driven by system function and their relative importance, are either unknown or can't be agreed on by experts (Marchau et al., 2019). For example, sea-level rise scenarios in national coastal guidance (MfE, 2017), derived from the AR5 IPCC projections, show near-term certainty of similar rises until 2050, but increasingly diverge thereafter (Figure 1). The severity of other hazard impacts, such as storm surge, erosion, coastal flooding, inundation[2] and associated rising groundwater are all influenced and exacerbated by RSLR; the more hazards that need to be considered when planning for infrastructure adaptation, the more complex and uncertain the future becomes.

Decision-Making under Deep Uncertainty (DMDU) is an approach for exploring the implications of decision making under the inherent uncertainty of a changing climate using a wide range of possible socio-economic futures. Indeed, one of the key ideas underpinning DMDU is the value in using models to explore uncertainty, rather than using models for predictive purposes (Kwakkel et al., 2016). Predictive modelling is limited by uncertainty, and aiming for optimal strategies can result in a plan that would work well in the one scenario used for prediction but is not robust across a suite of possible scenarios.

## Dynamic Adaptive Pathways Planning

DAPP is a fit-for-purpose method for climate-change adaptation planning to address widening uncertainty and long planning timeframes. Applying a DAPP approach is useful for anticipating risk and where we need to make decisions today to avoid lock-in of actions that are maladaptive and limit the actions available for adaptation over time; risks change over time and increasing flexibility is needed to adopt different adaptation pathways and options (Figure 2).

A key component of DAPP is identifying signals and triggers that can be monitored using indicators of change (including hazard risks and Levels of Service) and approaching thresholds. These can be environmental, social, cultural or economic indicators. These enable timely adaptive actions to be taken, through an early warning signal of the emergence of the trigger – when a decision needs to be made – before the harmful or inoperable threshold is reached.

In Aotearoa New Zealand, DAPP forms a central component of the Ministry for the Environment (MfE) Coastal Hazards and Climate Change guidance for local government (MfE, 2017), marking (as far as the authors are aware) the first time in the world that DAPP has been embedded into national guidance. Methods for identifying the indicators that need to be monitored, and the signals and triggers which lead to a change in adaptive action, are developing beyond the traditional use of extreme hazard events to initiate adaptation after the event. DAPP and scenario modelling, on the other hand, are based on anticipatory planning to reduce and avoid the worst coastal risks. Day-to-day WWTP operations and the consenting process for water infrastructure upgrades, for example, rely upon assurances of adequate outflow quality to prevent negative impacts on mahinga kai[3], and to manage costs. DAPP can help assess a suite of adaptation options that are robust and able to operate across a range of uncertain conditions and thus assure a community of two-and-three waters Levels of Service (Kool et al., 2020).

## Multi Objective Robust Decision Making

Once developed, a dynamic adaptive pathways plan offers a range of actions and potential pathways that may be

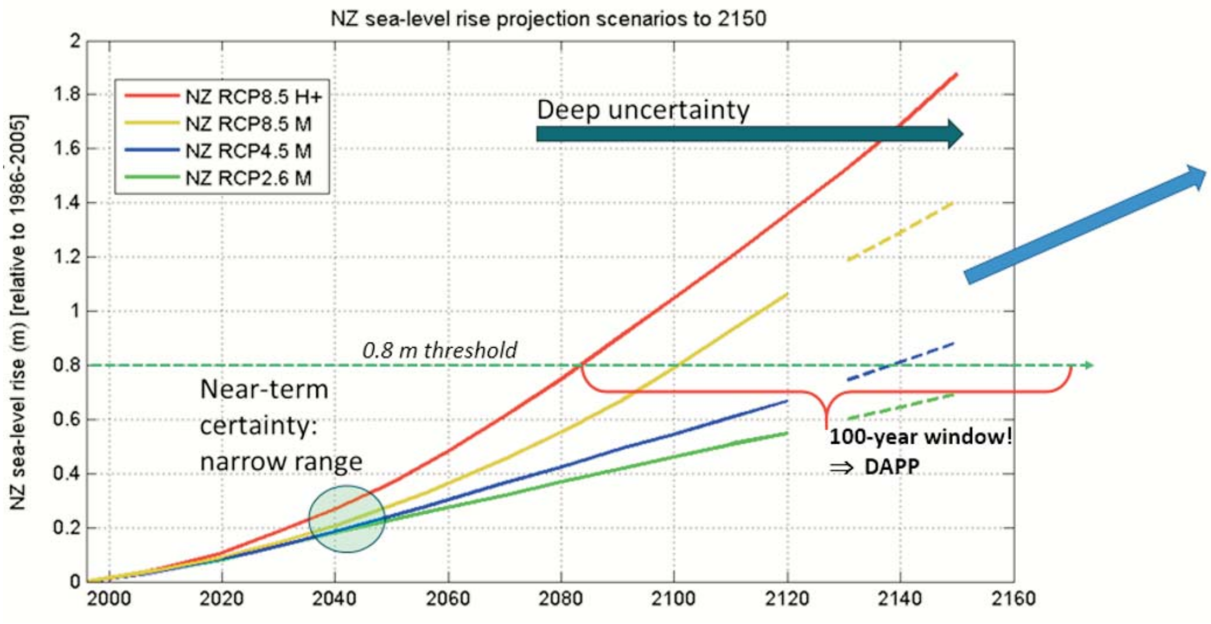

*Figure 1: SLR scenarios for Aotearoa New Zealand, highlighting the diversion of possible sea-level rise trajectories from 2050 onward (R Bell, pers. comm., adapted from MfE, 2017: Figure 27).*

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[2] We use the term 'coastal flooding' to describe periodic flooding during storm events, and 'inundation' to describe submergence of low-lying coastal land by RSLR.

[3] Mahinga kai is Te Reo Māori for the traditional value of food resources and their ecosystems, as well as the practices involved in producing, procuring, and protecting these resources.

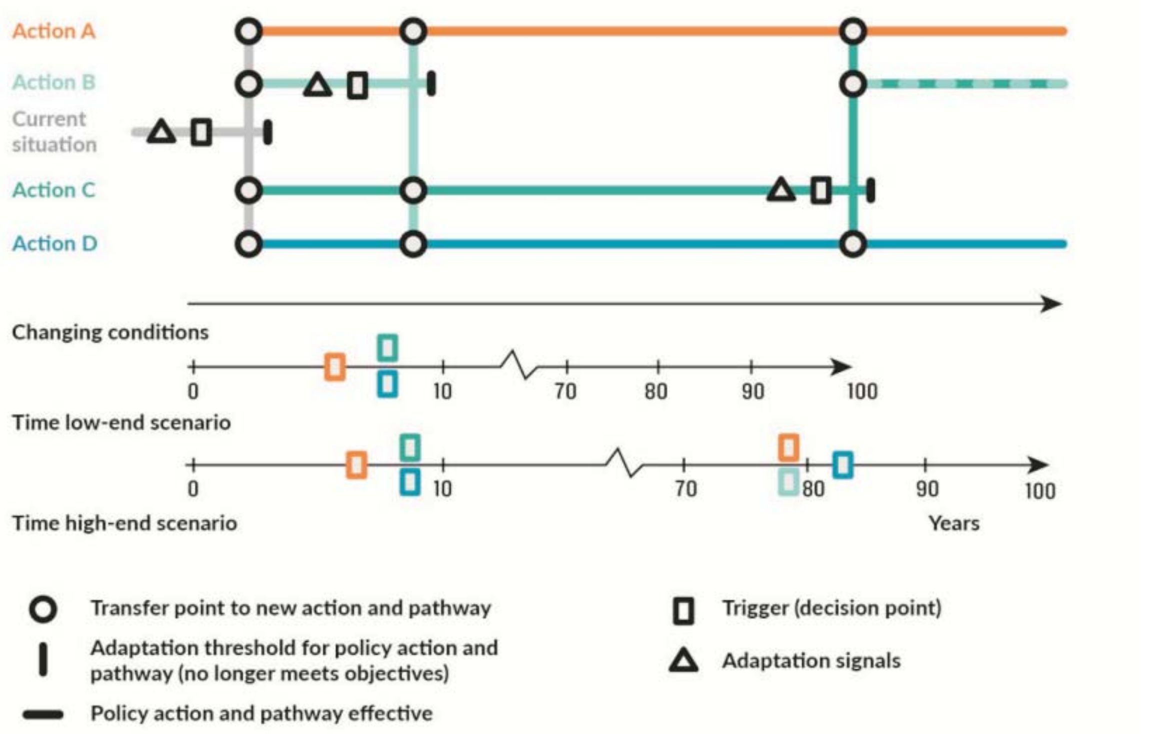

*Figure 2: Example DAPP map showing four possible adaptive actions, transfer points to new actions and pathways, and lifespan of actions (from MfE, 2017: 200, Figure 66). A sequence of adaptive actions constitutes a pathway.*

followed. However, it does not explicitly show which sequence of options should be followed to meet the objectives of hazard avoidance, cost management, and mitigation of social and regulatory pressures under an array of different possible futures. MORDM is an iterative process that can help determine the sequence of actions that best achieves a range of objectives (Lempert, 2019).

The purpose of MORDM is to stress test candidate strategies over a large ensemble of scenarios; to identify what it is that strategies that don't meet your objectives have in common. Subsequent tweaking of the strategies ideally leads to identification of one or more strategies that perform well under the greatest number of scenarios within the ensemble. Once those have been identified, research can also look specifically at trade-offs, considering the objectives of a variety of stakeholders.

MORDM considers multiple different futures, seeks robust rather than optimal strategies, and employs adaptive strategies to increase robustness, simulating these via modelling. Rather than being about optimisation and finding the 'best' pathway, MORDM focuses on finding the most robust pathway under conditions of deep uncertainty. MORDM helps decision makers to find the adaptation pathways that are least likely to fail regardless of what happens, while ensuring that costs are minimised by avoiding premature or unnecessary adaptation. In this work, the MORDM analysis is being conducted using the Exploratory Modelling and Analysis (EMA) workbench, developed at TU Delft in The Netherlands (Jan Kwakkel, a project member).

There is a lot of international interest in information, tools, processes and practices that enable decisions makers to implement dynamic plans and make investment decisions under deep uncertainty. However, there are few examples of where DAPP and MORDM have been applied in real decision settings.

## Case Studies

We are undertaking two case studies to test the use of DAPP-MORDM in tandem for WWTPs in Aotearoa New Zealand following the steps outlined in Figure 3. Both WWTPs are on low-lying coastal floodplains with elevations < 3 m above mean sea-level and each of the WWTPs represent significant long-term planning challenges. Each plant operator provides three-waters services for their respective communities, but faces uncertainty as to how they will continue to provide those services and adapt their WWTP ahead of the damage or the stranding of the assets. They service communities with increasing populations in areas vulnerable to coastal flooding hazards. WWTP 1 discharges into an adjacent river on the outgoing tide, ensuring dispersal of treated wastewater within a harbour.

Workshops were held with each of the plant operators to problem scope, and to identify critical points of interaction

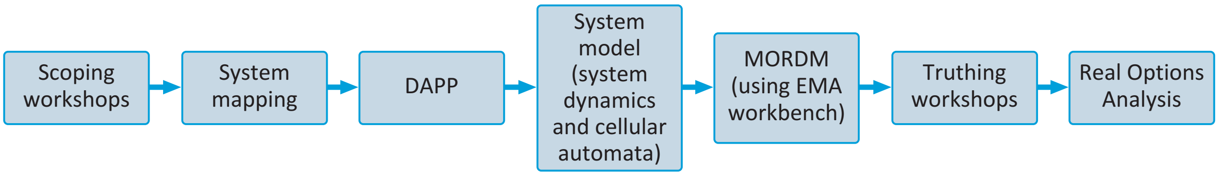

*Figure 3: Sequence of methods used in this research.*

between hazards and the infrastructure. Social and physical indicators of system stress and possible adaptation thresholds were identified. After the scoping workshops, we developed a systems diagram (a qualitative tool used to help understand and map a system, also known as a system map or a casual loop diagram) to ensure that the WWTP was considered within the broader human-environment system (Figure 4), and key adaptation thresholds for each plant were identified. Indicators were developed that would allow the plant operators to monitor hazards, and values were assigned to those indicators that would trigger a change in adaptive actions; the adaptation thresholds, signals, triggers and indicators were coupled with the adaptation options to produce a functional DAPP map.

***Case 1:*** The operators of WWTP 1 independently developed a dynamic adaptive pathways plan for the WWTP with population growth rate the key variable (Figure 5). Through discussions with the provider, we adapted the DAPP so that inflow volume to the WWTP became the key variable, independent of population growth, time or RSLR. This allows us to investigate the lifespans of the adaptive actions in the DAPP under different scenarios. Some of the actions in the DAPP for WWTP 1 are incremental in nature, such as increasing processing capacity and reducing holding time, while others are transformational and requiring system change, such as relocating the plant or outfall pipelines while decommissioning the existing plant. Incremental actions involve alterations to the existing plant while allowing it to remain at the existing location, while transformational actions involve wholesale alterations to plant location, form, or function. Incremental and transformational options are not mutually exclusive – incremental adaptation can proceed before a switch to transformational adaptation.

We have developed two models for WWTP 1. Initially a system dynamics model (a computational version of the system diagram) was developed to simulate water mass balance through WWTP 1 from inflow to outfall; this identified thresholds (conditions) under which the WWTP will fail to achieve its operational objectives, but not where that failure would occur (e.g., tank/outfall pipeline/filtration unit). Plant operating information from the system dynamics model is being converted for use in a cellular automata model of the plant. Cellular automata models are spatially explicit, temporally dynamic, and can identify both when and where the WWTP is likely to fail in a range of different scenarios. Four submodules are being developed for each model: 1) WWTP; 2) external factors (hazards and inflow projections); 3) policy levers (adaptation options/DAPP); and 4) performance metrics (avoidance of adaptation thresholds).

***Case 2:*** WWTP 2 is located on reclaimed coastal land subject to sea-level rise and land subsidence, which discharges into open ocean and has several emergency discharge points. This case study operator is in the process of commissioning a risk assessment and identifying a range of options to respond to the coastal hazards. The research team will workshop those findings with the plant operator to develop a dynamic adaptive pathways plan for WWTP 2 and associated assets (outfall pipeline and emergency discharges) using the same methodology as for Case 1.

## Future steps

The research presented in this article is showing how the case studies are being approached. While workshopping, optioneering and model development are completed for WWTP 1, we recently began these processes for WWTP 2. Once completed, the MORDM analysis is the next step.

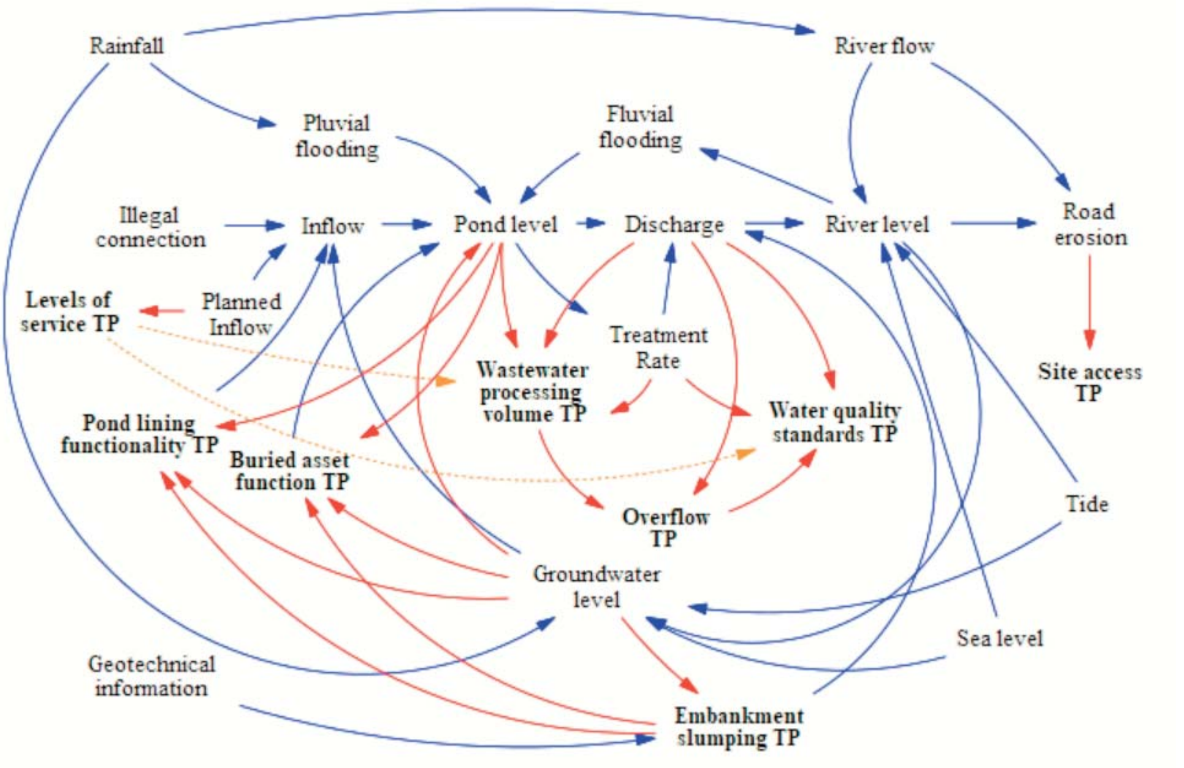

*Figure 4: System diagram of WWTP 1 highlighting that the WWTP is part of a broader human-environment system. System components (plain text) and human and environmental drivers (bold text) are linked with blue arrows, with red and orange arrows pointing from stressors to potential adaptation thresholds (adapted from Stephens et al., 2021).*

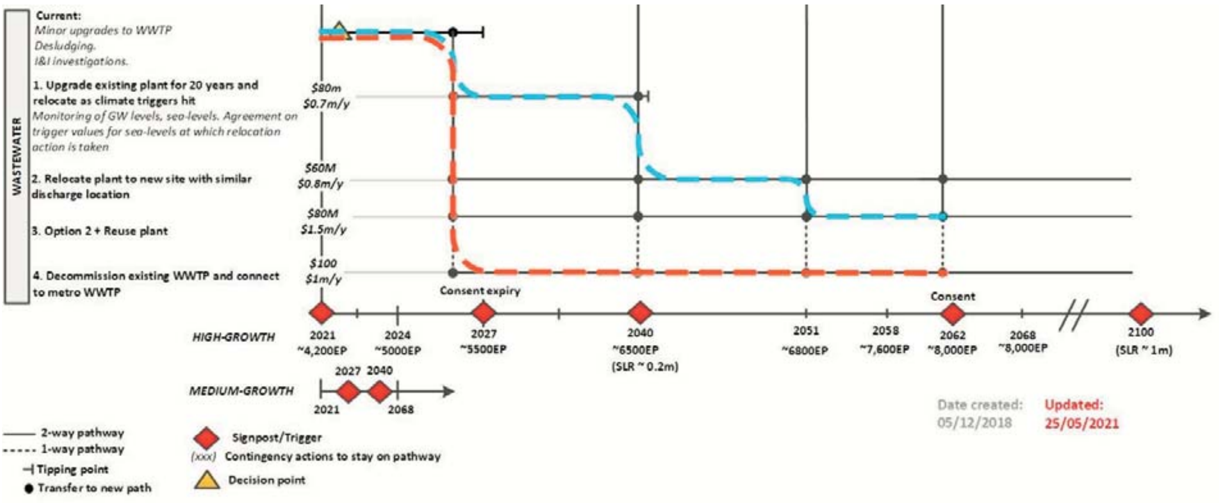

*Figure 5: Dynamic adaptive pathways plan for WWTP 1. The blue-dashed line shows an incremental adaptation pathway and the red-dashed line shows a transformational pathway (from Stephens et al., 2021).*

The sub-modules for each WWTP will be connected and a MORDM analysis undertaken. Unsuccessful combinations of adaptation actions will be ruled out iteratively until one or more strategies that meet the two main objectives of plant protection and regulatory objectives are identified. Trade-offs can then be analysed while considering the objectives of a variety of stakeholders such as social 'license to operate' and economic viability.

Following the MORDM process, a modified Real Options Analysis (ROA) will be undertaken on one plant to assess transfer costs (costs involved in changing from one adaptation action to another) at different times in the economic evaluation of pathways. In other analyses, ROA has shown that when economic transfer costs are included some actions are not as desirable as they may initially appear, and in cases may not be economically viable at all (Lawrence et al., 2019).

Once the research is complete, we will run workshops to upskill local government practitioners and decision makers in the adaptive tools we used – the grouping of MORDM, DAPP, EMA workbench and ROA. These workshops will be interactive and use qualitative exercises to demonstrate the combination of approaches and how they can improve decision making in the face of uncertainty compared to current approaches.

## Preliminary findings

International application of the mixed-methods adaptive tools approach has indicated that they provide a sound platform for making robust adaptation decisions. To date, our work is demonstrating the value of the combined approaches in New Zealand's unique socio-economic and geophysical environments.

Preliminary findings include:

- The value of the scoping workshops to highlight the importance of understanding interactions between multiple hazards and developing robust sequences of adaptive actions to avoid the worst impacts, as also found by Kool et al. (2020). In particular, the process of discussing system form, function and possible future states introduced participants to the systems thinking technique that allows decision makers to grapple with deep uncertainty (Marchau et al., 2019).
- Difficulties exist for three-waters providers in engaging with deep uncertainty because different departments have different mandates generating different desired outcomes and objectives, and because current legislation takes a static approach and is geared to single numbers for decision making. However, they will need to act in unison and take a dynamic approach to address complex infrastructure adaptation issues.
- Interdependencies and co-ordination challenges will need considered exploration. Complex problems facing water infrastructure providers will require coordinated responses from multiple agencies and multiple departments within agencies. These responses need support from robust science and assessment methodologies such as DAPP-MORDM, to facilitate discussions around the viability of the case study WWTPs and associated assets. ROA will enable sensitivity analyses to compare the value of the different options.
- System dynamics modelling shows us the interconnections between different parts of the system. The DAPP-MORDM process enables us to test the conditions under which the WWTPs could become inoperable.

In summary, our on-going research is both demonstrating the value of mixed-methods adaptive tools approaches and providing illustrative examples of how to apply the tools. Over the next 18 months we will work to improve the uptake of DAPP, MORDM and ROA in New Zealand and to upskill Aotearoa New Zealand-based researchers, practitioners and decision makers in these methods via two workshops and published outputs.

## Acknowledgements

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