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Outreach / Communication Report

Guidance on adaptive decision making for addressing compound climate change impacts for infrastructure

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TITLE	**Guidance on adaptive decision making for addressing compound climate change impacts for infrastructure**
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Introduction

Multiple interacting hazards in coastal areas pose increasing risks for infrastructure and to infrastructure providers in New Zealand and around the world. 65% of New Zealanders live within 5km of the coast (MfE and Stats NZ 2019). This means that our infrastructure is exposed to erosion, storm surge, heavy rain, overland and river flows, rising groundwater and tidal effects, and relative sea-level rise from climate changes and the effects of land subsidence (RSLR) and the compound impacts of these hazards. But there is uncertainty around the frequency, magnitude and timing of these hazards in the face of deeply uncertain physical and social responses to climate change.

Different types of infrastructure are exposed in different ways, and to different hazards. Wastewater treatment systems are often gravity-fed and have assets located immediately adjacent to the coast where storm surge and RSLR dominate. Parts of electrical, communications and three waters systems (stormwater, water supply and wastewater) are located underground where groundwater levels can infiltrate into pipes and make repairs difficult. Road and rail networks are susceptible to RSLR, storm surge, and river and overland flows that can render the network temporarily unusable. There are also interdependencies between different infrastructure systems that create cascading impacts (Lawrence et al., 2020); for example, if electricity is cut, pumping stations are unable to move water through the network and overflows result affecting human health and ecosystems. Changing demand for services and community expectations regarding environmental impact and levels of service, mean that infrastructure providers must find a balance between meeting agreed levels of service and performance standards, while keeping costs within budget and avoiding asset and system failures to adapt and upgrade infrastructure systems. Local government agencies are required to produce a plan for managing their infrastructure assets, including maintenance, renewal, replacement, changes in levels of service and resilience to hazards (Department of Internal Affairs, 2002).

This guidance has its origins in a proof-of-concept research project funded by the Deep South National Science Challenge – *'Adaptive tools for decisions on compounding climate change impacts on water infrastructure'* (hereafter: Adaptive Tools). The project was grounded in two real-life case studies developed with Wellington Water and Watercare[1] personnel and lead by NIWA and PSConsulting Ltd to test a set of methods that can address the impacts of compound hazards on infrastructure at or near the coast. This guidance gives infrastructure providers the tools to grapple with the risks and uncertainties that arise from ongoing and progressive climate change.

The approach

The approach on which this methodology is based (Dynamic Adaptive Pathways Planning—DAPP) can assess the lifetime and efficacy of adaptive actions and options. This enables ongoing flexibility to be built in, by enabling movement between different adaptive actions and options to address different pressures that render chosen actions unable to deliver agreed service levels. The approach provides greater flexibility to decision-makers to implement new adaptive actions as triggers are reached ahead of infrastructure performance loss and before damaging thresholds are reached (Kool et al., 2020). This is based on a robustness test using a range of scenarios of the future, which reflects uncertainties and increasing risks consequent upon climate change.

[1] Wellington Water and Watercare are two Council-owned water services agencies from Wellington and Auckland, respectively.

There is a clear distinction between traditionally used optimisation approaches to infrastructure adaptation, and decision making under deep uncertainty (DMDU) approaches. DMDU tools are more appropriate for infrastructure adaptation planning over the long ("at least 100 years") time frames required in New Zealand (NZCPS, 2011; MfE, 2024). Optimisation approaches, such as the Master Planning approach widely used in New Zealand wastewater management, focus on finding the best performing set of adaptive actions for a single scenario and are unsuitable when planning over long timeframes and when considering multiple future climate scenarios (Maynard et al., 2021; Allison et al., 2022). DMDU tools were developed for use in situations where three or more elements are in dispute: "(i) the external context of the system, (ii) how the system works and its boundaries, and/or (iii) the outcomes of interest from the system or their relative importance" (Marchau et al., 2019: 2). Curran et al. (2023) outline a range of methods suitable for use when making decisions under deep uncertainty.

Exploratory modelling and scenario analysis are key to DMDU. Simple models of complex systems are developed and tested using computational scenario modelling to improve decision-maker understanding of the external context of the system, system boundaries and how the system works when the three elements of deep uncertainty (Marchau et al. 2019) are at play. DMDU tools are also appropriate when compounding hazards are sufficiently well resolved but their impacts on infrastructure assets and infrastructure systems as-a-whole is uncertain.

DMDU tools are now more widely used to support infrastructure adaptation decision-making under an uncertain future climate (Kwakkel et al., 2016). Robust decision-making (RDM) can be used to analyse and stress-test potential adaptive actions included in a dynamic adaptive pathways plan (DAPP) – DAPP is recommended for use in coastal hazards and climate change adaptation planning by the Ministry for the Environment (2024). This stress-testing can ensure that adaptive actions are robust against a range of plausible climate change scenarios, demand scenarios, and socio-economic futures, while making explicit the impacts of locking-in maladaptive actions (Allison et al., 2024). RDM and DAPP can be used together and in conjunction with systems mapping, which is used to help researchers and stakeholders (asset managers, decision-makers, etc.) develop a common understanding of the system in question and its dependencies and externalities (Hamarat et al., 2013; 2014).

The Adaptive Tools project had two case studies where the methodologies were used in New Zealand – a wastewater treatment plant (WWTP) operated by Watercare Services, Auckland and a WWTP, trunk sewer and pipeline operated by Wellington Water. Using the Wellington Water Seaview case study as an example throughout this guidance, we show that the combined methods, used in sequence, can enable decision makers to stress-test potential adaptive actions, understand the lifetime and efficacy of proposed adaptive actions, the conditions under which they fail to meet objectives, and to understand which combinations or sequences of adaptive actions are the most robust. This approach offers a sound platform for making robust adaptation decisions over planning timeframes of at least 100 years.

Methodology overview

The methodology combines workshops, systems mapping, DAPP, exploratory modelling, RDM and real options analysis (ROA) to assess and stress-test adaptation options for specific water infrastructure assets (Figure 1). The seven analytical methods used do not have to be completed in isolation; the approach can also leverage existing work done or planned by water management agencies. For example, the Adaptive Tools Helensville case study used an existing DAPP plan for the Helensville WWTP. Box 1 defines terminology used in this guidance.

Box 1. Terminology.

Adaptation thresholds are critical points of failure to be avoided—equivalent to an Adaptation Tipping Point (Haasnoot et el. 2013). For example, overtopping or breach of a seawall.

Adaptive actions are those that avoid an adaptation threshold; in this application they are engineering actions.

Triggers are the decision point at which the efficacy of current and future actions are reviewed, and new adaptive actions or pathways chosen and implemented in order to avoid an adaptation threshold.

Indicators are elements that are monitored to warn that a trigger is approaching. For example, nuisance flooding.

Lead times are the time it takes to plan, consent and implement an adaptive action.

Lifetimes are how long the action will perform to meet the objectives under different conditions.

Systems mapping ensures the broader system, within which the infrastructure sits, is well-understood. The modelling investigates uncertainty arising from the frequency and magnitude of hazard impacts under a range of influent volume scenarios and climate change scenarios. Systems mapping, DAPP, exploratory modelling and RDM are applied sequentially to identify adaptation thresholds for infrastructure and to identify pathways that are robust against the uncertainties.

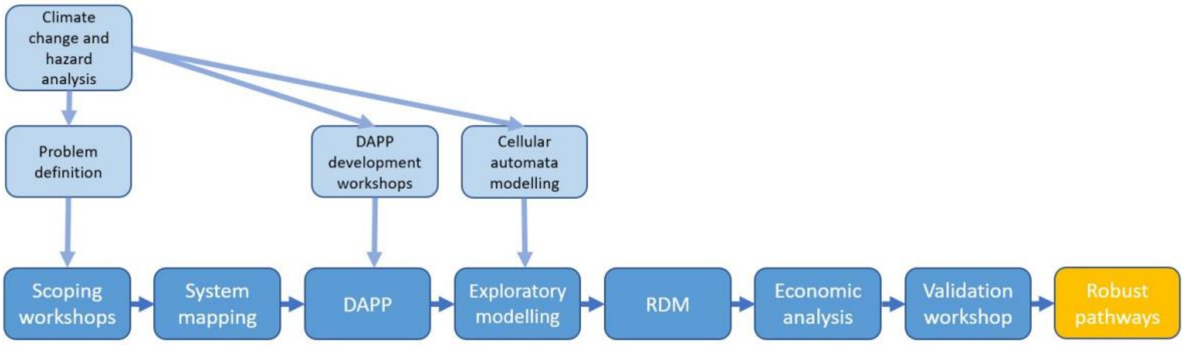

Figure 1. Elements of the methodology. Note: The seven methods can be used in different orders depending on how many of the steps have been undertaken and the needs of the infrastructure agency. Adapted from Allison et al., 2024.

Exploratory modelling is used to investigate the viability and lifetime of actions within alternative adaptive pathways (in a DAPP) and how the different pathways play out under different scenarios. Compound hazard impacts need to be incorporated into the model. Traditional joint probability analysis assumes that different types of hazards occur independently, so that a 1% AEP surge event, 1% fluvial event and 1% rainfall event will occur simultaneously once every million years (1% x 1% x 1% = 0.0001%), which we know to be inaccurate (Andrews, 2023). We suggest using the approach outlined by Heffernan and Tawn (2004), which recognises that various elements of extreme conditions are related.

An RDM framework is used to interrogate model outputs and refine model scope in an iterative process. Economic analysis is undertaken to assess the costs of the robust pathways, and the costs of delaying actions. Finally, results should be validated with the infrastructure provider, culminating in the identification of one or more robust pathways for each infrastructure asset.

This guidance outlines an approach to inform adaptation of infrastructure systems in New Zealand, comprising workshops, system mapping, DAPP, exploratory modelling RDM, and ROA. The steps involved in applying the methodology are presented in Figure 2.

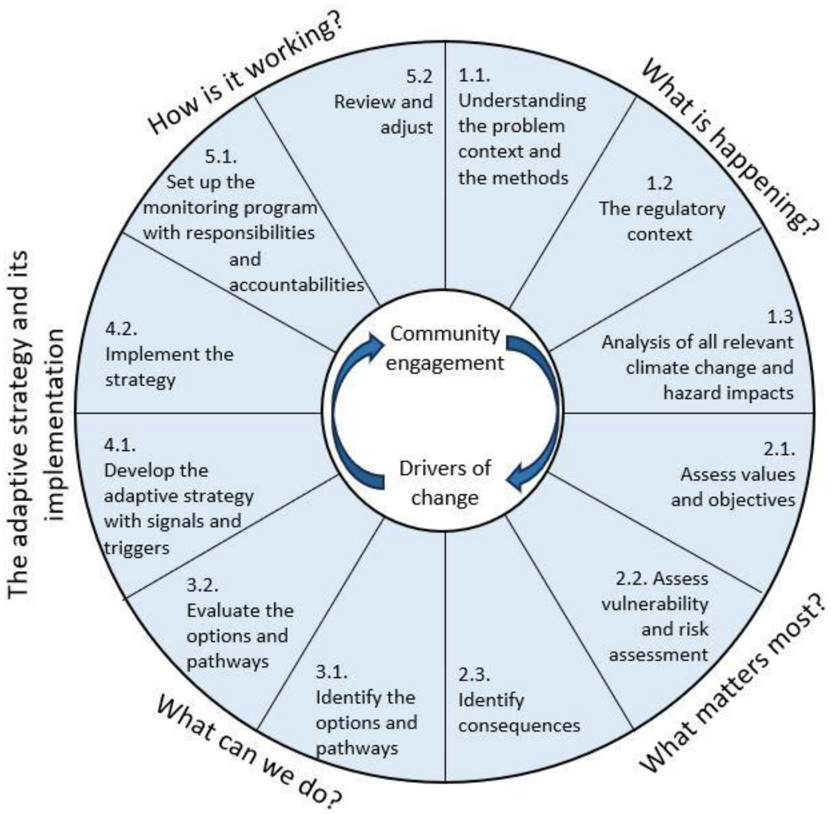

Figure 2. Steps for applying water infrastructure adaptation planning methodology. The seven elements of the guidance methodology set out in figure 1 occur during steps 1.1 - 3.2 in this figure. Source: Allison and Lawrence, 2023.

Methodology

Step 1. What is happening?

1.1 Understanding the problem context and the methods

Form a team with the mandate to develop the adaptive plan across engineering, planning, finance responsibilities and with requisite expertise in adaptive planning and climate change hazards and risk. Use workshop discussion(s) to ensure that the project team cover all aspects of the plan preparation process and share a common understanding of the problems facing the water infrastructure system. This will assist in developing an implementable adaptation plan (Stephens et al., 2021). This step relies on having adequate information to assess the problem context. This will include both information generated with the organisation responsible and where relevant community and iwi/ hapu Māori input at the early stages of defining the problem.

1.2 The regulatory context

All climate change and hazard analysis, adaptation planning, and plan implementation need to comply with legislative requirements, including (but not limited to): the MfE *Guidance for Local Climate Change Risk Assessments* (2021), the MfE *Coastal Hazards and Climate Change Guidance* (2024), the MfE *National Adaptation Plan* (2022), the *Resource Management Act 1991*, the *NZCPS 2010* and the *Building Act* (s71-73) and *Building Code*. ISO 14090: 2019 provides broad guidance on climate change adaptation, including systems thinking; ISO 14091:2021 provides guidance on climate change vulnerability, impacts and risk assessment which can both provide helpful context for application of the methodology in this guidance. The Water Services Association of Australia *Climate Change Adaptation Guidelines* (2016) is also relevant for water infrastructure adaptation. While there are some differences in these guidance documents, DMDU methods as set out in this guidance are being widely used globally for considering the effects of uncertainty and the consequent changing risk on critical infrastructure.

1.3 Analysis of all relevant climate change and hazard impacts

In-depth consideration of the full range of climate change impacts that may impact coastal infrastructure is key to developing an implementable adaptation plan. This includes, but is not limited to erosion, landslips, rainfall, fluvial and pluvial flooding, drought, changes in groundwater levels, RSLR (including sea-level rise and local subsidence – Vertical Land Movement (VLM)), storm surge, changes in storminess, wave overtopping, inundation, and air temperature changes. Hazards that may be considered, but that are not impacted by climate change, include earthquakes, liquefaction and tsunami. A full list of hazards to consider can be found in MfE (2021: Appendix A). MfE (2021: Figure 2) shows the steps required to undertake a local climate change risk assessment; we recommend following this process.

The analysis should use a range of climate scenarios - Ministry for the Environment coastal hazards and climate change guidance (2024) recommends a minimum of four scenarios. GIS investigation of the impacts of multiple interacting hazards across space is recommended if resources allow. Riskscape is one national-scale platform that can be used to assess the impacts of multiple interacting hazards at the local level and is widely used in New Zealand (Paulik et al., 2022; Kool, 2020).

Step 2. What matters most?

2.1 Assess values and objectives

The values and objectives of the adaptive plan are identified at this stage. They will include both compliance with statutory requirements and directions, and derived policies (values) and the agreed levels of service (objectives) for all elements of the infrastructure system identified in Step 1. These can be developed through workshops with the project team and build on existing levels of service and a review of them. Involving those responsible for agency performance indicators and audit functions is recommended. Engagement with mana whenua is also recommended if they are not already part of the project team. (Refer to MfE *Coastal Hazards and Climate Change Guidance* 2024 for appropriate engagement methods).

2.2 Assess vulnerability and risk assessment

Identification of vulnerability (exposure and adaptive capacity) as an input to a risk assessment should comply with the MfE *Guidance for Local Climate Change Risk Assessments*, which can be achieved by unbundling vulnerability. To do this a matrix can be developed that shows a 2-way interaction between sensitivity and adaptive capacity. This then enables a risk matrix of vulnerability and exposure to be developed that will be aligned with the MfE guidance.

This assessment should consider the infrastructure system in its entirety, specific infrastructure assets, any land owned or used by the infrastructure provider or under consideration for use in future (e.g. potential alternate locations for assets), and the wider community and service areas. Cascading impacts should also be considered, for example impacts on access to an asset or power supply to an asset.

To do this the climate change and hazard impact analysis and the vulnerability and exposure analysis will need to consider impacts on all parts of the infrastructure system and the entire service area. This may include a 'hot spots' analysis to identify critical vulnerabilities in the system. Understanding the conditions under which loss of current levels of service may occur are vital to the climate change and hazard analysis.

2.3 Identify consequences

Once vulnerability and risk have been assessed, the consequences need to be evaluated. For example, if groundwater reaches the level of underground infrastructure, the network may lose the ability to deliver influent to the infrastructure asset and raw sewage may enter the environment. Additionally, offsite risks will require engagement with other landowners and activities in the area that could pose risks to the infrastructure site to ensure that adaptive plans are aligned.

Understanding the consequences of vulnerability and risk will allow the infrastructure provider to better develop ways to avoid loss of current levels of service, through identifying appropriate adaptive options and actions.

Step 3. What can we do?

3.1 Identify the options and pathways

The project team should make a long list of all options based on the information available, without ruling out options at this stage. Options will also include suites of complementary options and for each part of the identified system based on the systems map (covered in section 3.2.1).

3.2 Evaluate the options and pathways

The seven methods can be used as shown in figure 2, in sequence for evaluating the options as a basis for the development of an implementable adaptation plan. The plan should account for and be robust under a range of climate scenarios to address the deep uncertainties in some of the climate change parameters, such as socio-economic changes, while in alignment with the relevant legislation and codes of practice and other relevant guidance (see 4.1). This section explains how the steps should be undertaken. The first method, scoping workshops and problem definition, occurs during step 1 and step 2.

3.2.1 System mapping

A system mapping exercise (e.g. Stephens et al., 2021) developed using an expert workshop, will provide a visual representation of the infrastructure system and the environmental, regulatory, social and economic drivers and constraints on its adaptation (Figure 3). The system map developed should be regularly referred to during the remaining steps, to ensure that the modelling and analysis are accounting for all necessary variables. The system map can also be updated after DAPP development (see 3.2.2) to include adaptation thresholds and adaptive actions.

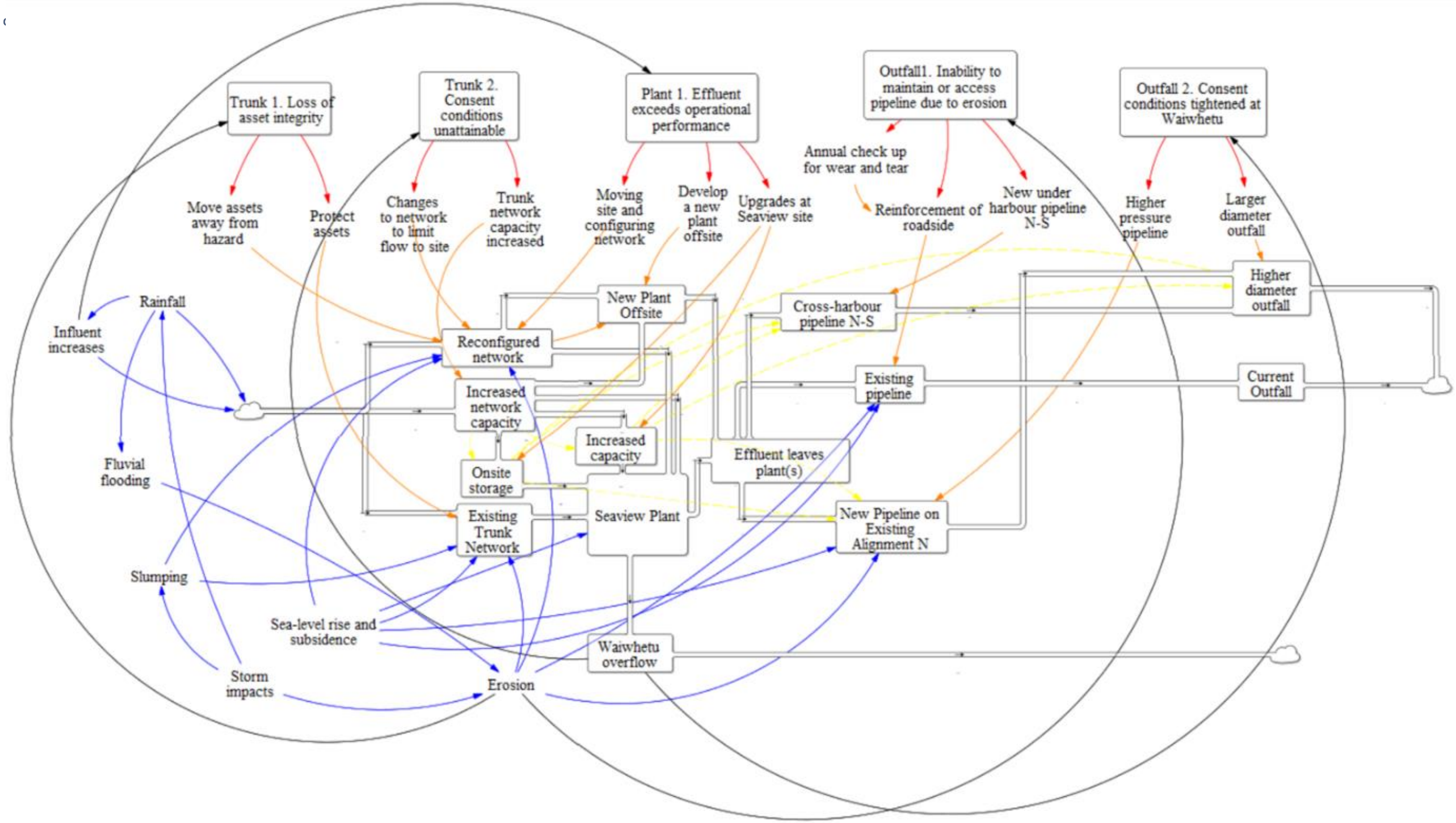

Figure 3. System map of the Seaview Wastewater Treatment Plant showing critical connections within the system. Central boxes linked by pipes show the trunk network, Seaview WWTP and outfall pipeline and the movement of wastewater through the system. Top boxes show triggers. Black arrows show the drivers that may lead to triggers being reached. Red arrows show options for adaptive actions for each trigger. Orange arrows show where actions are implemented in the system, yellow arrows show secondary actions that are required if an action is implemented. Blue arrows show the influence of one variable on another. Source: Allison et al., 2024.

3.2.2 DAPP development

Components of a DAPP should be considered and assembled using a team workshop. These include adaptation thresholds, actions/options, lead times, indicators and triggers. The suggested order of development is as follows.

a) Adaptation thresholds should be identified first. These are conditions that need to be avoided to ensure continued provision of services to the service area, and avoidance of damage to infrastructure and assets. For example, one adaptation threshold for wastewater infrastructure could be influent capacity exceeded processing capacity.

b) Once adaptation thresholds are developed, actions/options that can be used to avoid adaptation thresholds should be considered for each adaptation threshold and agreed internally within the infrastructure provider organisation to ensure buy in to the range of potential adaptive actions. These can be presented as a pathways map of the different routes to the objectives that has been agreed in 2.1 above. These can be physical actions (such as building a new outfall pipeline), regulatory actions (such as renegotiating discharge consents), social actions (such as renegotiating expected levels of service with the community), or other actions.

c) Each action/option must have an associated lead time. This is the time that it takes to consult on, plan, and implement the action once a decision has been made to implement it.

d) Indicators need to be identified. These are the factors that need to be monitored in order to know that a trigger (decision point) is approaching so as to avoid the adaptation threshold. Examples include increments of RSLR, number of unconsented discharges, or changes in level of service.

e) Triggers need to be identified. These are the point at which a decision whether to change the adaptive action is taken and includes the lead time to implementation begins. An example could be a specific increment of RSLR (e.g. 25cm), a specific number of unconsented discharges (e.g. 12 in 6 months), or a specific reduction in the level of service (e.g. influent volume exceeds processing capacity for 10 days out of 30).

f) Once the above components of a DAPP are identified, each needs to be checked with decision-making sectors within the infrastructure provider to ensure that the components are each viable, monitorable, implementable, and priced. Table 1 provides an example of DAPP components.

g) The DAPP can be visualised using existing open-access software platforms, such as the Pathways Generator (van Deursen and Haasnoot, 2017)[2], a metro map (Haasnoot et al 2013) or a range of other visualisation approaches used globally as set out in Haasnoot et al (2024 in review).

[2] https://publicwiki.deltares.nl/display/AP/Pathways+Generator

Table 1. The DAPP components for the Seaview Wastewater Treatment Plant. Note: Each adaptation threshold has an associated trigger, signal, indicator, and two or three adaptive actions each with associated lead times. Source: Allison et al., 2024.

	Trunk 1	Trunk 2	Plant 1	Outfalls 1	Outfalls 2
Adaptation Threshold	Loss of asset integrity	Consent conditions unattainable	Influent exceeds hydraulic capacity (hard)	Inability to maintain or access pipeline due to erosion	Consent conditions tightened for Waiwhetu emergency overflow
Trigger	Near miss event (e.g. landslip within 50m of main trunk)	Inability to gain a consent (date influence) / very short consent granted	Trunk network capacity is increased	Frequency or cost of maintenance events surpasses trigger level	Inability to gain a consent or very short consent granted
Signal	Community vulnerability signals (planners' judgement of likelihood of obtaining a consent on current terms)	Changes to the regulatory environment, or precursor to changes	Feedback from modelling on capacity and feedback that WWTP is likely to exceed capacity in a certain timeframe	Frequency or cost of maintenance events surpasses signal level	Changes to the regulatory environment, or precursor to changes
Indicator	Frequency / size of event (e.g. landslips)	Planners' judgement of the probability of obtaining a consent on expected terms	Monitoring modelling and any upgrades underway or planned	Cost or frequency of maintenance or access	Planners' judgement of the probability of obtaining a consent on expected terms
Action 1	Protecting asset	Changes to network to limit flows to site	Increase capacity onsite – options available for scale	Monitor state of road and pipe	Larger diameter outfall
Lead time 1	3-5 years (design, consent, deliver)	Would need to do it multiple times sequentially: 5-10 years, then 5-10 years	5 years	Ongoing - annual check- up on level of wear and tear	5-10 years
Action 2	Moving assets away from hazard	Trunk network capacity increased *1	Develop storage onsite	Reinforcement of roadside	Higher pressure outfall pipe
Lead time 2	5-10 years (scale dependent)	5-10 years	5 years	2-3 years	5-10 years
Action 3 (if applicable)			Transformational change - moving site and reconfiguring network	Fully down-harbour pipeline to outfall N-S eastern edge	
Lead time 3 (if applicable)			10-15 years	5-10 years	

3.2.3 Exploratory modelling

Exploratory modelling then takes place. Several different types of model can be used depending on the requirements of the infrastructure provider and the characteristics and location of the infrastructure being assessed[3]. A cellular automata model was used in the Adaptive Tools case studies (see worked example for Helensville WWTP in Appendix 1) for each system of concern; we hereafter refer to the Seaview WWTP, trunk network and outfall pipeline modelling case study from Adaptive Tools. The model includes data on groundwater, historic rainfall, rainfall/runoff projections, tides, erosion, RSLR and local vertical land movement (VLM), influent and effluent to/from the infrastructure as relevant, topography/elevation, and inflow scenarios. The model runs on a daily timestep based on the design life of the infrastructure (for Seaview WWTP the period used was 1 January 2020 to 1 January 2100, the design life of the plant (2080) plus 20 years). Multiple hazards interact to simulate plant viability at the current location. The modelling process simulated the implementation of the DAPP, with new actions chosen when triggers were reached in order to avoid adaptation thresholds.

In other words, the model needs to include the physical environment, built environment, climate change impacts, hazard impacts, and the DAPP needs to be coded in. The model simulates the effects of multiple interacting hazards on each component of the infrastructure, and the effects of proposed adaptive actions. The model is then tested within a robust decision-making framework.

3.2.4 Robust decision-making

Robust Decision Making (RDM) is used under conditions of uncertainty and runs a model many times to stress test proposed decisions (options and pathways) against a wide range of plausible futures, rather than using computer models and data as a predictive tool (Lempert, 2019). The RDM process tests the exploratory modelling described in step 3.2.3.

The model therefore should be run in stages. First, to identify the physical and temporal location of adaptation thresholds in the case of no adaptive actions being taken. Second, with the DAPP options and pathways operating to see if its implementation can avoid all adaptation thresholds, and to see if the timing of triggers is appropriate or if they need adjusting. Third, to identify actions that are robust and actions that are not. Non-robust actions should be removed from the DAPP. Fourth, the model should be run with the adjusted DAPP operating to see if its implementation can avoid all adaptation thresholds. If so, trigger values can be identified, along with the range of actions available once any trigger is reached. If not, another iteration of removing non-robust actions is required, and step four should be repeated. The pathways that emerge are archetypes of adaptation – sequences of adaptive actions that achieved performance and operational objectives. The end product is a stress-tested DAPP that is robust against future uncertainty (Box 2).

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[3] Cellular automata models are well-suited to this type of assessment and interrogation, being spatially explicit, temporally dynamic and able to simulate interactions between processes occurring in neighbouring cells (spatial area units) (e.g. Allison et al., 2024). System dynamics models are suitable for situations where the spatial layout and location of infrastructure does not need to be simulated (e.g. Hamarat et al., 2013; 2014). System dynamics models can also leverage system mapping work undertaken in step 3.2.1. Agent-based models are also spatially explicit and temporally dynamic but can also include interactions between autonomous decision-making entities and social interactions and variability (e.g. Allison et al., 2023). Agent-based modelling may be useful in situations where multiple competing interests are in play. As a caveat, agent-based modelling requires a more complicated qualitative and quantitative analysis. This list is not exhaustive and other modelling methods may be appropriate.

Box 2. 2023 Auckland Anniversary Weekend Floods

The Auckland Anniversary Weekend floods on 27 January 2023 provided a real-life test of the method outlined herein.

On 27 January 2023, a 1-in-220-year (0.4% AEP) rainfall event occurred in Auckland city. Out of a total 265mm of rain that fell in 24 hours, 211mm fell in 4 hours and the peak two-minute rainfall was 4.2mm. The Helensville WWTP case study site was impacted by this event.

The Kaipara River burst its banks upstream from the Helensville WWTP, flooding several hectares of rural land which mitigated the peak river flows. The peak river flows occurred at the lower half of the tidal cycle, and the Helensville WWTP was not inundated by river flooding. The magnitude of the Auckland floods exceeded the maximum event simulated in the Adaptive Tools case study modelling (1-in-100-years). Subsequent inclusion of the Auckland flood event in the model suggested that if the peak river flows had coincided with high tide, the Helensville WWTP would have been inundated.

In 2022, Watercare had upgraded the plant by implementing Action 1 from the plant DAPP plan, increasing processing capacity by 50%. Despite this upgrade, influent volumes from the heavy rainfall event exceeded the plant processing capacity, resulting in partially treated sewage being discharged into the Kaipara River. Simply put, the magnitude of the Auckland floods was far greater than the infrastructure design standards used for the Helensville WWTP.

The Auckland floods provided a living test of the methodology used for stress-testing the DAPP plan developed for the Helensville WWTP. With the processing capacity upgrade action already implemented, all remaining actions in the Helensville WWTP DAPP plan require moving the plant from its current location. The likely future for the Helensville WWTP is to move wastewater services in the area to a different location at the end of the design life of the plant upgrades.

3.2.5 Economic analysis

The final step in the analysis is an economic analysis which should be undertaken on the robust model outputs to price the costs of every available pathway. This can be done using the following methods (Figure 4), usually in combination depending on the purpose: multi-criteria analysis, ROA, cost-benefit analysis or cost effectiveness analysis (Allison et al., 2024). Depending on the type of economic analysis undertaken, this step can provide decision-makers with information on investment costs, maintenance and operational costs, transfer costs, benefit of avoided damage, residual loss, cost/benefit of delaying implementation, and non-monetary costs and benefits.

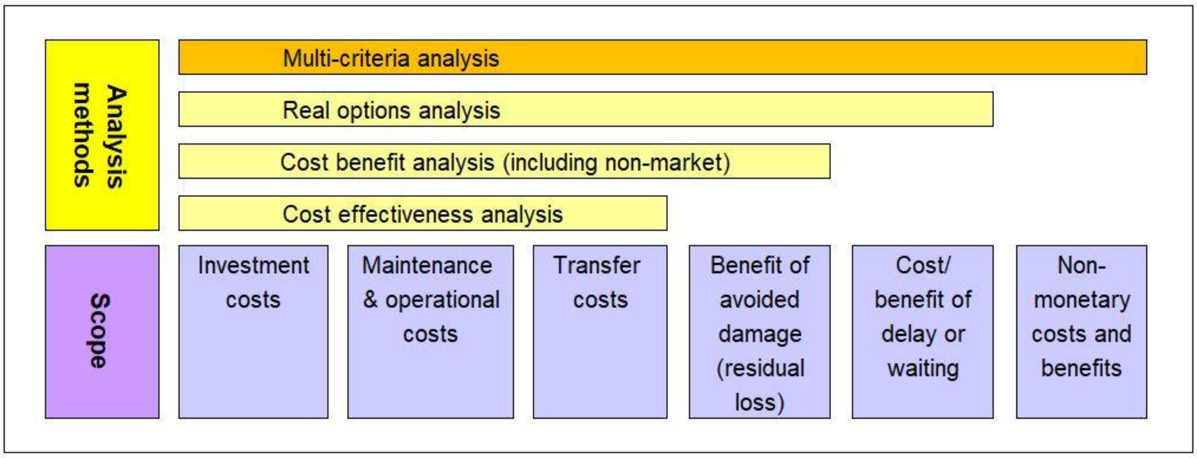

Figure 4. Analytical methods to assess adaptation strategies. In cost benefit analysis (CBA) and cost effectiveness analysis (CEA), the benefits are identical across all scenarios. CEA excludes the benefit side of the calculation as benefits are assumed to be the same across all options. CBA includes benefits but excludes consideration of the option to delay. Note that the delay option is not a benefit that is added to a project's other benefits. Rather it amends the evaluation of the project's benefits by allowing for multiple decision points rather than a single decision point. Source: Allison et al., 2024 – adapted from Stroombergen and Lawrence 2022.

The type of analysis chosen depends on the level of information available on non-monetary costs and benefits, the number of variables used to identify the pathways, and the impact of different climate change scenarios, demand scenarios and socio-economic scenarios on the timing and cost of implementation of actions. However, for large infrastructure projects which have long lifetimes, methods that address the long-term avoided damages will need to be fit for purpose. The methods will need to be tailored to address greater uncertainties in parameters and where probabilities are unknown and cannot be calculated, rather than methods that address short-term objectives where probabilities are known and there is greater certainty of the parameters.

This final step in the analysis is carried out on the archetypes applying a modified form of ROA (Stroombergen & Lawrence 2022). ROA is used to compare costs of different adaptive actions / adaptation archetypes and to assign a value on the option to delay an action that may reduce the uncertainties. The benefit of reduced uncertainty is compared to the cost of greater damage incurred by postponing investment (Allison et al., 2024). In this modified form of ROA, probabilities are risk-neutral and used to stress test the adaptive actions and adaptation archetypes to find the cutoff point at which investment sooner equals the cost of delaying the investment. The ROA is undertaken on each of the robust pathways identified during the RDM analysis.

Multi Criteria Analysis (MCA) can be used in parallel to convert qualitative assessments into quantitative scores. It can include non-monetary valuations of gains and losses such as environmental effects and social or cultural values; MCA has a wider span of applicability than the economic appraisal techniques shown in Figure 4. All the methods, however, can be used within a DAPP approach.

Figure 5 shows robust pathways (archetypes) for the Seaview Wastewater Treatment Plant case study that were identified by following the processes outlined herein.

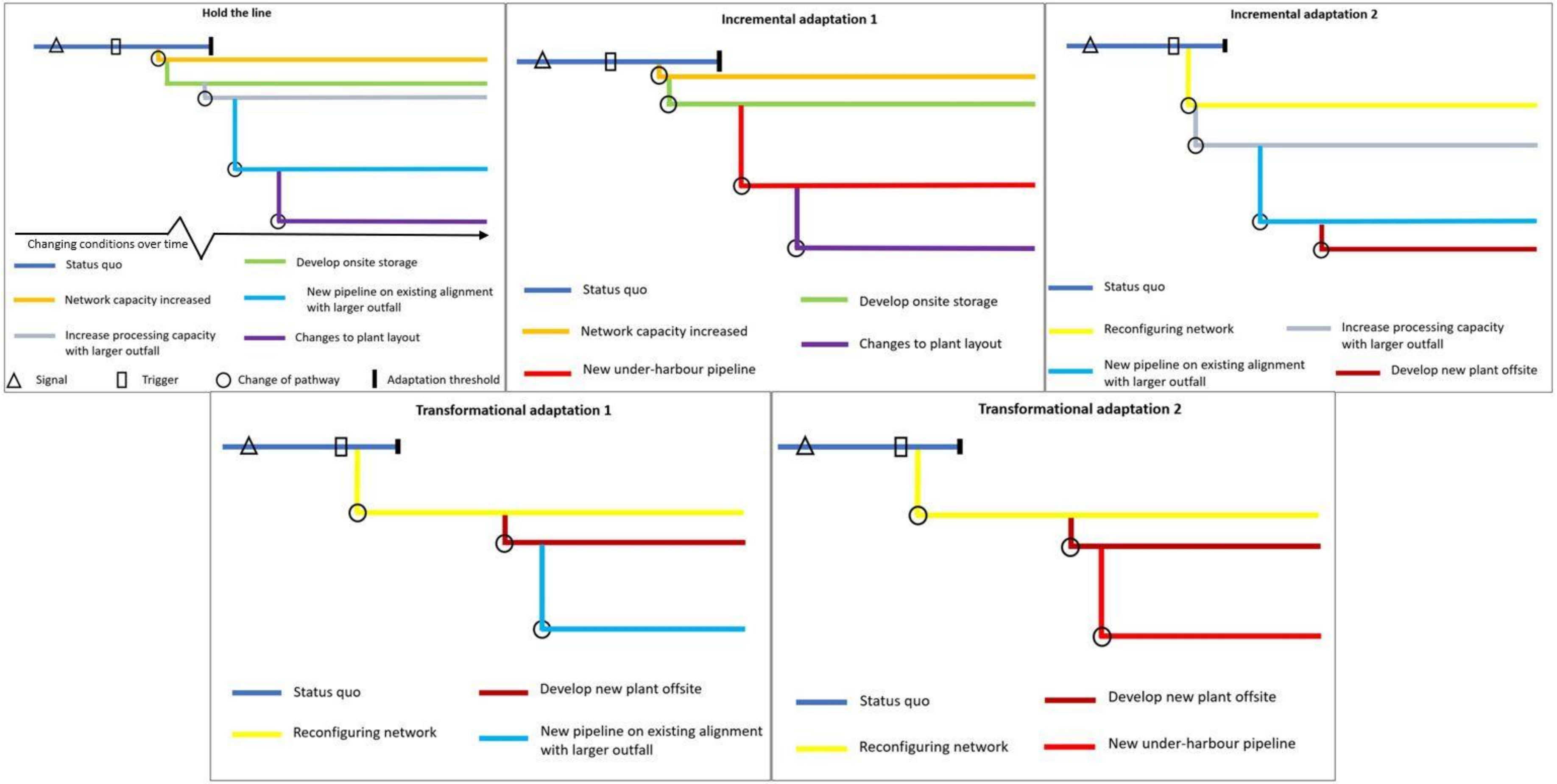

Figure 5. Example of robust pathways - sequences of adaptive actions that are robust against future uncertainty. Source: Allison et al., 2024.

Step 4. The adaptive strategy and its implementation

4.1 Develop the adaptive strategy with signals and triggers

A workshop should be held where the results of the simulation modelling, RDM and economic analysis are discussed, critiqued and the feasibility of the resulting DAPP strategy agreed. The modelling and RDM process should have left more than one option available at each trigger point, ensuring that the stress-tested DAPP is flexible, dynamic, adaptive, and offers multiple viable pathways and contains relevant triggers that can be monitored.

4.2 Implement the strategy

Implementation of the DAPP will require decisions on the detailed design and staging of the actions and an investment plan to fund the actions agreed with the responsible decision makers. The plan should be agreed through the LTP, asset management plan and infrastructure plan and aligned with the regulatory requirements such as design standards and consenting. Planning methods and techniques will be determined by the site locality but be broadly guided by the RMA plans and in particular the NZ Coastal Policy Statement for low-lying coastal locations. (see Step 8 of MfE *Coastal Hazards and Climate Change Guidance* 2024).

Step 5. How is it working?

5.1 Set up the monitoring program with responsibilities and accountabilities

The effectiveness of the adaptive strategy depends on having a monitoring system that can gauge the performance of the adaptive actions as the impacts and their consequences change progressively. An effective monitoring system depends on the organisation's ability to implement the strategy, the ability to sustain the monitoring system over time and a robust accountability system within the organisation for acting upon the signals and triggers.

A monitoring programme should be set up to track the achievement of objectives using the signals and triggers for reviewing what the indicator changes are showing. This can be done using existing monitoring systems or can be standalone for the particular infrastructure asset.

Responsibilities within the infrastructure provider agency for monitoring and accountability mechanisms and for actioning the trigger reviews should be assigned. A chain of decision making should be established in the responsible operational infrastructure provider, through to the council decision makers, for any change to the performance of the options and/or pathways. Review whether the objectives of the strategy can still be met with the agreed actions, options and available pathways, whether the levels of service can be met and whether the LTP investment funding can sustain the actions or set new ones including new triggers, options, pathways and monitor them in an ongoing manner.

5.2 Review and adjust

Water infrastructure provision involves many agencies including the provider, the funder, associated agencies like other above-ground and below-ground utilities, oversight agencies, and regulatory agencies, that are all involved in the implementation of the adaptive actions chosen. This means that a partnership mechanism will be required to integrate the review that emerges from the monitoring system. A formalised system will also enable effective communication and engagement with the communities that are served by the water infrastructure.

The monitoring programme can be embedded into implementation documents and regulatory processes if appropriate and considering the following questions will ensure a robust adaptive strategy can be implemented effectively.

- Who reviews the reporting on how the monitored indicators are tracking against the signals and triggers?
- Who audits the reporting when signals and triggers are reached?
- What resources are available to monitor indicators (including any longitudinal surveys)?
- How will the ongoing monitoring outcomes be communicated to the communities?

Note: Further detail on Steps 4 and 5 can be found in the Ministry for the Environment *Coastal Hazards and Climate Change Guidance* (2024).

Appendix 1. Helensville WWTP model example

For the Helensville WWTP case study Watercare provided data sets for tide, rainfall, influent and effluent, pond levels, topography, elevation and inflow scenarios. NIWA data was used for groundwater, rainfall/runoff projections, and erosion. NZSearise data was used for local VLM and local RSLR projections (VLM and global SSP data combined). Five SSP scenarios were used, and three influent scenarios were used (Table A1). An existing DAPP plan developed by Watercare was coded into the model (Figure A1).

To undertake this type of work, site-specific information is needed on:

- The asset(s) being assessed
- Topography
- Hazards
- RSLR
- Adaptive actions
- Impact of adaptive actions

Table A1. Scenarios modelled for case study one – Helensville WWTP. All combinations of SSP (climate change: X axis) and influent volumes (Y axis) were simulated.

	SSP1-1.9	SSP2-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
No change	✓	✓	✓	✓	✓
10% compounding increase per decade	✓	✓	✓	✓	✓
20% compounding increase per decade	✓	✓	✓	✓	✓

The code used for the research project on which this Guidance is based, was tailored for that research purpose. The code to be used in each use of the approach set out in this Guidance needs to be tailored to local conditions and specific pieces of infrastructure – the hazards considered, timestep, and spatial extent are site-specific. Therefore, rather than providing the research project code we outline the order of procedures in the Seaview model as a guide for writing code for the specific application of the approach.

The model was developed according to the XLRM framework (Kwakkel, 2017: 240), where "a simulation model is simply a function called with a set of parameters **X** and **L**. The return of the function is a set of outcomes of interest **M**."

M = ***f***(**X**,**L**)

Where **M** = outcomes of interest / performance metrics,

X = external factors.

L = policy levers.

R stands for relationships inside the system.

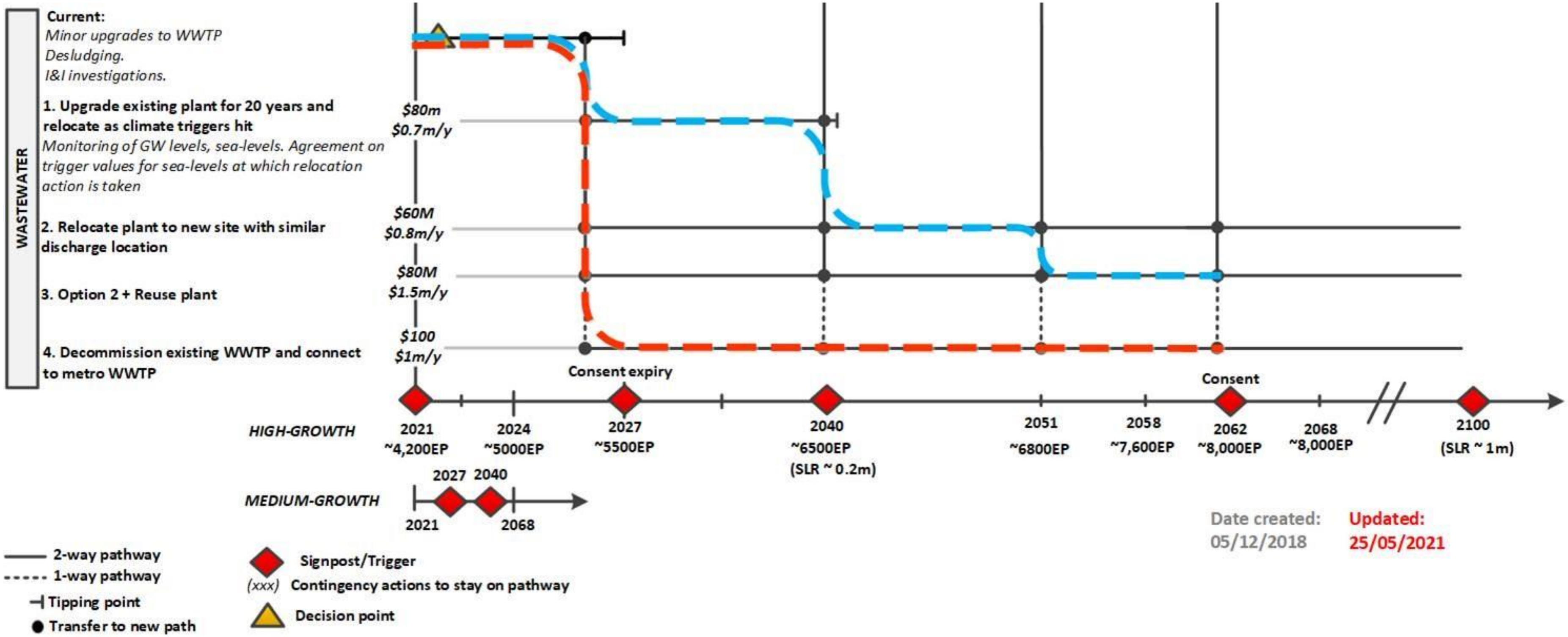

Figure A1. DAPP for Helensville-Parakai wastewater system. Blue line shows an incremental adaptation pathway, with gradual changes to the system prior to relocation of wastewater treatment elsewhere in the area. The red line shows a transformational change via a single shift to managed relocation. All actions in the DAPP were costed at the time of its development, so ROA was not used in the Helensville-Parakai wastewater case study. The plant upgrades implemented have a design life of 25 years, rather than the 20 years shown in the DAPP. Image courtesy of Watercare. Source: Allison et al., 2024.

Model order of procedures

Model setup:

- Physical layout of plant is defined.
- Setup elevation for each spatial area unit is fixed (to monitor RSLR).
- Values are assigned to each spatial area unit for:
    - season (wet/dry)
    - year
    - total SLR
    - total subsidence
    - high water level
    - forecast rain for each of the next three days
    - forecast river levels for each of the next three days
    - influent volume
    - volume of wastewater passing between each pond and ultrafiltration unit
    - depth of each pond
    - and timing of implementation of adaptive action 1

At each tick:

External factors (**X**: physical processes) occur:

- Sea level and vertical land movement update (according to SSP and VLM).
- Tide and surge height is selected (from a distribution).
- Forecast influent volumes for the next three days are selected (from a distribution).
- River flow rate is selected (based on influent volumes – influent and river flows are driven by the same driver: rainfall).
- River high water level is assigned (based on river flow).

Inundation of the WWTP by high water levels can occur at this timestep.

Relationships in system (**R**: internal plant wastewater transfers) occur:

- Pond levels are assessed based on forecast influent over the next three days. If influent levels pose a risk to plant operations, pond levels are lowered by increasing the processing rate, while ensuring discharge quality is maintained.
- Influent enters.
- Influent moves from pond 1 to pond 2.
- Influent moves from pond 2 to the ultrafiltration unit (in the case of unmanageable influent levels, an emergency discharge is available from pond 2 to the Kaipara River).
- Influent moves from the ultrafiltration unit to the tidal storage pond.
- Influent is discharged.

A discharge quality failure can occur at this timestep if plant processing capacity is exceeded.

Policy levers (**L**: adaptation) can be applied:

- Adaptive action one (plant processing capacity upgrade) will be implemented at the date selected by the model operator.

At each timestep, a multitude of site-specific performance metrics (**M**) relating to plant operations and ongoing plant viability on site are monitored.

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