Economic framework for analysis of climate change adaptation options

Framework specification

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Terms and definitions

In applying this model the following terms and definitions apply.

Adaptation
The process or outcome of a process that leads to a reduction in harm or risk of harm associated with climate variability and climate change (UKCIP, 2003).

Climate
The range of weather observed historically.

Climate change
A change in the range of weather.

Climate change scenarios
A set of scenarios adopted to reflect the range of uncertainty in projections (IPCC, 2010).

Discounting
Method for comparing the value of a dollar today to the value of that same dollar in the future, using specified discount rate.

Economic benefits
A benefit to a person, business, or society.

Event thresholds
Weather conditions under which the operation of an asset is affected

Greenhouse gas emission scenarios
Estimations of the future quantity of greenhouse gases that may be released into the atmosphere, based on global changes to society, economy, population and technology over time.

Infrastructure
Assets that support society (such as roads, bridges, dams and railways).

Mitigation
Reducing the impacts of climate change.

Net Present Value
Discounted benefits less discounted costs.

Probability distributions
Measure of likelihood associated with a range of possible outcomes, normalised so that the measure of all possible outcomes is 1.

Projections
Model-derived estimates of the future climate (IPCC, 2010).

Scenario
A plausible description of a possible future state of the world (IPCC, 2010).

Willingness to pay
The amount of money that individuals are prepared to pay to avoid the loss of a service.

1.0 Introduction

One of the key issues for asset owners and decision makers is how and when to adapt to the increased risks of impacts of climate change, especially when considering investment decisions. Knowledge of the physical impacts of climate change is growing, but is currently insufficient for decision makers. Decision makers and their advisors need methodologies to determine if/when, and how, to adapt to a changing climate. This study developed a methodology that bridges the gap between climate science and effective decision making in an uncertain environment.

1.1 Background

AECOM was engaged by the Australian Department of Climate Change and Energy Efficiency (DCCEE) to undertake a series of climate adaptation cost benefit analysis case studies of settlements and infrastructure. To do this, AECOM developed an economic framework that analysed the costs and benefits of adaptation in response to increased risks of climate change.

The economic framework was developed and then tested by application to three case studies. The specification of the economic framework was developed by AECOM, which then underwent a peer review process. Reviewers included the DCCEE, Dr Leo Dobes, Marsden Jacobs and Associates (MJA) and the Centre for International Economics (CIE). During the application of the framework, further adjustments and refinements were made.

The economic framework enables the costs and benefits of each adaptation option to be assessed against other options and the cost of inaction. The frameworking outputs suggest preferred timing of if/when to implement adaptation options for the case studies investigated.

Each case study involved combining scientific knowledge on the physical impacts of climate change, with technical expertise on adaptation options, and an analysis on the cost-benefit trade-off to the infrastructure owner and the community.

Three case studies were developed, namely:

- coastal inundation at Narrabeen Lagoon (‘the coastal settlement case study’);
- securing long-term water supply for Central Highlands Water (‘the water case study’); and
- temperature impacts on Melbourne’s metropolitan rail network (‘the rail case study’).

This report documents the process of undertaking an economic analysis of climate change adaptation options. It is anticipated this document will assist others to apply the framework to address knowledge gaps and guide the prioritisation of adaptation options.

1.2 Benefits of the framework

Infrastructure investors, owners, managers and governments need to understand the implications of the physical impacts of climate change. This new approach provides decision makers with detailed information about the preferred timing and scale to implement adaptation options, based on maximising the expected net present values of options to achieve greatest value for the community.

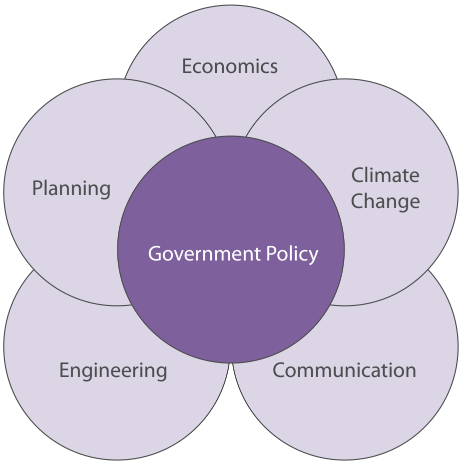
This economic framework enables options to be evaluated to generate information on the benefit and timing of each adaptation option. This information can be used to guide and inform decision makers on selecting which adaptation option to implement.

In applying this economic framework, the government and asset owners are able to robustly consider economics of the resilience and prosperity of settlements, governments and corporations in the face of increasing climate impacts. This approach to decision making has the potential to shape appropriate investment at the right time and scale, helping ensure assets are less likely to be over or under engineered.

The decision making approach is flexible and can be applied to all facets of infrastructure, including settlements, transport (roads, rail and bridges), utilities (water, power, telecommunications) and maritime (ports, offshore and subsurface structures). Decision makers can overlay their own specific asset requirements within this model to develop highly specialised results for their assets.

Most importantly the approach brings together six very distinct and separate disciplines into the one economic framework. The integration of a range of disciplines for addressing adaptation is represented in Figure 1.

Figure 1 **Integration of disciplines**



1.3 Project objectives

The objectives of this project were to:

- document the specification of an applied economic framework that assessed the economic viability of adaptation in response to increased risks arising from climate change; and
- develop a guideline for undertaking an economic assessment of climate change adaptation options.

1.4 Report outline

This report comprises three chapters:

- **Chapter 1** describes the objectives of the project, the nature of the analysis undertaken, and the benefits of the approach adopted.
- **Chapter 2** describes the framework.
- **Chapter 3** provides a step by step guide of how to apply the framework.

2.0 Economic framework

The economic framework analyses the trade-off between the loss of benefits in terms of loss of consumer welfare and/or socio-economic impacts, and the cost of adapting infrastructure in response to risks of changing climatic conditions. It relies on a cost-benefit analysis framework to compare the economic costs and benefits of the impacts of climate change, with the economic costs and benefits of adaptation.

To do this, the model of the economic framework is centred on a Base Case with no adaptation beyond business as usual and incorporates the projected changes in the climate. Adaptation options are drawn from an adaptation strategy space, refer to Section 3 for further discussion on adaptation options. Options in the adaptation strategy space are compared against the Base Case and the framework delivers a Net Present Value (NPV) for each chosen point. Subsequently the framework is iterated to choose adaptation strategies that maximise the NPV.

What follows is a discussion of the framework, including spreadsheets used to implement the framework, the economic parameters and the need to avoid double counting costs by establishing rules.

2.1 Model platform

The framework has been implemented using Microsoft Excel spreadsheets and, in the coastal settlements case, with the Palisade Decision Tools *@Risk Industrial* add-in. Microsoft Visual Basic for Applications (VBA) can also be used to program and automate certain routines.

@Risk enables Monte Carlo simulation to be undertaken. Monte Carlo simulation performs risk analysis by building models of possible results by substituting a range of values – *a probability distribution* – for any of the factors in the framework that has inherent uncertainty. It then calculates results (in this case, the present value of costs with/without adaptation) over and over, each time using a different set of random values from the probability functions. Depending on the number of uncertainties and the ranges specified for them, a Monte Carlo simulation could involve thousands or tens of thousands of recalculations before it is complete. Monte Carlo simulation produces a distribution of possible outcome NPVs.

There will be uncertainties with many of the framework inputs. Monte Carlo simulation involves the random sampling of these input variables (according to a predefined probability distribution), the recalculation of the spreadsheet using the sampled input variables, and the recording of the result. This is repeated for many thousands of iterations. A distribution of all the recorded results is then created, on which statistical analysis is undertaken (to determine the mean, maximum, minimum, standard deviation, 95th percentile, etc. of all the recorded results).

The *@Risk* software also allows the identification of the most significant input variables (i.e. which input variables have most impact upon the result). This can be used to inform the sensitivity analysis.

@Risk Industrial also includes a *RiskOptimizer*, which is used to identify real options in the analysis. During an optimisation, *RiskOptimizer* generates a number of trial solutions and uses genetic algorithms to continually improve results of each trial. For each trial solution, a Monte Carlo simulation is run, sampling probability distribution functions and generating a new value for the target cell - over and over again. The result for each trial solution is the statistic generates the minimum and maximum for the output distribution of the target cell (mean, standard deviation, etc.). For each new trial solution, another simulation is run and another value for the target statistic is generated.

Using the *RiskOptimizer* the preferred adaptation strategy is identified based on iterative evaluation to determine the suite of options maximising the NPV. This is achieved by varying the level of and year in which the adaptation intervention is introduced. The preferred adaptation strategy can then be determined.

2.2 Economic parameters

The economic parameters need to be established for each case study. Selection of the parameters should be guided by standard economic appraisal guidelines relevant to the case study under investigation and project parameters. This ensures the applicability of modelling results within the context of the infrastructure under investigation. For example, for the rail case study the economic parameters were aligned with the Australian Transport Council National Guidelines for Transportation System Management.

The economic parameters used in the framework that need to be established are listed in Table 1.

Table 1 **Economic parameters used in the framework**

PARAMETER	VALUE AND COMMENT
Appraisal period	Ideally the timeframe should cover the life of the asset under investigation at the minimum. For example the asset life of electricity distribution infrastructure is 40 – 60 years, therefore the recommended period of investigation is 60 years at the minimum. The coastal settlement case study and water case study used the appraisal period 2010 until 2100.
Time series	The recommended default value is a yearly time series. This should be checked against and reflect the duration of the appraisal period and the weather variables under investigation.
Discount rate	Reaching agreement on what discount rate to use for environmental projects is contentious. Standard infrastructure projects use a discount rate between 6% and 7%, the Victorian State Government typically uses 6.5%, while Infrastructure Australia uses a 7% discount rate. It is important to test sensitivities, say a 3% rate as well as a sensitivity test using a higher rate. Refer to discussion below.
Discount and base pricing periods	Should match the year the case study commences.

Discounting is a standard method to add and compare costs and benefits that occur at different points in time, allowing a comparison of future costs and benefits against today's costs and benefits (Garnaut, 2010).

In the context of the adaptation options considered for this study, costs are assumed to be accrued today, with benefits accruing in the future. For the NPV of a particular adaptation option to remain constant, the application of higher discount rates require benefits to be accrued either more quickly or in greater volume. As such, given the long term nature of climate impacts, a low discount rate, say 3% or less, will favour earlier adaptation, whereas a higher discount rate will favour later adaptation.

2.3 Establish economic framework rules

The framework stresses the need to avoid double counting benefits or costs even for combinations of adaptation options. These relationships need to be considered on a case by case basis when applying the framework. During the initial scoping phase these considerations will need to be carefully planned. In all cases, a clear justification of the approach taken will be required. A discussion on each consideration is presented below.

Correlation between weather events

It is possible that there is correlation between weather events, which must be properly considered. For example, drought does not occur at the same time as flooding and a drought typically occurs for longer than a year. In general, for ease of modelling, each weather event is assumed to be independent. It will be important to consider any possible correlated weather events on a case by case basis.

Catastrophic events

The framework could possibly select a catastrophic event that is likely to permanently damage or destroy the subject infrastructure assets. If the infrastructure has to be completely rebuilt it is assumed that it will be rebuilt to withstand future climate events (forced adaptation). This logical conclusion will need to be built into the Base Case as business as usual behaviour. In other words, when a catastrophic event occurs the asset will be rebuilt to higher standards, and this relationship will need to be reflected in the framework.

Cumulative impacts

When an infrastructure asset is affected by two or more extreme events simultaneously, the costs are not additive. A modelling relationship will need to be established to ensure this is considered.

Iteration loop

Different benefits can be derived from different adaptation options. Some adaptation options may reduce the impact of a particular weather event on infrastructure, while others may reduce the cost or increase the benefits and some may perform both functions. The framework should enable the maxima or minima of the objective function to be identified and the maximum net benefit of adaptation to be identified compared to a base case of no adaptation. To identify better adaptation options (in terms of combination of options, scale of each and timing) that improve the NPV the framework needs to be built with an iteration loop.

Selection of data for a climate variable

Data for each climate variable must be obtained from the same climate model to ensure the combinations of variables are physically plausible (CSIRO and BoM, 2007, Ch.6). For impact assessments involving combinations of weather variables such as this, this approach is not appropriate. Avoid mixing data from the different Global Climate Models (GCMs). Instead use each GCM individually for the full run of the economic framework and then compare results across each CGM.

3.0 Process

In applying the framework several inputs are needed– refer to Section 2.0 for a discussion on the framework. The relationships between the various inputs are built within the framework. The framework is run combining inputs and relationships to determine the NPV of each adaptation option under assessment.

Six stages are involved in applying the framework as outlined in Figure 2. A discussion on and a summary of the objective of each stage follows.

Figure 2 **Model methodology**

Stages	Key outcomes
1. Scope the study	• Project parameters are set • The study boundary is established • Modelling relationships are identified
2. Quantify impacts of historical weather events	• Weather thresholds are identified • Historic dates when thresholds were exceeded, and their impacts are identified • The relationship between a weather event and an impact is established
3. Quantify changes in future weather events	• The number of projected yearly events triggering thresholds are identified for different climate change scenarios
4. Model impacts without adaptation	• The assumptions and economic parameters governing the model are established • The model is designed, built and tested • The relationship between economic costs and events is determined
5. Model impacts with adaptation	• Adaptation options are identified • Costs and benefits for the prioritised adaptation options are developed • The model is run to maximise the NPV of adaptation options
6. Analyse portfolios of adaptation and communicate the findings	• Modelling results are analysed to prioritise adaptation options and determine the preferred timing for implementation

3.1 Scoping the study

For the asset under investigation a boundary of the study needs to be set. The objective is to define the weather variables and thresholds at which the operation of an asset is affected. To achieve this, seven parameters need to be defined in the initial stage of the investigation.

Key objective of this stage: To define the weather variables and thresholds at which the operation of an asset is affected.

3.1.1 Establish the physical boundary of the impacts

A clear definition of the asset under investigation needs to be established to enable the assessment to be undertaken. A physical boundary can be set based on an understanding of the infrastructure organisation's objectives and stakeholders. The internal and external factors to which the infrastructure is sensitive to a change in climate needs to be identified. The boundary of the assessment can then be defined based on the objectives, stakeholders and knowledge of the critical infrastructure points.

3.1.2 Establish the framework for the economic model

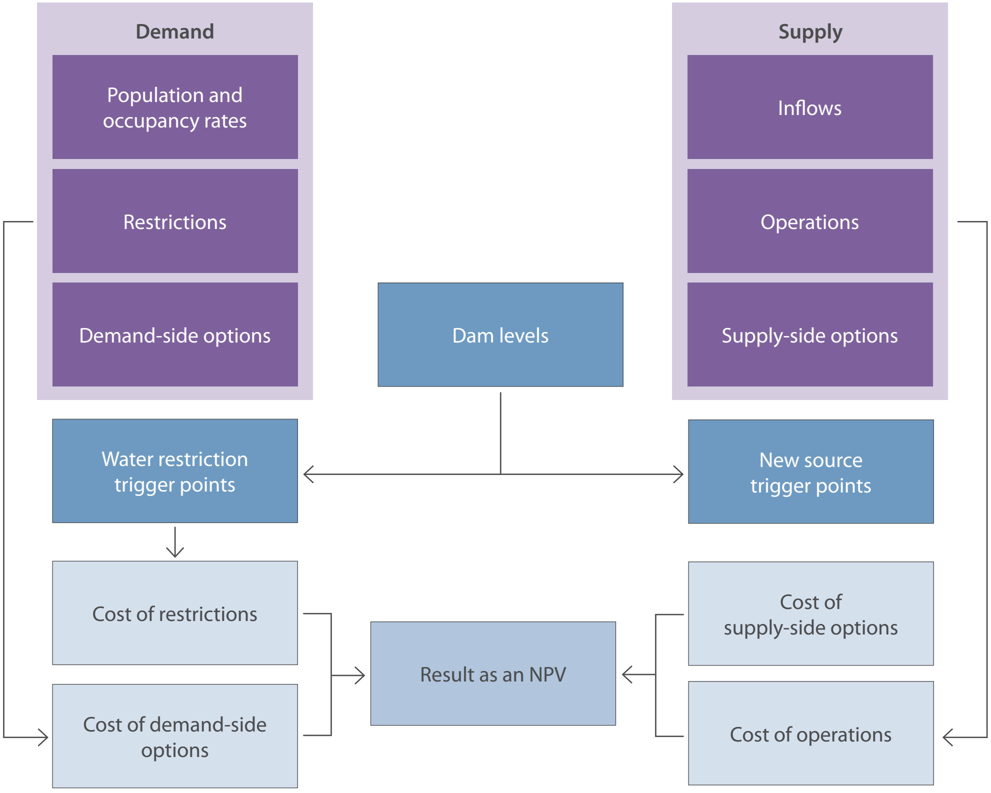
The framework of the economic model needs to be established based on the context of the investigation. Specifically, the platform used to build and run the framework, the economic parameters that will be used and the framework rules set. In all cases, a justification of the approach taken must be provided. Refer to Section 2.0 for a discussion on these items.

Another critical factor involves setting the relationships between the inputs to the economic model. For example in the water case study, to balance water demand and supply within the economic model designed. Using the principle of a water demand-supply balance, costs were determined based on combining:

- the capital cost of supply side options, for example new water sources if any are available;
- the cost of operating water sources each year;
- the cost to the community of water restrictions if any are available; and
- the cost of additional demand side options if any are available.

A diagrammatical representation of these relationships to determine the combined cost of balancing demand and supply for the water case study model is represented in Figure 3.

Figure 3: **Relationships within economic model for the water case study to balance demand and supply**



3.1.3 Define the climate variables

The identification of climate variables will be based on the sensitivity of the infrastructure to meet the objectives in a changing climate. This will need to consider the location, type of infrastructure, life of the asset and the impacts of climate change. The identified climate variables can be prioritised based on the level of risk the climate variable poses to the operation of the infrastructure. The critical climate variables are then taken forward for investigation.

For example, the coastal settlement case study utilised projections of climate change impacts on rainfall and sea level to determine flood heights. The study recognised flooding of Narrabeen Lagoon does not operate in isolation of the coastal and estuary processes, but interacts with them in complex ways. However, the coastal and estuary processes are complex to model and are likely to exacerbate climate change impacts on flooding. The full spectrum of the coastal processes interactions with the lagoon were not factored into the study, noteably coastal erosion. Instead the critical climate variables affecting flooding were investigated. Their exclusion makes the results of the study moderately more conservative yet no less informative for prioritising adaptation responses.

3.1.4 Identify weather event thresholds

For each critical climate variable, the weather threshold under which the operation of the asset will be affected needs to be identified.

For example, for the rail case study, the critical thresholds are the temperatures at which the operation of the metropolitan rail network is affected. Thresholds were identified by breaking the network into key infrastructure components including rail track, rolling stock and signalling. In consultation with rail engineers and the Victorian Department of Transport, temperature thresholds were identified at which the operation of the network starts to be affected.

3.1.5 Define the duration of the assessment period

The duration of the assessment should be based on the life of the asset under consideration (e.g. 100 years for a bridge). The framework's assessment of the risks of climate change impacts on infrastructure is recommended to be based on annual time slices.

3.1.6 Define greenhouse gas emission scenarios

Greenhouse gas (GHG) emission scenarios are estimates of the future quantity of GHGs that may be released into the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) has agreed to six GHG scenarios - each provides a different estimate of the future trajectory of GHG emissions. The Intergovernmental Panel on Climate Change (IPCC) developed scenarios in 1990, 1992 and 2000 and released a Special Report on Emission Scenarios (SRES). The IPCC emission scenarios are divided into four families: A1, A2, B1 and B2. A description of each scenario is provided in Table 2. To reflect the latest rapid changes in societies since 2000, new emission scenarios are currently under development.

Each scenario has been built based on demographic, economic and technological assumptions. These factors are likely to influence future emissions and, therefore, the extent of climate change. Recent observations of actual global GHG emissions are trending towards the upper end of the ranges described in the IPCC's fourth assessment report (Rahmstorf et al., 2007). As the lower GHG emission scenario is unlikely to be realised, it should be used with caution. It is therefore prudent to assess the impacts of climate change associated with the higher end emission scenarios.

The following specific scenarios were used for all three case studies:

- **The A1FI scenario** describes a future with the highest concentrations of GHGs, and therefore the greatest climate change, of the IPCC's emission scenarios.
- **The A1B scenario** describes a lower emissions future than the A1FI scenario, particularly in the latter half of the 21st century.

Table 2: **SRES Scenarios (Nakićenović & Swart, 2000)**

SRES SCENARIO	DESCRIPTION OF SCENARIO	
A1FI	Rapid economic growth, a global population that peaks mid 21st century and rapid introduction of new technologies	Intensive reliance on fossil fuel energy resources
A1T		Increased reliance on non-fossil fuel energy resources
A1B		Balance across all energy sources
A2	Very heterogeneous world with high population growth, slow economic development and slow technological change	
B1	Convergent world, same global population as A1 but with more rapid changes in economic structures toward a service and information economy	
B2	Intermediate population and economic growth, emphasis on development of solutions to economic, social and environmental sustainability	

3.1.7 Select the climate modelling

Climate scientists have developed Global Climate Models (GCMs) to simulate the Earth's climate system and to project climatic changes into the future. While there are 23 GCMs, not all are available or appropriate for use for all climate variables and locations. It is recommended the selection of GCMs is undertaken in consultation with CSIRO. Selection should be based on consideration of:

- the format of the outputs are compatible with the study (i.e. they can be applied within the framework of the framework); and
- their anticipated accuracy for projecting changes for the region under investigation.

For example, all climate variables were considered for the rail case study. However, all variables except extreme temperature were excluded due to a lack of specific data that could be provided in a format that could be used for the economic modelling of a rail network across all metropolitan Melbourne compared to data for a specific site.

3.2 Quantifying the cost impact of historic weather events

The objective of this stage of the investigation is to develop a relationship between an historic weather event and the cost of that event. This requires the definition of a performance measurement indicator (PMI), identification of the historic dates where weather thresholds were triggered (referred to as 'events') and the allocation of a cost impact for each event. This is achieved by building on the framework input developed in Section 3.1 – identification of the weather thresholds at which the operation of the asset is affected.

Key objective of this stage: Quantify the cost of a historic weather event.

3.2.1 Setting the performance measurement indicator

This step requires a performance measurement indicator (PMI) to be identified that enables modelling of the likely impact of future weather events on infrastructure. It is critical the PMI gives access to robust and meaningful data. This work concluded the most appropriate measure for evaluation is to use an existing PMI. This enables a relationship between historic weather events and the performance of infrastructure to be established.

For example, for the rail case study, Passenger Weighted Minutes (PWM) was the chosen PMI for recording network delays. By analysing historic weather data obtained from the Bureau of Meteorology (BoM), AECOM identified the dates on which these thresholds were exceeded. We then provided these dates to the Victorian Government Department of Transport (DoT), who gave us the PWM for each date the thresholds were exceeded (from their 'TOPS' database).

For the water case study, the PMI was a 95% level of service (LOS), that is, the ability of a water authority to provide security of supply, or the overall ability of a water supply system to meet demands. When expressed as a percentage, the LOS implies the frequency with which demands are expected to be met without imposing water restrictions. A 95% LOS implies that the water supply system should be capable of meeting demands without imposing restrictions in any more than one in 20 years.

3.2.2 Historic dates when weather thresholds were triggered

Historic weather data can be obtained from the BoM for the climate variables under investigation. Based on the weather event thresholds established in Section 3.1, the data is analysed to identify the dates on which these thresholds were exceeded.

For the rail case study, using historic recording of the PWM in the DOT TOPS database (that is the PMI), the relationship between a weather event threshold and the delay to network performance was established.

3.2.3 Cost of an event

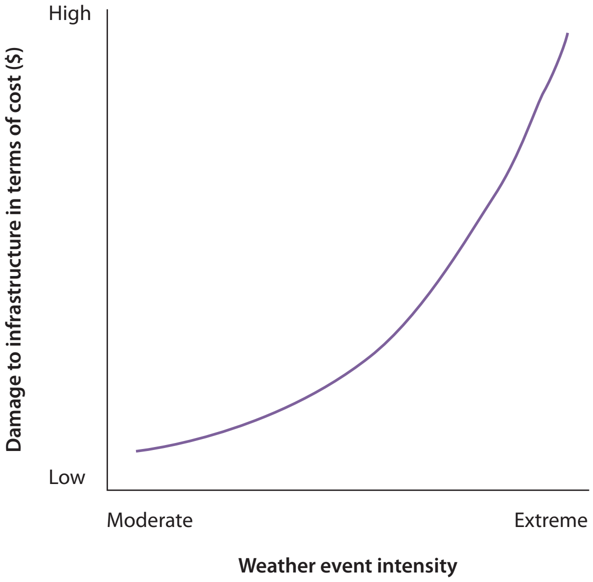
This step involves determining the impact on infrastructure from an historic event and the associated economic cost. Factors to consider include: costs from the damage to infrastructure, loss of infrastructure service and consequent loss of consumer welfare (i.e. measured as willingness to pay to avoid loss). Sourcing data on the economic impacts will be driven by the case study under investigation but may rely on historic data, standard engineering costs, level of exposure, design standards and industry guidelines. This is an important step in documenting the base case against which the adaptation options will be compared.

For example, the coastal settlement case study used willingness to pay to avoid flooding, based on values estimated in a study in the Hawkesbury region.

Based on the collated data, relationships need to be formed between the duration of the impact and the cost, in terms of loss of service and the flow on economic and social impacts. This is represented in Figure 4 – the shape of the curve is illustrative only.

In summary, this step involves determining the relationship between the weather event and the loss of welfare.

Figure 4: **Indicative relationship between an event and the cost impact of the event**



3.3 Quantifying future weather events

The projected change in an event over the period of investigation needs to be developed as a modelling input. The format of this data depends on several factors. The weather variables can be categorised as an extreme event, such as a heatwave or an incremental change over time, such as an increase in the long term average temperature. For each climate variable, a weather event probability distribution curve will need to be developed.

Key objective of this stage: To develop the model input representing the projected magnitude and number of future events.

3.3.1 Projected changes

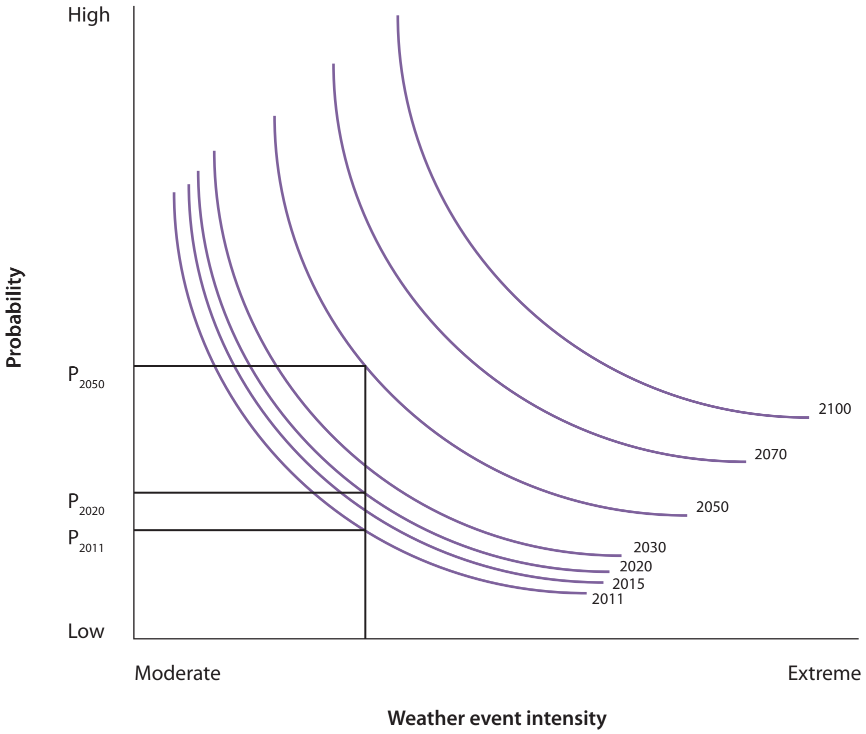
The projected change in a climate variable can be modelled by CSIRO based on the selected GHG emission scenarios, the GCMs and the climate variables – refer to the discussion in Section 3.1. This step is common to all climate variables. The configuration of the data can be presented in several formats. Whatever format is selected, it must align with the framework. For example, the projected changes could be expressed as:

- an incremental change based on historic weather (i.e. a percentage increase from the baseline);
- a change in the number of events occurring per year; and
- a percentage change in an extreme event.

3.3.2 Probability distributions

Probabilities need to be assigned to each climate variable to represent risk appropriately. For each climate variable, a weather event probability distribution curve will need to be developed. This should be based on historical data. The potential impact of climate change can then be modelled as a change in the shape of the curve over time. An illustrative representation of what the distributions look like is presented in Figure 5.

Figure 5 **Weather event intensity probability distribution curve**



For the rail case study, all climate variables except extreme temperature, were excluded due to a lack of appropriate and available data. The projected number of days when the temperature thresholds might be exceeded on a yearly basis due to future climate change was established in consultation with CSIRO. Projections were then generated by CSIRO for the annual number of days where the temperature is likely to exceed the thresholds (i.e. 34.5°C, 37.0°C and 40.0°C), for each GHG emission scenario (i.e. A1FI and A1B), from 2020 to 2099. . The Australian Water Availability Project was used to model these results. To provide a baseline for comparison with this projected data, the historic period 1970 to 2009 was used.

For the water case study, projections for annual rainfall and annual evaporation were sourced from OzClim - a tool developed by CSIRO. The projected changes in the rainfall runoff were determined on a yearly basis by combining two factors: the rainfall runoff sensitivity 'rule of thumb' established by Jones *et al*. and the projected changes in rainfall and evaporation (2006a).

For the coastal settlement case study, projecting the changes in the extreme climate variables involved a greater level of complexity. As per the two previously mentioned case studies, the projected changes in the climate variables were determined using CGM. As this case study involved extremes, weather event probability distributions were determined and translated into weather event model inputs.

3.4 Modelling impacts without adaptation

This stage involves building, testing and running a model implementing the framework to generate climate change cost without adaptation. The inputs developed in the previous stages are pulled together by forming relationships and rules within the framework. This governs how the framework analyses the impacts. The magnitude of the climate change costs will be generated in this stage, which will be used in the next stage to guide the selection of adaptation options.

A range of assumptions will need to be made in this stage of the investigation. An assumption that was made for this stage was that the majority of PMI will result from the shift in the climate variables. While in reality there are a range of other factors that may contribute to impacting the PMI, for the purposes of this study it is assumed that they are insignificant. Another critical assumption is that all parameters remain constant, while in reality the performance of the infrastructure will change over time.

During this project stage, a model is developed to calculate the impact on the PMI due to the projected change in the climate variables. All model inputs, excluding adaptation options, are developed and the framework is tested. A key aspect of this testing involves designing the framework to analyse the relationships identified in Section 3.1, by drawing on the framework inputs developed in Section 3.2 and 3.3.

The framework will draw together the following modelling inputs:

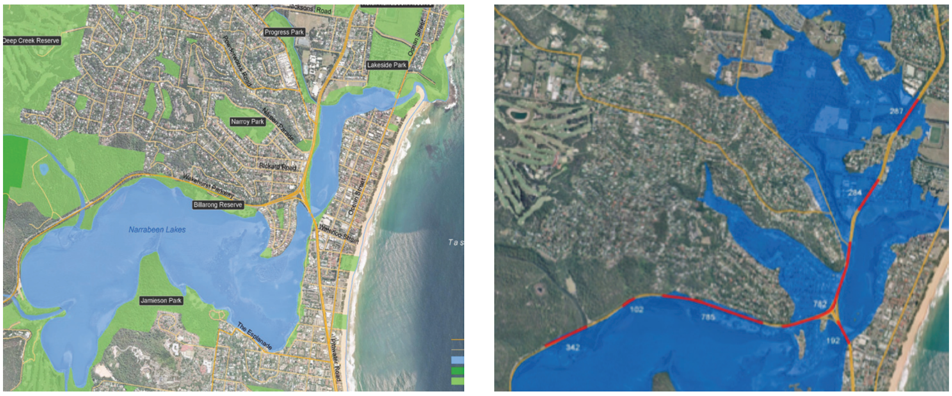
1. weather event thresholds ('events') at which the operation of an asset is affected
2. cost of an historic event
3. projected changes in the climate variables
4. probability distributions for the magnitude of an event and the number of future events per year.

Key objective of this stage: To run the model to generate estimates of the order of magnitude of climate change costs that will guide the selection of adaptation options.

For the coastal settlement case study, flooding may result in building damage, plus loss of personal belongings, memorabilia and pets, and the need for temporary accommodation. It could also result in property damage and travel disruptions, creating both short-term inconvenience and long-term reconstruction issues. Most significant is the loss of life from accidents, drowning or stress.

A visual image illustrating the extent flooding could impact the community around Narrabeen Lagoon is provided in Figure 6.

Figure 6: **An aerial map of Narrabeen (left) and of the likely flood impact (right)**



3.5 Modelling impacts with adaptation

The previous stage of the investigation will have modelled the cost of climate change without implementing adaptation options – refer to Section 3.4. This information will be used to identify the largest economic impact and to give a sense of scale to the impacts being mitigated. Adaptation options are then identified to mitigate the impacts and the economic model is run. A discussion on these two stages follows.

Key objective of this stage: To run the model and generate NPV outputs of each adaptation option for analysis.

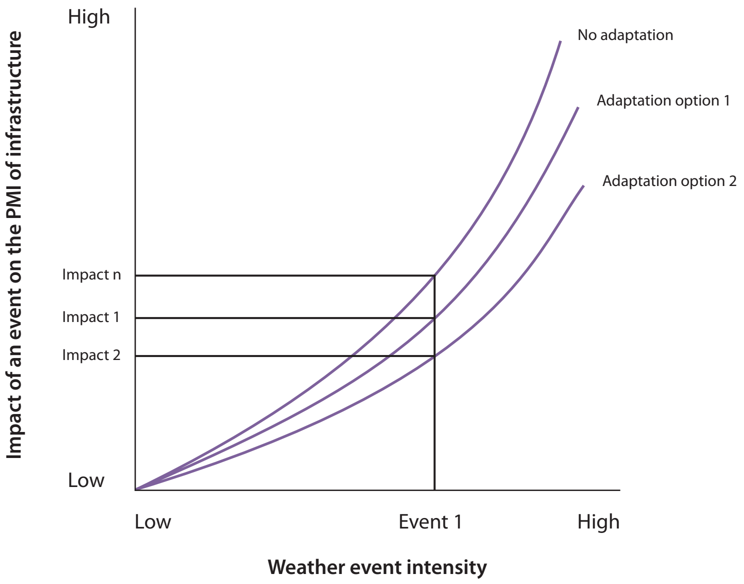
3.5.1 Identifying adaptation options

This stage identifies a 'strategy space' of adaptation strategies that can preferably be combined.

A key part of identifying adaptation strategies will be through consideration of where the biggest impacts occur. A workshop could be held with key stakeholders to establish a set of adaptation options. It will be important to consider a range of adaptation strategies, from engineering solutions to non-technical solutions. For example, changes in planning laws or behaviour change. It is very important to be able to combine adaptation strategies and calculate combined costs and benefits.

An illustrative representation of adaptation options identified to reduce the impact associated with a weather event is provided in Figure 7. The same event causes a lower impact on infrastructure with adaptation. Examples of this include adding more drainage so that the same weather event causes less flooding and hence less damage.

Figure 7: **Weather event versus infrastructure impact curve**



There is no limit on the number of adaptation strategies that can be investigated. However, as the number of options increases, the complexity of the framework will also increase. Based on previous case studies, it is recommended no more than ten options are identified. Selection of the number of options should be governed by the objectives of the case study under investigation

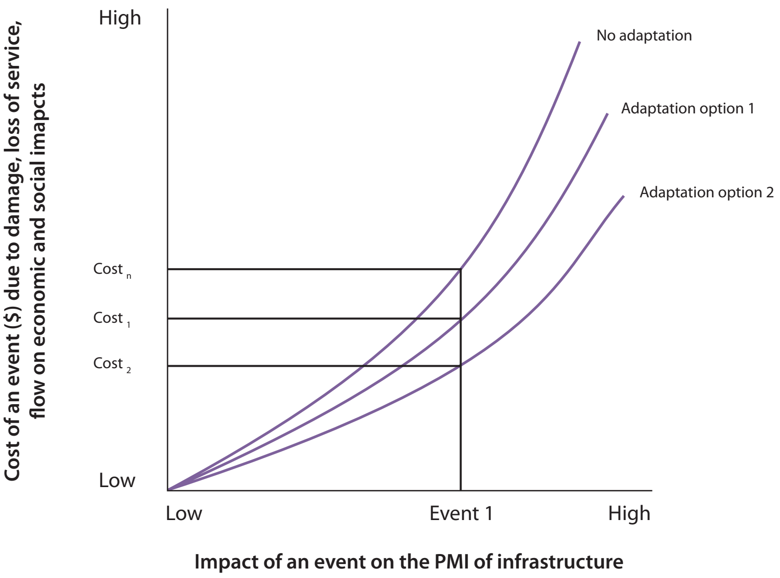
Each adaptation option has an associated cost of implementation, along with potential benefits.

Benefits are derived from maintaining the PMI, avoiding asset failure and improving the operational response cost. Additional benefits may arise depending on the adaptation option. For example, an adaptation option may be to install double glazing into residential dwellings to minimise the impact from future temperature rises. This improved insulation will also generate benefits in winter and result in lower energy bills and greenhouse gas emissions.

Costs will be incurred to implement and derive the benefits from the preventative measures. For each identified option the associated cost and benefit needs to be translated into an economic modelling input. A willingness to pay approach can be used to measure benefits.

An illustrative representation of adaptation options designed to reduce the economic costs associated with a particular infrastructure impact is provided in Figure 8. The same impact on infrastructure results in a lower cost with adaptation. Examples of this include building a new road so that when the road floods there is an alternative route and fewer people are affected.

Figure 8: **Weather event versus infrastructure impact curve**



For the urban rail case study, a set of adaptation options that might reduce the impact of the projected changes in extreme temperature events was identified. This case study considered a range of adaptation responses, including infrastructure and non-infrastructure options. The adaptation options explored include:

- concrete sleeper replacement;
- replacement of air conditioners in all rolling stock to ensure they operate up to at least 45°C;

- installation of regenerative braking;
- changing the cabling in the power lines and/or tensioning of the lines;
- signalling equipment replacement and installing backups for their electronics;
- behaviour change mechanisms to influence commuter travel behaviour (i.e. phone-based early-warning systems);
- heatwave behaviour change program (i.e. messages, issuing water and providing shade); and
- providing alternative modes of transport (i.e. buses).

Data on the adaptation costs and benefits were then collected.

For each adaptation option there is a benefit and a cost. Benefits are derived from avoiding network delays, asset failure and operational response cost. Costs will be incurred to implement and derive the benefits from the preventative measures.

A summary of the selected adaptation options and the inputs developed for each option is provided in Table 3.

Table 3: **Summary of the adaptation options and the data inputs**

ADAPTATION OPTION	LIFE OF BENEFIT (YEARS)	REDUCED DELAYS (% ↓)	CAPITAL COST ($)	ADDITIONAL OPERATIONAL COST ($ / YEAR)	TIME TO IMPLEMENT ADAPTATION OPTION (YEARS)
Concrete sleeper replacement	60 (100+)	20%	$122.4M	Some minor reduction in replacement of timber sleepers.	5
Replace air conditioners in all rolling stock to 45°C	20	20%	$23.2M	$4M every 6 years	1
Regenerative braking	15	5%	$65M	$10M saving in energy per year	6
Change the cabling in the power lines and/or tensioning of the lines	60	10%	$1.2M	$0.12M (cost to inspect and keep the pits clean assumed to be 10% of capital)	4
Signalling equipment protection of the electronics	30	5%	$200M	Nil	3
Heatwave behaviour change program	Ongoing program	Less than 5%	Nil capital cost requires $1M p.a. operational cost	$10,000 per event	1

In summary, this stage involves:

- identifying up to ten adaptation strategies that could mitigate climate change impacts;
- estimating the costs and benefits for each adaptation option (capital and operating); and
- identifying how the adaptation option will affect the impact of the weather event on infrastructure and the economic benefits generated.

3.5.2 Run the economic model

The model operates with a range of inputs in a Microsoft Excel spreadsheet. The framework is run to simulate each climate change scenario and each adaptation option to identify the preferred timing for implementation. The preferred timing correlates to the year the NPV for an adaptation option is at its maximum over the appraisal period.

For each time step in the appraisal period, the economic model is run with all model inputs to simulate a series of scenarios on the projected weather events and the associated impacts. The framework is run to determine the:

1. impact on the PMI for each scenario (with and without adaptation options); and
2. cost of the impact (with and without adaptation options).

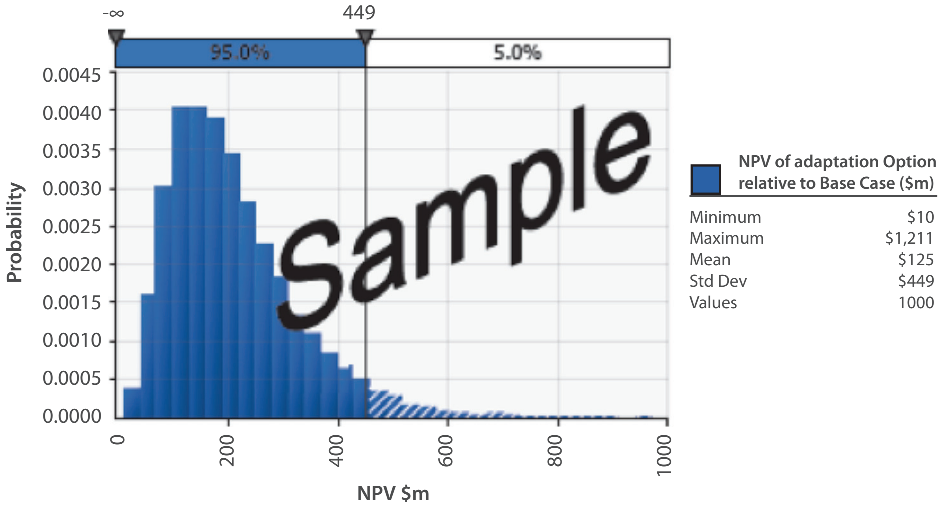
Once the impacts and costs are generated for each event, the framework then:

3. discounts an event's impact costs for each year of appraisal;
4. discounts adaptation capital costs; and
5. summarises all discounted costs across the entire appraisal period and records the results.

The process is then repeated, running scenarios to maximise the NPV of adaptation options to identify the preferred timing for implementing each option. This generates an adaptation option distribution statistic for each option.

An example distribution of the NPV modelling results for an adaptation option is represented in Figure 9. The distribution shows the NPV for 95% of the 10,000 iterations run is under $449m, with a mean of $213m. Some higher costs were recorded at a maximum NPV of $1,211m.

Figure 9: **Net Present Value with adaptation**



Optimisation can be employed to determine the preferred set of adaptation options by comparing the net benefits under different adaptation combinations. The probabilistic modelling can be extended to seek out combinations that maximise the net benefits of combined adaptation.

To achieve this:

- the optimisation feature, ideally using a risk-based modelling environment is used to maximise expected NPV of benefits;
- the maximising model is used statistically; and
- different combinations of adaptation options are assessed to search for portfolios with higher benefits.

Outputs generated by the framework for each option include a distribution of the adaptation:

- costs under each climate change scenario;
- costs under all climate change scenarios; and
- present value of cost with adaptation less present value of cost without adaptation.

3.6 Analyse outputs and suggest portfolio

The final stage of the investigation involves analysing the outputs generated from running the economic framework. The distribution statistic is then assessed to determine the economic viability and preferred timing to implement an adaptation option. This is based on maximising the NPV of the option. The results and analysis of the NPV of the adaptation options are then captured and communicated in a report.

The analysis of the adaptation options will identify the preferred timing to implement options to mitigate the risk of climate change impacts.

3.6.1 Coastal settlement case study findings

Climate change is expected to increase sea level, the frequency and intensity of storms, and rainfall in the Narrabeen catchment over the coming century. Decision makers will need a better understanding of the social costs and benefits to their communities of the different adaptation measures that could be implemented to reduce inundation. This pioneering study estimated the social benefits of adaptation to climate change in terms of willingness to pay, rather than just costs avoided. It also employed Monte Carlo analysis to generate more realistic probabilities of overall costs and benefits, as well as modelling the expected future values of variables such as rainfall using extreme value analysis rather than just taking averages. Six possible adaptation measures were analysed:

- Lagoon entrance opening
- Lake Park Road levee
- Progress Park levee
- Nareen Creek levee
- Flood awareness
- Planning control

Opening the ocean entrance to Narrabeen Lagoon permanently by excavating a channel through the headland rock shelf would lower the water level by up to 1 metre. Modelling results suggests that a 70-metre wide channel is economically viable now, but the benefits increase if deferred until 2035. However, the study suggests that a 100-metre wide channel would be far more expensive, with little additional benefit, and could therefore not be justified economically. Construction today of a 3 metre high levee on Lake Park Road along the southern boundary of the Sydney Lakeside Holiday Park would generate net economic benefits of $0.9 million, and is therefore a viable proposition. However, a similar levee at Progress Park is unlikely to generate sufficient social benefit to outweigh the costs involved. A floodwall and floodgates along Wakehurst Parkway would prevent rising floodwaters in the lagoon from backing up into Nareen Creek, which feeds into it. Although almost 300 houses would be protected, the study suggests that the cost involved outweighs the benefits.

A system to provide Pittwater residents with early warning of floods would be relatively inexpensive, and would allow them to move valuable belongings and business merchandise to higher ground to avoid damage. With net benefits of $12 million in present value terms, it would be worthwhile implementing this strategy immediately.

Amending planning regulations to require an increase in floor height by at least one metre for all new buildings and renovations to existing buildings would reduce flood damage over time. Although a house is renovated only every 40 years on average, the beneficial NPV from immediate adoption of this measure would be at least $13.8 million. Overall, a socially and economically justifiable strategy for the Narrabeen community would be to immediately institute an early flood warning system, amend planning regulations, and build the Lake Park Road levee, followed by channel widening in 2035. The following table shows an appropriate portfolio of measures that, together, have higher benefits than individual actions.

Table 4 **Summary of modelling results for the coastal settlement case study (Narrabeen Lagoon)**

ADAPTATION MEASURE	DIMENSIONS (M)	TIMING
Lagoon opening: Permanent opening of the lagoon entrance. By controlling the build up of sand, flood waters can flow out unimpeded reducing the severity of flood events.	70.0 width	2035
Lakeside levee: Increase the level of existing flood protection at Lakeside by increasing the height and length of the levee.	2.7 height	2010
Progress Park levee: Construction of a new earth mound levee in Progress Park for flood protection for mainly commercial/ industrial properties.	2.5 height	After 2100
Nareen Creek levee: Flood wall and flood gates constructed to protect the lower reaches of the Nareen Creek catchment from backwater flooding from the lagoon.	2.3 height	After 2100
Flood awareness: Early flood warning systems designed to prepare residents and businesses to take steps to minimise damage to property, contents and operations.	Not applicable	2010
Planning control: Planning regulations increasing minimum floor height for all new buildings and building renovations to reduce severity of floods and the number of buildings impacted.	Height not modelled	2010

3.6.2 Water case study findings

The study modelled water supply and demand over time to identify when new sources of water supply would be required to balance demand and supply, based on a series of different strategies. This modelling found late 2050s to be a critical period for water shortages and identified when a future additional supply measure would be required. In determining which measure to implement, the cost of not supplying water was accounted for (based on consumer willingness to pay for water). The costs for the strategies are shown in Table 5 including the preferred timing for their implementation. The average total cost of each strategy includes their average operating and capital costs combined with the average cost of water restrictions.

Table 5 **Summary of cost by strategy**

STRATEGY (EACH STRATEGY INCLUDES A COMBINATION OF MEASURES)		YEAR OF FIRST NEW SOURCE	AVERAGE COST (PRESENT VALUE $M)		
			OPERATING AND CAPITAL	WATER RESTRICTIONS	TOTAL
1	Forward planning based on 100 year history of inflows	2065	153	7.6	161
2	No new household connections	2087	95	2,101	2,195
3a	Forward planning based on reduced inflows	2057	151	1.6	153
3b	Forward planning based on reduced inflows with a reduced reliability of supply	2064	142	5.1	147
4	Dual reticulation to new developments	2057	163	2.4	166
5a	Scarcity pricing	2057	150	1.4	151
5b	Scarcity pricing with a reduced reliability of supply	2064	141	4.8	146

Key conclusions drawn from this study include:

1. **Accepting a lower security of supply implies lower cost:** The results indicate that accepting a lower security of supply reduces infrastructure costs by $9m (Strategy 1, 3b and 5b). However, under the model, the cost of water restrictions increases. The key consideration here is whether the lower infrastructure costs more than compensate for the higher frequency and additional cost of water restrictions (which is approximately $3m to $4m). Water restrictions (Stage 3 and 4) were found to occur in two to three % of years and generally only in the latter half of the century.
2. **Benefits of scarcity pricing:** The scarcity pricing options (Strategies 5a and 5b) indicate marginal benefits in the range of $1m to $2m when compared with the current pricing counterparts (Strategies 3a and 3b).

3. **High cost of providing alternative water sources:** The alternative water supply options examined, stormwater and recycled water, have a higher cost than upgrading the existing infrastructure that delivers water from the neighbouring Goulburn catchment (for example, augmenting the recently connected 'Superpipe' is a lower cost option than other alternative water supply options). This result reflects the particular options available for Central Highlands Water and should not be assumed to be similar for 'alternative' options available in other cities and regional centres.
4. **High cost of constraining new connections:** The results demonstrate the extremely high cost associated with limiting new household connections to the reticulated network (Strategy 2). The cost of this strategy is approximately 12 times higher than the cost of any other strategy considered.

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