Simplified real options analysis for climate change adaptation

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Executive Summary

1. Uncertainty about the magnitude of climate change will remain high for many decades. If climate change is less severe than communities expect, they may end up spending too much on adaptation; if it is more severe than expected, they may not adapt quickly enough.

2. Policymakers should choose adaptation actions that minimise total climate-related costs to society, where these costs include the funds spent on adapting and the costs incurred by the community when weather-related events occur. Real options analysis (ROA) is an ideal decision-support tool because it handles the flexibility embedded in investment programmes, such as the ability to accelerate, delay, or rescale investment.

3. ROA is complex and resource-intensive, so it is not widely used for relatively small projects. This is unfortunate because much adaptation spending will fund relatively small projects under the jurisdiction of local authorities. These authorities have the local knowledge and incentives that are essential to good decision-making, but many of them have limited analytical resources. They need approaches that are simple enough to be useful for evaluating small- and medium-scale adaptation decisions yet retain a degree of economic rigour.

4. This report evaluates the performance of six alternatives to ROA, which are listed here in increasing order of complexity:

   - Standard cost–benefit analysis (CBA), implemented at fixed intervals.
   - Three small modifications of CBA, which are straightforward to implement.
     - Invest when the project's benefit–cost ratio (BCR) exceeds a particular constant threshold.
     - Invest when the project's internal rate of return (IRR) exceeds a particular constant threshold.
     - Invest when the net present value of investing immediately is greater than the net present value of investing at each of a small set of fixed future investment dates.

  - Two representatives of the type of ROA that analysts might carry out in practice, which involve simplifying assumptions that potentially adversely affect their performance.
    - Ignore climatic volatility when calculating option values.
    - Ignore economic volatility when calculating option values.

5. This report evaluates the performance of these alternatives to ROA using a theoretical framework with the following key components:
    - The model covers multiple time periods. The decision-maker is able to choose when investment occurs.
    - Future climatic and economic conditions are uncertain. The decision-maker knows the probability distribution from which changes in economic conditions are drawn randomly, but she is uncertain about the distribution from which changes in climatic conditions are drawn. As time passes and more information about climate change becomes available, her uncertainty about the latter distribution falls.

6. I derive fully optimal policies for three stylised adaptation projects, giving a baseline of the present value of the gain in overall welfare that is theoretically achievable. For each of the six simple rules featured in this report, I calculate the present value of the gain in overall welfare that will occur if the decision-maker uses this simple rule rather than the welfare-maximising rule to implement each project. I carry out extensive sensitivity analysis to assess the robustness of my results.

7. In all the cases considered in this report, the value of the flexibility embedded in the project is economically significant. It is important that decision-makers attempt to exploit this investment flexibility in ways that benefit society as a whole.

8. The welfare-maximising investment timing rule can be expressed in terms of a threshold that a project's BCR must exceed in order for investment to occur. I find the optimal threshold varies over time and is sensitive to:
    - the decision-maker's assessment of the speed and magnitude of climate change;
    - the mean and standard deviation of the growth rate of an economic factor; and
    - the current capacity of infrastructure to cope with climate change.

9. For typical projects in typical conditions, it is possible to capture most of the benefits of "full" ROA using simple techniques that will make scarce analytical resources stretch further.
    - If standard CBA is used, then projects should be evaluated at fixed intervals. Decision-makers should resist the temptation to reevaluate a delayed project ahead of schedule in response to news that the project's benefits have increased.
    - Constant BCR and IRR thresholds are better than standard CBA. A constant IRR threshold is preferred, because it implies a non-constant BCR threshold with qualitative properties that are similar to the welfare-maximising threshold.
    - If even better performance is required, then decision-makers can use the fixed-date-approximation approach. This simple rule delivers small welfare losses, even though the calculation is not much more complicated than standard CBA.

10. When analysts apply ROA to relatively large adaptation projects, for which some form of bespoke analysis might be worthwhile, they often assume the decision-maker uses one source of information to make investment timing decisions. The decision-maker might choose when to invest based on the level of a climatic variable, or alternatively on the level of an economic variable. This can keep the analysis relatively tractable, but at the price of oversimplifying the decision-maker's problem. The analysis summarised in this report suggests that either approach will probably lead to investment behaviour that is close to optimal. Welfare losses are likely to be small in both cases.

Author's biography

Graeme Guthrie is an independent economist who was Professor of Economics and Finance at Victoria University of Wellington from 2006 until 2020. He has written books on real options analysis and corporate governance, both published by Oxford University Press. A more detailed biography is available at https://sites.google.com/view/graemeguthrie

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Introduction

1.1 Overview

The scale of public investment needed to successfully adapt to climate change will depend on the magnitude of that change. For example, communities will need to increase the capacity of their stormwater systems to cope with intense rainfall, but they do not know how much additional capacity will be required.[1] Uncertainty about the magnitude of climate change will remain high for many years (decades, according to some experts), before gradually falling as scientists learn more about the change in climate. If climate change is less severe than communities expect, they may end up spending too much on adaptation; if it is more severe than expected, they may not spend enough. The nature of adaptation investment makes these errors extremely costly for society. Much adaptation investment will be irreversible, so if communities build too much, they will be left servicing debt used to build capacity they will never need. On the other hand, if communities do not build enough, they will either be stuck with high flooding costs in the future or they will need to invest again—with all the additional cost that entails. The final option—that communities delay investment until they have a clear idea of how much capacity will be needed—would leave communities under-protected in the meantime.

Even if there are no low-cost adaptation policies, some policies will be less costly than others. Policymakers' aim should be to choose adaptation actions that minimise the overall cost to society, where these costs include the funds spent on adapting and the costs incurred by the community when flooding and other weather-related events occur. Real options analysis (ROA) is an ideal decision-support tool because it can handle the flexibility embedded in investment programmes, such as the ability to accelerate, delay, or rescale investment. It takes mathematical techniques originally developed for pricing particular types of financial securities and uses them to calculate the values of the various investment options available to decision-makers (Dixit and Pindyck, 1994; Guthrie, 2009). Perhaps the most important type of flexibility is the option to wait, learn more about the

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[1] The situation facing Dunedin is typical. NIWA estimates that a 1-in-100 year rainfall event will currently see 141mm of rain falling in a 24-hour period. By 2090, this estimate increases to 148mm under RCP2.6 and 172mm under RCP8.5 (Macara et al., 2019, Table 4-11). The demands on Dunedin's stormwater system, and the amount of new investment required, depend crucially on which climate scenario unfolds.

magnitude of climate change, and then invest. In particular, investment is socially optimal only if the payoff from investing is greater than the option value of waiting.

Many practitioners regard real options analysis as complex and resource-intensive (Dawson et al., 2018; Wreford et al., 2020). It is not widely used, particularly for relatively small projects. This is unfortunate because much adaptation spending will fund relatively small projects under the jurisdiction of local authorities. These authorities have the local knowledge and incentives that are essential to good decision-making, but many of them have limited analytical resources. The importance of the flexibility in these projects is too costly to ignore. If society is to retain the benefits of local decision-making, then the decision-makers need approaches that are simple enough to be useful for evaluating small- and medium-scale adaptation decisions yet retain a degree of economic rigour, as recommended in recent reviews of decision-support tools for adaptation assessment (Watkiss et al., 2015; Wreford et al., 2020). This report evaluates several such approaches.

1.2 Adaptation decision-making

Adapting to climate change will require substantial investment of public funds over the coming decades, creating enormous potential for inefficient decisions involving the timing, scale, and location of investment. Decision-makers need to overcome several challenges: future benefits are uncertain; reversing investment is costly, if it is possible at all; and decisions can be spread over time as uncertainty is resolved. Modern decision-support tools can potentially improve the efficiency of investment in these circumstances.

Decision-makers contemplating investing in adaptation projects face a common problem. As the future benefits of their projects are uncertain, the decision-makers are exposed to the risk that after they invest the benefits will turn out to be so low that their project does not recover the cost of undertaking it. For example, if the sea level rises more slowly than expected, then the benefits generated by a new sea wall will be lower than expected. Decision-makers can reduce this risk by delaying investment until the expected benefits are relatively large, because the more demanding the investment threshold for the *expected* benefits, the more likely it is that a project's *actual* benefits will cover its cost. Decision-makers must weigh this benefit of waiting against the cost, which is that they forgo receiving any of their project's benefits for as long as they delay investment.

Optimal decision-making involves calculating the present value of the net benefits for each possible action and then choosing the action with the greatest present value. The crucial insight of ROA is that one of the possible actions is usually *inaction*. More precisely, action can be delayed, so that acting immediately can only be optimal if the present value of acting is greater than the present value of waiting. That is, a necessary condition for immediate investment to be optimal is that

$$\begin{pmatrix}\text{Present value}\\ \text{of future}\\ \text{net benefits}\end{pmatrix} - \begin{pmatrix}\text{Investment}\\ \text{expenditure}\end{pmatrix} \geq \begin{pmatrix}\text{Option}\\ \text{value of}\\ \text{waiting}\end{pmatrix}. \tag{1.1}$$

The present value of waiting is difficult to calculate accurately in practical applications because it depends on the actions that the decision-maker will take *after* the period of waiting is over. In principle, ROA is helpful here because it uses dynamic programming to simultaneously solve for the value of the delay option and the optimal future policy. However, actually implementing the solution process can be complicated, especially for realistic adaptation problems featuring uncertainty about future climatic and economic conditions.

I evaluate the performance of six alternatives to ROA in this report. The first is standard cost–benefit analysis (CBA), implemented at fixed intervals. The next three alternatives involve small modifications of CBA, so they are straightforward to implement. The final two alternatives, which are more complicated than the others, are included here to represent the type of ROA that some analysts might carry out in practice. They are much more difficult to implement than CBA and its variants, but easier to implement than "full" ROA. However, this simplicity is only possible because of some simplifying assumptions that potentially adversely affect their performance. I include these methods here in order to evaluate the costs of making these simplifying assumptions. The specific rules I consider are listed here in increasing order of complexity:

Standard CBA at fixed intervals A decision-maker who evaluates the project using standard CBA will invest immediately if the present value of the future net benefits is greater than the capital expenditure, where the present value is calculated using the social discount rate. The decision-maker will otherwise wait and reevaluate the project in the future. She uses all currently available information when calculating the present values used to make this decision. I consider the case in which the project is evaluated at fixed regular intervals.

Constant BCR threshold This minor modification of standard CBA changes one parameter used in CBA and leaves the approach otherwise unchanged. A project's benefit–cost ratio (BCR) equals the present value of the project's net benefits divided by the required investment expenditure. When using CBA, the decision-maker invests if the project's BCR is greater than one. This modification increases the threshold for the BCR to some arbitrary fixed number $\hat{B} > 1$. For example, if $\hat{B} = 1.5$ then investment occurs only if the present value of the future net benefits is at least 50 percent larger than the capital expenditure.

Constant IRR threshold This minor modification of standard CBA changes a different parameter used in CBA and leaves the approach otherwise unchanged. A project's internal rate of return (IRR) equals the discount rate that implies the present value of the project's net benefits equals the required investment expenditure. When using CBA, the decision maker effectively invests if the project's IRR is greater than the social discount rate. This modification uses a threshold $\hat{h}$ for the IRR that is larger than the social discount rate.

Fixed-delay option value This rule involves estimating the option value of waiting by assuming investment is delayed until the best *fixed* future date. This is simpler to calculate than the full option value because all it requires is one standard cost–benefit calculation for each possible future investment date. A decision-maker using this alternative rule invests if and only if the net present value of investing immediately is greater than the net present value of investing at each of the considered fixed future investment dates.

Ignoring climate volatility This rule is intended to mimic the work of an analyst who simplifies the problem by ignoring the effects of climate uncertainty. The analyst still allows for changes in climatic conditions, but the changes follow a predetermined path. However, the analyst does allow for uncertainty about future economic conditions. This simplifies the construction of an optimal investment policy because it means the analyst only needs to allow for one source of volatility.

Ignoring economic volatility This rule is intended to mimic the work of an analyst who simplifies the problem by ignoring the effects of economic uncertainty. The analyst still allows for changes in economic conditions, but the changes follow a predetermined path. However, the analyst does allow for uncertainty about future climatic conditions. This simplifies the construction of an optimal investment policy because it means the analyst only needs to allow for one source of volatility.

All of these rules can be interpreted as different ways to approximate the option value of waiting that plays such an important role in equation (1.1). Interpreting them in this way is not essential for their implementation, but it helps us understand the effects different rules have on investment timing.

Standard CBA at fixed intervals Standard CBA requires only that the present value of a project's future net benefits is greater than the capital expenditure. This corresponds to the rule in equation (1.1) if the option value of waiting is set equal to zero.

Constant BCR threshold An analyst using this approach effectively uses the product of the constant $\hat{B}-1$ and the capital expenditure as their estimate of the option value of waiting. Provided the decision-maker chooses $\hat{B} > 1$, the investment test will be more demanding than standard CBA. However, it may be more or less demanding than optimal decision-making, depending on the level of $\hat{B}$ adopted.

Constant IRR threshold The present value of the project's benefits changes when the discount rate changes from the social discount rate to the hurdle rate $\hat{h}$. Provided the decision-maker sets $\hat{h}$ above the social discount rate, the present value will fall. The size of the reduction is effectively the analyst's estimate of the option value of waiting. This estimate is positive, so the investment test will be more demanding than standard CBA. However, it may be more or less demanding than optimal decision-making, depending on the level of the hurdle rate adopted.

Fixed-delay option value This rule estimates the option value of waiting by assuming investment is delayed a fixed number of years. A decision-maker using this rule invests as soon as immediate investment is better than delaying investment a fixed number of years and then investing. Investment is delayed significantly past the date when the BCR equals one. However, this approach restricts the set of investment strategies used to calculate the value of the delay option, which means that it will underestimate the option value. The resulting investment test will therefore be less demanding than optimal decision-making.

Ignoring climate volatility When the analyst calculates the option value of waiting she assumes there is no uncertainty surrounding future climate change. Delay option values are usually (but not always) lower when the underlying volatility is smaller, so this approach will likely underestimate the option value of waiting, leading to an investment test that will be less demanding than optimal decision-making.

Ignoring economic volatility When the analyst calculates the option value of waiting she assumes there is no uncertainty surrounding future economic conditions, which will likely underestimate the option value of waiting, leading to an investment test that will be less demanding than optimal decision-making.

1.3 Analytical framework

I use a single approach to evaluate all these rules. All the action takes place in the hypothetical world described by the theoretical model described in Chapter 2. I assume the decision-maker operates in this world and makes investment decisions using the simple rule being evaluated. For example, if she uses a fixed BCR threshold of $\hat{B} = 1.5$ then she will invest the first time the present value of the project's benefits is more than 50 percent larger than the investment expenditure. The decision-maker uses all the climate and economic information available at the time she makes her decisions, but feeds this information into the particular rule she is using. I evaluate the welfare performance of the simple rule by calculating the present value of the project's net benefits that results from these decisions and comparing it to the present value that can be achieved using the welfare-maximising investment policy.

The key components of the theoretical model are:

- The model is dynamic, in the sense that it covers multiple time periods. The decision-maker is able to choose when investment occurs.
- The future is uncertain. This uncertainty has two sources, economic conditions and climatic conditions. I assume the decision-maker knows the probability distribution from which changes in economic conditions are drawn randomly. In contrast, she is uncertain about the particular probability distribution from which changes in climatic conditions are drawn. However, as time passes and more information about climate change becomes available, her uncertainty about the identity of this distribution falls. Thus, the extent of climate change is initially uncertain, but this uncertainty falls over time.
- I derive fully optimal policies to give a baseline of welfare that is theoretically achievable.
- For each of the six simple rules featured in this report, I use the theoretical model to calculate the present value of future net welfare gains if the decision-maker uses this simple rule rather than the welfare-maximising rule.

The model is expressed in continuous time and features two separate sources of uncertainty. This makes calculating present values and identifying optimal investment policies technically demanding. As such, the model is not intended for practical use—but its *insights* are intended for practical use. For example, if a particular simple decision-making rule performs well in the theoretical model, then we can have some degree of confidence that it will also perform well in the real world. We cannot compare the performance of different rules in the real world, so the best we can do is compare their performance in a realistic theoretical world and hope that the insights carry across to the real world.

Whether or not this goal is achieved depends on the modelling choices made along the way. There is an important trade-off to consider.

- On the one hand, the insights gained in the theoretical world are more likely to carry over to the real world if the model is more realistic. This suggests tailoring the model—and especially the adaptation projects considered—closely to specific real-world adaptation projects.

- On the other hand, my aim is that readers will be able to draw fairly general lessons about the simple alternatives to ROA. For example, I want readers to learn how different rules perform in various circumstances and when applied to different types of project. As it is not feasible to consider every possibility in detail, this suggests keeping the model specification reasonably general and considering adaptation projects that are representative of different *classes* of project. That is, the projects considered need to be kept quite stylised.

I have attempted to navigate a path between these two extremes. My aim is that readers can identify the relevant characteristics of a project they are interested in, match this combination of characteristics to one of the cases considered here, and draw appropriate conclusions. This has influenced the modelling choices I have made.

- This report does not include detailed individual case studies in the traditional sense, in which the model is specified in order to make the model as close as possible to the real-world situation. That serves a useful purpose when evaluating individual projects, but the "bespoke" nature of the modelling limits its usefulness for the things I am trying to do here.
- Instead, I have attempted to identify the key characteristics of adaptation projects and develop a model that features these characteristics. I consider three separate, representative families of adaptation projects in Chapters 4–6. This list is not exhaustive, but it covers many different types of adaptation project.
- I carry out extensive sensitivity analysis to ensure the results are robust to changes in parameters. This should give readers confidence that the findings are likely to be applicable to other projects with the same key characteristics.

1.4 Results

In all the cases considered in this report, welfare is much higher if the decision-maker follows a socially optimal investment policy than if she continuously monitors a project and invests the first time that its BCR is greater than one. That is, the value of the flexibility embedded in the project is economically significant. It is therefore important that decision-makers attempt to exploit this investment flexibility in ways that benefit society as a whole.

The welfare-maximising investment timing rule can be expressed in terms of a threshold that a project's BCR must exceed in order for investment to occur. I find that the optimal threshold varies over time and is sensitive to:

- the decision-maker's assessment of the speed and magnitude of climate change;
- the level of parameters including the mean and standard deviation of the annual growth rate of the economic factor; and
- the current capacity of infrastructure to cope with climate change.

It will not usually be economically viable to determine the precise threshold that is optimal for the relatively small projects considered in this report.

For typical projects in typical conditions, it is possible to capture most of the benefits of "full" ROA using simple techniques that will make scarce analytical resources stretch further.

- If standard CBA is used, then projects should be evaluated at fixed intervals. In particular, decision-makers should resist the temptation to reevaluate a delayed project ahead of schedule in response to news that the project benefits have increased.
- Using constant thresholds for the project's BCR and IRR produces higher levels of overall welfare than standard CBA. A constant IRR threshold is the preferred approach, because it implies a non-constant BCR threshold with qualitative properties that tend to be similar to the welfare-maximising threshold.
- If even better performance is required, then decision-makers can use the fixed-date-approximation approach. This simple rule delivers small welfare losses, even though the calculation is not much more complicated than standard CBA.

When analysts apply ROA to relatively large adaptation projects, for which some form of bespoke analysis might be worthwhile, they often assume the decision-maker uses one source of information to make investment timing decisions. The decision-maker might choose when to invest based on the level of a climatic variable, or alternatively on the level of an economic variable. This can keep the analysis relatively tractable, but at the price of oversimplifying the decision-maker's problem. The analysis summarised in this report suggests that either approach will probably lead to investment behaviour that is close to optimal. Welfare losses are likely to be small in both cases.

1.5 Suitability for bespoke real options analysis

The theoretical framework in this report was developed in order to evaluate simple rules. Although the framework was not intended for practical use, it can also be useful for evaluating larger projects using bespoke ROA. This would involve retaining the parts of the current model that specify the uncertainty surrounding future economic and climatic conditions, but enhancing the current approach to estimating the annual flow of benefits associated with investment.

All that is required for compatibility is that the annual benefit flow is a function of contemporaneous climatic and economic conditions. For example, Chapter 4 analyses the option to retrofit buildings to improve occupants' ability to cope with high outside temperatures. The benefit-flow function measures the value of the benefits of the retrofit for all possible combinations of climatic and economic factors. In Chapter 5, which analyses the option to upgrade an urban stormwater system, the benefit-flow function estimates the value of the benefits from upgrading the system for all possible combinations of climatic and economic factors. The analysis here uses very stylised benefit-flow functions, but application-specific functions would work just as well. In principle, practitioner-generated benefit-flow functions could be substituted into the model with little loss of tractability. With such a change, the framework used here could be used to implement ROA and derive welfare-maximising investment policies. This would be suitable for relatively large or complicated adaptation projects, for which the simple rules of the type considered here may not be sufficient.

1.6 Roadmap

Chapter 2 This chapter introduces the framework I use to model adaptation decision-making. It begins with a high-level description of the way I model climate-change uncertainty and then describes how I calculate the benefits of investing in adaptation projects. The rest of the chapter describes how the two main drivers of project benefits—a climatic factor and an economic one—evolve randomly over time.

Chapter 3 This chapter introduces ROA and interprets optimal decision-making in terms of the value of the option to delay investment. It goes on to describe several practical alternative approaches that are simple enough to be useful for evaluating small- and medium-scale adaptation decisions, yet retain a degree of economic rigour.

Chapter 4 This chapter considers the simplest, and most commonly studied, example of a real option: the option to choose when to undertake a one-off, irreversible investment. The choice of investment timing is the only flexibility embedded in the investment opportunity. In some examples, this will be because there really is no flexibility about what to build or where to build it, only about when to build it. In reality, most projects will have some "what" or "where" flexibility, but if this flexibility is minor compared to the embedded "when" flexibility, then the project will be a good fit for the one studied in this chapter. The key features are that the decision-maker can take the action (that is, invest) at most once, that she can take the action at any point during some (possibly quite long) period of time, that the cost of reversing the action is prohibitively high, and that the flow of future benefits initiated by taking the action is uncertain.

Chapter 5 This chapter considers projects that feature ongoing investment programmes involving relatively large numbers of relatively small investments. The rate of investment in these programmes is usually able to be scaled up or down reasonably easily and the project starts to generate benefits even before the overall programme is complete. The decision-maker can act at any point during a specified period of time, the cost of reversing an action is prohibitively high, and the flow of future benefits initiated by taking the action is uncertain. This chapter follows the same format as Chapter 4 in order to emphasise the consistent approach to evaluating the various decision-making rules and to make it easier for readers to compare results across different types of adaptation options.

Chapter 6 In Chapters 4 and 5, the decision-maker's choice of investment timing is the only flexibility embedded in the investment opportunity. In contrast, in this chapter the decision-maker chooses what to do as well as when to do it. This additional flexibility might involve the scale of the project, its location, its salvage value, or some other aspect that influences the project's cost or the future benefits that it will generate. As in Chapter 4, the decision-maker can take the action (that is, invest) at most once, she can take the action at any point during a specified period of time, the cost of reversing the action is prohibitively high, and the flow of future benefits initiated by taking the action is uncertain. This chapter follows the same format as Chapters 4 and 5.

Chapter 7 This chapter collects the results from Chapters 4–6 that are most relevant for adaptation decision-making involving small- and medium-scale projects. It identifies the types of projects for which some form of ROA is most valuable and identifies simple alternative decision-making rules that will result in only small welfare losses.

Chapter

2

Theoretical framework

This chapter introduces the framework I use to model adaptation decision-making. It begins with a high-level description of the way I model climate-change uncertainty and then describes how I calculate the benefits of investing in adaptation projects. The rest of the chapter describes how the two main drivers of project benefits—a climatic factor and an economic one—evolve randomly over time. A full, technical description of the framework can be found in Guthrie (2023a,b).

2.1 Modelling climate uncertainty

There are two layers to the underlying climate model. Following Auffhammer (2018) and Hsiang and Kopp (2018), this framework interprets "climate" as the set of factors determining the underlying distribution of weather events and "climate change" as a slow shift in this distribution. During any particular period of time, the weather-related costs incurred by a community depend on the weather events that occur during the period. The magnitude and timing of these weather events are random variables drawn from a distribution determined by the contemporaneous state of the climate. If there were no climate uncertainty, then there would be a single weather-event distribution and the decision-maker would know what that distribution is. However, the decision-maker is uncertain about the state of the climate, which I model by assuming there are many possible weather-event distributions and that the decision-maker knows the probability that each of these distributions is the correct one. That is, there is a "distribution of distributions," which I assume has properties that are determined by a single climate factor. This factor ultimately determines the distribution of weather events. It changes over time as the climate changes and the decision-maker's uncertainty about the climate changes.

This framework is flexible enough to handle many different applications. For example, I will specify the possible distributions of the daily maximum outdoor temperature when I analyse retrofitting buildings in Chapter 4, rainfall intensity when I analyse investment in an urban stormwater system in Chapter 5, and peak sea levels when I analyse investment in a sea wall in Chapter 6. Take the example of Dunedin City Council's plans to upgrade the city's stormwater system (Dunedin City Council, 2019, 2022).[1] I adopt the

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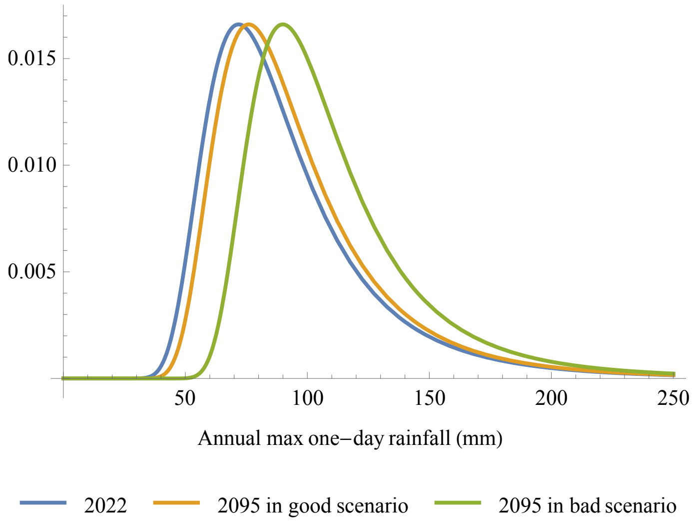
[1] Hughes et al. (2019) evaluate the impact of climate change on New Zealand stormwater systems.

Figure 2.1: Distribution of the annual maximum one-day rainfall in Dunedin



Notes. The blue curve plots the estimated density function for the annual maximum one-day rainfall in Dunedin, New Zealand, given current climatic conditions. The estimated density functions for the same variable in 2095 are shown by the yellow (RCP2.6) and green (RCP8.6) curves.

annual maximum one-day rainfall for the area as the weather variable and assume it is currently drawn from a generalised extreme value distribution that matches the estimated distribution generated by the NIWA High Intensity Rainfall Design System (HIRDS).[2] Its location, scale, and shape parameters equal 75.71, 22.54, and 0.1908, respectively. There is initially no climate uncertainty, so there is just one possible rainfall distribution. The blue curve in Figure 2.1 plots the current density function of the annual maximum one-day rainfall. The mean of this distribution is 94mm/day, corresponding to the current average of this variable for Dunedin.

I model climate change by assuming the location parameter of this distribution changes over time and I model climate change *uncertainty* by assuming the location parameter follows one of two possible paths. Thus, at any particular future date there are two possible distributions of the annual maximum one-day rainfall for the area. The yellow and green curves in Figure 2.1 plot the density functions of the two possible distributions in 2095. The location parameter has increased by 3.12 and 13.66, respectively, implying that the means of these two distributions equal 98mm/day and 112mm/day, corresponding to the predicted averages in 2095 under RCP2.6 and RCP8.5.[3] For this example, the climate factor is the probability that the bad scenario holds. That is, I assume the maximum one-day rainfall in 2095 is drawn from a compound distribution that is a mixture of the distributions with density functions shown by the yellow and green curves in Figure 2.1.

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[2] Extreme rainfall projections for any New Zealand location can be viewed at https://hirds.niwa.co.nz/. Data from the “Leith at Pine Hill” site (ID 508510), which I use here, is also used by the Otago Regional Council to monitor Dunedin’s rainfall.

[3] HIRDS generates separate distributions for the periods 2031–2050 and 2081–2100.

2.2 Calculating climate-related benefit flows

The decision-maker's objective is to choose adaptation policies that minimise the present value of all future climate-related costs. These costs include the expenditure needed to repair damage caused by extreme weather events, the cost of disruption caused by these events, health costs, and so on. Realised total costs depend on weather conditions during the period over which the costs are measured, so I calculate the average total cost over all possible weather conditions. The resulting expected values will depend on the parameter that determines the distribution of weather events—that is, on the climate factor.

The first step when calculating climate-related cost flows is to calculate the total economic cost for each possible weather event. The terminology will differ across applications, but the principles are common to them all. For concreteness, here I suppose that the application involves the possibility of flooding events. When calculating the cost associated with a breach of flood defences, the decision-maker needs to know how the event affects the surrounding land. Specifically, for each potential flooding event, she needs to know the depth of the floodwaters on each unit of land in the locality. Analysts often use either resource-intensive hydrodynamic modelling or simpler flood-fill algorithms to determine the distribution of the depth of floodwaters in a locality as a function of the amount by which the peak rainfall exceeds the capacity of the stormwater system.[4] This information is combined with a depth–damage function, which estimates the cost of damage to a flooded property as a function of the depth of the floodwaters on that property.[5] Summing these costs over the entire locality yields the macroscopic damage function, which gives the total flooding cost as a function of the scale of the breach.

In order to focus on the role of climate uncertainty, and not the hydrological characteristics of a particular locality, I assume the macroscopic damage function equals $M(b, x) = bx$, where b is the scale of the breach and x is an economic factor introduced in the next section.[6] The resulting function will obviously not give perfect results for any particular situation, but it is a useful approximation in many situations. For example, the resulting functional form generates expected flooding costs that are smaller if the current flood-protection infrastructure has greater capacity, and are larger when the annual maximum one-day rainfall is more variable. Furthermore, the benefits of investment are negligible when the system's capacity is high, they are substantial when it is low, and investing in additional capacity has diminishing returns. These are all realistic properties and play important roles in determining optimal investment policies.

The second step when calculating climate cost flows is to calculate the expected value of the macroscopic damage function, averaged over all possible weather outcomes. I construct the weather-event distribution as a compound distribution. That is, the weather event is distributed according to some parametrised distribution, with one or more of the parameters of that distribution themselves being random variables drawn from a distribu-

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[4] Flood-fill algorithms identify all land that is below the assumed water level and is not cut off from the water source by land that lies above the assumed water level. That is, low lying areas that are not connected to the flood source are assumed to be unaffected by the flood. Boettle et al. (2011) use a flood-fill algorithm to construct a flooding cost function for Copenhagen; Prahl et al. (2018) use one to estimate flooding cost functions for the 600 largest European coastal cities.

[5] Damage to buildings is just one component of flooding costs. Depth–damage functions can also be constructed for damage to infrastructure. Similarly, depth–disruption functions can be constructed to estimate the costs of the disruption to the transport sector caused by flooding events (Pregnolato et al., 2017).

[6] The breach equals the annual maximum one-day rainfall minus the capacity of the local stormwater system, or zero if this quantity is negative.

tion parametrised by the climate factor. I therefore calculate the expected climate-related costs using a two step process. First, I calculate the expected value for each possible weather-event distribution and then I calculate the (appropriately weighted) average over all possible weather-event distributions.

I use two separate approaches to specifying the uncertainty about which weather-event distribution holds. The simpler approach assumes there are two possible climate-change scenarios, labelled "good" and "bad." At each point in time, there is a "good" distribution of weather outcomes and a "bad" distribution. The decision-maker attaches a subjective probability to each scenario and uses this probability to calculate the expected value of the flooding costs. The more complicated approach assumes there are infinitely many possible distributions of weather outcomes. At each point in time, the decision-maker attaches a subjective probability to each distribution and uses these probabilities to calculate the expected value of the flooding costs. The first approach is relatively simple, but the second approach is possibly more realistic. In order to demonstrate them both, I will use the first approach in Chapters 4 and 5 and the second one in Chapter 6.

In summary, the process involves carrying out the following three steps:

1. For each future date t and each future weather event, calculate the climate-related cost flow.

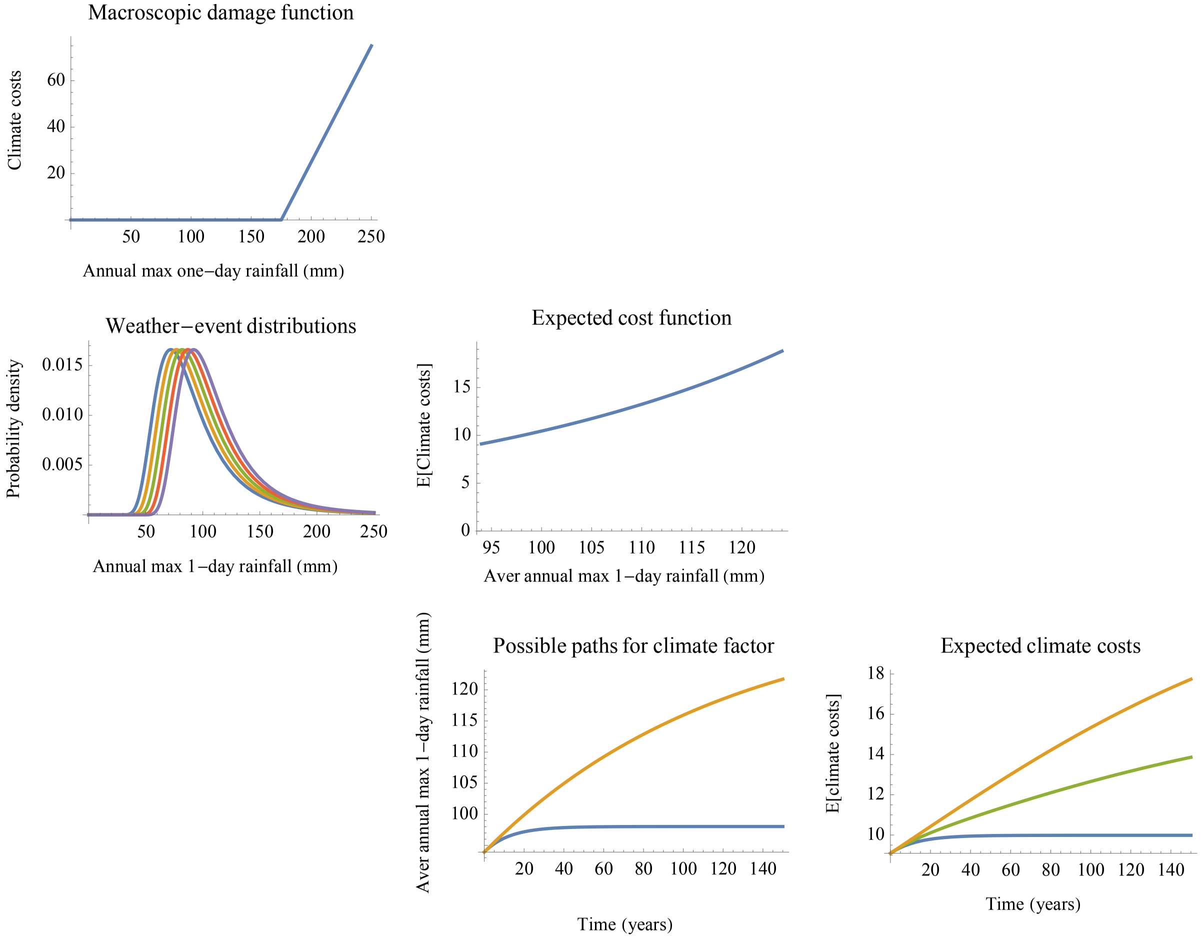
2. For each future date t and each future weather-event distribution, calculate the expected value of the climate-related cost flow. That is, average the outputs of step 1 over all possible weather events.

3. For each future date t, calculate the expected value of the climate-related cost flow. That is, average the outputs of step 2 over all possible weather-event distributions.

This process yields the expected climate-related costs at each future date as a function of the contemporaneous levels of an economic factor and a climatic factor that describes the decision-maker's beliefs regarding the state of the climate.

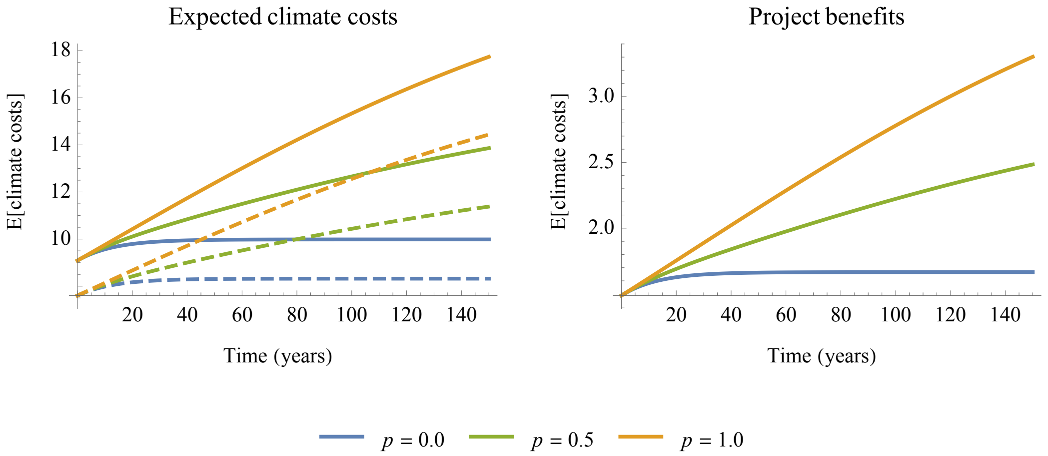
Figure 2.2 shows this process in action, working from the top-left hand graph to the bottom right-hand one. It continues the example of an urban stormwater system. The top graph in the left-hand column plots the macroscopic damage function, which maps the magnitude of the weather event (in this case, the annual maximum one-day rainfall) into realised climate-related costs. The graph below it plots several different weather-event distributions, which are parametrised by the distributions' mean. Combining these two graphs yields the top graph in the middle column. It maps the average annual maximum one-day rainfall into the expected value of climate-related costs. That is, it shows the expected climate-related costs for each possible weather-event distribution. The graph below it plots the two possible paths for the average annual maximum one-day rainfall, corresponding to the good (blue curve) and bad (yellow curve) climate scenarios. Finally, combining the two graphs in the middle column yields the bottom right-hand graph, which plots the expected climate-related cost as a function of time. The blue and yellow curves in this graph correspond to the situation when the probability that the bad scenario holds equals 0 and 1 respectively. The green curve shows the situation when the two climate scenarios are equally likely. For example, the bottom graph in the middle column shows that if the two climate scenarios are believed to be equally likely, then 60 years from now the average annual maximum one-day rainfall is equally likely to be to 98mm/day or 109mm/day. The graph above it shows that these two average rainfall intensities imply

Figure 2.2: Calculating expected climate costs



Notes. This figure illustrates the steps involved in calculating the expected value of climate-related costs. I combine the macroscopic damage function and the weather-event distributions in the left-hand column to obtain the mapping from weather-event distributions to expected costs in the top of the middle column. I combine this with the description of the two possible climate scenarios in the bottom of the middle column to obtain the mapping from the future date to expected climate-related costs in the right-hand column.

Figure 2.3: Calculating project benefits



Notes. The left-hand graph plots the expected flow of climate-related costs, with the solid and dashed curves corresponding to an urban stormwater system with capacities of 175mm/day and 185mm/day respectively. The right-hand graph plots the avoided costs if capacity is increased from 175mm/day to 185mm/day.

expected climate-related costs of 10.0 and 13.0 respectively, implying an expected value of 11.5.

The benefits of undertaking any particular adaptation project are the expected climate-related costs that will be avoided once the project is in place. These are calculated by subtracting the with-project climate-related costs away from the without-project climate-related costs. For example, the calculations illustrated in Figure 2.2 assume the stormwater system's capacity is 175mm/day. I can calculate the benefits of increasing its capacity to 185mm/day by repeating the exercise in Figure 2.2 with the increased capacity and then calculating the reduction in the expected climate costs.[7] This gives the expected avoided costs attributable to the system's increased capacity. The left-hand graph in Figure 2.3 plots the two sets of expected costs, with the solid and dashed curves corresponding to capacities of 175mm/day and 185mm/day respectively. The right-hand graph plots the avoided costs. In all cases, the blue and yellow curves in this graph correspond to the situation when the probability that the bad scenario holds (that is, the climate factor) equals 0 and 1 respectively. The green curve shows the situation when the two climate scenarios are equally likely. The project's expected benefit flow becomes more sensitive to the climate factor further into the future, because the good and bad climate scenarios initially imply similar distributions of weather events and is only further into the future that the two scenarios imply quite different distributions.

2.3 Behaviour of the climate factor

The previous section shows how to calculate the expected value of an adaptation project's benefits as a function of the contemporaneous values of a climatic factor and an economic factor. The climatic factor is a parameter that determines the subjective probabilities

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[7] In order to focus on the role of climate uncertainty, in these graphs I fix the economic factor $x = 1$.

that the decision-maker attaches to each climate scenario. This ultimately determines the subjective distribution of weather outcomes, which partly determines the project's expected benefit flow. The economic factor provides the remaining information needed to completely determine the expected benefit flow. The next step is to specify how these factors vary over time. This section focusses on the evolution of the climate factor. (Section 2.4 covers the evolution of the economic factor.)

Out of the multiple possible climate-change scenarios, exactly one holds, but the decision-maker does not know which one this is. Instead, the decision-maker attaches a probability to each possible scenario. She continuously monitors new information and uses it to update these probabilities over time. In order to operationalise this arrangement, I assume the decision-maker can observe a noisy signal of some characteristic of the distribution of weather outcomes, such as its mean. For example, each month the decision-maker observes the monthly maximum one-day rainfall. After adjusting for seasonal patterns, this quantity contains (noisy) information about the *average* annual maximum one-day rainfall and how this average has been affected by climate change. I use Bayes' theorem to calculate the decision-maker's updated probabilities at each point in time based on the noisy signal she observes. The updating process injects volatility into the decision-maker's beliefs regarding which climate scenario holds, which makes the project's expected benefit flow volatile as well. The decision-maker's response to new information is greater when the identity of the actual climate scenario is more uncertain and when the signal contains less noise.

2.3.1 Two climate scenarios

In the simplest non-trivial example, there are only two possible climate-change scenarios.[8] I assume the decision-maker knows exactly what will happen in each scenario, but does not know which scenario is the correct one. This arrangement is unrealistic, but it is useful for illustrating the overall approach and is actually quite powerful. This is the approach I will adopt in Chapter 4, when I analyse retrofitting buildings, and Chapter 5, when I analyse ongoing investment in flood-protection infrastructure. The left-hand graph in Figure 2.4 plots the two possible paths for the average annual maximum one-day rainfall in Chapter 5, one for each scenario. The trajectories are reasonably similar in the short term, but then they diverge, so there is little potential for observation-based learning in the short run, but more in the long run. The middle graph in Figure 2.4 plots two simulated paths for the subjective probability that the bad scenario holds, both assuming that the decision-maker initially believes the two scenarios are equally likely. The right-hand graph plots the corresponding paths for the average annual maximum one-day rainfall, which equals the appropriately weighted average of the two paths in the left-hand graph. As expected, very little happens to the subjective probabilities during the first ten years, but they are highly volatile for the next 50 years. The true scenario is revealed by the time 75 years have passed, but even as late as 50 years from now, there is uncertainty about which scenario holds. The behaviour in the right-hand graph illustrates how changes in beliefs drive the volatility of the expected rainfall intensity (and, ultimately, the volatility of the project's expected benefits). The expected value of the average annual maximum one-day rainfall evolves smoothly for the first ten years, but is volatile for the next 50 years. Eventually, the average annual maximum one-day rainfall moves smoothly along one of the two possible paths—but which path it will be is not known for several decades.

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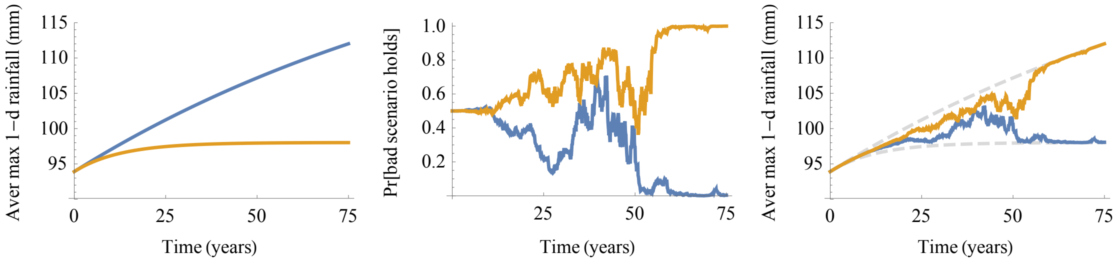
[8] Appendix A.1 contains a detailed description of how the decision-maker's beliefs evolve in this case.

Figure 2.4: Two simulated paths for the decision-maker's climate-scenario beliefs



Notes. The left-hand graph plots the evolution of the average annual maximum one-day rainfall in Dunedin under the two climate scenarios. The middle graph plots two simulated paths for the decision-maker's subjective probability that the bad scenario holds, assuming she initially believes the two scenarios are equally likely. The right-hand graph plots the corresponding paths for the expected value of the average annual maximum one-day rainfall.

Figure 2.4 highlights three distinct phases of the decision-maker's information about climate change. Initially, there is substantial uncertainty about climate change, but too little information arriving for the uncertainty to fall significantly. This is followed by a period of substantial volatility, during which uncertainty falls. The simulated paths for the decision-maker's subjective probability that the bad scenario holds start to diverge during this period because the possible paths for the average annual maximum one-day rainfall start to diverge, so that the noisy signal contains more information. Finally, the uncertainty is largely resolved and the decision-maker knows which path the climate is evolving along.

This behaviour is confirmed by the graphs in Figure 2.5, which plot the distributions of the decision-maker's subjective probability that the bad scenario holds for six horizons.[9] The top left-hand graph shows that ten years from now, the decision-maker has learned little about the true climate scenario: the subjective probability is close to its initial value of 1/2 for all 10,000 simulations. The top right-hand graph shows there will be considerable variation in this probability 20 years from now; the bottom left-hand graph shows the very beginning of a bimodal distribution 40 years from now. The bottom right-hand graph shows that by the time 80 years have passed, the decision-maker will be almost certain about the true climate scenario: the subjective probability will be extremely close to zero or one.[10]

The mathematical formula for updating the decision-maker's subjective probability depends on the amount of noise in the signal that she observes. If the signal contains more noise then she will attach less significance to the signal and more to her existing beliefs regarding climate change. In this case, the change in her subjective probability will be smaller and her uncertainty about the magnitude of climate change will decline more slowly. One measure of this uncertainty is the standard deviation of the average annual maximum one-day rainfall at a fixed point in the (possibly distant) future. The green curve

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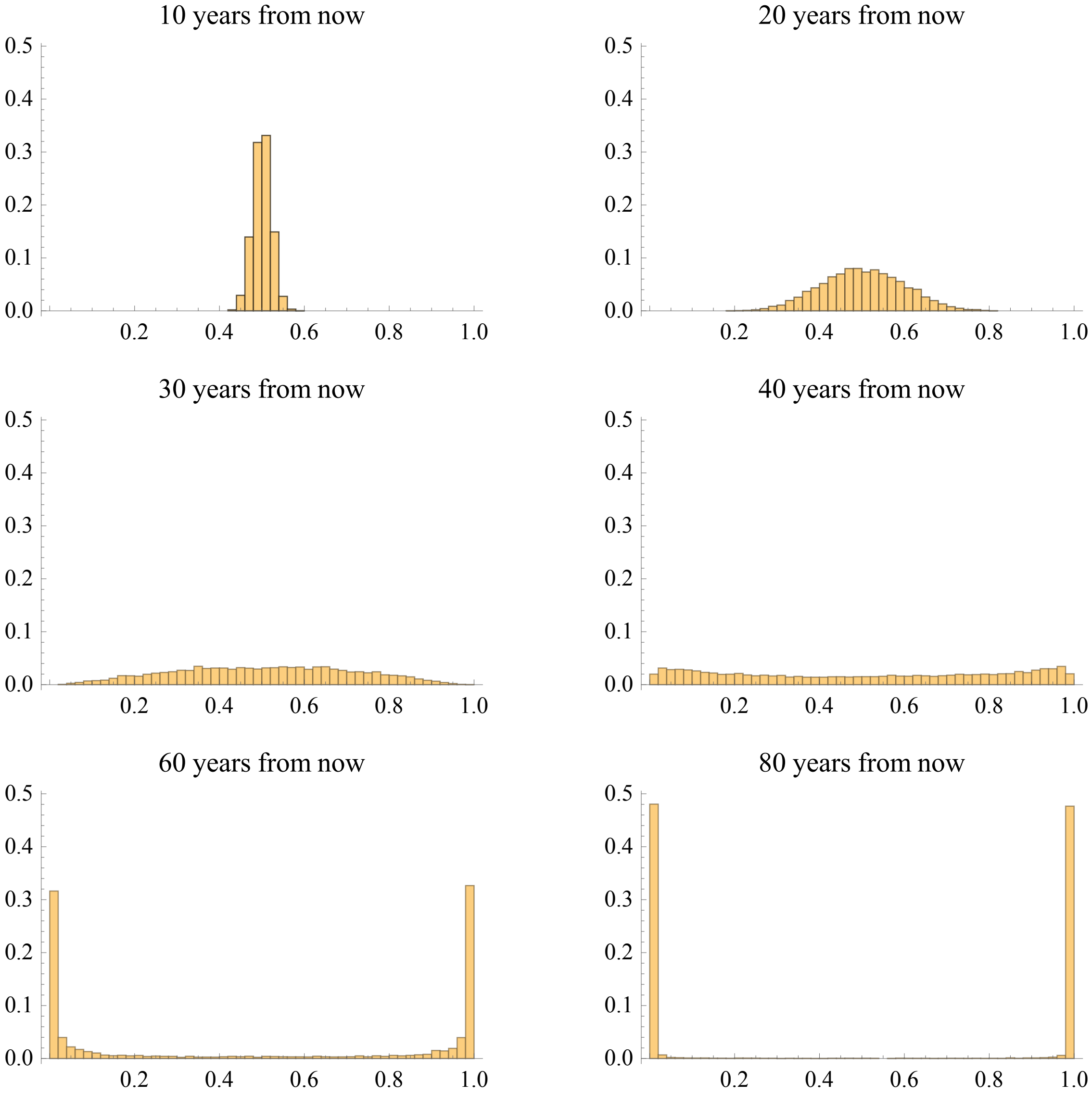
[9] The graphs are constructed by simulating 10,000 paths for p each starting with $p = 1/2$ and spanning 80 years, using the same method to simulate each path as is used to construct the paths in Figure 2.4. I extract the values of p at each $t \in \{10, 20, 30, 40, 60, 80\}$ from each simulated path. The graphs in Figure 2.5 plot the histograms for each of these slices.

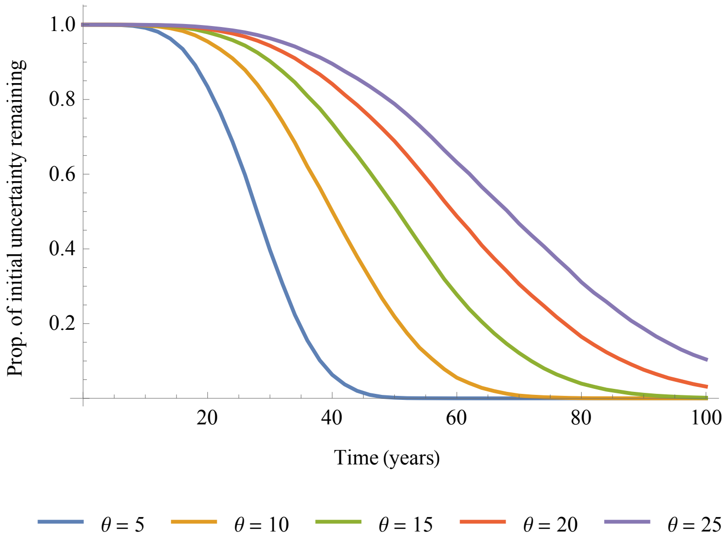
[10] If the decision-maker initially believes the bad scenario is twice as likely as the good one, then the long-run distribution of p will be a discrete distribution with $p = 1$ being twice as likely to occur as $p = 0$.

Figure 2.5: Distribution of the future bad-scenario probability when $p_0 = 1/2$



Notes. The graphs plot the distributions of the decision-maker's subjective probability that the bad scenario holds for six different horizons. Each histogram is drawn using 10,000 paths for this probability, each assuming she initially believes the two scenarios are equally likely and each calculated with the method used to construct Figure 2.4.

Figure 2.6: Noise in the climate signal and the speed of learning



Notes. The graph plots the standard deviation of year-100 estimated rainfall intensity when viewed from year t, expressed as a proportion of the standard deviation of the same quantity when viewed from year 0, averaged across 5,000 simulated paths.

in Figure 2.6 plots the standard deviation of this measure of rainfall intensity in year 100 as a function of t, expressed as a proportion of the standard deviation in year 0, for the parameter settings used in Chapter 5. It shows that uncertainty does not fall for the first 20 years, but then falls steadily for the next 60 years, by which time the uncertainty is largely eliminated. The other curves in Figure 2.6 repeat this exercise for different amounts of noise in the climate signal. The noise is smaller in the lower curves, which results in faster learning about climate change.

2.3.2 Infinitely many climate scenarios

When I analyse investment in a sea wall in Chapter 6, I need to model the gradual increase in peak sea levels due to climate change. The weather variable in this example is the annual maximum sea level. The decision-maker knows the initial weather-event distribution but the average annual maximum sea level increases by an unknown constant amount each year. I assume there are infinitely many climate scenarios, each one corresponding to a different rate of sea-level rise. The decision-maker initially believes that the (constant) rate of sea-level rise is normally distributed with a mean of 7mm/yr and a standard deviation of 3mm/yr. This is another example of the distribution-of-distributions approach in use. The decision-maker observes a noisy signal of the average annual maximum sea level and updates her beliefs over time.[11] The climate factor in this example is the expected rate of sea-level rise, which is sufficient to completely describe the decision-maker's beliefs at any point in time.

Figure 2.7 illustrates some of the properties of the stochastic process for the climate factor. The left-hand graph shows ten simulated paths of the climate factor, assuming the

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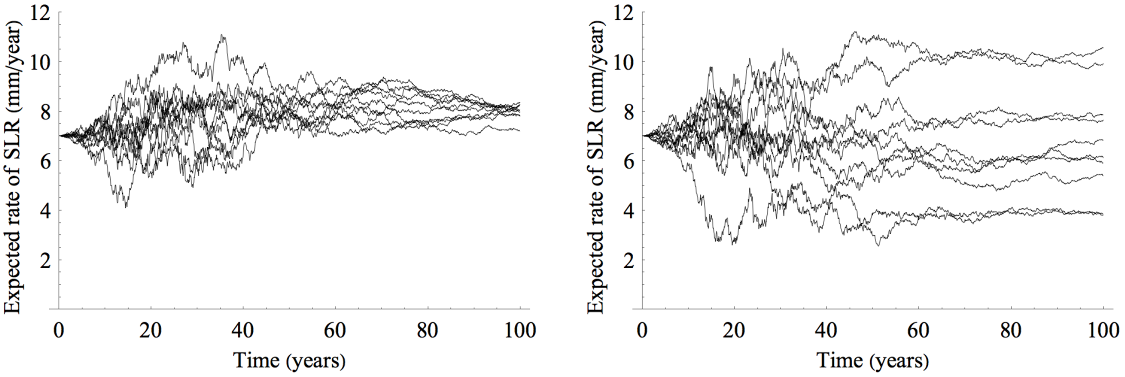
[11] Appendix A.2 contains a detailed description of how the decision-maker's beliefs evolve in this case.

Figure 2.7: Simulated behaviour of the expected rate of sea-level rise



Notes. The left-hand graph shows ten simulated paths of the decision-maker's expected rate of sea-level rise, assuming the sea level is actually rising at a rate of 8mm/year and the decision-maker's initial expected value is 7mm/year. The right-hand graph shows ten simulated paths of the decision-maker's expected rate of sea-level rise, with each one corresponding to a different possible value of the actual rate of sea-level rise.

actual rate of sea-level rise is 8mm/yr. That is, the decision-maker initially underestimates the actual rate of sea-level rise in these simulations. This illustrates the evolution of the decision-maker's beliefs for one of the infinitely many possible climate-change scenarios. Each path starts at the initial level of 7mm/yr and evolves according to the process implied by Bayesian updating. The graph shows that the climate factor's volatility is initially increasing, before peaking and then eventually declining to zero as the decision-maker's expected rate of sea level rise converges to the true value of 8mm/yr. However, the decision-maker's estimate of the rate of sea-level rise can deviate significantly from the actual value before this convergence occurs, illustrating the risks of under- or over-investment due to uncertainty about the magnitude of climate change.

The left-hand graph shows paths for the climate factor for one particular *actual* rate of sea-level rise. However, at date 0, the decision-maker believes the constant rate of sea-level rise is drawn from a normal distribution with a mean of 7mm/yr and a standard deviation of 3mm/yr. The right-hand graph in Figure 2.7 illustrates the situation from this restricted point of view. It shows ten paths of the climate factor, with each one corresponding to a different possible value of the actual rate of sea-level rise.[12] This graph illustrates the variety of possible paths the decision-maker should anticipate from the perspective of date 0. They all eventually converge to the actual rate of sea-level rise, but when viewed from date 0 the decision-maker does not know what this rate is. The right-hand graph in Figure 2.7 demonstrates the wide variety of possible paths for the climate factor that she must anticipate.

It is important to understand the various measures of uncertainty and volatility that arise naturally in this framework. There are three main measures. Their behaviour over time is illustrated in the three graphs in Figure 2.8.

Uncertainty about sea-level rise The left-hand graph in Figure 2.8 plots the root

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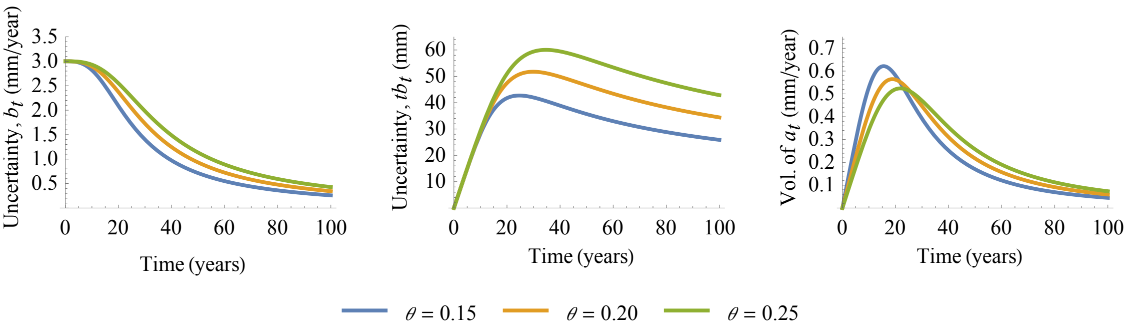
[12] Each path is constructed by randomly drawing a value of the actual rate of sea-level rise and then simulating a path for the climate factor using the stochastic process implied by Bayesian updating.

Figure 2.8: Evolution of climate uncertainty and volatility



Notes. The left-hand graph plots the RMSE of the decision-maker's estimate of the rate of sea-level rise. The middle graph plots the RMSE of the decision-maker's estimate of the average annual maximum sea level. The right-hand graph plots the volatility of the decision-maker's estimate of the rate of sea-level rise. The parameter θ measures the amount of noise in the climate signal.

mean square error (RMSE) of the decision-maker's estimate of the rate of sea-level rise. The three curves correspond to different amounts of noise in the signal observed by the decision-maker. Uncertainty about the rate of sea-level rise falls over time, but if the signal is noisier then it falls more slowly.

Uncertainty about the sea level The middle graph in Figure 2.8 plots the RMSE of the decision-maker's estimate of the sea level (more precisely, of the average annual maximum sea level). The decision-maker's uncertainty about the contemporaneous average annual maximum sea level is initially zero, increases for a few decades, and then decreases to zero. There are two opposing forces at work. Each year, the sea level rises by an uncertain constant amount, so that uncertainty about the cumulative change grows over time. However, this is offset by the ongoing learning process resulting from the noisy observations of the sea level. The first effect dominates initially, but eventually the second effect dominates.

Climate-factor volatility Finally, the right-hand graph in Figure 2.8 plots the volatility of the decision-maker's estimate of the rate of sea-level rise. This can be interpreted as an annualised measure of the standard deviation of changes in this estimate. This volatility is an important determinant of the value of the option to delay investment. It is initially low, but increases for approximately two decades and then decreases to zero. The decision-maker's estimate of the rate of sea-level rise is more volatile when her uncertainty about the rate of sea-level rise is falling more rapidly. As the rate of learning accelerates in the left-hand graph, the volatility in the right-hand graph grows. As the learning process slows down, the volatility falls.

2.4 Behaviour of the economic factor

The economic factor influences the expected economic consequences of weather events for any given state of local infrastructure. Its behaviour determines the answer to the question: how would the costs associated with a weather event change if an identical event occurred one year later? For example, when I model flooding risk, the level of the economic factor reflects potential clean-up and disruption costs, environmental damage, and health effects, but perhaps the most important influence is the depreciated replacement cost of vulnerable assets (Merz et al., 2010; Penning-Rowsell et al., 2013). All of these components fluctuate over time. For example, the depreciated replacement cost of vulnerable assets changes due to a combination of depreciation of the existing assets, spending on maintenance and improvement of existing assets as the economy grows, investment in additional assets, and changes in the prices of inputs into the repair and replacement process.

I assume the economic factor evolves according to geometric Brownian motion. That is, changes in the natural logarithm of the economic factor are normally distributed with a constant mean and standard deviation and changes are serially uncorrelated. I estimate the mean and standard deviation for a collection of proxies for the economic factor and then make an overall assessment of plausible values of these parameters.

When I model flooding risk, I use the depreciated replacement cost of vulnerable assets as the main proxy for the economic factor. However, changes in local GDP, or some other measure of economic activity, are also potentially a useful proxy for changes in the disruption costs associated with flooding.[13] Changes in local population might give useful information about changes in the health effects and number of fatalities associated with flooding. Changes in traffic volumes might give useful information about disruption costs when transport infrastructure is affected by flooding.

Shocks to these variables are typically serially correlated, whereas geometric Brownian motion assumes that changes in any two non-overlapping time periods are independent. For example, positive serial correlation in annual growth rates means that a relatively small shock to the current depreciated replacement cost of vulnerable assets can have a larger impact on the long-run depreciated replacement cost because it leads to a persistent sequence of changes in subsequent years. In order to address this issue, I focus on the long-term effects of shocks to the variables above. Specifically, for each variable, I fit an AR(1) model to annual changes in the natural logarithm of the variable and then calculate the effect of a one-standard deviation annual shock on the variable over the subsequent ten years.

In Chapter 4, when I model retrofitting buildings to help their occupants cope with high outside temperatures, I calibrate the economic factor to match the situation in Canterbury. The top panel in Table 2.1 reports the results of this procedure. The first row shows the results for median rent levels implied by data from tenancy bonds for the Canterbury region, whereas the second row shows results from a regional rent index, both adjusted for CPI inflation. The remaining rows of this panel show results for two measures of local economic activity.[14] I adopt 1.5% and 6.0% as my baseline estimates of the drift and volatility of the economic factor in Chapter 4.

When I model upgrading an urban stormwater system in Chapter 5, I calibrate the economic factor to match the situation facing Dunedin City Council. The middle panel in Table 2.1 reports the results of this procedure using data for Dunedin and the surrounding region. The first row shows the results for a depreciated replacement cost index, which suggest that 1.5% and 7.0% are reasonable estimates of the drift and volatility of the

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[13] To be clear, I would not be using the change in GDP in the aftermath of a flood to measure the cost of flooding. Rather, I would be supposing that if GDP grows by ten percent over time, then—all else equal—expected disruption costs due to flooding grow by ten percent as well.

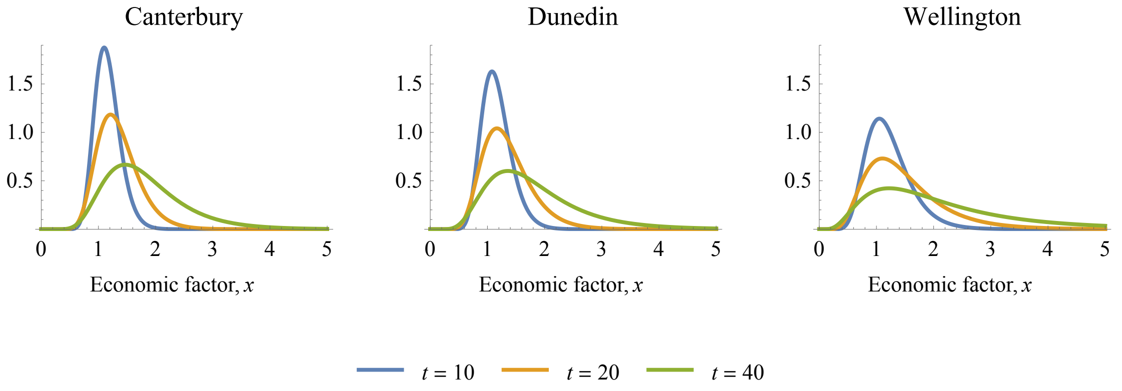
[14] I use per capita GDP rather than total GDP here because the benefits relate to a single building rather than a region. Regional growth is more likely to lead to more buildings, not more occupants per building.

Table 2.1: Proxies for the drift and volatility of the economic factor x_t

Variable	Long-run mean of $\Delta \log x$	Effect of a one std dev shock on $\Delta \log x$					
		1	2	3	5	10	∞
(a) Application to retrofitting buildings in Canterbury							
Rent (MBIE)	0.019	0.036	0.050	0.056	0.059	0.059	0.059
Rent index (Stat NZ)	0.007	0.038	0.038	0.038	0.038	0.038	0.038
Regional per capita GDP (owner-occupied property)	0.015	0.054	0.071	0.076	0.078	0.078	0.078
Regional per capita GDP	0.018	0.035	0.036	0.036	0.036	0.036	0.036
(b) Application to Dunedin's urban stormwater system							
Depreciated replacement cost	0.015	0.023	0.039	0.049	0.061	0.069	0.070
Regional GDP (total)	0.029	0.026	0.035	0.038	0.040	0.040	0.040
Regional per capita GDP (total)	0.017	0.024	0.030	0.032	0.032	0.032	0.032
Regional per capita GDP (total) × local pop'n	0.022	0.026	0.034	0.036	0.037	0.037	0.037
Regional GDP (owner-occupied property)	0.047	0.038	0.054	0.061	0.065	0.066	0.066
(c) Application to a sea wall in Wellington Harbour							
Depreciated replacement cost	0.020	0.025	0.043	0.057	0.075	0.092	0.098
Regional GDP (total)	0.022	0.016	0.007	0.012	0.011	0.010	0.010
Regional per capita GDP (total)	0.012	0.013	0.004	0.010	0.009	0.007	0.007
Regional per capita GDP (total) × local pop'n	0.018	0.018	0.011	0.014	0.013	0.013	0.013
Regional GDP (owner-occupied property)	0.037	0.031	0.046	0.054	0.060	0.062	0.062

Notes. I fit an AR(1) model to annual changes in the natural logarithm of each variable and then calculate the effect of a one-standard deviation annual shock over the subsequent ten years.

Figure 2.9: Distribution of future values of the economic factor



Notes. The graph plots the density functions for the distribution of the economic factor for Canterbury, Dunedin, and Wellington at 10, 20, and 40 years into the future, assuming its current value equals 1.

economic factor. The remaining rows of this panel show results for various measures of local economic activity. GDP is available only for the wider Otago region (rather than just Dunedin City), so the table includes results for regional GDP, per capita regional GDP, and the product of per capita regional GDP and the population of Dunedin city. It also shows results for the component of regional GDP corresponding to the services generated by owner-occupied property. The values of the drift parameter are higher than the drift of depreciated replacement cost, which is not surprising because none of these measures of economic activity allow for depreciation. In contrast, the values of the volatility parameter are lower than the volatility of depreciated replacement cost, which reflects the relatively high volatility of real construction costs. Bearing in mind the importance of depreciation and construction (repair) costs for the calculation of flooding costs, I will adopt 1.5% and 7.0% as my baseline estimates of the drift and volatility of the economic factor in Chapter 5.

When I model increasing the height of an existing sea wall in Chapter 6, I calibrate the economic factor to match the situation in Wellington Harbour. The bottom panel in Table 2.1 reports the results of the calibration procedure using data for Wellington and the surrounding region. The first row shows the results for a depreciated replacement cost index, which suggest that 2.0% and 10.0% are reasonable estimates of the drift and volatility of the economic factor. As in the top panel, the remaining rows of this panel show results for various measures of local economic activity.[15] Consistent with the importance of depreciation and construction (repair) costs for the calculation of flooding costs, I will adopt 2.0% and 10.0% as the baseline parameter values in Chapter 6.

The graphs in Figure 2.9 plot the density functions of the distribution of the economic factor for Canterbury, Dunedin, and Wellington. In each case, the three curves show the distribution 10, 20, and 40 years into the future, scaling the factor so that it currently

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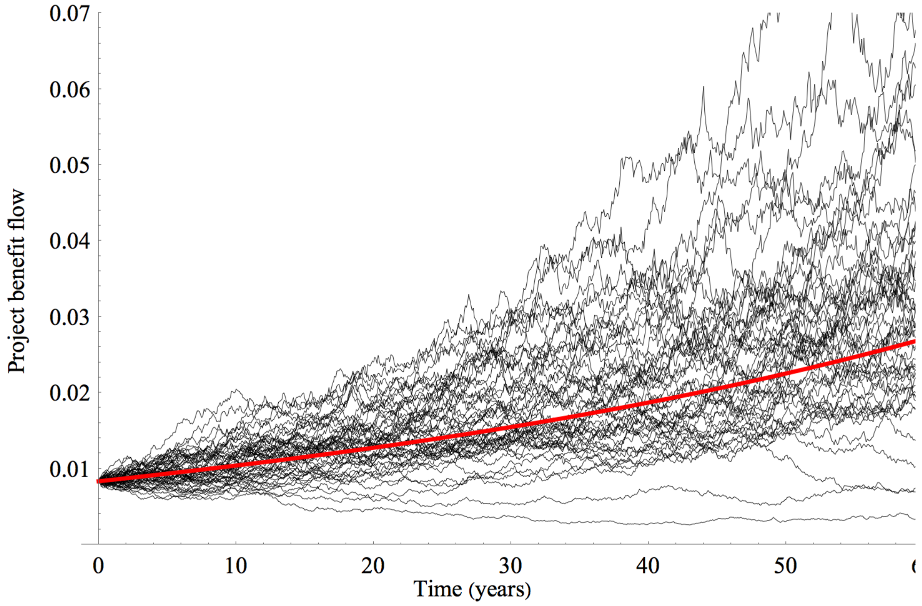
[15] GDP is available only for the wider Wellington region (rather than just the Eastern Bays), so I report results for regional GDP, per capita regional GDP, and the product of per capita regional GDP and the population of Lower Hutt city. I also report results for the component of regional GDP corresponding to the services generated by owner-occupied property.

Figure 2.10: Simulated paths for the flow of project benefits



Notes. The black curves show 50 simulated paths for the flow of project benefits of upgrading the urban stormwater system described in Chapter 5. The red curve plots the expected value of future benefits conditional on the information available to the decision-maker at date 0.

equals 1.0. Even though the volatility estimates above might seem low, the long time frames involved in the decision-maker's investment problem mean there will be considerable variation in the economic factor over relevant time frames. The greater volatility for Wellington (10% compared to 6% for Canterbury and 7% for Dunedin) is reflected in the greater dispersion of the distribution. The results are especially noticeable over longer time frames.

2.5 Putting the pieces together

The project benefit flows that occur in the future are the avoided climate-related costs, averaged over all possible weather events. The weather-event distribution depends on the contemporaneous level of the climatic factor and the magnitude of these costs depends on the contemporaneous level of the economic factor. As both of these variables evolve randomly over time, so must the project benefit flows. The volatility of a project's benefit flows depends on the volatility of the climatic and economic factors and on the sensitivity of the benefit flow to the level of these factors.

Figure 2.10 shows 50 simulated paths for the flow of project benefits of upgrading an urban stormwater system, which is covered in Chapter 5. The underlying project benefit function is the one plotted in the right-hand graph in Figure 2.3. The climatic factor evolves according to the stochastic process illustrated in the middle graph in Figure 2.4 and the economic factor evolves according to a geometric Brownian motion with drift of 1.5% and volatility of 7.0%. The red curve plots the expected value of future benefits conditional on the information available to the decision-maker at date 0.

In this example, the project's benefit flow can deviate significantly from the initial expected path. This exposes the decision-maker to asset-stranding risk, which is the possibility that the benefits turn out to be insufficient to justify the investment expenditure, leaving the public to incur the cost of an ex-post unnecessary investment (such as the cost of servicing any debt incurred to fund the project). In some situations, there can also be a cost associated with unexpectedly high benefits: if the decision-maker has the option to choose the scale of investment (as well as the timing), then she is exposed to the risk that she chooses an insufficient scale of investment, leaving the community with unachieved benefits or the need to undertake an additional round of investment. When decision-makers consider investing immediately rather than waiting for better information about the future paths of the climatic and economic factors they must weigh these costs associated with early investment against the benefits of generating *some* benefits in the short-term. The next chapter describes the decision-making rules that I consider.

Chapter

3

Approaches to decision-making

The benefits of using ROA can be significant, but it is regarded by many practitioners as complex and resource-intensive. This chapter describes several practical alternative approaches that are simple enough to be useful for evaluating small- and medium-scale adaptation decisions, yet retain a degree of economic rigour. The remaining chapters evaluate the potential of these approaches against the real-options benchmark.

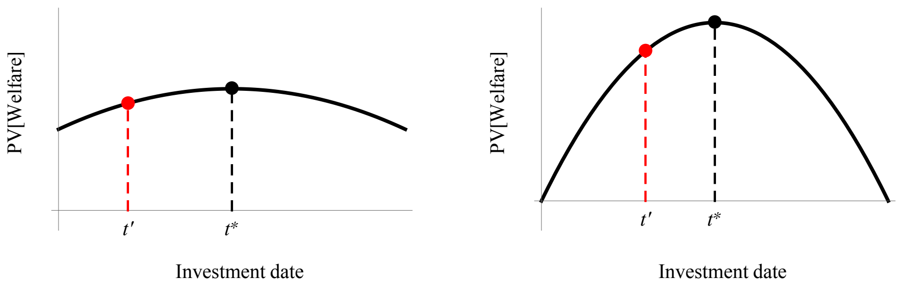
The key task is to identify simple decision-making rules that keep the welfare costs of deviating from optimal decision-making low. The relevant issue is whether welfare falls significantly if a simplified rule is used, not whether the resulting policy is significantly different from the optimal one. Consider Figure 3.1, which is a stylised depiction of the problem decision-makers face. The graphs plot the present value of the overall welfare associated with an adaptation project as a function of the date when the project is initiated. The black dots show the best time to invest and the red dots show the investment date if the decision-maker adopts some simple alternative policy for choosing the investment date. In the left-hand graph, welfare is relatively insensitive to investment timing, so the simple policy performs well even though the gap between the two investment dates is large. In contrast, in the right-hand graph, welfare is relatively sensitive to investment timing, so the simple policy performs poorly even though the gap between the two investment dates is small.

The lesson to draw from these graphs is that even if a simple decision-making approach results in large errors in investment timing, the approach may be suitable for practical use if the welfare loss is small. In contrast, for some projects a simple rule may potentially lead to a small error in investment timing but a large loss of welfare. For these projects, the simple rule is not appropriate. I therefore use the present value of future welfare to measure the performance of each candidate rule.

3.1 Real options analysis

At each evaluation date, the decision-maker should identify the various actions she can take, estimate the present value of the welfare associated with each action, and then take the action that generates the most welfare. In the simplest non-trivial case, she can either invest immediately or wait and reevaluate the project at some future date. It is optimal to invest immediately if and only if the net present value from investing is greater than the

Figure 3.1: The importance of focussing on welfare rather than timing



Notes. The graphs plot the present value of the overall welfare associated with an adaptation project as a function of the date when the project is initiated. The black dots show the best time to invest and the red dots show the investment date if the decision-maker adopts some simple alternative policy for choosing the investment date.

value of the delay option, provided the option value is consistent with the decision-maker adopting an optimal investment policy in the future. That is, it is optimal to invest as soon as

$$\begin{pmatrix} \text{Present value} \\ \text{of future} \\ \text{net benefits} \end{pmatrix} - \begin{pmatrix} \text{Investment} \\ \text{expenditure} \end{pmatrix} > \begin{pmatrix} \text{Option} \\ \text{value of} \\ \text{waiting} \end{pmatrix}.$$

It is this option value that is difficult to calculate in practical applications.

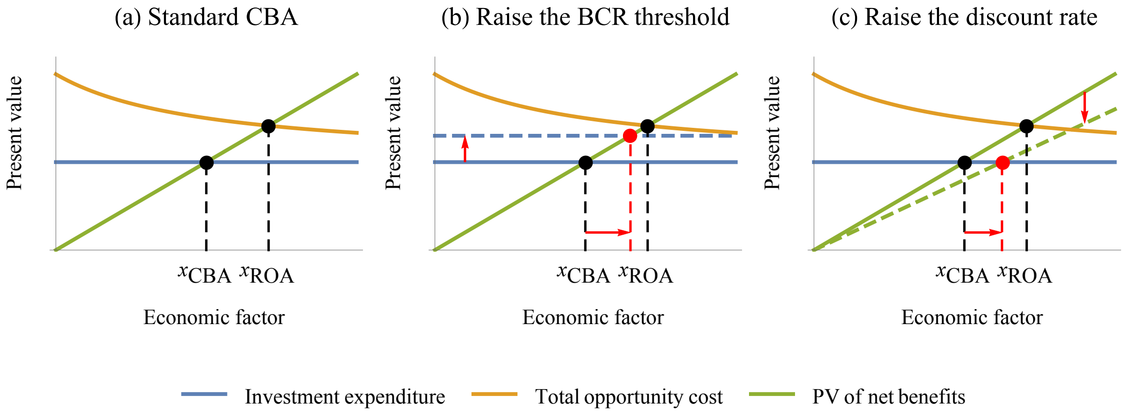
The condition for immediate investment to be optimal can be rearranged so that it takes the form

$$\begin{pmatrix} \text{Present value} \\ \text{of future} \\ \text{net benefits} \end{pmatrix} > \begin{pmatrix} \text{Investment} \\ \text{expenditure} \end{pmatrix} + \begin{pmatrix} \text{Option} \\ \text{value of} \\ \text{waiting} \end{pmatrix}. \tag{3.1}$$

The left-hand side is the present value of the project's benefits and the right-hand side is the opportunity cost of investment, which equals the investment expenditure plus the value of the delay option that is destroyed as soon as the decision-maker invests.

This approach is summarised in the left-hand graph in Figure 3.2. The graph is a stylised representation of the situation facing the decision-maker at a point in time. The green curve plots the present value of the future net benefits as a function of the level of the economic factor. The height of the blue curve equals the project's investment expenditure and the height of the yellow curve shows the total opportunity cost of investing. That is, the distance between these two curves equals the option value of delaying investment. It is socially optimal to invest if and only if the height of the green curve is greater than the height of the yellow curve. The optimal investment policy can be expressed in the form of a trigger point. For example, the decision-maker might invest when the economic factor reaches a certain level, shown by the level x_{ROA} in Figure 3.2. The welfare-maximising level of this threshold will depend on the current date and the level of the climatic factor. Alternatively, the investment rule can be expressed as a threshold for the climatic factor, the level of the benefit flow that investment would initiate, and so on.

Figure 3.2: Cost–benefit analysis and rules of thumb



Notes. The graph is a stylised representation of the situation facing the decision-maker at a point in time. It is socially optimal to invest if and only if the height of the green curve is greater than the height of the yellow curve. That is, the decision-maker should invest only if the economic factor is greater than the level x_{ROA} shown on the horizontal axis.

3.2 Cost–benefit analysis

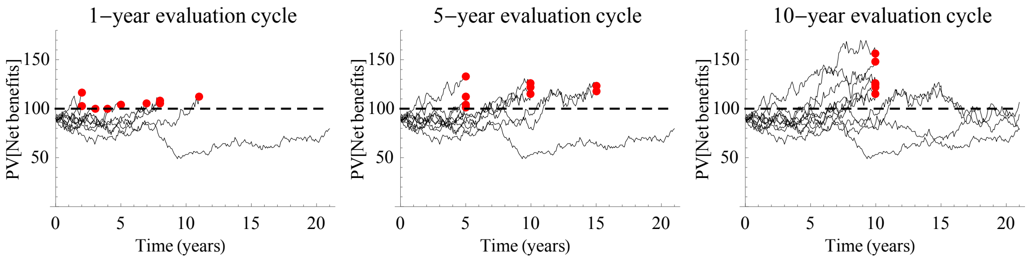
A decision-maker who evaluates a project using standard cost–benefit analysis (CBA) will invest immediately if the present value of the project's future net benefits is greater than the present value of the required investment expenditure. If this condition is not met then she will wait and reevaluate the project at some future date. I consider the possibility that the project is evaluated at fixed regular intervals.

Optimal investment timing requires that investment only occurs when the present value of the project's future net benefits is greater than the total opportunity cost of investment, which equals the sum of the present value of the required investment expenditure and the value of the real option to delay investment. CBA ignores the second component of this cost calculation. The investment test is thus insufficiently demanding under CBA, which will lead to premature investment and welfare being less than or equal to the maximum achievable level.

This is apparent in the left-hand graph in Figure 3.2. If the decision-maker uses CBA, she will invest if and only if the height of the green curve (the present value of the project's future net benefits) is greater than the height of the blue one (the project's investment expenditure), That is, she will invest if and only if the economic factor is greater than the level x_{CBA} shown on the horizontal axis. In particular, if the level of the economic factor lies between x_{CBA} and x_{ROA}, then she invests even though it is socially optimal to wait.

The performance of CBA improves if the project is evaluated less frequently. Suppose, for example, that the present value of the project's future net benefits is currently slightly less than the present value of the required investment expenditure, so that investment does not occur. If the decision-maker waits a fixed amount of time before reevaluating the project, there is a possibility that the present value of the project's future net benefits will climb significantly above the present value of the required investment expenditure before the next evaluation date. This is unlikely to happen if the project is evaluated frequently, because there is then not enough time for the project's net benefits to grow significantly.

Figure 3.3: CBA performance and evaluation frequency



Notes. Each graph shows the same ten simulated paths for the present value of the project's future net benefits. Each path starts at the current date (when the present value equals 90% of the project's required investment expenditure) and ends at the first evaluation date when the present value is greater than the investment expenditure.

However, with an evaluation period of five or ten years, these benefits have the opportunity to grow significantly.

Figure 3.3 illustrates what happens. Each graph shows the same ten simulated paths for the present value of the project's future net benefits. Each path starts at the current date (when the present value equals 90% of the project's required investment expenditure) and ends at the first evaluation date when the present value is greater than the investment expenditure. This is when investment occurs if the decision-maker uses standard CBA. The red dots show the present value on the investment date for each path. When the project is evaluated each year (the left-hand graph), there is simply not enough time for the benefits to grow much above the level of investment expenditure. Whenever investment occurs, the payoff will not be much greater than zero. In contrast, if the project is evaluated every ten years, there is a good chance that when investment occurs the present value of the project's future net benefits is substantially greater than the investment expenditure. The disadvantage is that investment is likely to occur later than would be the case if project evaluation occurred more frequently. Nevertheless, there is a clear practical implication: if the decision-maker uses CBA to choose investment dates, it would generally be best if projects are evaluated relatively infrequently.

3.3 Rules of thumb

I consider two minor modifications of standard CBA that are easily implemented. Each modification changes one parameter used in CBA and leaves the approach otherwise unchanged.

3.3.1 Constant threshold for the benefit–cost ratio

Motivation

An adaptation project's benefit–cost ratio (BCR) can be calculated by dividing the present value of the project's future net benefits by the present value of the required expenditure. Standard CBA states that the decision-maker should invest immediately if and only if the benefit–cost ratio is greater than one.

Optimal investment requires that the decision-maker invests immediately if and only if the present value of the project's benefits is greater than the sum of the present value of the required expenditure and the value of the delay option. Suppose, for example, that the present value of the project's required expenditure is \$1000. If the delay option is currently worth \$500, then the decision-maker should delay investment if the present value of the project's benefits is less than \$1500; that is, if the BCR is less than 1.5. If the delay option is currently worth \$800, then she should delay investment if the present value of the project's benefits is less than \$1800; that is, if the BCR is less than 1.8.

One approach to investment decision-making that is easily implemented is therefore to invest immediately if the project's BCR is greater than some constant threshold that equals the sum of one and an estimate of the value of the delay option expressed as a proportion of the required investment expenditure. If the estimated option value is correct, then this approach will lead to optimal decision-making. However, the value of the delay option is sensitive to the contemporaneous levels of the climatic and economic factors, so this condition will almost certainly not hold. Nevertheless, it has the potential to improve performance relative to standard CBA without requiring any additional calculations.

The approach is summarised in the middle graph in Figure 3.2. This has the same format as the left-hand graph, except that the decision-maker has effectively raised the "calculated" level of investment expenditure by a factor of $\hat{B}$, which has the effect of shifting the blue line upwards, as shown in the graph. Now she invests if and only if the height of the green line is greater than the height of the dashed blue line. The investment threshold increases, as shown by the location of the red dot. The higher the threshold for the BCR, the more demanding the investment test.

Implementation

Each time a project is evaluated, the decision-maker calculates the present value of the project's benefits and the present value of the investment expenditure. She invests in the project immediately if and only if the implied benefit–cost ratio is greater than a constant threshold that she specifies.

The threshold is constant during the period that a project is being evaluated, but there is no reason to use the same constant threshold for different projects. If a rule of thumb based on the BCR threshold is to be simple enough to use in practice, then the decision-maker needs a simple method for selecting the level of the threshold to use. Ideally it will be an explicit function of parameters that are easily estimated. The solution I adopt is to use the level of the BCR threshold that will be optimal once the climate has converged to its long-run equilibrium. The limiting value of the optimal BCR threshold equals

$$\hat{B} = \frac{\beta}{\beta - 1}, \tag{3.2}$$

where

$$\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} + \sqrt{\frac{2r}{\sigma^2} + \left(\frac{1}{2} - \frac{\mu}{\sigma^2}\right)^2}. \tag{3.3}$$

Here r is the social discount rate, μ is the average annual growth rate in the economic factor, and σ is the annualised volatility of the economic factor.

Table 3.1 reports values of $\hat{B}$ for a range of values of μ and σ. In all cases, the social discount rate equals five percent. For example, if the economic factor grows at two percent per annum on average, with a standard deviation of eight percent, then the rule-of-thumb

Table 3.1: Proposed constant threshold for the BCR

σ	μ								
	−0.010	−0.005	0.000	0.005	0.010	0.015	0.020	0.025	0.030
0.05	1.09	1.12	1.17	1.25	1.37	1.53	1.76	2.10	2.60
0.06	1.12	1.15	1.21	1.29	1.41	1.57	1.80	2.14	2.64
0.07	1.15	1.19	1.25	1.33	1.45	1.61	1.84	2.18	2.69
0.08	1.18	1.23	1.29	1.37	1.49	1.66	1.89	2.23	2.75
0.09	1.21	1.26	1.33	1.42	1.54	1.71	1.94	2.29	2.81
0.10	1.25	1.30	1.37	1.46	1.59	1.76	2.00	2.35	2.88
0.11	1.29	1.34	1.41	1.51	1.64	1.81	2.06	2.41	2.96
0.12	1.32	1.38	1.46	1.56	1.69	1.87	2.12	2.48	3.04
0.13	1.36	1.42	1.50	1.61	1.74	1.93	2.19	2.56	3.12
0.14	1.40	1.47	1.55	1.66	1.80	1.99	2.25	2.63	3.21
0.15	1.44	1.51	1.60	1.71	1.86	2.05	2.32	2.71	3.31

Notes. The entries in the table report the proposed constant BCR threshold that triggers immediate investment. They are calculated using equations (3.2) and (3.3).

BCR threshold equals 1.89. The decision-maker will invest the first time that the project's benefits have a present value that is more than 89% higher than the required investment expenditure.

3.3.2 Constant threshold for the internal rate of return

Motivation

As with the first rule of thumb, the starting point for this one is CBA. If the decision-maker uses CBA, she invests if and only if the present value of the project's future net benefits is greater than the expenditure needed to complete the project—that is, the BCR must be greater than one. In Section 3.3.1, I allowed for the option value of delaying investment by increasing the required level of the BCR to some constant $\hat{B}$ that is greater than 1. The main problem with this approach is that the optimal BCR threshold fluctuates significantly over time, so setting the BCR threshold to a constant might be making the investment test too demanding or not demanding enough.

The approach I use in this section is to scale down the calculated BCR. That is, when the decision-maker calculates the present value of the project's future net benefits—the BCR's numerator—she discounts them using a rate that is greater than the social discount rate. The decision-maker invests immediately if and only if this adjusted BCR is greater than one. Equivalently, she invests if the adjusted present value of future net benefits is greater than the investment expenditure, knowing that if the *adjusted* present is greater than the investment expenditure then the *actual* present value will be even higher.

The approach is summarised in the right-hand graph in Figure 3.2. This has the same format as the left-hand graph, except that the decision-maker has effectively lowered the "calculated" present value of the project's future net benefits, which has the effect of shifting the green line downwards, as shown in the graph. Now she invests if and only if the height of the dashed green line is greater than the height of the blue line. The investment threshold increases, as shown by the location of the red dot. The higher the discount rate used to calculate the present value of future net benefits, the more demanding the investment test.

Table 3.2: Proposed constant threshold for the IRR

σ	μ								
	−0.010	−0.005	0.000	0.005	0.010	0.015	0.020	0.025	0.030
0.05	5.53	5.66	5.86	6.13	6.47	6.86	7.29	7.74	8.20
0.06	5.71	5.85	6.04	6.30	6.62	7.00	7.40	7.84	8.29
0.07	5.89	6.04	6.24	6.49	6.79	7.14	7.53	7.95	8.39
0.08	6.09	6.24	6.43	6.68	6.97	7.31	7.68	8.08	8.50
0.09	6.29	6.45	6.64	6.88	7.16	7.48	7.83	8.22	8.63
0.10	6.50	6.66	6.85	7.08	7.35	7.66	8.00	8.37	8.77
0.11	6.72	6.88	7.07	7.29	7.55	7.85	8.18	8.53	8.91
0.12	6.94	7.10	7.29	7.51	7.76	8.05	8.36	8.71	9.07
0.13	7.18	7.34	7.52	7.74	7.98	8.25	8.56	8.89	9.24
0.14	7.41	7.57	7.76	7.97	8.20	8.47	8.76	9.08	9.42
0.15	7.66	7.82	8.00	8.20	8.44	8.69	8.97	9.28	9.61

Notes. The entries in the table report the proposed constant IRR threshold that triggers immediate investment. They are calculated using equations (3.3) and (3.4).

The rule is dependent on the level of the discount rate used. I will assume it is a constant, chosen by the decision-maker and greater than the social discount rate.

Implementation

Each time a project is evaluated, the decision-maker calculates the present value of the project's benefits using a discount rate that is greater than the social discount rate. She invests in the project immediately if and only if the implied benefit–cost ratio is greater than one. Equivalently, the decision-maker invests if and only if the project's internal rate of return (IRR) is greater than the threshold chosen by the decision-maker.

Many adaptation projects can be implemented in various ways. For example, the decision-maker can choose the height of a sea wall, the capacity of an upgraded stormwater system, and the location of re-located infrastructure. If this is the case, when the decision-maker ranks the alternative choices she should use the actual social discount rate to calculate the net present value of each option. She should only use the adjusted social discount rate at the final step, when deciding whether or not to invest immediately.

The same problem arises when using a constant threshold for the IRR as it does when using a constant threshold for the BCR; that is, the decision-maker needs to choose the level of the threshold. I adopt the same solution here, which is to use the level of the IRR threshold that will be optimal once the climate has converged to its long-run equilibrium. This value of the IRR threshold equals

$$\hat{h} = r + \frac{r - \mu}{\beta - 1}, \tag{3.4}$$

where β is given by equation (3.3).

Table 3.2 reports values of $\hat{h}$ for a range of values of μ and σ. In all cases, the social discount rate equals five percent. For example, if the economic factor grows at two percent per annum on average, with a standard deviation of eight percent, then the rule-of-thumb IRR threshold equals 7.68 percent. The decision-maker will invest the first time that the project's IRR exceeds the social discount rate by more than 2.68 percentage points.

3.4 Approximating the value of waiting

The three approaches described so far can all be interpreted in terms of the optimal investment condition in equation (3.1), which is rewritten here:

$$\begin{pmatrix}\text{Present value}\\ \text{of future}\\ \text{net benefits}\end{pmatrix} > \begin{pmatrix}\text{Investment}\\ \text{expenditure}\end{pmatrix} + \begin{pmatrix}\text{Option}\\ \text{value of}\\ \text{waiting}\end{pmatrix}.$$

In particular, each of them effectively makes a crude approximation of the value of the delay option that is destroyed as soon as the decision-maker invests.

- Standard CBA proceeds as though the option value is zero. That is, investment occurs when the present value of the future net benefits is greater than the investment expenditure.

- Using a constant BCR threshold effectively assumes that the option value is proportional to the investment expenditure. For example, using a threshold of 1.80 leads to investment behaviour that would be optimal if the value of the delay option equals 80% of the investment expenditure.

- Setting the discount rate at a level greater than the social discount rate effectively assumes that the value of the delay option is equal to the resulting reduction in the present value of the project's future net benefits.

This section describes some more sophisticated approaches to approximating the option value.

3.4.1 Assuming a fixed future investment date

Motivation

The option value of *optimally* waiting is the maximum attainable present value of the investment payoff when the decision-maker can choose from all possible investment policies. This includes policies that exploit information that becomes available while she waits. Under the fixed-date approach introduced in this section, she selects from a more restrictive set of choices. In particular, when the decision-maker calculates the maximum attainable value of waiting she only chooses from policies that involve investing at a *fixed* investment date in the future. This is much easier to calculate than the "optimal" value of waiting, because she just has to calculate the present value of the investment payoff for a set of fixed dates. The calculation is not much more complicated than standard CBA.

Suppose the decision-maker is deciding whether to invest in a project that will require upfront expenditure of \$1000. If she invests immediately (that is, in 2023), the project will generate a perpetual stream of expected benefits equal to \$45 in 2024, \$55 in 2025, \$65 in 2026, and so on. The net-benefit flow is shown in the top row of Table 3.3. On the other hand, if she waits and invest in 2024, then the project will generate expected benefits of \$55 in 2025, \$65 in 2026, and so on. This net-benefit flow is shown in the second row of Table 3.3. The only difference from investing immediately is that the initial outlay is delayed one year and the project does not start generating benefits until a year later. Delaying investment until later dates generates the same pattern of benefits.

Table 3.3: An example of project evaluation using the fixed-date approach

Investment date	2023	2024	2025	2026	2027	2028	2029	···	Present value
2023	−1000	45	55	65	75	85	95	···	3900
2024	0	−1000	55	65	75	85	95	···	3905
2025	0	0	−1000	65	75	85	95	···	3900
2026	0	0	0	−1000	75	85	95	···	3887

Notes. Each row reports the investment expenditure and net benefit flows generated by an adaptation project for a different fixed investment date, using all information available in 2023. The final column reports the corresponding net present value, calculated from the viewpoint of 2023.

The final column of Table 3.3 shows the present values of the net-benefit flows, measured in 2023, assuming the social discount rate is 5%. For example, if the decision-maker invests immediately, the investment payoff is $3900. On the other hand, if she decides to invest in 2024, the present value of the investment payoff will be $3905. Note that in this case, shown by the second row in Table 3.3, all net-benefit flows are discounted back to 2023 (not to the investment date of 2024).[1] Out of all the possible fixed future investment dates, investing in 2024 gives the investment payoff with the largest present value in 2023. As this present value is $3905, our estimate of the option value of waiting is $3905. As this is greater than the investment payoff from investing immediately, the decision-maker will not invest and instead will wait and reevaluate the project in the future.

It is important to note what this result does *not* mean: the policy is *not* to invest in 2024. Rather, the decision-maker will wait until the next scheduled evaluation date and repeat the fixed-date calculations. All new relevant information will be incorporated in the calculations, which will potentially alter the best fixed investment date. If the investment payoff is greater than the approximate value of waiting, then the decision-maker invests immediately, otherwise she waits until the next evaluation date. That is, the fixed-date assumption is only for the purpose of estimating the option value of waiting; it is not used to set the actual investment date. For as long as the decision-maker delays investment, she continues to gather relevant climatic and economic information, and uses it to recalculate the option value—but each time she calculates the option value, she assumes that any delayed investment will occur at the best fixed future date. That is, the scope of this assumption is strictly limited to calculating an approximate value for the delay option.

Table 3.4 shows how new information is incorporated in the fixed-date approach. Recall that, based on the calculations in Table 3.3, the decision-maker chose to delay investment in 2023. At that time, 2024 was the best fixed investment date. Table 3.4 shows what happens when the project is reevaluated in 2024, assuming that new information has induced the decision-maker to revise her annual benefit estimates downwards by $6. The immediate investment payoff is $3980, but the approximate value of waiting is $3981 (which is the present value of the investment payoff if she decides to invest in 2025).[2] Once more, she should delay investment and reevaluate the project in the future.

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[1] The present value evaluated in 2024 would be $4100, but that is not relevant for our evaluation in 2023.

[2] All present values are calculated from the viewpoint of 2024. Note that the new information has changed the best fixed investment date from 2024 to 2025.

Table 3.4: An example of project evaluation using the fixed-date approach (cont.)

Investment date	2023	2024	2025	2026	2027	2028	2029	⋯	Present value
2024	n/a	−1000	49	59	69	79	89	⋯	3980
2025	n/a	0	−1000	59	69	79	89	⋯	3981
2026	n/a	0	0	−1000	69	79	89	⋯	3973

Notes. Each row reports the investment expenditure and net benefit flows generated by an adaptation project for a different fixed investment date, using all information available in 2024. The final column reports the corresponding net present value, calculated from the viewpoint of 2024.

Implementation

Implementation of this approach is straightforward. Each time a project is evaluated, the decision-maker calculates the present values of the investment payoffs for a selection of possible *fixed* future investment dates. She invests in the project immediately if and only if, when viewed from the current date, it is better to invest immediately than to commit to invest at any fixed future date. If this condition does not hold, then she waits and repeats the evaluation process at the next scheduled evaluation date.

As the method has been presented so far, the decision-maker should consider all possible future evaluation dates when she carries out this exercise. However, a simpler approach is to just use one or two future fixed investment dates (for example, dates five and ten years in the future). The quality of the approximation of the option value of waiting will fall, but the effect is likely to be small. Decision-making is now based on a simple rule: evaluate the present value of investment payoffs from investing immediately, investing five years from now, and investing ten years from now, and invest immediately if and only if the first present value is larger than the other two.

3.4.2 Ignoring climatic or economic uncertainty

Calculating the option value of waiting is made especially difficult by the presence of two distinct sources of uncertainty: climatic and economic. One way to simplify calculation of the option value is to ignore one of these sources of uncertainty. For example, the decision-maker can assume that the economic factor does not deviate from its expected path. Alternatively, she can incorporate economic volatility but assume the climatic factor does not deviate from its expected path. In either case, the decision-maker only needs to incorporate one source of volatility when she calculates the value of the delay option.

Note that, as for the fixed-date approach described in Section 3.4.1, the decision-maker only ignores this source of uncertainty when she calculates the option value. If she delays investment, then when she reevaluates the project she incorporates all information that has arrived since the last evaluation date—even though her past calculation of the option value assumed there would be no such information. That is, the decision-maker updates the investment payoff and the option value of waiting for the arrival of new climatic and economic information since the most recent evaluation. However, she does not allow for the arrival of *future* information when she calculates the value of waiting.

Chapter

4

Simple timing options

4.1 Introduction

This chapter analyses the simplest, and most commonly studied, example of a real option: the option to choose when to undertake a one-off, irreversible investment. The choice of investment timing is the only flexibility embedded in the investment opportunity. In some examples, this will be because there really is no flexibility about what to build or where to build it, only about when to build it. In reality, most projects will have some "what" or "where" flexibility, but if this flexibility is minor compared to the embedded "when" flexibility, then the project will be a good fit for the one studied in this chapter. The key features are that the decision-maker can take the action (that is, invest) at most once, she can take the action at any point during some (possibly quite long) period of time, the cost of reversing the action is prohibitively high, and the flow of future benefits initiated by taking the action is uncertain.

I illustrate this class of projects using the example of a programme to retrofit new technology to existing buildings that will enable them to cope with higher outside temperatures.[1] This can involve fitting fixed shading, movable external louvers, and extractor fans to buildings and repainting them with materials that reflect heat. The flow of benefits generated by investment includes reduced heat-related illness and, for many types of project, reduced energy use. A suitable climate factor is therefore the average daily maximum temperature and suitable economic factors are average wages or other measures of lost productivity. The decision-maker must decide when to upgrade the building. The benefits generated by upgraded buildings may not cover the upgrading costs if climate change turns out to be less severe than predicted, or if future measures of lost productivity are lower than predicted. As investment is effectively irreversible, the decision-maker needs to weigh these risks against the flow of near-term benefits generated by early investment.

Many other adaptation projects can be modelled using a similar framework. For example, culverts carry water under roads at natural drainage and stream crossings. When heavy rain and storm debris exceed the capacity of a culvert, the result can be a flooded

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[1] A closely related example is the option to retrofit living (or green) roofs on existing buildings in order to reduce peak stormwater flows (Fassman et al., 2010a,b).

road and disrupted traffic.[2] Investing in a new culvert, or increasing the capacity of an existing one, results in less frequent flooding and reduced disruption costs. The main sources of uncertainty surrounding the magnitude of these benefits are climatic (the frequency and severity of extreme rainfall events) and economic (the volume of traffic on the road and the value road users attach to avoiding disruption). Suitable climatic and economic factors are therefore the average annual maximum rainfall in the vicinity of the culvert and traffic volume, respectively. Decision-makers need to decide when to invest.

There are many other examples of adaptation projects with timing flexibility. For example, Dunedin City Council is planning to redirect waste water from a treatment plant on vulnerable land to one in a location that is less vulnerable, which will reduce wastewater flooding in South Dunedin during times of heavy rain (Miller, 2018).[3] The benefits generated by the completed project comprise the avoided flooding costs in South Dunedin. The main sources of uncertainty surrounding the magnitude of these benefits are climatic (the frequency and severity of extreme rainfall events) and economic (the value of assets in South Dunedin that will be exposed to flooding risk until the wastewater system is relocated). Suitable climatic and economic factors are therefore the average annual maximum rainfall in the Dunedin area and the value of potentially affected assets in South Dunedin. Their behaviour determines when it will be optimal for Dunedin City Council to carry out the investment.

Similarly, when a local government considers abandoning a coastal road prone to erosion, it must decide when to implement this policy. Doing so will generate benefits in the form of avoided maintenance and repair costs, minus the lost economic surplus generated by road users who must travel by a different route. A suitable climatic factor is any variable that determines the frequency and severity of storm surges. A suitable economic factor is any variable that determines the economic surplus generated by road users. This could be as simple as the existing road's traffic volume. It will be costly to reverse the decision once the road is abandoned, especially if the erosion has been allowed to occur.

Many smaller-scale adaptation projects can be interpreted using the framework in this chapter. For example, the owners of agricultural land confront a similar problem when they consider changing the ways in which they use their land. One response to increased erosion risk is to change from sheep and beef farming to forestry (Awatere et al., 2018). Alternatively, riparian planting can reduce erosion, provide more shade, and make it easier to manage stock, thereby boosting the profitability of surrounding land and potentially generating additional revenue directly.[4] Agricultural land can be used to produce biomass energy feedstocks (Regan et al., 2017). The economic benefits of a change in land use equal the difference in profitability between the old and new activities. These benefits are uncertain. First, future climatic conditions are uncertain and the state of the climate will affect the land's productivity with different activities.[5] Second, future economic conditions are also uncertain and these conditions affect what the outputs of these activities are worth.

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[2] For example, in July 2021, the combination of a blocked culvert and a heavy rainstorm turned a 40-minute commute into a nine-hour journey in Wellington (Te, 2021).

[3] Hughes et al. (2019, 2021) evaluate the impact of climate change on New Zealand's wastewater systems.

[4] For example, riparian planting of flax can restore habitat in the short term and generate revenue in the future (Hardy et al., 2019).

[5] Ausseil et al. (2019) investigate the likely impact of climate change on the suitability of some primary production activities in three regions of New Zealand (Hawke's Bay, Southland, Waikato). Land-use changes might be driven more by some types of climate change than others. For example, the results in Bell et al. (2021) suggest that an increased frequency and severity of droughts may have a moderate effect on the profitability of sheep/beef and dairy farming.

There is little point switching to a more productive land use if the market price of the new output is very low. The landowner must decide when to change land use, but the timing decision is not straightforward. For example, a new land-use might boost profitability during droughts, but reduce it during non-drought periods, so the payoff from changing land-use will depend on whether a good or bad climate scenario holds. It will be costly to reverse some land-use changes, so the decision-maker will not want to switch from one land-use to another too soon.

Similar issues can arise in situations where investment is not a consequence of climate change, but is nevertheless affected by climate change. Consider the option to construct houses on coastal land that is potentially vulnerable to climate change.[6] Even if the climate were not changing, the landowner may still want to develop the land, but the prospect of climate change affects the development decision. The economic benefits generated by the investment (which equal the imputed rent of the houses built on the land) are sensitive to future climate conditions. The expected value of these benefits declines over time due to a combination of increasing flooding costs and potentially even abandonment of the houses due to erosion. The future benefits will be especially low if the climate scenario is bad. In addition to the usual cost of waiting, in this situation the landowner must also consider the fact that the longer she waits to develop the land, the shorter the length of time the developed land will be able to generate economic benefits before factors such as erosion render the land unusable.

Table 4.1 shows how these adaptation projects can be interpreted in terms of the model in this chapter. It suggests ways to specify benefit flows that capture the key net benefits generated by the completed project, as well as adopt climatic and economic factors that are appropriate for each example. I present a model of the first of these examples in this chapter. Like all models used for decision-making, it is stylised. This is partly to ensure the model is tractable and partly so its insights are applicable to other adaptation projects, such as the other examples in Table 4.1. Many more complicated investment opportunities can be analysed using essentially the same model. The key feature is that the decision-maker can choose when to invest in the project. For example, even if the investment programme spans several years, if construction cannot be abandoned or suspended prior to completion, then the decision-maker can treat investment as a single event, as in the model in this chapter. She simply sets the one-off lump sum investment outlay in the model equal to the present value of the sequence of investment outlays in the real world example.

4.2 Model framework

Details of the model can be found in Appendix B.1. Its key components are:

- A building's occupants only suffer heat-related costs when the outside temperature exceeds q degrees. The building's owner has the option to retrofit new technologies that will lift this temperature threshold to q' degrees. The building upgrade costs c dollars.

- The economic factor equals the (annualised) heat-related costs incurred by the occupants for each degree the outside temperature exceeds the no-cost threshold. Each

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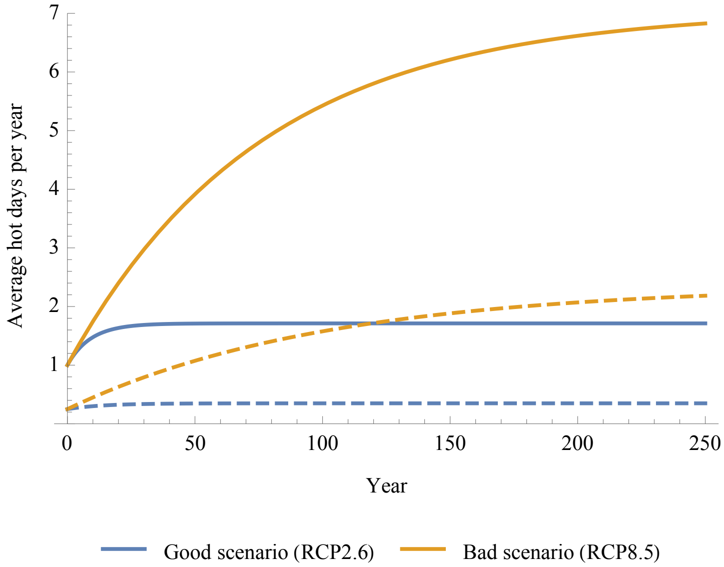
[6] For example, one of the options considered for Māori-owned coastal land in Horowhenua is to use it for sustainable housing developments (Hardy et al., 2019).

Table 4.1: Adaptation projects compatible with the framework in Chapter 4

Type of project	Benefit flow	Climate factor	Economic factor
Retrofitting buildings to cope with heat waves	Avoided heat-related costs	Average daily maximum temperature	Average wages or other measures of lost productivity
Upgrading road culverts	Avoided traffic disruption due to flooding	Average annual maximum rainfall	Traffic volume
Relocating wastewater infrastructure	Avoided flooding costs	Average annual maximum rainfall	Value of assets in vulnerable area
Abandoning a coastal road prone to erosion	Avoided maintenance and repair costs, minus lost economic surplus generated by road users	Any variable that determines the frequency and severity of storm surges	Traffic volume
Switching land use of drought-prone agricultural land	Difference in profitability between the old and new activities	Average rainfall	Agricultural commodity price
Building houses on potentially vulnerable land	Imputed rent generated by the land before it succumbs to erosion, minus expected flooding and insurance costs	Frequency and severity of storm surges	Value of developed land, which might be proxied by house prices in the local area

Figure 4.1: Average number of hot days with and without building retrofits



Notes. The graph plots the average number of days each year when the outside temperature exceeds the no-cost threshold under the two climate scenarios. The solid and dashed curves plot the average number of "hot" days before and after the building retrofit occurs.

year, the growth rate in this factor is normally distributed with a mean of 1.5% and a standard deviation of 6.0%.

- The distribution of the daily maximum outdoor temperature shifts over time according to one of two possible climate scenarios, which correspond approximately to RCP 2.6 and RCP 8.5. Figure 4.1 plots the average number of days each year when the outside temperature exceeds the no-cost threshold under the two climate scenarios. In each case, the solid and dashed curves plot the average number of "hot" days before and after the building retrofit occurs.

- All future costs and benefits are discounted using a constant social discount rate of 5% per annum.

- The baseline values of the model's parameters have been chosen to approximate the situation facing a building owner in Canterbury.

4.3 Optimal investment policy

The optimal policy does not involve fixed investment dates. Instead, it can be described in terms of trigger points. Each time the project is evaluated, the decision-maker calculates the current values of the climatic and economic factors and determines whether or not the calculated combination triggers immediate investment. The timing of investment is therefore determined by when a trigger point is reached, not by some fixed schedule of investment dates. This section describes the form these trigger points take, both in the baseline case and when the model's parameters are varied around this baseline.

4.3.1 Baseline case

I start by describing the socially optimal adaptation policy when the model's parameters take their baseline values. The top graph in Figure 4.2 summarises the optimal investment policy for this problem. The curves plot the trigger points as a function of the probability p that the bad climate scenario holds, with each curve corresponding to a different evaluation date t. In principle, the decision-maker can use this graph in the following way:

1. Calculate the current levels of the climatic and economic factors and identify the corresponding point on the graph.
2. If this point is on or below the curve corresponding to the current date, then wait and reevaluate the project in the future.
3. If this point is above the curve corresponding to the current date, then invest immediately.

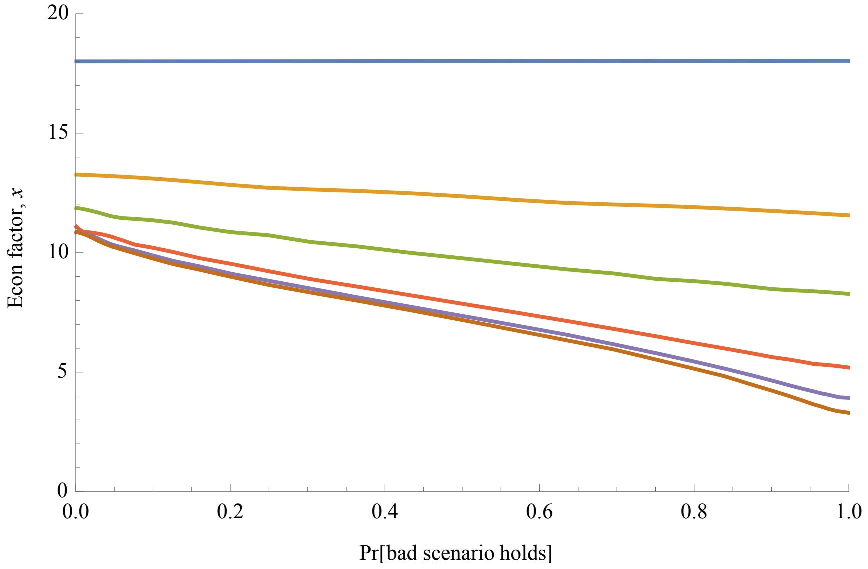
For example, if it is currently year 10 and the decision-maker believes the two scenarios are equally likely (that is, $p = 0.5$), then she should invest immediately if and only if the economic factor is greater than approximately 12.4, which is the height of the yellow curve. On the other hand, if the decision-maker believes the bad scenario is three times more likely than the good scenario (that is, $p = 0.75$), then the economic factor needs to exceed 12.0 in order for investment to be socially optimal in year 10.

The investment trigger points can also be expressed in terms of the benefit–cost ratio associated with retrofitting the building. That is, instead of waiting for the economic factor to be sufficiently high before investing, the decision-maker waits until the BCR is sufficiently high. The socially optimal thresholds are shown in the bottom graph in Figure 4.2. The key results to note are:

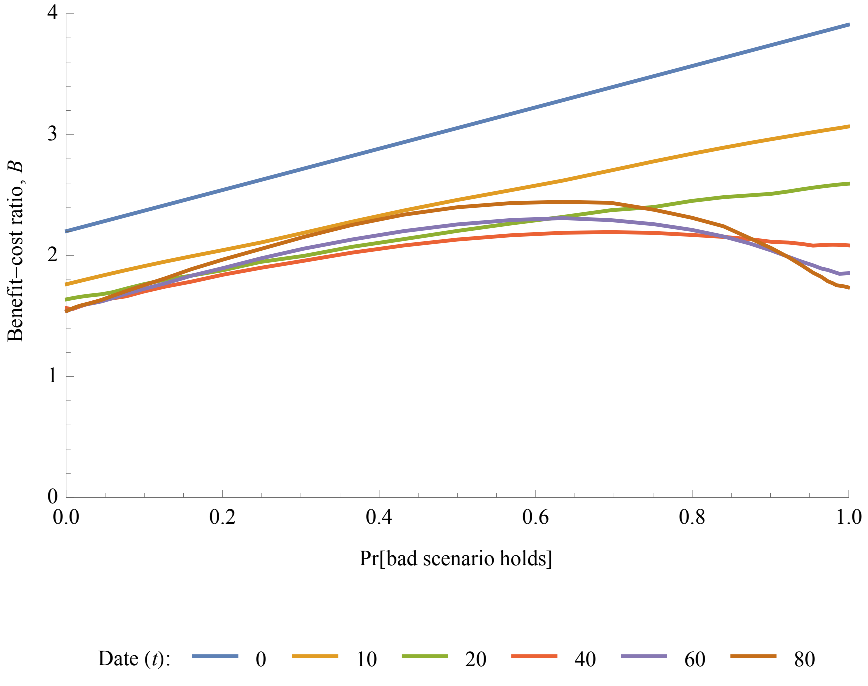
- The optimal BCR threshold is much greater than one in all cases. The present value of the benefits of investment therefore need to be significantly greater than the required expenditure before investment can be socially optimal. The margin above the required expenditure reflects the value of the real option to delay investment, which is destroyed when investment occurs and is therefore part of the opportunity cost of investment. At least in the baseline case considered here, this option value is significant.
- The causes of this high option value vary. In the near term, the high threshold is due to the possibility that the climate scenario is bad (so that the expected growth rate in benefits is high); in the longer-term, it is due to uncertainty about the climate scenario (and the resulting high level of p-volatility).
- In the short-term, the socially optimal BCR threshold is strongly increasing in p, so the investment test is more demanding when the bad scenario is believed to be more likely. Equivalently, the option to delay investment is initially more valuable when the bad scenario is believed to be more likely.
- The behaviour of the optimal BCR threshold over time depends on the degree of climate uncertainty.
    - If climate uncertainty is low (that is, p is close to 0 or 1), then the threshold falls over time, so that the investment test becomes less demanding. Once the

Figure 4.2: Optimal investment triggers for building retrofits

(a) Trigger for economic factor

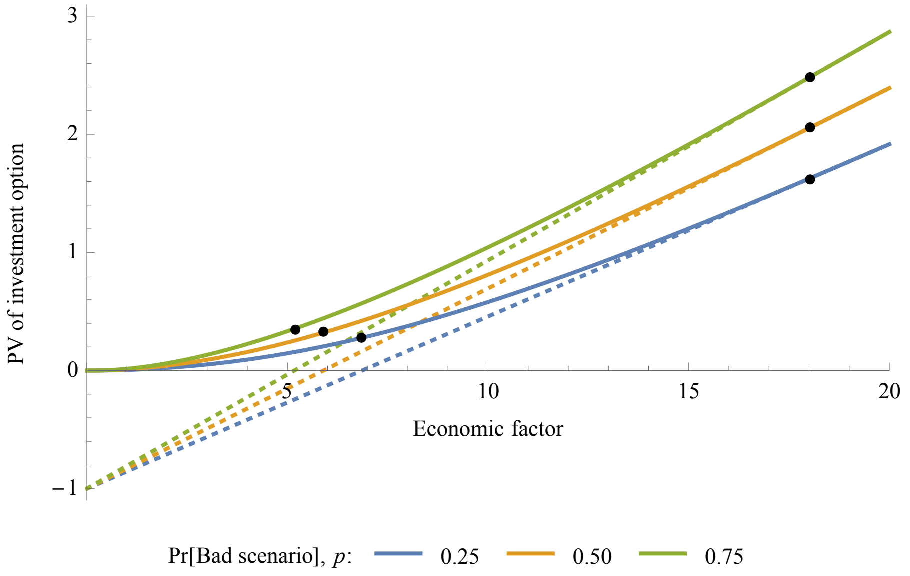


(b) Trigger for benefit–cost ratio



Notes. The top graph plots the optimal investment threshold for the economic factor as a function of the contemporaneous level of the climate factor, for the indicated evaluation dates. The bottom graph plots the optimal investment threshold for the BCR. All model parameters take their baseline values.

Figure 4.3: Value of the investment option under the optimal investment policy



Notes. The graph plots the value of the investment option at date $t = 0$ as a function of the level of the economic factor for three different levels of the probability that the bad climate scenario holds. The solid curves show the option's value if the decision-maker adopts the optimal investment policy and the dashed lines show the net payoffs from investing immediately.

average daily maximum temperature has converged to its long-run value, the value of the delay option derives solely from the volatility of the economic factor. For the baseline parameter values, the long-run value of the BCR threshold is 1.57.

– In the unlikely event that climate uncertainty remains high (that is, p is close to 0.5), the threshold starts to increase again, so that the investment test becomes more demanding. This reflects the fact that, as is evident from Chapter 2, p becomes much more volatile if it hovers around 0.5 as the possible paths for the average daily maximum temperature diverge. This leads to an increase in the volatility of the investment payoff, which increases the option value of waiting. In this situation, the true climate scenario will be revealed reasonably quickly, in which case p will move towards either 0 or 1. In either case, the high BCR thresholds will fall.

4.3.2 Sensitivity analysis

I use sensitivity analysis in this section in order to investigate two related issues:

- How important is the real option to choose the timing of investment?
- What does the welfare-maximising investment policy look like?

Figure 4.3 illustrates the approach I use. The solid curves plot the option value at date 0 as a function of the level of the economic factor, for the indicated bad-scenario probabilities. The dashed lines show the net payoffs from investing immediately.

- The importance of timing flexibility—that is, the value of the real option to delay investment—is captured by how far the solid curves are above the corresponding dashed lines. Obviously, the height difference depends on where along the horizontal axis the height is measured. I will measure the difference at the breakeven level of the economic factor—that is, where the dashed line cuts the horizontal axis. This quantity corresponds to the heights of the left-hand dots in the graph. In this example, I have normalised investment expenditure to equal one, so the option values are approximately 30% of the required investment expenditure.

- The three right-hand dots in Figure 4.3 show the optimal investment point for different bad-scenario probabilities. The optimal trigger point for the economic factor equals the horizontal coordinate of each point, but it is more intuitive to express the optimal investment policy in terms of the BCR. The heights of the three right-hand dots equal the value of the investment option when the economic factor is at the level that triggers immediate investment. As investment expenditure has been normalised to equal one in this example, this also equals the amount by which the optimal BCR investment threshold exceeds one. In this case, the margins are approximately 1.5–2.5, implying BCR thresholds of 2.5–3.5.

Each row in Table 4.2 reports the maximum attainable option value for various evaluation dates and probabilities that the bad climate scenario holds, where the option value is evaluated at the breakeven-level of the economic factor. The top row shows results when all parameters take their baseline values. The other panels report results when I vary one of the model's parameters, as described in the first entry in each row. The table shows the following:

- The value of timing flexibility is economically significant across the full range of parameter settings. That is, the value of the option is a significant percentage of the investment expenditure required to complete the adaptation project. Thus, some form of ROA, or a simplified approximation to this method, is important for achieving good welfare gains from investing in the project.

- In the short term, the option value is higher if the bad climate scenario is more likely.

- In the short term, investment timing flexibility is more valuable if the economic factor is more volatile or is expected to grow more quickly. Climate noise has little effect on the option value.

- In the medium term, the option value is higher if the economic factor is more volatile or is expected to grow more quickly, or there is less noise in climate data (that is, more volatility in the climate factor).

I also use sensitivity analysis to analyse the optimal investment policy. Each row in Table 4.3 reports the welfare-maximising trigger point for the BCR for various evaluation dates and probabilities that the bad climate scenario holds. The top row shows results when all parameters take their baseline values. For example, if the decision-maker is evaluating the project in year 40 and she believes the two scenarios are equally likely, then it is optimal to invest immediately if and only if immediate investment has a BCR greater

Table 4.2: Maximum attainable option value at breakeven level of economic factor

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Baseline case											
	0.277	0.250	0.285	0.305	0.321	0.273	0.282	0.289	0.353	0.263	0.239	0.229
σ	Volatility of economic factor											
0.04	0.265	0.240	0.277	0.299	0.310	0.264	0.276	0.285	0.344	0.253	0.228	0.218
0.05	0.271	0.245	0.281	0.301	0.315	0.268	0.278	0.287	0.348	0.258	0.233	0.223
0.06	0.277	0.250	0.285	0.305	0.321	0.273	0.282	0.289	0.353	0.263	0.239	0.229
0.07	0.285	0.257	0.289	0.309	0.328	0.278	0.286	0.293	0.359	0.269	0.245	0.236
0.08	0.293	0.263	0.294	0.313	0.335	0.284	0.291	0.297	0.366	0.276	0.253	0.243
μ	Drift of economic factor											
0.005	0.188	0.180	0.232	0.260	0.225	0.199	0.229	0.246	0.253	0.180	0.170	0.168
0.010	0.229	0.211	0.255	0.279	0.270	0.232	0.252	0.265	0.301	0.218	0.201	0.195
0.015	0.277	0.250	0.285	0.305	0.321	0.273	0.282	0.289	0.353	0.263	0.239	0.229
0.020	0.333	0.298	0.322	0.338	0.379	0.321	0.319	0.321	0.412	0.315	0.285	0.272
0.025	0.396	0.356	0.369	0.379	0.444	0.379	0.367	0.364	0.477	0.377	0.340	0.325
θ	Noise in climate information											
0.672	0.281	0.277	0.323	0.346	0.327	0.290	0.300	0.311	0.358	0.270	0.243	0.233
1.372	0.279	0.264	0.304	0.327	0.323	0.284	0.294	0.302	0.355	0.268	0.242	0.232
2.072	0.277	0.250	0.285	0.305	0.321	0.273	0.282	0.289	0.353	0.263	0.239	0.229
2.772	0.277	0.240	0.267	0.285	0.320	0.263	0.269	0.275	0.353	0.257	0.233	0.224
3.472	0.276	0.232	0.252	0.267	0.319	0.255	0.256	0.261	0.352	0.253	0.227	0.218

Notes. Each row reports the maximum attainable option value for various evaluation dates and probabilities that the bad climate scenario holds, where the option value is evaluated at the breakeven-level of the economic factor. The top row shows results when all parameters take their baseline values. The other panels report results when I vary one of the model's parameters, as described in the first entry in each row. All parameters other than those listed take their baseline values.

than 2.13. The other panels report results when I vary one of the model's parameters, as described in the first entry in each row. The table shows the following:

- BCR trigger points are high across the full range of parameter settings.
- In the short term, the optimal BCR threshold is higher if the bad climate scenario is more likely.
- In the short term, the drift in the economic factor is a much more important factor in determining the optimal threshold than economic volatility or noise in the climate variable. If the economic factor is expected to grow more quickly then the optimal BCR threshold is higher (that is, a more demanding investment test is optimal).
- In the medium term, the investment threshold is higher if the economic factor is more volatile or there is less noise in climate data (that is, more volatility in the climate factor). Climate volatility is more important than economic volatility in the medium term.

Overall, it is clear that the real option to choose the timing of investment is very valuable and that optimal investment involves waiting until the benefits of investment are much larger than the required investment expenditure. The remainder of this chapter evaluates the potential of simple alternatives to ROA to deliver the economic benefits associated with investment-timing flexibility.

Table 4.3: Optimal threshold for the BCR

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Baseline case											
	2.63	1.90	2.06	2.17	3.05	2.13	2.40	2.58	3.48	2.19	2.38	2.58
σ	Volatility of economic factor											
0.04	2.60	1.83	1.99	2.09	3.03	2.06	2.33	2.54	3.46	2.13	2.34	2.52
0.05	2.61	1.87	2.02	2.15	3.04	2.09	2.36	2.55	3.47	2.16	2.36	2.54
0.06	2.63	1.90	2.06	2.17	3.05	2.13	2.40	2.58	3.48	2.19	2.38	2.58
0.07	2.64	1.94	2.11	2.21	3.07	2.17	2.44	2.63	3.50	2.22	2.42	2.59
0.08	2.65	1.98	2.14	2.27	3.08	2.21	2.47	2.68	3.51	2.26	2.44	2.61
μ	Drift of economic factor											
0.005	1.91	1.53	1.72	1.84	2.16	1.70	2.00	2.19	2.41	1.71	1.96	2.14
0.010	2.22	1.69	1.86	1.98	2.54	1.88	2.16	2.35	2.86	1.91	2.14	2.32
0.015	2.63	1.90	2.06	2.17	3.05	2.13	2.40	2.58	3.48	2.19	2.38	2.58
0.020	3.19	2.21	2.36	2.46	3.79	2.48	2.73	2.92	4.38	2.58	2.73	2.90
0.025	4.02	2.65	2.77	2.89	4.88	3.02	3.22	3.42	5.74	3.15	3.21	3.38
θ	Noise in climate information											
0.672	2.63	2.05	2.34	2.50	3.05	2.50	3.00	3.29	3.48	2.74	3.48	3.88
1.372	2.63	1.96	2.17	2.29	3.05	2.26	2.68	2.91	3.48	2.36	2.79	3.05
2.072	2.63	1.90	2.06	2.17	3.05	2.13	2.40	2.58	3.48	2.19	2.38	2.58
2.772	2.63	1.86	1.97	2.07	3.05	2.06	2.22	2.36	3.48	2.10	2.15	2.25
3.472	2.63	1.83	1.91	1.98	3.05	2.01	2.09	2.19	3.48	2.07	2.01	2.06

Notes. Each entry in the table reports the optimal investment threshold for the BCR for the indicated parameter combination. All parameters other than those listed take their baseline values.

4.4 Performance of simple rules

4.4.1 Baseline case

The aim of this subsection is to show how various simple alternatives to ROA perform. I focus on two key questions, which are closely related to the issues investigated in Section 4.3.2. Specifically, for each simple rule:

- What proportion of the maximum-attainable welfare can be achieved if the decision-maker adopts this rule?
- What does the investment policy implied by a simple rule look like?

Table 4.4 summarises the welfare performance of various decision-making rules. The top row reports the maximum attainable present value of future welfare associated with the option to undertake the adaptation project, evaluated at the break-even level of the economic factor. That is, the values in this row show the option value that can be attained if the decision-maker adopts the optimal investment policy. In contrast, the subsequent rows report the option value if she uses various simple decision-making rules. In each case, the option value is evaluated at the break-even level of the economic factor and is expressed as a proportion of the maximum attainable option value.[7] For example, if the decision-maker uses a constant IRR threshold of six percent and the two climate scenarios

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[7] Unless stated otherwise, these calculations assume that the project is evaluated every five years under the simple policies, and continuously under the optimal policy.

Table 4.4: Welfare performance of simple rules in baseline case

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
Optimal policy												
	0.277	0.250	0.285	0.305	0.321	0.273	0.282	0.289	0.353	0.263	0.239	0.229
Standard CBA												
$\Delta t = 0.25$	0.071	0.219	0.302	0.328	0.061	0.163	0.282	0.332	0.094	0.150	0.211	0.263
$\Delta t = 1$	0.192	0.336	0.515	0.563	0.168	0.327	0.500	0.568	0.140	0.275	0.392	0.463
$\Delta t = 2$	0.299	0.473	0.652	0.709	0.275	0.459	0.643	0.711	0.245	0.377	0.524	0.593
$\Delta t = 5$	0.513	0.682	0.821	0.854	0.484	0.672	0.828	0.874	0.459	0.596	0.731	0.781
$\Delta t = 10$	0.746	0.828	0.871	0.866	0.712	0.842	0.909	0.912	0.699	0.797	0.868	0.888
Constant BCR threshold												
$\hat{B} = 1.00$	0.513	0.682	0.821	0.854	0.484	0.672	0.828	0.874	0.459	0.596	0.731	0.781
$\hat{B} = 1.25$	0.775	0.884	0.921	0.930	0.736	0.854	0.917	0.934	0.692	0.830	0.893	0.916
$\hat{B} = 1.50$	0.955	0.958	0.959	0.956	0.914	0.953	0.970	0.972	0.884	0.960	0.981	0.982
$\hat{B} = 1.75$	0.987	0.970	0.965	0.960	0.977	0.981	0.973	0.960	0.963	0.986	0.966	0.944
$\hat{B} = 2.00$	0.965	0.950	0.951	0.948	0.987	0.966	0.931	0.901	0.989	0.962	0.905	0.862
Constant IRR threshold												
$\hat{h} = 0.05$	0.513	0.682	0.821	0.854	0.484	0.672	0.828	0.874	0.459	0.596	0.731	0.781
$\hat{h} = 0.06$	0.884	0.911	0.934	0.938	0.850	0.898	0.931	0.944	0.834	0.892	0.923	0.940
$\hat{h} = 0.07$	0.985	0.973	0.965	0.959	0.980	0.979	0.978	0.974	0.971	0.986	0.983	0.977
$\hat{h} = 0.08$	0.970	0.962	0.961	0.957	0.987	0.970	0.950	0.934	0.992	0.966	0.932	0.907
$\hat{h} = 0.09$	0.917	0.920	0.929	0.933	0.954	0.924	0.881	0.849	0.968	0.910	0.848	0.811
Fixed-date approximation of delay-option value												
All	0.988	0.981	0.965	0.956	0.990	0.985	0.977	0.972	0.991	0.987	0.984	0.982
$\Delta t = 1$	0.990	0.980	0.963	0.954	0.991	0.984	0.977	0.969	0.992	0.988	0.984	0.982
$\Delta t = 2$	0.991	0.978	0.962	0.954	0.992	0.984	0.974	0.968	0.993	0.988	0.984	0.981
$\Delta t = 5$	0.991	0.974	0.958	0.951	0.992	0.980	0.970	0.965	0.994	0.986	0.981	0.978
$\Delta t = 10$	0.984	0.962	0.951	0.947	0.986	0.969	0.960	0.957	0.989	0.977	0.973	0.967
Approximate value of waiting												
Ignore clim vol	0.985	0.981	0.969	0.960	0.987	0.983	0.978	0.974	0.989	0.984	0.977	0.975
Ignore econ vol	0.989	0.976	0.961	0.953	0.990	0.980	0.973	0.968	0.991	0.985	0.982	0.980

Notes. The top row reports the maximum attainable option value for various evaluation dates and probabilities that the bad climate scenario holds, where the option value is evaluated at the breakeven-level of the economic factor. The subsequent rows report the option value if the decision-maker uses various simple rules. In each case, the option value is evaluated at the break-even level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters take their baseline values.

are equally likely, then the option value is initially 85.0% of its value under the optimal policy, assuming the economic factor is currently at the break-even level.

Standard CBA

- The welfare performance is poor if the project is evaluated frequently. If standard CBA is used, then it is better to evaluate the project infrequently, perhaps every five or ten years.

- Even standard CBA, if applied infrequently, can achieve more than half of the maximum achievable welfare.

- CBA performs better as time goes on.

Constant BCR threshold

- In this case, the project is evaluated every five years, so the row corresponding to $\hat{B} = 1$ gives the same results as standard CBA with the same evaluation interval. That is, the top row of the second panel is identical to the fourth row of the top panel.
- The welfare performance of this rule is sensitive to the chosen level of the BCR threshold. Starting from a threshold of $\hat{B} = 1$, welfare performance first improves then worsens as the threshold increases.
- It is possible to achieve more than 90% of the maximum attainable welfare using this approach.

Constant IRR threshold

- The project is evaluated every five years, so that the row corresponding to $\hat{h} = 0.05$, which is the assumed level of the social discount rate, gives the same results as standard CBA with the same evaluation interval. That is, the top row of the third panel is identical to the fourth row of the top panel.
- The welfare performance of this rule is sensitive to the chosen level of the IRR threshold. Starting from a threshold of $\hat{h} = 0.05$, welfare performance first improves then worsens as the threshold increases.
- It is possible to achieve more than 90% of the maximum attainable welfare using this approach.

Fixed-date delay option approximation

- In the first row of this panel, the decision-maker invests only if the net present value of investing immediately is greater than the net present value of waiting until *any* future date. In the other rows, the decision-maker invests only if the net present value of investing immediately is greater than the net present value of waiting Δt years and then investing, where the value of Δt is specified at the start of each row.
- The performance of this approach is quite insensitive to the level of Δt.
- This approach typically achieves more than 95% of the maximum attainable welfare. The performance is robust over time and over changes in the climate factor.
- The performance of this approach is superior to both rules of thumb (constant BCR and IRR thresholds).

Ignoring climate or economic volatility

- The performance of these approaches is comparable to the fixed-date approximation approach, but of course these approaches are much more challenging to implement.
- The difference in performance between ignoring climate volatility and ignoring economic volatility are small.

Table 4.5: Investment timing implied by simple rules in baseline case

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
Optimal policy												
	2.63	1.90	2.06	2.17	3.05	2.13	2.40	2.58	3.48	2.19	2.38	2.58
Standard CBA												
$\Delta t = 0.25$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 1$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 2$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 5$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 10$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Constant BCR threshold												
$\hat{B} = 1.00$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\hat{B} = 1.25$	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
$\hat{B} = 1.50$	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
$\hat{B} = 1.75$	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
$\hat{B} = 2.00$	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Constant IRR threshold												
$\hat{h} = 0.05$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\hat{h} = 0.06$	1.38	1.32	1.30	1.29	1.42	1.33	1.30	1.29	1.45	1.34	1.31	1.29
$\hat{h} = 0.07$	1.77	1.64	1.60	1.58	1.87	1.67	1.61	1.59	1.94	1.70	1.62	1.59
$\hat{h} = 0.08$	2.18	1.96	1.90	1.87	2.34	2.02	1.92	1.88	2.47	2.05	1.93	1.88
$\hat{h} = 0.09$	2.60	2.28	2.20	2.16	2.82	2.36	2.23	2.17	3.02	2.41	2.24	2.18
Fixed-date approximation of delay-option value												
All	2.60	1.68	1.54	1.48	3.02	1.83	1.59	1.50	3.44	1.93	1.62	1.51
$\Delta t = 1$	2.51	1.65	1.52	1.46	2.91	1.80	1.57	1.48	3.32	1.90	1.60	1.49
$\Delta t = 2$	2.43	1.63	1.51	1.45	2.83	1.77	1.55	1.47	3.22	1.87	1.58	1.48
$\Delta t = 5$	2.23	1.58	1.47	1.42	2.59	1.70	1.51	1.43	2.94	1.79	1.53	1.44
$\Delta t = 10$	1.98	1.50	1.41	1.37	2.28	1.60	1.44	1.38	2.57	1.67	1.46	1.39
Approximate value of waiting												
Ignore clim vol	2.63	1.77	1.64	1.58	3.05	1.91	1.69	1.60	3.48	2.00	1.70	1.62
Ignore econ vol	2.58	1.77	1.92	2.04	3.01	2.01	2.28	2.46	3.43	2.09	2.31	2.48

Notes. The top row reports the optimal threshold for the BCR for the indicated combinations of the climate factor and the current date. The subsequent rows report the BCR thresholds the decision-maker effectively adopts if she uses the indicated simple decision-making rules. All parameters take their baseline values.

Turning to the question of investment timing, Table 4.5 summarises the investment policies implied by simple alternatives to ROA that appear in Table 4.4. The top row reports the optimal threshold for the BCR for the indicated combinations of the climate factor and the current date. It is the same as the top row in Table 4.3. The subsequent rows report the BCR threshold that the decision-maker effectively adopts if she uses the indicated simple decision-making rules. For example, if the decision-maker uses a constant IRR threshold of six percent and the two climate scenarios are equally likely, then the effective BCR threshold at date 0 is 1.42.

Standard CBA By definition, if the decision-maker uses standard CBA, then she invests whenever the project's benefits exceed its costs; that is, when the BCR is greater than or equal to one.

Constant BCR threshold In each case, the simple rule is to invest if the project's BCR is greater than or equal to some constant. Thus, the implied BCR threshold takes the same value for all bad-scenario probabilities and all evaluation dates.

Constant IRR threshold In this case, the investment threshold is constant when expressed in terms of the project's IRR, but non-constant when expressed in terms of the BCR.

- Higher levels of the constant IRR threshold lead to higher levels of the implied BCR threshold—that is, to later investment.
- Holding the IRR threshold constant, the implied BCR threshold is greater (that is, the investment test is more demanding) if the bad climate scenario is more likely. The sensitivity is greater for higher IRR thresholds.
- The implied threshold for the BCR shares some of the qualitative properties of the optimal BCR threshold. In particular, it is higher if the bad climate scenario is more likely.

Fixed-date delay option approximation This is only a very slight modification of standard CBA, but it leads to significant delay.

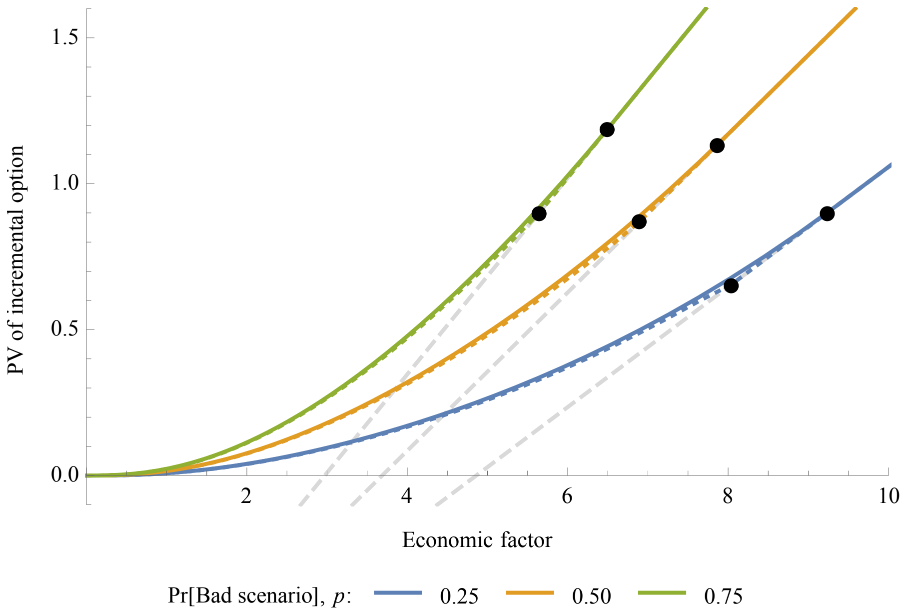
- In the short-term, the implied BCR threshold is typically greater than 2; that is, the present value of the project's benefits has to be more than twice as large as the project's cost for immediate investment to occur.
- The implied BCR threshold is higher if the bad scenario is more likely, if the fixed delay used to approximate the value of the delay option is shorter, and if the evaluation date is earlier.

Ignoring climate or economic volatility

- Investment timing is similar in the two cases, although ignoring climate volatility leads to a slightly higher implied BCR threshold in the short term.
- The implied BCR threshold is higher (that is, the investment test is more demanding) than most instances of the rule based on the fixed-date approximation of the option value.

Table 4.4 shows that most of these rules perform very well—that is, welfare losses are small. Figure 4.4 shows why this is the case. The graph plots the value of the investment option at date $t = 40$ as a function of the level of the economic factor for three different levels of the probability that the bad climate scenario holds. The solid curves show the value of the investment option if the decision-maker adopts the optimal investment policy and the dashed curves show its value if she adopts the fixed-date approximation approach instead. The dashed grey lines show the investment payoffs. The lower and upper dots on each curve show the alternative and optimal investment thresholds, respectively. Comparing the two sets of points shows that the simple rule leads to investment occurring too soon. That is, the points' horizontal coordinates show the simple rule implies a lower investment threshold for the economic factor. Similarly, the points' vertical coordinates show that it implies a lower threshold for the BCR. However, comparing the height of each solid curve

Figure 4.4: Value of the investment option under two investment policies



Notes. The graph plots the value of the investment option at date $t = 40$ as a function of the level of the economic factor for three different levels of the probability that the bad climate scenario holds. The solid curves show the option's value if the decision-maker adopts the optimal investment policy and the dashed curves show its value if she uses the fixed-date approximation approach. The dashed grey lines show the investment payoffs. The lower and upper dots on each curve show the alternative and optimal investment thresholds, respectively.

with its dashed counterpart shows the loss of welfare is small. Indeed, at the breakeven levels of the economic factor, the solid and dashed curves are almost indistinguishable.

Even under the simple rule featuring in Figure 4.4, investment is delayed well past the breakeven point. The corresponding dots are thus well up the dashed lines, which pulls the option value up as well. In contrast, if the decision-maker invests much earlier, so that the left-hand dots slide down the dashed grey lines, then gaps between the dashed and solid curves start to appear. The important thing that a simple rule must ensure is that there is *some* delay past the breakeven point. It is not necessary to closely match optimal investment timing to achieve most of the potential welfare.

4.4.2 Sensitivity analysis

This section uses sensitivity analysis to determine the robustness of the results in Section 4.4.1 and to identify situations in which these simple alternatives to ROA perform particularly well or particularly poorly. I focus on the welfare performance of each alternative. In particular, for each approach, I report the option value if the decision-maker uses this approach, evaluated at the break-even level of the economic factor and expressed as a proportion of the maximum attainable option value. An approach's welfare performance is better when the reported value is closer to one. The tables of results in this section have the same format as Table 4.2.

Table 4.6: Welfare implications of using standard CBA

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.04	0.479	0.677	0.826	0.859	0.452	0.672	0.836	0.882	0.433	0.588	0.746	0.805
0.05	0.495	0.679	0.823	0.857	0.467	0.672	0.833	0.879	0.444	0.591	0.738	0.792
0.06	0.513	0.682	0.821	0.854	0.484	0.672	0.828	0.874	0.459	0.596	0.731	0.781
0.07	0.530	0.684	0.818	0.851	0.500	0.673	0.823	0.869	0.474	0.603	0.726	0.772
0.08	0.547	0.686	0.815	0.848	0.517	0.674	0.818	0.862	0.490	0.611	0.723	0.766
μ	Drift of economic factor											
0.005	0.612	0.763	0.858	0.875	0.552	0.751	0.862	0.882	0.540	0.699	0.810	0.849
0.010	0.551	0.724	0.848	0.873	0.511	0.715	0.851	0.883	0.507	0.643	0.773	0.818
0.015	0.513	0.682	0.821	0.854	0.484	0.672	0.828	0.874	0.459	0.596	0.731	0.781
0.020	0.459	0.628	0.783	0.827	0.445	0.627	0.792	0.847	0.431	0.549	0.677	0.730
0.025	0.430	0.579	0.728	0.782	0.406	0.581	0.742	0.804	0.382	0.509	0.625	0.671
θ	Noise in climate information											
0.672	0.508	0.882	0.908	0.892	0.478	0.895	0.966	0.953	0.453	0.746	0.839	0.868
1.372	0.511	0.761	0.882	0.899	0.481	0.760	0.909	0.936	0.457	0.656	0.795	0.840
2.072	0.513	0.682	0.821	0.854	0.484	0.672	0.828	0.874	0.459	0.596	0.731	0.781
2.772	0.514	0.637	0.769	0.807	0.485	0.623	0.767	0.817	0.459	0.565	0.683	0.732
3.472	0.514	0.609	0.731	0.768	0.486	0.593	0.723	0.773	0.460	0.548	0.651	0.696

Notes. Each row reports the option value if the decision-maker uses standard CBA with five-yearly project evaluations, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Standard CBA Table 4.6 reports the results for the case when the decision-maker evaluates the project using standard CBA at five-yearly intervals.

- In most cases, standard CBA achieves more than half the maximum attainable welfare associated with the adaptation project.
- Welfare losses are greater in the short term, when the bad climate scenario is more likely, when the economic factor is less volatile, and when the economic factor is expected to grow more quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

Comparing the maximum attainable welfare with that achieved by standard CBA with a fixed evaluation period is more informative about the importance of using some form of ROA than just calculating the maximum-achievable option value. Therefore, the low-value entries in Table 4.6 reveal the types of projects for which some form of ROA will add the most value.

Constant BCR threshold There is an obvious way to implement ROA, CBA, and fixed-future-date approximations when model parameters change: just do the same thing as in the baseline case. The situation is not so simple, however, when carrying out sensitivity analysis of the two rules of thumb. For the cases of constant BCR and IRR thresholds, the decision-maker needs to choose the level of the threshold. The threshold should be constant during the period that a project is being evaluated, but there is no reason to use the same constant threshold for different projects. Indeed, the sensitivity analysis in Table 4.3 shows

Table 4.7: Welfare implications of using a constant threshold for the BCR

p	$\hat{B}$	0.25				0.50				0.75			
t		0	40	80	120	0	40	80	120	0	40	80	120
σ						Volatility of economic factor							
0.04	1.50	0.963	0.959	0.959	0.956	0.916	0.955	0.972	0.973	0.884	0.965	0.986	0.986
0.05	1.53	0.961	0.965	0.962	0.957	0.929	0.963	0.975	0.973	0.902	0.971	0.986	0.980
0.06	1.57	0.974	0.966	0.963	0.958	0.942	0.968	0.976	0.974	0.917	0.976	0.984	0.978
0.07	1.61	0.971	0.970	0.966	0.960	0.948	0.972	0.977	0.972	0.928	0.978	0.982	0.973
0.08	1.66	0.978	0.970	0.966	0.961	0.957	0.974	0.976	0.971	0.938	0.980	0.979	0.971
μ						Drift of economic factor							
0.005	1.29	0.953	0.942	0.932	0.924	0.903	0.946	0.945	0.936	0.872	0.956	0.962	0.951
0.010	1.41	0.965	0.955	0.950	0.942	0.921	0.956	0.962	0.957	0.893	0.966	0.975	0.967
0.015	1.57	0.974	0.966	0.963	0.958	0.942	0.968	0.976	0.974	0.917	0.976	0.984	0.978
0.020	1.80	0.979	0.976	0.976	0.973	0.958	0.977	0.985	0.983	0.936	0.982	0.990	0.984
0.025	2.14	0.984	0.983	0.985	0.984	0.964	0.985	0.991	0.989	0.951	0.988	0.993	0.990
θ						Noise in climate information							
0.672	1.57	0.966	0.979	0.950	0.927	0.934	0.975	0.983	0.967	0.911	0.980	0.987	0.981
1.372	1.57	0.971	0.965	0.964	0.954	0.939	0.968	0.981	0.976	0.914	0.978	0.986	0.980
2.072	1.57	0.974	0.966	0.963	0.958	0.942	0.968	0.976	0.974	0.917	0.976	0.984	0.978
2.772	1.57	0.975	0.971	0.965	0.960	0.944	0.970	0.975	0.973	0.918	0.976	0.983	0.978
3.472	1.57	0.975	0.975	0.968	0.963	0.945	0.973	0.976	0.973	0.919	0.977	0.982	0.977

Notes. Each row reports the option value if the decision-maker uses the constant BCR threshold in equation (3.2), for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

that sensible choices of the thresholds are likely to vary with the model's parameters. The approach I adopt here for the constant-BCR approach is to use the threshold defined in equation (3.2). Table 4.7 considers this case when the decision-maker evaluates the project at five-yearly intervals.

- In most cases, using this constant BCR threshold achieves more than 90% of the maximum attainable welfare associated with the adaptation project.
- Welfare losses are greater in the short term, unless the bad climate scenario is unlikely. In the short term, the losses are greater when the bad climate scenario is more likely, when the economic factor is less volatile, and when the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

Constant IRR threshold The same problem arises when using a constant threshold for the IRR as it does when using a constant threshold for the BCR; that is, the decision-maker needs to choose the level of the threshold. The approach I adopt here is to use the threshold defined in equation (3.4). Table 4.8 considers the case when the decision-maker evaluates the project at five-yearly intervals.

- In most cases, using this constant IRR threshold achieves more than 95% of the maximum attainable welfare associated with the adaptation project.
- Welfare losses are greater in the short term, unless the bad climate scenario is unlikely. In the short term, the losses are greater when the bad climate scenario is

Table 4.8: Welfare implications of using a constant threshold for the IRR

p	$\hat{h}$	0.25				0.50				0.75			
t		0	40	80	120	0	40	80	120	0	40	80	120
σ						Volatility of economic factor							
0.04	0.0674	0.981	0.968	0.962	0.957	0.965	0.972	0.976	0.974	0.956	0.981	0.988	0.984
0.05	0.0686	0.986	0.973	0.965	0.958	0.973	0.977	0.978	0.974	0.966	0.984	0.986	0.980
0.06	0.0700	0.985	0.973	0.965	0.959	0.980	0.979	0.978	0.974	0.971	0.985	0.983	0.977
0.07	0.0714	0.987	0.976	0.968	0.961	0.982	0.981	0.978	0.972	0.979	0.986	0.980	0.972
0.08	0.0731	0.987	0.975	0.967	0.961	0.985	0.981	0.976	0.970	0.983	0.985	0.977	0.968
μ						Drift of economic factor							
0.005	0.0630	0.973	0.950	0.933	0.924	0.956	0.954	0.946	0.937	0.946	0.967	0.962	0.947
0.010	0.0662	0.980	0.964	0.952	0.943	0.968	0.970	0.966	0.958	0.958	0.978	0.975	0.965
0.015	0.0700	0.985	0.973	0.965	0.959	0.980	0.979	0.978	0.974	0.971	0.985	0.983	0.977
0.020	0.0740	0.991	0.983	0.978	0.974	0.987	0.987	0.986	0.983	0.983	0.991	0.988	0.983
0.025	0.0784	0.994	0.989	0.986	0.984	0.992	0.992	0.991	0.988	0.990	0.994	0.992	0.988
θ						Noise in climate information							
0.672	0.0700	0.981	0.981	0.950	0.927	0.974	0.987	0.983	0.964	0.968	0.990	0.985	0.978
1.372	0.0700	0.984	0.972	0.965	0.954	0.978	0.980	0.981	0.974	0.970	0.987	0.984	0.978
2.072	0.0700	0.985	0.973	0.965	0.959	0.980	0.979	0.978	0.974	0.971	0.985	0.983	0.977
2.772	0.0700	0.986	0.976	0.967	0.961	0.981	0.980	0.977	0.973	0.972	0.985	0.982	0.976
3.472	0.0700	0.986	0.979	0.970	0.964	0.982	0.982	0.977	0.974	0.972	0.986	0.982	0.976

Notes. Each row reports the option value if the decision-maker uses the constant IRR threshold in equation (3.4), for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

more likely, when the economic factor is less volatile, and when the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

- Welfare losses are smaller using the constant IRR threshold in equation (3.4) than they are using the constant BCR threshold in equation (3.2).

Approximating the option value of waiting Table 4.9 considers the case when the decision-maker approximates the value of the delay option using a fixed one-year delay and evaluates the project at five-yearly intervals.

- In the short–medium term, using this approach achieves more than 98% of the maximum attainable welfare associated with the adaptation project.

- In the long term, welfare losses are greater when the bad climate scenario is less likely and when the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

Tables 4.10 and 4.11 consider the case when the decision-maker ignores climatic and economic volatility, respectively, when calculating the option value of waiting. The decision-maker evaluates the project at five-yearly intervals.

Table 4.9: Welfare implications of assuming a fixed future investment date

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ					Volatility of economic factor							
0.04	0.992	0.981	0.964	0.954	0.993	0.986	0.979	0.971	0.994	0.990	0.988	0.986
0.05	0.991	0.981	0.963	0.954	0.992	0.985	0.978	0.970	0.993	0.989	0.986	0.984
0.06	0.990	0.980	0.963	0.954	0.991	0.984	0.977	0.969	0.992	0.988	0.984	0.982
0.07	0.989	0.978	0.963	0.954	0.991	0.983	0.975	0.968	0.992	0.986	0.982	0.979
0.08	0.988	0.977	0.962	0.953	0.990	0.981	0.973	0.966	0.991	0.985	0.980	0.976
μ					Drift of economic factor							
0.005	0.980	0.942	0.915	0.906	0.985	0.956	0.929	0.917	0.988	0.970	0.950	0.935
0.010	0.987	0.967	0.943	0.932	0.989	0.974	0.958	0.948	0.991	0.981	0.974	0.967
0.015	0.990	0.980	0.963	0.954	0.991	0.984	0.977	0.969	0.992	0.988	0.984	0.982
0.020	0.992	0.987	0.978	0.971	0.993	0.989	0.986	0.983	0.994	0.991	0.990	0.989
0.025	0.994	0.991	0.987	0.983	0.995	0.993	0.991	0.990	0.995	0.994	0.992	0.992
θ					Noise in climate information							
0.672	0.990	0.986	0.952	0.929	0.991	0.990	0.984	0.968	0.992	0.990	0.988	0.986
1.372	0.990	0.980	0.966	0.954	0.991	0.986	0.982	0.975	0.992	0.989	0.987	0.985
2.072	0.990	0.980	0.963	0.954	0.991	0.984	0.977	0.969	0.992	0.988	0.984	0.982
2.772	0.990	0.981	0.964	0.953	0.992	0.984	0.975	0.965	0.993	0.987	0.983	0.979
3.472	0.990	0.982	0.966	0.954	0.992	0.984	0.975	0.965	0.993	0.987	0.982	0.978

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option using a fixed one-year delay, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

- In the short–medium term, using either approach achieves more than 98% of the maximum attainable welfare associated with the adaptation project. The performance of the two approaches is similar across a wide range of parameter settings.
- In the long term, welfare losses are greater when the bad climate scenario is less likely, the economic factor is expected to grow less quickly, and climate uncertainty falls more quickly.

4.5 Conclusions

The analysis in this chapter shows the value of the option to delay investment is economically significant across a wide range of parameter settings. It is therefore important to identify decision-making rules that allow society to benefit from investment-timing flexibility. This chapter has demonstrated that even something as simple as only using standard CBA at fixed intervals can capture a substantial amount of the option value. Rules of thumb based on constant BCR and IRR thresholds are even more effective and almost as easy to implement. The best approach is probably to use a fixed-date approximation to estimate the option value of delaying investment. This can be done with just two applications of standard CBA and does not require analysts to estimate any additional parameters. In most cases considered in this chapter, this approach results in only negligible welfare losses.

Table 4.10: Welfare implications of ignoring climatic volatility

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.04	0.989	0.983	0.967	0.957	0.991	0.986	0.980	0.974	0.992	0.987	0.985	0.984
0.05	0.987	0.981	0.967	0.958	0.989	0.985	0.979	0.974	0.990	0.986	0.981	0.979
0.06	0.985	0.981	0.969	0.960	0.987	0.983	0.978	0.974	0.989	0.984	0.977	0.975
0.07	0.982	0.978	0.969	0.961	0.986	0.981	0.976	0.972	0.988	0.980	0.975	0.972
0.08	0.980	0.978	0.970	0.962	0.984	0.979	0.974	0.970	0.986	0.979	0.972	0.968
μ	Drift of economic factor											
0.005	0.973	0.962	0.937	0.924	0.979	0.969	0.951	0.937	0.983	0.969	0.959	0.948
0.010	0.979	0.973	0.954	0.943	0.984	0.977	0.967	0.958	0.986	0.977	0.970	0.965
0.015	0.985	0.981	0.969	0.960	0.987	0.983	0.978	0.974	0.989	0.984	0.977	0.975
0.020	0.989	0.986	0.980	0.974	0.990	0.988	0.985	0.983	0.991	0.988	0.985	0.983
0.025	0.991	0.989	0.987	0.984	0.993	0.991	0.989	0.988	0.993	0.991	0.989	0.988
θ	Noise in climate information											
0.672	0.985	0.985	0.951	0.928	0.988	0.984	0.978	0.963	0.989	0.985	0.976	0.974
1.372	0.985	0.981	0.968	0.956	0.988	0.984	0.979	0.974	0.989	0.985	0.977	0.974
2.072	0.985	0.981	0.969	0.960	0.987	0.983	0.978	0.974	0.989	0.984	0.977	0.975
2.772	0.985	0.981	0.971	0.963	0.987	0.983	0.977	0.973	0.989	0.984	0.978	0.976
3.472	0.985	0.981	0.973	0.966	0.987	0.983	0.978	0.974	0.989	0.983	0.979	0.976

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option by ignoring climate volatility, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Table 4.11: Welfare implications of ignoring economic volatility

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.04	0.990	0.975	0.960	0.952	0.991	0.980	0.974	0.968	0.992	0.986	0.985	0.984
0.05	0.989	0.975	0.961	0.953	0.990	0.980	0.973	0.968	0.991	0.986	0.984	0.982
0.06	0.989	0.976	0.961	0.953	0.990	0.980	0.973	0.968	0.991	0.985	0.982	0.980
0.07	0.988	0.976	0.962	0.953	0.990	0.980	0.972	0.967	0.991	0.984	0.981	0.978
0.08	0.987	0.976	0.962	0.954	0.989	0.979	0.972	0.967	0.990	0.983	0.979	0.976
μ	Drift of economic factor											
0.005	0.981	0.955	0.928	0.916	0.985	0.961	0.940	0.926	0.986	0.970	0.957	0.945
0.010	0.986	0.967	0.946	0.934	0.988	0.972	0.959	0.950	0.989	0.979	0.973	0.968
0.015	0.989	0.976	0.961	0.953	0.990	0.980	0.973	0.968	0.991	0.985	0.982	0.980
0.020	0.991	0.983	0.973	0.968	0.992	0.986	0.983	0.980	0.993	0.989	0.988	0.987
0.025	0.993	0.988	0.983	0.980	0.994	0.990	0.989	0.988	0.994	0.992	0.992	0.992
θ	Noise in climate information											
0.672	0.988	0.983	0.951	0.928	0.989	0.988	0.983	0.968	0.990	0.990	0.988	0.986
1.372	0.989	0.976	0.961	0.950	0.990	0.982	0.978	0.971	0.991	0.987	0.986	0.984
2.072	0.989	0.976	0.961	0.953	0.990	0.980	0.973	0.968	0.991	0.985	0.982	0.980
2.772	0.989	0.978	0.963	0.955	0.990	0.980	0.972	0.966	0.991	0.984	0.980	0.978
3.472	0.989	0.980	0.966	0.958	0.991	0.981	0.972	0.967	0.991	0.985	0.980	0.977

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option by ignoring economic volatility, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Chapter

5

Ongoing investment programmes

5.1 Introduction

This chapter considers projects that feature ongoing investment programmes involving relatively large numbers of relatively small investments. The rate of investment in these programmes is usually able to be scaled up or down reasonably easily and the project starts to generate benefits even before the overall programme is complete. The decision-maker can act at any point during a specified period of time, the cost of reversing an action is prohibitively high, and the flow of future benefits initiated by taking the action is uncertain.

I illustrate this class of project using the example of a programme to upgrade stormwater systems in response to climate change. For example, Dunedin City Council is planning to spend $35 million in the next ten years upgrading its stormwater systems in order to reduce flooding in South Dunedin during times of heavy rain (Dunedin City Council, 2019, 2022).[1] This will involve improving maintenance of stormwater grates, upgrading pumping stations, installing backflow prevention valves, and replacing old wastewater pipes. Although the overall budget is significant, much of this investment programme can be scaled up or down as new information about future flood risk arrives. The benefits generated by the system upgrades comprise the avoided flooding costs in South Dunedin, which include the costs of disruption as well as the cost of repairs. The main sources of uncertainty surrounding the magnitude of these benefits are climatic (the frequency and severity of extreme rainfall events) and economic (the value of assets in South Dunedin affected by flooding if the stormwater system is not upgraded). Suitable climate and economic factors are therefore the average annual maximum one-day rainfall in the Dunedin area and the replacement cost of potentially affected assets in South Dunedin respectively. The status of the system at any point in time is summarised by its capacity, such as the maximum level of daily rainfall that the system can handle without flooding occurring. The decision-maker must choose how rapidly to increase the system's capacity.

Many other adaptation projects can be modelled using a similar framework. They are typically ongoing programmes involving investments that are costly to reverse, have low fixed costs (so that an almost continuous series of small investments is feasible), and

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[1] Hughes et al. (2019) evaluate the impact of climate change on New Zealand stormwater systems.

start to generate benefits even before the overall programme is complete. One example is the afforestation of land as a natural flood management measure (Cooper et al., 2021). Afforestation can potentially slow the rate at which water runs off into rivers, reducing the risk of flooding following extreme rainfall events.[2] The benefits generated by investment comprise the avoided flooding costs, minus any lost benefits generated by the land in its current use. A sensible climate factor for modelling the decision-maker's problem is the average annual maximum rainfall or river flow, or anything else that determines the frequency and severity of flooding in the region. A sensible economic factor is the value of the land that will be protected by the scheme (the value of buildings if urban land is being protected; the value of farmland if rural land is being protected).[3] The system-status factor is the amount of land that has been afforested. The decision-maker must decide how much land to plant in trees each year.[4]

Another example of an adaptation project that can be modelled using the framework in this chapter involves the redesign of urban areas to reduce the amount of paved land in response to higher temperatures (ESMAP, 2020). These projects typically involve land being reconfigured to create cooling zones in order to reduce heat stress. Like the other examples described here, these projects can generate benefits even before the overall investment programme is complete. These benefits include reduced heat-related illness and, for many types of project, reduced energy use, minus the opportunity cost of the lost benefits from the current land use. A model of this investment problem could use the average annual maximum one-day temperature as the climate factor and average wages or other measures of lost productivity as the economic factor. (Alternatively, if the main benefit of the project is reduced energy use, then the economic factor could be the price of the relevant energy source.) A sensible system-status factor would be the amount of cooling provided by the project in its current state. The decision-maker must decide how quickly to roll out the investment programme, which can be done incrementally. All else equal, an optimal programme would involve redesigning land with a low opportunity cost first.

The final example features more complicated versions of the building retrofit programme in Chapter 4. This investment can be done incrementally, at the level of a portfolio of buildings, such as a stock of social housing. The flow of benefits generated by investment includes reduced heat-related illness and, for many types of project, reduced energy use. A suitable climate factor is therefore the average daily maximum one-day temperature. Suitable economic factors are average wages or other measures of lost productivity (for individual buildings) and the size of the affected population (for portfolios of buildings). The system-status factor could be the number of buildings that have been upgraded to a specified standard. The decision-maker must decide how many buildings to upgrade each year when retrofitting a portfolio of buildings. An optimal policy will start by retrofitting older houses, where the benefits are greater, and only move onto newer houses once the probability that the high-temperature climate scenario holds is sufficiently high.[5]

Table 5.1 summarises how these adaptation projects can be interpreted in terms of

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[2] Afforestation has also been proposed as a response to the increased prospects of future erosion due to climate change (Awatere et al., 2018). Programmes to restore dunes and wetlands can be analysed using a similar framework to the one described here.

[3] If the land being planted in trees is currently used for farming, then a sensible economic factor could also be the price of the output currently being produced on the land.

[4] Dittrich et al. (2019) investigate optimal afforestation policies for parts of Scotland using a simplified form of ROA.

[5] Similarly, if the government wants to use subsidies to motivate building owners to make such changes, it could adopt eligibility criteria that are gradually relaxed over time.

the framework used in this chapter. The table proposes climate and economic factors that are appropriate for each example, as well as a system-status factor that reflects the fact that the investment programme is spread over time. The decision-maker faces a similar problem in all of these examples. The uncertainty surrounding the future benefits of each individual investment exposes the decision-maker to the risk that after she invests the benefits will turn out to be so low that the project does not recover the cost of undertaking it. For example, if the frequency of extreme rainfall events rises more slowly than expected, then the benefits generated by upgrading the capacity of an urban stormwater system will be smaller than expected. The decision-maker can reduce this risk by delaying each incremental system upgrade until the expected benefits are relatively large, which makes it relatively unlikely that the project's actual benefits will not cover its cost.

5.2 Model framework

Details of the model can be found in Appendix B.2 and Guthrie (2023b). Its key components are:

- An urban stormwater system can cope with daily rainfall less than or equal to 175mm. The system's capacity can be increased at any time and by any amount. Investment costs are scaled so that each round of investment requires expenditure of one "dollar" for each millimetre/day increase in the system's capacity.
- The economic factor equals the (annualised) flooding-related costs incurred by the local community for each millimetre that daily rainfall exceeds the system's capacity. Each year, the growth rate in this factor is normally distributed with a mean of 1.5% and a standard deviation of 7.0%.
- The distribution of the annual maximum one-day rainfall shifts over time according to one of two possible climate scenarios, which correspond approximately to RCP 2.6 and RCP 8.5. The distribution and the scenarios are described in Chapter 2.
- All future costs and benefits are discounted using a constant social discount rate of 5% per annum.
- The baseline values of the model's parameters have been chosen to approximate the situation facing the Dunedin City Council.

5.3 Optimal investment policy

As in Chapter 4, the optimal policy can be described in terms of trigger points. Each time the system-upgrade project is evaluated, the decision-maker calculates the current values of the climatic and economic factors and determines whether or not the calculated combination triggers immediate investment. This section describes the form that these trigger points take, both in the baseline case and when the model's parameters are varied around this baseline.

5.3.1 Baseline case

I start by describing the socially optimal adaptation policy when the model's parameters take their baseline values. For the type of adaptation project studied in this chapter, it is

Table 5.1: Adaptation projects compatible with the framework in Chapter 5

Type of project	Benefit flow	Climate factor	Economic factor	System-status factor
Upgrading stormwater systems	Avoided flooding costs, including disruption and repair costs	Average annual maximum one-day rainfall	Replacement cost of potentially affected assets	Maximum level of daily rainfall without flooding occurring
Afforestation as a natural flood management measure	Avoided flooding costs, minus any lost benefits generated by the land in its current use	Average annual maximum one-day rainfall or river flow	Value of the land that will be protected by the scheme	Amount of land that has been afforested
Reduced paved areas in response to higher temperatures	Reduced heat-related illness and energy use	Average annual maximum one-day temperature	Average wages or other measures of lost productivity; energy price	Amount of cooling provided by the project
Retrofitting portfolios of buildings to adapt to higher temperatures	Reduced heat-related illness	Average daily maximum temperature	Average wages or other measures of lost productivity	Number of buildings that have been upgraded

most natural to describe the optimal investment policy in terms of an optimal, or target, level of stormwater system capacity. At each point in time, the decision-maker invests in just enough additional capacity to stop the system's capacity falling below the optimal level. No investment should occur while the system's current capacity is greater than the optimal level. Each graph in Figure 5.1 plots this optimal capacity as a function of the contemporaneous level of the economic factor for the indicated evaluation date. The three curves in each graph correspond to different probabilities that the bad climate scenario holds. The optimal system capacity has the following properties:

- The optimal system capacity is greater when the economic factor is larger, when the bad climate scenario is more likely to hold, and when the evaluation date is further in the future.
- The optimal system capacity is initially insensitive to the probability that the bad scenario holds, but the sensitivity grows as the evaluation date is further in the future.

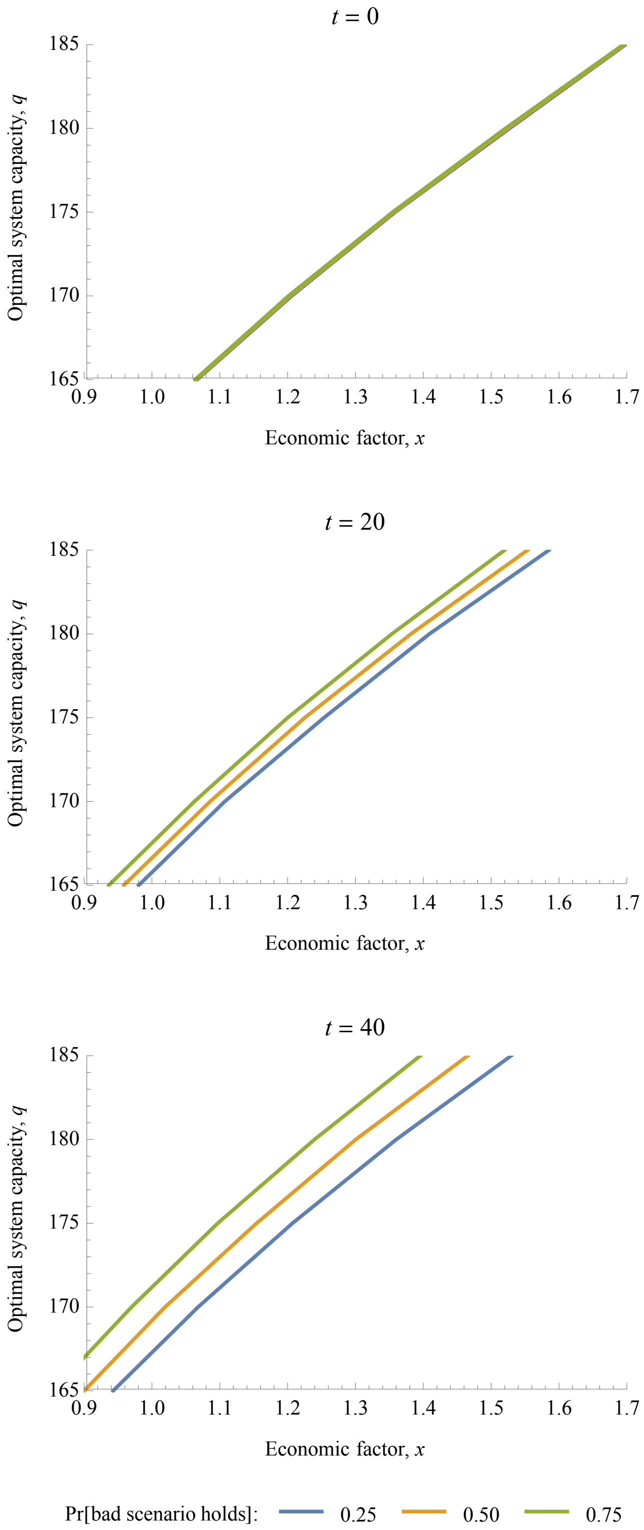
The optimal policy can be expressed in various other ways. It helps put the adaptation problem in this chapter in the wider context of this report if the optimal policy is expressed in a way that is comparable with the representation in Chapter 4. The graphs in Figure 5.2 summarise the optimal investment policy using this format. Unlike the case in Chapter 4, where only one graph was needed to describe the complete policy, the ongoing nature of investment here means that multiple graphs are now required. Each graph illustrates the trigger points for a different system capacity. Within each graph, each curve plots the trigger points for a different evaluation date t. In principle, the decision-maker can use these graphs in the following way:

1. Calculate the current levels of the climatic and economic factors and identify the corresponding point on each graph.
2. Make the investment decision for each graph separately:
    - If this point is on or below the curve corresponding to the current date, then wait and reevaluate the project in the future.
    - If this point is above the curve corresponding to the current date, then incrementally increase the system's capacity immediately.

Note that higher capacities are associated with higher curves. Therefore, if it is optimal to upgrade the system when its capacity equals q then it will also be optimal to upgrade it for any smaller capacity q'. This means it is optimal for the decision-maker to immediately increase the system's capacity to the level where the economic factor is equal to the current trigger level for that level of capacity.

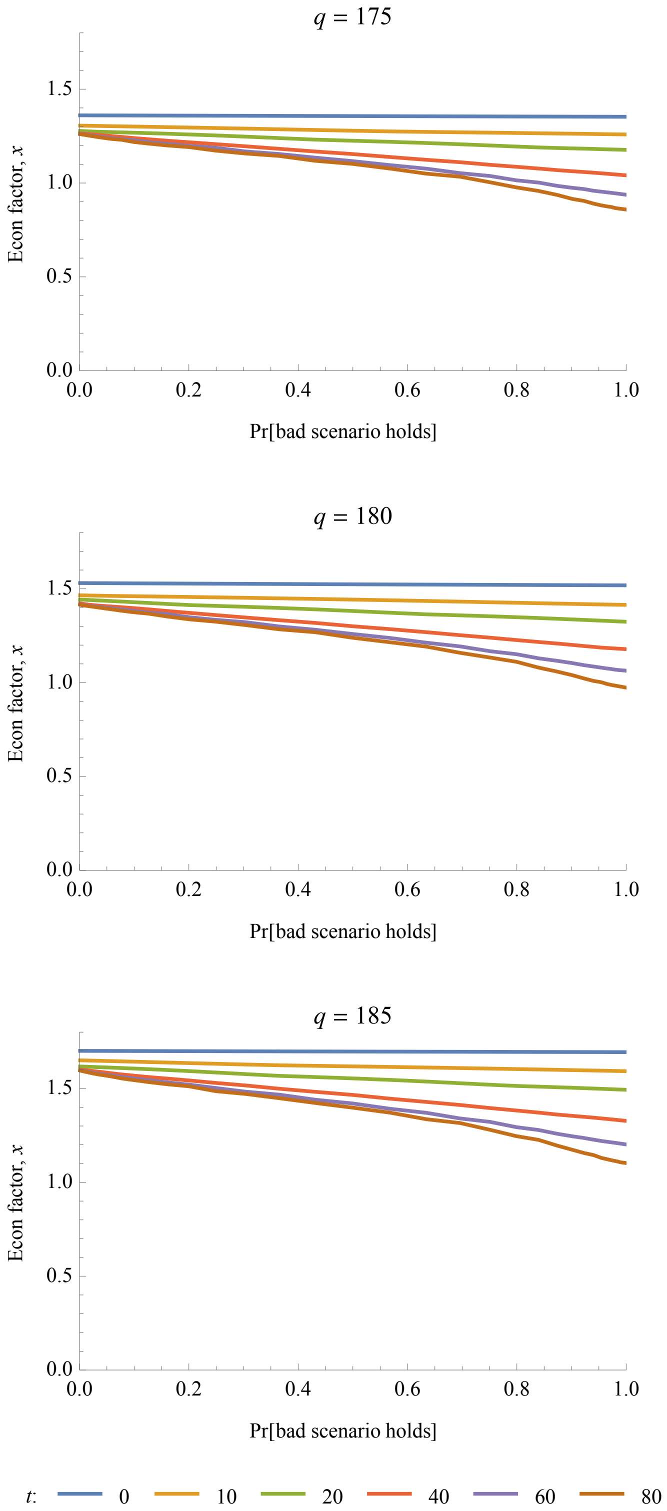
Consider the situation at date 10, shown by the yellow curves. Suppose that the two scenarios are equally likely (that is, $p = 0.5$) and the economic factor is equal to $x = 1.44$. The point (p, x) lies above the yellow curve in the top graph, on this curve in the middle graph, and above this curve in the bottom graph. Therefore, if the system's capacity is currently 185 (the bottom graph), then the decision-maker should not invest immediately because x is less than the trigger point implied by this graph. However, if the system's capacity is just 175 (the top graph) then the decision-maker should invest immediately and increase the system's capacity to 180.

Figure 5.1: Optimal system capacity



Notes. Each graph plots the optimal system capacity as a function of the contemporaneous level of the economic factor for the indicated evaluation date. The three curves in each graph correspond to different probabilities that the bad climate scenario holds. All model parameters take their baseline values.

Figure 5.2: Optimal investment triggers for economic factor



Notes. Each graph plots the optimal investment threshold for the economic factor as a function of the contemporaneous level of the climate factor, for the indicated system capacity and evaluation dates. All model parameters take their baseline values.

Regardless of what the decision-maker does immediately, she should reevaluate the project in the future because investment is ongoing. What she does next depends on how the climatic and economic factors evolve. If the point (p, x) moves above the investment threshold curve, then she will invest; if it does not, then she will not invest. In both cases, she then waits again and reevaluates the project in the future. The stormwater system's capacity may remain constant for long periods of time, but it will start to increase again once the benefits of investing rise to a sufficiently high level. Investment can be triggered by increases in the economic factor (the costs avoided due to investment rise), increases in the climatic factor (floods become more likely), and the passage of time (the progression of climate change).

The investment trigger points can also be expressed in terms of the benefit–cost ratio associated with incrementally upgrading the system's capacity. That is, instead of waiting for the economic factor to be sufficiently high before investing, the decision-maker waits until the BCR is sufficiently high. Then, when the decision-maker invests, she keeps increasing capacity until the BCR of adding any more is less than the corresponding threshold. The socially optimal thresholds are shown in Figure 5.3, which has a similar format to Figure 5.2. Each graph illustrates the trigger points for a different system capacity. Within each graph, each curve plots the trigger points for a different evaluation date t. Note that in this case the curves corresponding to different current capacities are almost indistinguishable. The key results to note are:

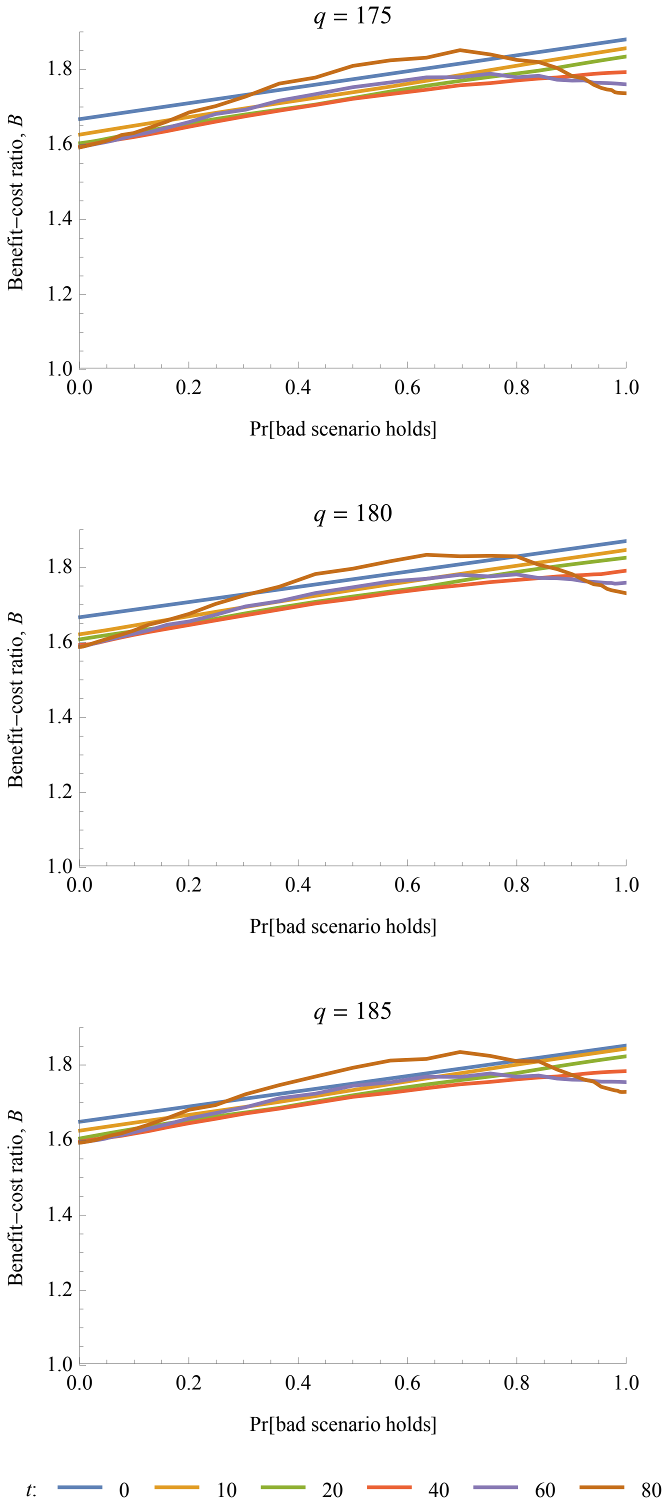
- The optimal BCR threshold is much greater than one in all cases. The present value of the benefits of investment therefore need to be significantly greater than the required expenditure before investment can be socially optimal. The margin above the required expenditure reflects the value of the real option to delay investment, which is destroyed when investment occurs and is therefore part of the opportunity cost of investment. At least in the baseline case considered here, the option value is significant.

- The causes of this high option value vary. In the near term, the high threshold is due to the possibility the climate scenario is bad (so that the expected growth rate in benefits is high); in the longer term, it is due to uncertainty about the climate scenario (and the resulting high level of p volatility).

- In the short term, the socially optimal BCR threshold is strongly increasing in p, so the investment test is more demanding when the bad scenario is believed to be more likely. Equivalently, the option to delay investment is initially more valuable when the bad scenario is believed to be more likely.

- The behaviour of the optimal BCR threshold over time depends on the degree of climate uncertainty.
  - If climate uncertainty is low (that is, p is close to 0 or 1), then the threshold falls slowly over time, so that the investment test becomes less demanding. Once rainfall intensity has converged to its long-run value, the value of the delay option derives solely from the volatility of the economic factor. For the baseline parameter values, the long-run value of the BCR threshold is 1.61.
  - However, if climate uncertainty remains high (that is, p is close to 0.5), then the threshold increases over time, so that the investment test becomes more demanding. When the possible paths for rainfall intensity start to diverge, climate

Figure 5.3: Optimal investment triggers for benefit–cost ratio



Notes. Each graph plots the optimal investment threshold for the BCR as a function of the contemporaneous level of the climate factor, for the indicated system capacity and evaluation dates. All model parameters take their baseline values.

uncertainty starts to fall rapidly, and p volatility starts to rise. This leads to an increase in the volatility of the investment payoff, which increases the option value of waiting. In this situation, the true climate scenario will be revealed reasonably quickly, in which case p will move towards either 0 or 1. In either case, the high BCR thresholds will fall.

5.3.2 Sensitivity analysis

As in Chapter 4, the analysis in this section addresses two fundamental questions. First, how much is the investment-timing option worth? Second, what does the socially optimal investment policy look like? I use the value of the incremental-upgrade option when the economic factor is at the breakeven point to help answer the first question. I use the level of the welfare-maximising BCR threshold plotted in Figure 5.3 to help answer the second question. In both cases, I carry out sensitivity analysis, varying the model's parameters around their baseline values and reporting the effects on these two outputs.

Table 5.2 reports the results of the sensitivity analysis of the value of the incremental upgrade option. Each row reports the values of the incremental upgrade option when the economic factor is at the breakeven level, for the indicated evaluation dates and probabilities that the bad climate scenario holds. All parameters take their baseline values in the top row. The subsequent panels each vary one of the model's parameters over a range around that parameter's baseline levels while holding all other parameters at their baseline levels. For example, if the two climate scenarios are equally likely at date $t = 40$ in the baseline case, then the incremental upgrade option will be worth 20.2% of the investment expenditure when the economic factor is just large enough for the benefits of immediate investment to cover the cost of the investment expenditure. The key results to note are:

- The option value is economically significant in all the cases I consider. For example, in the baseline case the option is worth approximately 20% of the cost of upgrading capacity. Thus, some form of ROA, or a simplified approximation to this method, is important for achieving good welfare gains from investing in the project.
- The option value is greater if the bad climate scenario is more likely.
- Investment-timing flexibility is more important if the economic factor is more volatile and if it is expected to grow more quickly.
- Varying the speed with which climate uncertainty falls has almost no effect on the value of the investment-timing option. Neither does the current capacity of the stormwater infrastructure.

Now I turn to the second key question: what does the socially optimal investment policy look like? Each entry in Table 5.3 reports the optimal BCR threshold for a different combination of parameters. The format is identical to Table 5.2. For example, if all parameters take their baseline values, it is currently date 40, and the two climate scenarios are equally likely, then the decision-maker should carry out an incremental system upgrade if doing so has a BCR greater than 1.72. The key results to note are:

- The welfare-maximising BCR threshold is significantly above one in all cases. Values above 1.6 are typical. That is, the present value of the project's benefits typically needs to exceed the investment expenditure by more than 60% in order for investment to be socially optimal.

Table 5.2: Maximum attainable option value at breakeven level of economic factor

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Baseline case											
	0.196	0.191	0.198	0.208	0.208	0.202	0.208	0.214	0.218	0.210	0.208	0.207
σ	Volatility of economic factor											
0.05	0.179	0.174	0.182	0.193	0.191	0.186	0.192	0.200	0.202	0.194	0.192	0.191
0.06	0.187	0.182	0.190	0.200	0.199	0.194	0.200	0.206	0.210	0.201	0.199	0.199
0.07	0.196	0.191	0.198	0.208	0.208	0.202	0.208	0.214	0.218	0.210	0.208	0.207
0.08	0.206	0.200	0.207	0.216	0.217	0.212	0.216	0.222	0.228	0.219	0.217	0.216
0.09	0.216	0.210	0.216	0.224	0.227	0.221	0.225	0.231	0.237	0.228	0.226	0.225
μ	Drift of economic factor											
0.005	0.121	0.118	0.131	0.147	0.128	0.127	0.139	0.153	0.135	0.131	0.134	0.138
0.010	0.154	0.150	0.160	0.173	0.164	0.160	0.169	0.179	0.173	0.166	0.167	0.168
0.015	0.196	0.191	0.198	0.208	0.208	0.202	0.208	0.214	0.218	0.210	0.208	0.207
0.020	0.247	0.240	0.245	0.251	0.260	0.253	0.256	0.259	0.273	0.262	0.258	0.255
0.025	0.307	0.300	0.303	0.306	0.324	0.315	0.314	0.314	0.338	0.325	0.318	0.313
θ	Noise in climate information											
5	0.196	0.193	0.200	0.210	0.208	0.204	0.209	0.215	0.219	0.211	0.208	0.207
10	0.196	0.192	0.200	0.209	0.208	0.203	0.209	0.215	0.219	0.210	0.208	0.207
15	0.196	0.191	0.198	0.208	0.208	0.202	0.208	0.214	0.218	0.210	0.208	0.207
20	0.196	0.190	0.196	0.205	0.208	0.201	0.206	0.213	0.218	0.209	0.207	0.206
25	0.196	0.189	0.195	0.203	0.208	0.201	0.204	0.211	0.218	0.208	0.206	0.205
q	Current capacity of infrastructure											
165	0.197	0.192	0.200	0.210	0.209	0.204	0.210	0.217	0.221	0.212	0.210	0.209
170	0.197	0.191	0.199	0.209	0.208	0.203	0.209	0.215	0.220	0.211	0.209	0.208
175	0.196	0.191	0.198	0.208	0.208	0.202	0.208	0.214	0.218	0.210	0.208	0.207
180	0.196	0.190	0.197	0.206	0.207	0.202	0.207	0.213	0.218	0.209	0.207	0.206
185	0.195	0.190	0.196	0.205	0.206	0.201	0.206	0.211	0.217	0.208	0.206	0.205

Notes. Each row reports the maximum attainable option value for various evaluation dates and probabilities that the bad climate scenario holds, where the option value is evaluated at the breakeven-level of the economic factor. The top row shows results when all parameters take their baseline values. The other panels report results when I vary one of the model's parameters, as described in the first entry in each row. All parameters other than those listed take their baseline values.

- The optimal BCR threshold is higher if the economic factor is more volatile and if it is expected to grow more quickly.

- The optimal BCR threshold is relatively insensitive to the speed with which climate uncertainty falls (unless the evaluation date is far into the future) and the current capacity of the stormwater infrastructure.[6]

As in Chapter 4, the real option to choose the timing of investment is very valuable, so it is optimal to pause system upgrades unless the benefits of investment are much larger than the required investment expenditure. The remainder of this chapter evaluates the potential of simple alternatives to ROA to deliver the economic benefits associated with investment-timing flexibility.

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[6] If investment does not occur for many decades, then the optimal BCR threshold will be a slightly decreasing function of the amount of noise in the signal.

Table 5.3: Optimal threshold for the BCR

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
					Baseline case							
	1.72	1.66	1.70	1.76	1.77	1.72	1.81	1.92	1.83	1.76	1.84	1.98
σ					Volatility of economic factor							
0.05	1.65	1.58	1.63	1.69	1.71	1.65	1.73	1.84	1.76	1.69	1.78	1.92
0.06	1.68	1.62	1.67	1.73	1.73	1.68	1.77	1.90	1.78	1.73	1.80	1.96
0.07	1.72	1.66	1.70	1.76	1.77	1.72	1.81	1.92	1.83	1.76	1.84	1.98
0.08	1.76	1.70	1.74	1.81	1.82	1.77	1.84	1.97	1.87	1.81	1.88	2.03
0.09	1.81	1.75	1.79	1.87	1.86	1.81	1.89	2.03	1.92	1.86	1.91	2.06
μ					Drift of economic factor							
0.005	1.38	1.36	1.40	1.46	1.41	1.39	1.48	1.59	1.44	1.41	1.50	1.63
0.010	1.53	1.48	1.53	1.58	1.56	1.53	1.61	1.72	1.60	1.56	1.65	1.78
0.015	1.72	1.66	1.70	1.76	1.77	1.72	1.81	1.92	1.83	1.76	1.84	1.98
0.020	2.00	1.91	1.96	2.02	2.07	1.99	2.08	2.20	2.15	2.06	2.12	2.29
0.025	2.39	2.28	2.31	2.38	2.51	2.39	2.46	2.61	2.62	2.49	2.55	2.70
θ					Noise in climate information							
5	1.72	1.68	1.75	1.81	1.77	1.77	1.95	2.10	1.83	1.81	2.05	2.32
10	1.72	1.67	1.73	1.80	1.77	1.73	1.85	1.98	1.83	1.78	1.91	2.10
15	1.72	1.66	1.70	1.76	1.77	1.72	1.81	1.92	1.83	1.76	1.84	1.98
20	1.72	1.66	1.69	1.74	1.77	1.71	1.77	1.87	1.83	1.76	1.79	1.90
25	1.72	1.66	1.68	1.72	1.77	1.71	1.75	1.83	1.83	1.76	1.77	1.84
q					Current capacity of infrastructure							
165	1.73	1.66	1.71	1.77	1.78	1.73	1.82	1.94	1.84	1.77	1.86	2.01
170	1.72	1.66	1.71	1.78	1.78	1.72	1.81	1.95	1.83	1.77	1.84	2.01
175	1.72	1.66	1.70	1.76	1.77	1.72	1.81	1.92	1.83	1.76	1.84	1.98
180	1.72	1.66	1.70	1.77	1.77	1.72	1.80	1.92	1.82	1.76	1.83	1.98
185	1.70	1.66	1.69	1.75	1.75	1.72	1.79	1.90	1.80	1.76	1.82	1.96

Notes. Each row reports the optimal investment threshold for the BCR for various evaluation dates and probabilities that the bad climate scenario holds. All parameters other than those listed take their baseline values.

5.4 Performance of simple rules

5.4.1 Baseline case

Table 5.4 summarises the welfare performance of various decision-making rules. The top row reports the maximum attainable present value of future welfare associated with the option to undertake the adaptation project, evaluated at the break-even level of the economic factor, for the indicated combinations of the climate factor and the current date. That is, the values in this row show the option value that can be attained if the decision-maker adopts the optimal investment policy. Investment expenditure is normalized so that exercising each incremental upgrade option costs one dollar, so these option values are economically significant (approximately 20% of investment expenditure at the breakeven level of the economic factor). The subsequent rows of Table 5.4 report the option value if the decision-maker uses various simple alternatives to ROA. In each case, the option value is evaluated at the break-even level of the economic factor and is expressed as a proportion of the maximum attainable option value.[7] For example, if the decision-maker uses a constant BCR threshold of 2.00 and the two climate scenarios are equally likely, then the option

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[7] Unless stated otherwise, these calculations assume the project is evaluated every five years under the simple policies, and continuously under the optimal policy.

Table 5.4: Welfare performance of simple rules in baseline case

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
Optimal policy												
	0.196	0.191	0.198	0.208	0.208	0.202	0.208	0.214	0.218	0.210	0.208	0.207
Standard CBA												
$\Delta t = 0.25$	0.167	0.141	0.191	0.248	0.154	0.148	0.205	0.297	0.143	0.132	0.166	0.220
$\Delta t = 1$	0.287	0.288	0.379	0.488	0.273	0.287	0.389	0.504	0.259	0.266	0.324	0.397
$\Delta t = 2$	0.394	0.402	0.503	0.603	0.380	0.396	0.517	0.630	0.365	0.379	0.446	0.518
$\Delta t = 5$	0.579	0.612	0.692	0.758	0.567	0.607	0.707	0.787	0.550	0.585	0.651	0.699
$\Delta t = 10$	0.770	0.780	0.816	0.831	0.764	0.779	0.831	0.863	0.740	0.767	0.804	0.831
Constant BCR threshold												
$\hat{B} = 1.00$	0.579	0.612	0.692	0.758	0.567	0.607	0.707	0.787	0.550	0.585	0.651	0.699
$\hat{B} = 1.25$	0.901	0.906	0.921	0.939	0.888	0.892	0.907	0.927	0.873	0.879	0.893	0.909
$\hat{B} = 1.50$	0.984	0.981	0.981	0.980	0.982	0.981	0.982	0.983	0.979	0.981	0.983	0.983
$\hat{B} = 1.75$	0.952	0.946	0.947	0.947	0.968	0.961	0.958	0.953	0.977	0.970	0.963	0.955
$\hat{B} = 2.00$	0.885	0.883	0.884	0.882	0.912	0.907	0.900	0.889	0.934	0.921	0.907	0.892
Constant IRR threshold												
$\hat{h} = 0.06$	0.931	0.937	0.943	0.954	0.921	0.930	0.937	0.945	0.919	0.925	0.932	0.935
$\hat{h} = 0.07$	0.978	0.976	0.975	0.975	0.983	0.981	0.980	0.979	0.986	0.984	0.982	0.980
$\hat{h} = 0.08$	0.914	0.910	0.911	0.911	0.931	0.926	0.922	0.916	0.943	0.935	0.927	0.919
$\hat{h} = 0.09$	0.849	0.850	0.849	0.844	0.859	0.860	0.850	0.839	0.872	0.864	0.849	0.836
$\hat{h} = 0.10$	0.336	0.379	0.427	0.469	0.604	0.588	0.614	0.631	0.768	0.714	0.712	0.708
Fixed-date approximation of delay-option value												
All	0.984	0.983	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
$\Delta t = 1$	0.984	0.982	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
$\Delta t = 2$	0.984	0.982	0.981	0.980	0.986	0.984	0.983	0.983	0.987	0.985	0.984	0.983
$\Delta t = 5$	0.981	0.978	0.978	0.977	0.983	0.981	0.980	0.980	0.985	0.983	0.982	0.981
$\Delta t = 10$	0.972	0.968	0.968	0.969	0.974	0.971	0.971	0.971	0.977	0.974	0.973	0.971
Approximate value of waiting												
Ignore clim vol	0.971	0.970	0.971	0.971	0.973	0.973	0.972	0.970	0.975	0.974	0.973	0.970
Ignore econ vol	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.985	0.984	0.983

Notes. The top row reports the maximum attainable option value for various evaluation dates and probabilities that the bad climate scenario holds, where the option value is evaluated at the breakeven-level of the economic factor. The subsequent rows report the option value if the decision-maker uses various simple rules. In each case, the option value is evaluated at the break-even level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters take their baseline values.

value is initially 91.2% of its value under the optimal policy, assuming the economic factor is currently at the break-even level.

Exercising an incremental upgrade option is similar to exercising the simple timing option in Chapter 4, so it is not surprising that the performance of simple alternatives to ROA here is similar to their performance in Chapter 4.

Standard CBA

- The welfare performance is poor if the project is evaluated frequently. If standard CBA is used, then it is better to evaluate the project infrequently, perhaps every five or ten years.

- Even standard CBA, if applied infrequently, can achieve more than half of the maximum achievable welfare.
- CBA performs better as time goes on.

Constant BCR threshold

- The welfare performance of this rule is sensitive to the chosen level of the BCR threshold. Starting from a threshold of $\hat{B} = 1$, welfare performance first improves then worsens as the threshold increases.
- It is possible to achieve more than 90% of the maximum attainable welfare using this approach.

Constant IRR threshold

- The welfare performance of this rule is sensitive to the chosen level of the IRR threshold. Starting from a threshold of $\hat{h} = 0.06$, welfare performance first improves then worsens as the threshold increases. Very high levels of the IRR threshold can result in large welfare losses.
- It is possible to achieve more than 90% of the maximum attainable welfare using this approach.

Fixed-date delay option approximation

- In the first row of this panel, the decision-maker invests only if the net present value of investing immediately is greater than the net present value of waiting until *any* future date. In the other rows, the decision-maker invests only if the net present value of investing immediately is greater than the net present value of waiting Δt years and then investing, where the value of Δt is specified at the start of each row.
- The performance of this approach is quite insensitive to the level of Δt.
- This approach typically achieves more than 95% of the maximum attainable welfare. The performance is robust over time and over changes in the climate factor.
- The performance of this approach is superior to both rules of thumb (constant BCR and IRR thresholds).

Ignoring climate or economic volatility

- The performance of these approaches is comparable to the fixed-date approximation approach, but these approaches are much more challenging to implement.
- The difference in performance between ignoring climate volatility and ignoring economic volatility are small.

Table 5.5 summarises the investment-timing policies that are implied by these simple approaches. For each decision-making rule, the table reports the minimum level of the BCR that triggers immediate investment. The format is similar to that of Table 5.4, with results shown for various bad-scenario probabilities and evaluation dates.

Table 5.5: Investment timing implied by simple rules in baseline case

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
Optimal policy												
	1.72	1.66	1.70	1.76	1.77	1.72	1.81	1.92	1.83	1.76	1.84	1.98
Standard CBA												
$\Delta t = 0.25$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 1$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 2$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 5$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\Delta t = 10$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Constant BCR threshold												
$\hat{B} = 1.00$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\hat{B} = 1.25$	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25
$\hat{B} = 1.50$	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
$\hat{B} = 1.75$	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
$\hat{B} = 2.00$	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Constant IRR threshold												
$\hat{h} = 0.06$	1.30	1.30	1.29	1.29	1.32	1.31	1.30	1.30	1.33	1.31	1.31	1.30
$\hat{h} = 0.07$	1.61	1.59	1.59	1.59	1.63	1.61	1.60	1.60	1.65	1.63	1.62	1.60
$\hat{h} = 0.08$	1.92	1.89	1.88	1.88	1.95	1.92	1.91	1.89	1.99	1.95	1.92	1.91
$\hat{h} = 0.09$	2.23	2.19	2.18	2.17	2.27	2.23	2.21	2.19	2.32	2.27	2.23	2.21
$\hat{h} = 0.10$	2.54	2.49	2.48	2.46	2.59	2.54	2.51	2.49	2.65	2.59	2.54	2.51
Fixed-date approximation of delay-option value												
All	1.58	1.49	1.48	1.47	1.63	1.55	1.52	1.50	1.68	1.60	1.55	1.52
$\Delta t = 1$	1.56	1.48	1.47	1.46	1.61	1.53	1.51	1.49	1.66	1.58	1.54	1.51
$\Delta t = 2$	1.55	1.47	1.46	1.44	1.60	1.52	1.49	1.47	1.65	1.57	1.53	1.49
$\Delta t = 5$	1.50	1.43	1.42	1.41	1.55	1.48	1.46	1.44	1.59	1.53	1.49	1.46
$\Delta t = 10$	1.43	1.38	1.37	1.36	1.47	1.42	1.40	1.38	1.52	1.46	1.43	1.40
Approximate value of waiting												
Ignore clim vol	1.72	1.65	1.64	1.62	1.77	1.70	1.68	1.65	1.83	1.75	1.71	1.68
Ignore econ vol	1.57	1.50	1.53	1.58	1.62	1.56	1.64	1.75	1.67	1.60	1.70	1.84

Notes. The top row reports the optimal threshold for the BCR for the indicated combinations of the climate factor and the current date. The subsequent rows report the BCR thresholds that the decision-maker effectively adopts if she uses the indicated simple decision-making rules. All parameters take their baseline values.

Standard CBA By definition, if the decision-maker uses standard CBA, then she invests whenever the project's BCR is greater than or equal to one.

Constant BCR threshold In each case, the simple rule is to invest if the project's BCR is greater than or equal to some constant threshold.

Constant IRR threshold In this case, the investment threshold is constant when expressed in terms of the project's IRR, but non-constant when expressed in terms of the BCR.

- Higher levels of the constant IRR threshold lead to higher levels of the implied BCR threshold—that is, to later investment.
- Holding the IRR threshold constant, the implied BCR threshold is greater (that is, the investment test is more demanding) if the bad climate scenario is more likely.

- The implied threshold for the BCR shares some of the qualitative properties of the optimal BCR threshold. In particular, it is higher if the bad climate scenario is more likely.

Fixed-date delay option approximation This is only a very slight modification of standard CBA, but it leads to significant delay.

- In the short term, the implied BCR threshold is typically greater than 1.5; that is, the present value of the project's benefits has to be more than 50% larger than the project's cost for immediate investment to occur.
- The implied BCR threshold is higher if the bad scenario is more likely, if the fixed delay used to approximate the value of the delay option is shorter, and if the evaluation date is earlier.

Ignoring climate or economic volatility

- Ignoring climate volatility leads to a slightly higher implied BCR threshold in the short term compared to ignoring economic volatility.
- The implied BCR threshold is higher (that is, the investment test is more demanding) than most instances of the rule based on the fixed-date approximation of the option value.

5.4.2 Sensitivity analysis

This section uses sensitivity analysis to determine the robustness of the results in Section 5.4.1 and to identify situations in which these simple alternatives to ROA perform particularly well or particularly poorly. I focus on the welfare performance of each alternative. In particular, for each approach, I report the option value if the decision-maker uses this approach, evaluated at the break-even level of the economic factor and expressed as a proportion of the maximum attainable option value. The tables of results in this section have the same format as Table 5.2.

Standard CBA Table 5.6 reports the results for the case when the decision-maker evaluates the project using standard CBA at five-yearly intervals.

- In most cases, standard CBA achieves more than half the maximum attainable welfare associated with the adaptation project.
- Welfare losses are greater in the short term. In this case, they are greater when the bad climate scenario is more likely, the economic factor is less volatile, and the economic factor is expected to grow more quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls and the initial capacity of the stormwater system.

Constant BCR threshold Table 5.7 considers the case when the decision-maker uses the constant BCR threshold in equation (3.2) and evaluates the project at five-yearly intervals.

Table 5.6: Welfare implications of using standard CBA

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.05	0.532	0.576	0.684	0.763	0.520	0.577	0.717	0.814	0.504	0.548	0.643	0.708
0.06	0.558	0.596	0.689	0.761	0.545	0.592	0.711	0.800	0.528	0.567	0.646	0.702
0.07	0.579	0.612	0.692	0.758	0.567	0.607	0.707	0.787	0.550	0.585	0.651	0.699
0.08	0.598	0.626	0.696	0.755	0.586	0.620	0.705	0.776	0.569	0.601	0.657	0.699
0.09	0.614	0.639	0.699	0.752	0.603	0.632	0.704	0.767	0.586	0.615	0.663	0.699
μ	Drift of economic factor											
0.005	0.707	0.726	0.790	0.836	0.684	0.720	0.801	0.861	0.672	0.701	0.761	0.799
0.010	0.636	0.671	0.751	0.812	0.617	0.661	0.762	0.839	0.600	0.638	0.706	0.764
0.015	0.579	0.612	0.692	0.758	0.567	0.607	0.707	0.787	0.550	0.585	0.651	0.699
0.020	0.541	0.548	0.617	0.679	0.508	0.546	0.640	0.719	0.499	0.527	0.590	0.641
0.025	0.479	0.498	0.566	0.623	0.455	0.498	0.589	0.659	0.452	0.479	0.540	0.584
θ	Noise in climate information											
5	0.578	0.670	0.749	0.786	0.566	0.671	0.767	0.821	0.551	0.624	0.691	0.716
10	0.579	0.632	0.728	0.783	0.567	0.629	0.747	0.815	0.550	0.599	0.677	0.713
15	0.579	0.612	0.692	0.758	0.567	0.607	0.707	0.787	0.550	0.585	0.651	0.699
20	0.580	0.604	0.663	0.725	0.568	0.596	0.674	0.750	0.550	0.578	0.630	0.680
25	0.580	0.601	0.644	0.697	0.568	0.590	0.651	0.718	0.550	0.574	0.616	0.661
q	Current capacity of infrastructure											
165	0.581	0.610	0.696	0.768	0.565	0.604	0.710	0.797	0.557	0.581	0.651	0.709
170	0.592	0.608	0.681	0.746	0.583	0.605	0.701	0.784	0.571	0.585	0.647	0.705
175	0.579	0.612	0.692	0.758	0.567	0.607	0.707	0.787	0.550	0.585	0.651	0.699
180	0.595	0.610	0.680	0.740	0.583	0.601	0.698	0.776	0.570	0.579	0.647	0.695
185	0.586	0.606	0.686	0.754	0.574	0.601	0.701	0.781	0.555	0.582	0.647	0.700

Notes. Each row reports the option value if the decision-maker uses standard CBA, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

- In the short term, in most cases, using this constant BCR threshold achieves more than 96% of the maximum attainable welfare associated with the adaptation project.
- In the short term, welfare losses are greater when the bad climate scenario is less likely, the economic factor is more volatile, and the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls and the initial capacity of the stormwater system.

Constant IRR threshold Table 5.8 considers the case when the decision-maker uses the constant IRR threshold in equation (3.4) and evaluates the project at five-yearly intervals.

- In the short term, in most cases, using this constant IRR threshold achieves more than 95% of the maximum attainable welfare associated with the adaptation project.
- In the short term, welfare losses are greater when the bad climate scenario is less likely, the economic factor is more volatile, and the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls and the initial capacity of the stormwater system.

Table 5.7: Welfare implications of using a constant threshold for the BCR

p	$\hat{B}$	0.25				0.50				0.75			
t		0	40	80	120	0	40	80	120	0	40	80	120
σ						Volatility of economic factor							
0.05	1.53	0.985	0.980	0.980	0.980	0.989	0.985	0.985	0.985	0.989	0.988	0.988	0.987
0.06	1.57	0.981	0.975	0.975	0.975	0.987	0.982	0.982	0.981	0.988	0.986	0.985	0.982
0.07	1.61	0.977	0.971	0.970	0.970	0.984	0.979	0.977	0.976	0.987	0.983	0.981	0.977
0.08	1.66	0.972	0.970	0.970	0.970	0.980	0.977	0.976	0.973	0.985	0.981	0.978	0.975
0.09	1.71	0.968	0.964	0.965	0.964	0.976	0.973	0.971	0.968	0.981	0.978	0.975	0.970
μ						Drift of economic factor							
0.005	1.33	0.948	0.943	0.945	0.937	0.961	0.956	0.955	0.948	0.969	0.963	0.958	0.951
0.010	1.45	0.965	0.961	0.962	0.960	0.974	0.970	0.969	0.966	0.980	0.976	0.972	0.967
0.015	1.61	0.977	0.971	0.970	0.970	0.984	0.979	0.977	0.976	0.987	0.983	0.981	0.977
0.020	1.84	0.985	0.981	0.981	0.981	0.989	0.986	0.985	0.984	0.991	0.989	0.988	0.986
0.025	2.18	0.990	0.986	0.985	0.985	0.993	0.990	0.989	0.989	0.993	0.992	0.992	0.990
θ						Noise in climate information							
5	1.61	0.975	0.969	0.970	0.968	0.982	0.978	0.977	0.976	0.986	0.983	0.981	0.977
10	1.61	0.977	0.970	0.970	0.969	0.983	0.978	0.977	0.976	0.986	0.983	0.981	0.977
15	1.61	0.977	0.971	0.970	0.970	0.984	0.979	0.977	0.976	0.987	0.983	0.981	0.977
20	1.61	0.977	0.972	0.970	0.970	0.984	0.979	0.977	0.975	0.987	0.984	0.981	0.977
25	1.61	0.978	0.973	0.971	0.970	0.984	0.980	0.977	0.975	0.987	0.984	0.981	0.978
q						Current capacity of infrastructure							
165	1.61	0.978	0.975	0.975	0.975	0.984	0.981	0.980	0.979	0.987	0.984	0.983	0.979
170	1.61	0.977	0.973	0.973	0.973	0.984	0.980	0.979	0.978	0.987	0.984	0.982	0.979
175	1.61	0.977	0.971	0.970	0.970	0.984	0.979	0.977	0.976	0.987	0.983	0.981	0.977
180	1.61	0.975	0.971	0.971	0.971	0.983	0.979	0.978	0.976	0.986	0.983	0.981	0.978
185	1.61	0.969	0.969	0.970	0.970	0.979	0.978	0.977	0.976	0.984	0.983	0.981	0.978

Notes. Each row reports the option value if the decision-maker uses the constant BCR threshold in equation (3.2), for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

- Welfare losses are similar using the constant IRR threshold in equation (3.4) to the losses when using the constant BCR threshold in equation (3.2).

Approximating the option value of waiting Table 5.9 considers the case when the decision-maker approximates the value of the delay option using a fixed one-year delay, and evaluates the project at five-yearly intervals.

- In the short–medium term, using this approach typically achieves more than 96% of the maximum attainable welfare associated with the adaptation project.
- In the long term, welfare losses are greater when the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

Tables 5.10 and 5.11 consider the case when the decision-maker ignores climatic and economic volatility, respectively, when calculating the option value of waiting. She evaluates the project at five-yearly intervals.

Table 5.8: Welfare implications of using a constant threshold for the IRR

p	h	0.25				0.50				0.75			
t		0	40	80	120	0	40	80	120	0	40	80	120
σ		Volatility of economic factor											
0.05	0.0686	0.983	0.980	0.980	0.980	0.988	0.985	0.984	0.983	0.990	0.988	0.987	0.983
0.06	0.0700	0.979	0.974	0.974	0.974	0.984	0.980	0.979	0.978	0.988	0.984	0.982	0.979
0.07	0.0714	0.973	0.969	0.968	0.968	0.980	0.976	0.974	0.972	0.984	0.980	0.977	0.973
0.08	0.0731	0.968	0.967	0.968	0.968	0.975	0.973	0.972	0.970	0.980	0.977	0.974	0.971
0.09	0.0748	0.962	0.962	0.962	0.962	0.970	0.968	0.967	0.965	0.976	0.973	0.969	0.965
μ		Drift of economic factor											
0.005	0.0649	0.944	0.940	0.943	0.936	0.955	0.952	0.951	0.944	0.962	0.957	0.953	0.945
0.010	0.0679	0.962	0.959	0.961	0.958	0.970	0.967	0.966	0.963	0.976	0.971	0.968	0.963
0.015	0.0714	0.973	0.969	0.968	0.968	0.980	0.976	0.974	0.972	0.984	0.980	0.977	0.973
0.020	0.0753	0.982	0.979	0.979	0.979	0.986	0.984	0.983	0.981	0.989	0.987	0.985	0.982
0.025	0.0795	0.987	0.985	0.984	0.983	0.990	0.988	0.987	0.986	0.992	0.991	0.989	0.988
θ		Noise in climate information											
5	0.0714	0.973	0.968	0.969	0.965	0.979	0.975	0.975	0.971	0.983	0.980	0.978	0.973
10	0.0714	0.973	0.968	0.969	0.967	0.980	0.975	0.975	0.971	0.984	0.980	0.977	0.973
15	0.0714	0.973	0.969	0.968	0.968	0.980	0.976	0.974	0.972	0.984	0.980	0.977	0.973
20	0.0714	0.973	0.970	0.968	0.968	0.980	0.976	0.974	0.972	0.984	0.980	0.977	0.973
25	0.0714	0.973	0.970	0.969	0.968	0.980	0.976	0.975	0.972	0.984	0.980	0.977	0.973
q		Current capacity of infrastructure											
165	0.0714	0.974	0.973	0.974	0.973	0.981	0.978	0.977	0.975	0.985	0.981	0.979	0.975
170	0.0714	0.974	0.971	0.972	0.971	0.980	0.977	0.976	0.974	0.985	0.981	0.978	0.974
175	0.0714	0.973	0.969	0.968	0.968	0.980	0.976	0.974	0.972	0.984	0.980	0.977	0.973
180	0.0714	0.971	0.969	0.969	0.969	0.978	0.976	0.975	0.973	0.983	0.980	0.977	0.974
185	0.0714	0.966	0.967	0.969	0.969	0.974	0.975	0.974	0.973	0.979	0.979	0.977	0.974

Notes. Each row reports the option value if the decision-maker uses the constant IRR threshold in equation (3.4), for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

- In the short–medium term, using either approach typically achieves more than 95% of the maximum attainable welfare associated with the adaptation project. The performance of the two approaches is similar across a wide range of parameter settings.

5.5 Conclusions

As in Chapter 4, the analysis in this chapter shows the value of investment-timing flexibility is economically significant across a wide range of parameter settings, this time for projects involving ongoing investment programmes. Once more, using standard CBA at fixed intervals can capture a substantial amount of the option value. Simple rules of thumb based on constant BCR and IRR thresholds are even more effective. The approach that uses a fixed-date approximation to estimate the option value of delaying investment is still probably the best one to adopt, because it can be implemented with just two applications of standard CBA and—at least for the cases considered in this chapter—results in negligible welfare losses.

Table 5.9: Welfare implications of assuming a fixed future investment date

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.05	0.988	0.987	0.987	0.985	0.989	0.988	0.988	0.987	0.990	0.989	0.989	0.988
0.06	0.986	0.985	0.984	0.983	0.988	0.986	0.986	0.986	0.988	0.987	0.987	0.986
0.07	0.984	0.982	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
0.08	0.981	0.979	0.979	0.978	0.983	0.981	0.981	0.980	0.985	0.983	0.982	0.981
0.09	0.978	0.976	0.975	0.974	0.980	0.978	0.977	0.977	0.983	0.980	0.979	0.978
μ	Drift of economic factor											
0.005	0.946	0.928	0.928	0.925	0.955	0.941	0.940	0.939	0.964	0.951	0.947	0.943
0.010	0.973	0.968	0.967	0.963	0.977	0.973	0.971	0.970	0.980	0.976	0.974	0.973
0.015	0.984	0.982	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
0.020	0.989	0.989	0.988	0.988	0.990	0.989	0.989	0.989	0.991	0.990	0.990	0.989
0.025	0.992	0.992	0.992	0.991	0.993	0.992	0.992	0.992	0.993	0.993	0.993	0.992
θ	Noise in climate information											
5	0.984	0.983	0.983	0.980	0.986	0.985	0.985	0.984	0.987	0.986	0.985	0.984
10	0.984	0.983	0.983	0.981	0.986	0.985	0.984	0.984	0.987	0.986	0.985	0.984
15	0.984	0.982	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
20	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.985	0.984	0.983
25	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.981	0.987	0.985	0.984	0.983
q	Current capacity of infrastructure											
165	0.984	0.983	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
170	0.984	0.982	0.981	0.980	0.986	0.984	0.983	0.983	0.987	0.986	0.985	0.984
175	0.984	0.982	0.982	0.981	0.986	0.984	0.984	0.983	0.987	0.986	0.985	0.984
180	0.983	0.982	0.981	0.980	0.985	0.984	0.983	0.983	0.987	0.985	0.985	0.984
185	0.980	0.981	0.980	0.979	0.982	0.983	0.983	0.982	0.984	0.985	0.984	0.984

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option using a fixed one-year delay, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Table 5.10: Welfare implications of ignoring climatic volatility

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.05	0.978	0.978	0.977	0.978	0.981	0.980	0.979	0.979	0.983	0.982	0.981	0.979
0.06	0.975	0.976	0.976	0.976	0.978	0.977	0.976	0.976	0.979	0.978	0.976	0.975
0.07	0.971	0.970	0.971	0.971	0.973	0.973	0.972	0.970	0.975	0.974	0.973	0.970
0.08	0.965	0.965	0.965	0.966	0.969	0.969	0.967	0.967	0.972	0.971	0.968	0.967
0.09	0.961	0.960	0.960	0.960	0.964	0.964	0.964	0.962	0.967	0.967	0.965	0.962
μ	Drift of economic factor											
0.005	0.940	0.939	0.942	0.935	0.944	0.946	0.946	0.941	0.945	0.947	0.946	0.940
0.010	0.956	0.957	0.958	0.957	0.961	0.961	0.960	0.960	0.965	0.963	0.960	0.958
0.015	0.971	0.970	0.971	0.971	0.973	0.973	0.972	0.970	0.975	0.974	0.973	0.970
0.020	0.979	0.978	0.978	0.977	0.981	0.980	0.980	0.978	0.983	0.981	0.981	0.979
0.025	0.986	0.985	0.985	0.985	0.987	0.986	0.986	0.986	0.988	0.987	0.986	0.986
θ	Noise in climate information											
5	0.971	0.971	0.971	0.967	0.973	0.973	0.973	0.970	0.976	0.974	0.973	0.970
10	0.971	0.971	0.971	0.969	0.973	0.973	0.972	0.970	0.975	0.974	0.973	0.970
15	0.971	0.970	0.971	0.971	0.973	0.973	0.972	0.970	0.975	0.974	0.973	0.970
20	0.971	0.970	0.971	0.971	0.973	0.973	0.973	0.971	0.975	0.974	0.973	0.971
25	0.971	0.970	0.971	0.971	0.973	0.973	0.973	0.972	0.974	0.974	0.973	0.971
q	Current capacity of infrastructure											
165	0.971	0.971	0.971	0.971	0.973	0.973	0.972	0.971	0.977	0.975	0.973	0.971
170	0.971	0.969	0.969	0.969	0.974	0.972	0.971	0.971	0.976	0.974	0.971	0.971
175	0.971	0.970	0.971	0.971	0.973	0.973	0.972	0.970	0.975	0.974	0.973	0.970
180	0.969	0.968	0.967	0.968	0.972	0.971	0.969	0.970	0.974	0.973	0.970	0.971
185	0.963	0.965	0.966	0.967	0.967	0.970	0.970	0.969	0.970	0.973	0.971	0.969

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option by ignoring climate volatility, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Table 5.11: Welfare implications of ignoring economic volatility

p	0.25				0.50				0.75			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.05	0.988	0.987	0.985	0.982	0.989	0.987	0.987	0.986	0.990	0.988	0.988	0.988
0.06	0.986	0.985	0.983	0.981	0.988	0.986	0.985	0.984	0.988	0.987	0.986	0.986
0.07	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.985	0.984	0.983
0.08	0.981	0.980	0.979	0.977	0.983	0.982	0.981	0.980	0.985	0.983	0.982	0.981
0.09	0.978	0.976	0.976	0.975	0.981	0.979	0.978	0.977	0.983	0.981	0.979	0.978
μ	Drift of economic factor											
0.005	0.944	0.935	0.938	0.930	0.956	0.952	0.951	0.944	0.964	0.959	0.955	0.948
0.010	0.973	0.969	0.969	0.963	0.977	0.974	0.973	0.969	0.980	0.977	0.974	0.971
0.015	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.985	0.984	0.983
0.020	0.989	0.988	0.988	0.987	0.990	0.989	0.989	0.988	0.991	0.990	0.990	0.989
0.025	0.992	0.991	0.991	0.991	0.993	0.992	0.992	0.992	0.993	0.993	0.993	0.992
θ	Noise in climate information											
5	0.984	0.983	0.983	0.979	0.986	0.985	0.985	0.984	0.987	0.986	0.985	0.984
10	0.984	0.983	0.982	0.980	0.986	0.984	0.984	0.984	0.987	0.986	0.985	0.984
15	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.985	0.984	0.983
20	0.984	0.982	0.981	0.979	0.986	0.984	0.982	0.981	0.987	0.985	0.984	0.983
25	0.984	0.982	0.981	0.978	0.986	0.984	0.982	0.980	0.987	0.986	0.984	0.982
q	Current capacity of infrastructure											
165	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.986	0.984	0.984
170	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.986	0.984	0.984
175	0.984	0.982	0.981	0.979	0.986	0.984	0.983	0.982	0.987	0.985	0.984	0.983
180	0.983	0.982	0.981	0.979	0.985	0.984	0.983	0.982	0.987	0.985	0.984	0.983
185	0.980	0.980	0.979	0.977	0.982	0.983	0.982	0.981	0.984	0.985	0.984	0.983

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option by ignoring economic volatility, for various evaluation dates and probabilities that the bad climate scenario holds. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Chapter

6

One-off investments with scale and timing flexibility

6.1 Introduction

In Chapters 4 and 5, the decision-maker's choice of investment timing is the only flexibility embedded in the investment opportunity. In contrast, in this chapter the decision-maker chooses what to do as well as when to do it. I refer to this additional optionality as "scale" flexibility, but this label includes a wide variety of project characteristics. For example, this additional flexibility might involve the scale of the project, its location, its salvage value, or some other aspect that influences the project's cost or the future benefits that it will generate. As in Chapter 4, the decision-maker can take the action (that is, invest) at most once, she can take the action at any point during a specified period of time, the cost of reversing the action is prohibitively high, and the flow of future benefits initiated by taking the action are uncertain.

This chapter uses the example of an option to invest in upgrading an existing seawall to evaluate the performance of simple decision-making rules when faced with scale and timing flexibility. The decision-maker must choose when to undertake the investment and by how much to raise the existing seawall when investment occurs. The benefits generated by the completed seawall comprise the avoided inundation costs minus any ongoing maintenance costs (and potentially the cost attributed to the loss of the amenity value of nearby land). The avoided inundation costs equal the expected value of all flooding-related costs with the original seawall in place, minus the expected value of all flooding-related costs with the upgraded seawall in place. A suitable climate factor for this example is the average annual maximum sea level, which I assume determines the distribution of the annual maximum sea level, which in turn determines the frequency and scale of seawall breaches. A suitable economic factor is the value of the assets that are protected by the seawall and the system-status factor is the height of the seawall.

Many adaptation projects involve a similar scale choice. For example, when constructing a new water reservoir in response to the increasing frequency and severity of droughts, the decision-maker must choose the size of the new reservoir and the timing of its construction (Sood and Mullan, 2020). The benefits of this project comprise the avoided costs of water scarcity, less any ongoing costs associated with maintaining the reservoir itself. These benefits are subject to two main sources of uncertainty. A suitable climate factor is any variable that summarises the distribution of future streamflow and a suitable economic factor is the size of the local population. There is currently considerable uncertainty about both. For example, Kamish et al. (2020) investigate the effect of drought on drinking-water availability in ten locations around New Zealand and conclude that the likely impact of climate change on stream flows varies across climate scenarios.

Another (smaller-scale) response to increased drought risk is the installation of rainwater harvesting systems for individual buildings (Kim et al., 2014; Pacheco and Campos, 2019). The decision-maker needs to choose the timing of investment and storage capacity of the system. The benefits of such projects include the reduced costs of supplying water to the buildings, plus the value of the reduced pressure on the local stormwater system, minus the cost of maintaining the rainwater harvesting system. These systems are typically implemented at the level of individual buildings, so are a good example of the small-scale adaptation projects that might benefit from a simplified form of ROA.

Scale does not just refer to the physical capacity of an adaptation project. For example, when a decision-maker evaluates a policy of managed retreat in response to rising sea levels, she must decide how far to retreat as well as when to retreat. Rather than physical capacity, in this case the “scale” aspect of the problem relates to distance: how far should assets be relocated from the coast? The benefits generated by such an action include the disruption and repair costs that are avoided because infrastructure has been moved out of harm’s way. In general, the greater the distance retreated, the lower the future costs, and therefore the greater the benefits of the policy. Suitable climate and economic factors are the average annual maximum sea level and the value of assets in the vulnerable location. Delaying the decision allows the decision-maker to acquire more information about the magnitude of the threat—and the appropriate distance to move infrastructure—but means that disruption and repair costs must be incurred for longer.[1]

Scale flexibility is also relevant to decision-making concerning the development of land that is potentially vulnerable to future climate change. Landowners (or, in practice, perhaps the local council during the development-approval process) must choose the level of resilience to embed in the development. For example, houses in locations vulnerable to flooding can be built with elevated foundations to reduce the risk of flooding damage, but the height of the foundations must be chosen before the full magnitude of climate change is known with certainty. Similarly, valuable flexibility can be created when developing coastal land that allows houses to be relatively easily relocated when sea levels rise. That is, the decision-maker effectively chooses the “salvage value” of a house (and pays more upfront for a house with a greater salvage value).

Table 6.1 shows how these adaptation projects can be interpreted in terms of the model in this chapter. It suggests climate and economic factors that are appropriate for each example. In addition to specifying benefit flows that capture the key net benefits generated by the completed project, a model must specify a relevant measure of the scale of investment. The rest of this chapter contains a model of the first of these examples. Like all models used for decision-making, it is stylised. This is partly to ensure the model is tractable and partly so its insights are applicable to other adaptation projects, such as the other examples in Table 6.1. The key feature of the model is that the decision-maker chooses when to invest and what to build.

The decision-maker faces a similar problem in all of these examples. As in Chapter 4, the uncertainty surrounding the future benefits of the project exposes the decision-maker

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[1] However, the costs of delay can be reduced using interim measures (Guthrie, 2021). For example, coastal dairy farms could use extensive re-vegetated buffers on coastlines or some other “Protect, Adapt/Anticipate, Retreat” adaptation pathway (Smith et al., 2017).

Table 6.1: Adaptation projects compatible with the framework in Chapter 6

Type of project	Benefit flow	Climate factor	Economic factor	Scale
Seawall upgrade	Avoided inundation costs	Average maximum sea level	Value of assets in vulnerable area	Height of seawall
Water reservoir	Avoided costs of water scarcity	Any variable that summarises the distribution of future streamflow	Local population	Reservoir capacity
Irrigation scheme	Reduced cost of lost harvests; reduced by irrigation	Average rainfall	Price of primary crop	Storage capacity
Rainwater harvesting systems for individual buildings	Reduced costs of water supply; reduced pressure on stormwater system; allow for maintenance costs	Average rainfall	Value of water; flooding-related costs	Storage capacity
Managed retreat from vulnerable land	Reduced clean-up, disruption, repair costs	Average maximum sea level, rainfall, peak river flow	Value of assets in vulnerable area	Distance moved from source of flooding
Raised foundations of houses built on potentially vulnerable land	Reduced clean-up, disruption, repair costs	Average maximum sea level, rainfall, peak river flow or other factors influencing flood risk	Value of assets in vulnerable area	Height of foundations
Building relocatable houses on coastal land	Reduced cost of moving houses away from the coast in the future	Average maximum sea level or other factors influencing erosion risk	Value of assets in vulnerable area	Salvage value of houses

to the risk that after she invests the benefits will turn out to be so low that the project does not recover the cost of undertaking it. For example, if the frequency of droughts rises more slowly than expected, then the benefits generated by a new water reservoir will be smaller than expected. In Chapter 4, the only way that the decision-maker could reduce this risk was by delaying investment until the expected benefits were relatively large, which made it relatively unlikely that the project's actual benefits would not cover its cost. However, flexibility about what to build offers the decision-maker another means of managing this risk. For example, scale flexibility allows the decision-maker to choose a smaller scale if she invests early, which reduces the risk associated with early investment. As before, the decision-maker must weigh the benefit of waiting against the cost, which is that she forgoes receiving any of the project's benefits for as long as she delays investment. Now, however, the benefit of waiting includes the value of the option to choose what to build.

6.2 Model framework

Details of the model can be found in Appendix B.3 and Guthrie (2023a). Its key components are:

- An existing seawall can cope with a maximum sea level 136cm above the average annual maximum sea level. The seawall's height can be increased at any time and by any amount, but it can only be raised once. Investment costs are chosen so that the cost of increasing the sea wall's height by 50cm is equally split between fixed and variable costs.

- The economic factor equals the (annualised) flooding-related costs incurred by the local community for each centimetre that the annual maximum sea level exceeds the seawall's height. Each year, the growth in this factor is normally distributed with a mean of 2.0% and a standard deviation of 10.0%.

- The average annual maximum sea level increases by R centimetres each year. The rate of sea level rise is uncertain. The decision-maker initially believes that R is normally distributed with a mean of 0.7 and a standard deviation of 0.3. Climate uncertainty falls over time as more is learnt about climate change. This aspect of the set-up matches the model of sea-level rise described in Chapter 2.

- All future costs and benefits are discounted using a constant social discount rate of 5% per annum.

- The baseline values of the model's parameters have been chosen to approximate the Hutt City Council's project upgrading the seawall around the Eastern Bays of Wellington harbour.

6.3 Optimal investment policy

As in Chapters 4 and 5, the optimal policy can be described in terms of trigger points. Each time the seawall project is evaluated, the decision-maker calculates the current values of the climatic and economic factors and determines whether or not the calculated combination triggers immediate investment. This section describes the form these trigger points take, both in the baseline case and when the model's parameters are varied around this baseline.

6.3.1 Baseline case

As was the case in Chapter 4, this adaptation project involves one-off investment. Now, however, the decision-maker needs to choose the scale of investment as well as the timing. The welfare-maximising rule for choosing the timing of investment can be described using the same format as in Chapter 4—that is, by plotting the optimal trigger point for the economic factor as a function of the climate factor, for various evaluation dates. The key difference here is due to the different underlying model of climate uncertainty. Rather than plotting the investment threshold as a function of the probability of the bad scenario occurring, the threshold is a function of the expected rate of sea-level rise. The top graph in Figure 6.1 plots the optimal trigger point for the economic factor as a function of the expected rate of sea-level rise. Each curve corresponds to a different evaluation date. In principle, the decision-maker can use this graph in the following way:

1. Calculate the current levels of the climatic and economic factors and identify the corresponding point on the graph.

2. If this point is on or below the curve corresponding to the current date, then wait and reevaluate the project in the future.

3. If this point is above the curve corresponding to the current date, then invest immediately.

The trigger point is lower if the sea level is believed to be rising more quickly and if the evaluation date is further into the future.

As in the previous two chapters, it is possible to express the rule for investment timing in terms of a trigger point for the project's BCR. The middle graph in Figure 6.1 plots this trigger point as a function of the expected rate of sea-level rise on the indicated evaluation dates. The key results to note are:

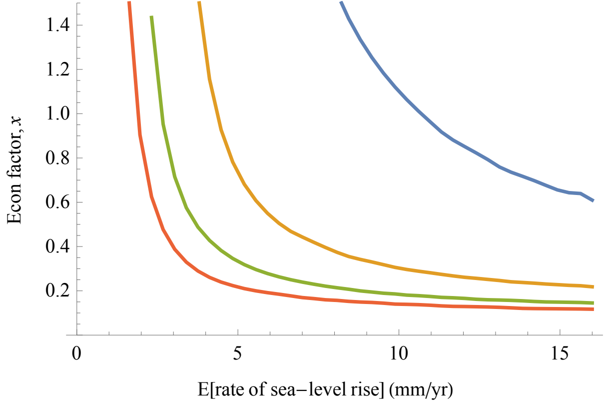
- The welfare-maximising threshold for the BCR is (very) significantly greater than one—in particular, it is optimal to require that the present value of the project's benefits is more than double the cost before investing. In the short term, the threshold is even greater than this. These results show that the value of the investment timing option is large—in fact, several times the required investment expenditure, especially in the short term.

- The optimal BCR threshold is much larger than in Chapter 4. The main benefit of delaying investment in Chapter 4 was the ability to reduce the risk of the adaptation project being stranded. This is still a benefit here, but now delaying investment also allows the decision-maker to make a better-informed choice of investment scale. That is, waiting is more valuable in this chapter (especially in the short term) because it allows the decision-maker to learn more about what to build, rather than just when to build it. This makes the option value of waiting larger, which increases the opportunity cost of investing and raises the BCR trigger point.

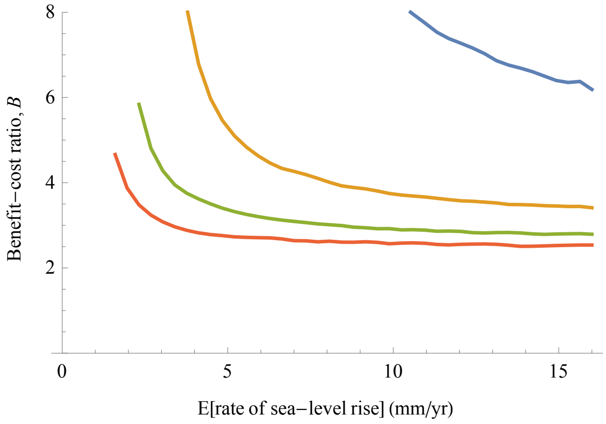
- The option value falls over time as the remaining uncertainty about the rate of sea-level rise falls. Holding time (and hence uncertainty) constant, the option value is lower when the expected rate of sea level rise is greater (so that the risk of stranding is lower).

Figure 6.1: Optimal investment policy

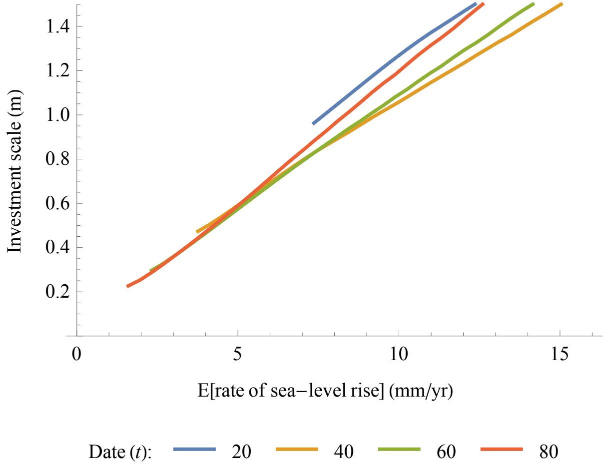
(a) Trigger for economic factor



(b) Trigger for benefit−cost ratio



(c) Investment scale



Notes. The top graph plots the welfare-maximising trigger point for the economic factor as a function of the expected rate of sea-level rise on the indicated evaluation dates. The middle graph plots the corresponding trigger point for the BCR as a function of the expected rate of sea-level rise. The bottom graph plots the optimal investment scale when the economic factor is at the level that triggers immediate investment. All parameters take their baseline values.

The second component of the welfare-maximising investment policy is the rule for determining the scale of investment. The bottom graph in Figure 6.1 plots the optimal investment scale as a function of the expected rate of sea-level rise on the indicated evaluation dates. This is the scale of investment the decision-maker should choose when the economic factor is at the level that triggers immediate investment. Combining all three graphs in Figure 6.1 reveals the following:

- If the expected rate of sea-level rise is low, then it is optimal to wait for a relatively high level of the economic factor or BCR and then build a small extension to the sea wall.
- If the expected rate of sea-level rise is high, then it is optimal to wait for a relatively low level of the economic factor or BCR and then build a large extension to the sea wall.

6.3.2 Sensitivity analysis

As in Chapters 4 and 5, the analysis in this section addresses two fundamental questions. First, how much is the investment-timing option worth? Second, what does the socially optimal investment policy look like? Now, however, the second question has two components: what does optimal timing look like and what is the optimal scale of investment? As in the two preceding chapters, I use the value of the investment option when the economic factor is at the breakeven point to help answer the first question. I use the level of the welfare-maximising BCR threshold and the scale of investment when the BCR triggers investment to help answer the two components of the second question. In all cases, I carry out sensitivity analysis, varying the model's parameters around their baseline values and reporting the effects on these three outputs.

Table 6.2 reports the results of the sensitivity analysis of the value of the investment option. Each row reports the values of the investment option when the economic factor is at the breakeven level, for the indicated evaluation dates and expected rates of sea-level rise.[2] All parameters take their baseline values in the top row. The subsequent panels each vary one of the model's parameters over a range around that parameter's baseline level while holding all other parameters at their baseline levels. For example, if the expected rate of sea-level rise equals 7mm/year at date 40 in the baseline case, then the investment option will be worth 44.2% of the cost of a 50cm increase in height when the economic factor is just large enough for the benefits of immediate investment to cover the cost of the investment expenditure. The key results to note are:

- The option value is economically significant in all the cases I consider. Thus, some form of ROA, or a simplified approximation to this method, is important for achieving good welfare gains from investing in the project.
- Scale and timing flexibility is more valuable if the economic factor is more volatile and if it is expected to grow more quickly. However, economic volatility has a relatively small effect on the option value, especially if the expected rate of sea-level rise is low.

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[2] The cost parameters are normalised so that increasing the height of the sea wall by 50cm costs one "dollar."

Table 6.2: Maximum attainable option value at breakeven level of economic factor

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
					Baseline case							
	0.804	0.427	0.299	0.247	0.727	0.442	0.401	0.381	0.805	0.509	0.514	0.527
σ					Volatility of economic factor							
0.08	0.801	0.418	0.287	0.231	0.718	0.425	0.379	0.355	0.791	0.486	0.484	0.490
0.09	0.803	0.422	0.293	0.239	0.722	0.433	0.390	0.368	0.798	0.497	0.499	0.508
0.10	0.804	0.427	0.299	0.247	0.727	0.442	0.401	0.381	0.805	0.509	0.514	0.527
0.11	0.806	0.432	0.306	0.255	0.733	0.451	0.413	0.395	0.814	0.521	0.530	0.546
0.12	0.808	0.437	0.314	0.264	0.738	0.461	0.425	0.410	0.822	0.534	0.547	0.566
μ					Drift of economic factor							
0.010	0.704	0.329	0.210	0.170	0.592	0.291	0.258	0.257	0.626	0.318	0.322	0.352
0.015	0.752	0.375	0.252	0.205	0.652	0.356	0.322	0.314	0.704	0.401	0.406	0.432
0.020	0.804	0.427	0.299	0.247	0.727	0.442	0.401	0.381	0.805	0.509	0.514	0.527
0.025	0.854	0.487	0.358	0.297	0.823	0.551	0.498	0.463	0.942	0.655	0.649	0.650
0.030	0.903	0.554	0.424	0.357	0.939	0.686	0.615	0.562	1.119	0.844	0.815	0.789
$\hat{t}$					Noise in climate information							
30	0.872	0.404	0.297	0.245	0.736	0.439	0.400	0.381	0.806	0.507	0.513	0.527
40	0.839	0.414	0.298	0.246	0.731	0.440	0.400	0.381	0.806	0.508	0.514	0.527
50	0.804	0.427	0.299	0.247	0.727	0.442	0.401	0.381	0.805	0.509	0.514	0.527
60	0.771	0.440	0.303	0.248	0.724	0.444	0.402	0.381	0.806	0.510	0.514	0.526
70	0.740	0.452	0.308	0.250	0.723	0.446	0.403	0.381	0.807	0.512	0.515	0.526
q					Current height of seawall							
1.26	0.498	0.336	0.290	0.262	0.588	0.417	0.411	0.402	0.692	0.501	0.528	0.549
1.31	0.628	0.371	0.292	0.254	0.655	0.426	0.405	0.391	0.748	0.504	0.521	0.538
1.36	0.804	0.427	0.299	0.247	0.727	0.442	0.401	0.381	0.805	0.509	0.514	0.527
1.41	1.040	0.510	0.317	0.242	0.800	0.465	0.398	0.371	0.863	0.518	0.508	0.516
1.46	1.361	0.623	0.348	0.240	0.873	0.499	0.397	0.361	0.917	0.531	0.502	0.505

Notes. Each row reports the maximum attainable option value for various evaluation dates and expected rates of sea-level rise, where the option value is evaluated at the breakeven-level of the economic factor. The top row shows results when all parameters take their baseline values. The other panels report results when I vary one of the model's parameters, as described in the first entry in each row. All parameters other than those listed take their baseline values.

- In the short term, investment flexibility is more valuable if climate uncertainty falls more quickly, but only if the expected rate of sea-level rise is low. In the medium term, investment flexibility is more valuable if climate uncertainty falls more slowly, but again only if the expected rate of sea-level rise is low.

- In the short term, investment flexibility is more valuable if the sea wall is already relatively high.

Now I turn to the first part of the second key question: what does the socially optimal investment-timing policy look like? Each entry in Table 6.3 reports the optimal BCR threshold for a different combination of parameters.[3] The format is identical to Table 6.2. For example, if the expected rate of sea-level rise equals 7mm/year at date 40 in the baseline case, then the decision-maker should increase the height of the sea wall if doing so has a BCR greater than 4.27. The key results to note are:

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[3] The missing entries correspond to situations where the optimal trigger point for the economic factor is outside the grid I use to evaluate the options. In these situations, the optimal investment threshold is so high that early investment is very unlikely.

Table 6.3: Optimal threshold for the BCR

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Baseline case											
	–	–	3.08	2.33	–	4.27	2.64	2.16	–	3.67	2.58	2.21
σ	Volatility of economic factor											
0.08	–	–	2.98	2.22	–	4.18	2.56	2.13	–	3.53	2.47	2.08
0.09	–	–	3.02	2.29	–	4.23	2.61	2.15	–	3.60	2.49	2.09
0.10	–	–	3.08	2.33	–	4.27	2.64	2.16	–	3.67	2.58	2.21
0.11	–	–	3.14	2.40	–	4.31	2.70	2.27	–	3.73	2.63	2.27
0.12	–	–	3.21	2.46	–	4.37	2.77	2.32	–	3.80	2.68	2.30
μ	Drift of economic factor											
0.010	–	–	2.16	1.73	–	2.72	1.89	1.69	–	2.37	1.81	1.70
0.015	–	–	2.59	1.97	–	3.38	2.20	1.92	–	2.89	2.14	1.93
0.020	–	–	3.08	2.33	–	4.27	2.64	2.16	–	3.67	2.58	2.21
0.025	–	–	3.98	2.73	–	5.66	3.32	2.65	–	4.86	3.17	2.62
0.030	–	–	5.14	3.46	–	7.70	4.32	3.24	–	6.64	4.17	3.33
$\hat{t}$	Noise in climate information											
30	–	7.82	3.10	2.31	–	4.25	2.64	2.16	–	3.66	2.58	2.21
40	–	–	3.06	2.32	–	4.26	2.64	2.16	–	3.66	2.58	2.21
50	–	–	3.08	2.33	–	4.27	2.64	2.16	–	3.67	2.58	2.21
60	–	–	3.12	2.35	–	4.27	2.64	2.16	–	3.67	2.58	2.21
70	–	–	3.19	2.28	–	4.26	2.63	2.16	–	3.67	2.58	2.21
q	Current height of seawall											
1.26	–	3.69	2.61	2.21	–	3.31	2.52	2.20	–	3.20	2.49	2.13
1.31	–	5.61	2.79	2.28	–	3.68	2.58	2.19	–	3.40	2.53	2.17
1.36	–	–	3.08	2.33	–	4.27	2.64	2.16	–	3.67	2.58	2.21
1.41	–	–	3.78	2.43	–	5.29	2.74	2.24	–	4.02	2.60	2.23
1.46	–	–	5.45	2.62	–	7.55	2.87	2.26	–	4.57	2.68	2.23

Notes. Each row reports the optimal investment threshold for various evaluation dates and expected rates of sea-level rise. All parameters other than those listed take their baseline values.

- The welfare-maximising BCR threshold is significantly above one in all cases. In most cases it is greater than two. The optimal BCR threshold is lower when the expected rate of sea-level rise is higher.

- The optimal BCR threshold is higher if the economic factor is more volatile and if it is expected to grow more quickly.

- The optimal BCR threshold is relatively insensitive to the speed with which climate uncertainty falls.

- The optimal BCR threshold is larger when the existing sea wall is higher.

Finally, I carry out sensitivity analysis on the welfare-maximising scale of investment. Each row in Table 6.4 reports the amount (measured in metres) that the decision-maker should raise the sea wall by for various evaluation dates and expected rates of sea-level rise. The optimal scale is evaluated assuming the level of the economic factor equals the trigger point for socially optimal investment. The table's format is the same as Tables 6.2 and 6.3. The key results to note are:

- The optimal scale is larger if the sea level is expected to be rising more rapidly and if the evaluation date is further into the future.

Table 6.4: Optimal investment scale

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Baseline case											
	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49
σ	Volatility of economic factor											
0.08	–	–	0.36	0.38	–	0.79	0.83	0.92	–	1.13	1.29	1.49
0.09	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.30	1.49
0.10	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49
0.11	–	–	0.36	0.39	–	0.80	0.84	0.93	–	1.15	1.32	1.49
0.12	–	–	0.36	0.39	–	0.80	0.84	0.93	–	1.16	1.33	1.50
μ	Drift of economic factor											
0.010	–	–	0.32	0.37	–	0.57	0.70	0.88	–	0.81	1.07	1.43
0.015	–	–	0.34	0.37	–	0.66	0.76	0.90	–	0.94	1.17	1.46
0.020	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49
0.025	–	–	0.39	0.40	–	0.90	0.90	0.95	–	1.42	1.45	1.52
0.030	–	–	0.41	0.41	–	0.96	0.95	0.97	–	1.52	1.52	1.55
$\hat{t}$	Noise in climate information											
30	–	0.38	0.36	0.38	–	0.79	0.84	0.92	–	1.14	1.31	1.49
40	–	–	0.36	0.38	–	0.79	0.84	0.92	–	1.14	1.31	1.49
50	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49
60	–	–	0.37	0.39	–	0.80	0.84	0.93	–	1.15	1.31	1.49
70	–	–	0.37	0.40	–	0.80	0.84	0.93	–	1.15	1.31	1.49
q	Current height of seawall											
1.26	–	0.40	0.43	0.48	–	0.79	0.91	1.02	–	1.15	1.38	1.59
1.31	–	0.40	0.40	0.43	–	0.79	0.88	0.97	–	1.14	1.35	1.54
1.36	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49
1.41	–	–	0.33	0.35	–	0.80	0.80	0.88	–	1.16	1.27	1.45
1.46	–	–	0.32	0.31	–	0.81	0.77	0.83	–	1.19	1.24	1.40

Notes. Each row reports the optimal investment scale for various evaluation dates and expected rates of sea-level rise, where the scale is evaluated at the optimal investment trigger point for the economic factor. The top row shows results when all parameters take their baseline values. The other panels report results when I vary one of the model's parameters, as described in the first entry in each row. All parameters other than those listed take their baseline values.

- Economic volatility has little effect on the scale of investment (although it does affect the optimal timing of investment).
- The optimal scale of investment is larger if the economic factor is expected to grow more rapidly.
- The optimal scale of investment is relatively insensitive to the speed with which climate uncertainty falls.
- The optimal scale of investment is smaller when the existing sea wall is higher, but the effect is minor. That is, the height of the existing sea wall has a larger effect on the timing of investment than it does on the scale.

As in Chapters 4 and 5, the real option to choose the timing of investment is very valuable, so it is optimal to delay raising the sea wall until the benefits of investment are much larger than the required investment expenditure. The remainder of this chapter evaluates the potential of simple alternatives to ROA to deliver the economic benefits associated with the flexibility to choose the scale and timing of investment.

Table 6.5: Welfare performance of simple rules in baseline case

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Optimal policy											
	0.804	0.427	0.299	0.247	0.727	0.442	0.401	0.381	0.805	0.509	0.514	0.527
Δt	Standard CBA											
0.25	0.038	0.119	0.142	0.079	0.052	0.067	0.115	0.094	0.052	0.160	0.101	0.490
1	0.084	0.217	0.228	0.201	0.103	0.176	0.127	0.128	0.107	0.220	0.174	0.529
2	0.134	0.320	0.285	0.323	0.177	0.273	0.234	0.237	0.182	0.289	0.259	0.577
5	0.259	0.518	0.504	0.554	0.322	0.456	0.466	0.477	0.338	0.448	0.458	0.691
10	0.456	0.709	0.695	0.756	0.528	0.650	0.680	0.701	0.547	0.630	0.670	0.814
$\hat{B}$	Constant BCR threshold											
1.50	0.499	0.767	0.875	0.942	0.591	0.808	0.893	0.963	0.619	0.823	0.902	0.971
1.75	0.599	0.856	0.952	0.983	0.707	0.908	0.966	0.985	0.731	0.922	0.971	0.984
2.00	0.673	0.915	0.984	0.976	0.786	0.959	0.988	0.977	0.816	0.969	0.988	0.966
2.25	0.730	0.952	0.989	0.949	0.845	0.984	0.984	0.947	0.876	0.988	0.981	0.934
2.50	0.775	0.974	0.981	0.914	0.888	0.991	0.965	0.898	0.918	0.990	0.962	0.896
$\hat{h}$	Constant IRR threshold											
0.06	0.630	0.777	0.829	0.876	0.689	0.769	0.831	0.887	0.681	0.767	0.843	0.901
0.07	0.819	0.929	0.965	0.980	0.883	0.942	0.970	0.984	0.884	0.941	0.970	0.980
0.08	0.910	0.983	0.991	0.976	0.961	0.990	0.989	0.975	0.966	0.991	0.988	0.966
0.09	0.955	0.993	0.976	0.933	0.989	0.987	0.966	0.926	0.993	0.984	0.963	0.932
0.10	0.979	0.983	0.946	0.880	0.994	0.963	0.927	0.881	0.992	0.955	0.922	0.876
	Approximating delay-option value											
Fixed	0.989	0.994	0.991	0.985	0.996	0.993	0.990	0.985	0.996	0.993	0.990	0.985
Ignore econ vol	0.993	0.992	0.992	0.985	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
Ignore clim vol	0.982	0.991	0.984	0.978	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.978

Notes. The top row reports the maximum attainable option value for various evaluation dates and expected rates of sea-level rise, where the option value is evaluated at the breakeven-level of the economic factor. The subsequent rows report the option value if the decision-maker uses various simple rules. In each case, the option value is evaluated at the break-even level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters take their baseline values.

6.4 Performance of simple rules

6.4.1 Baseline case

As in the preceding two chapters, for each simple alternative to ROA I focus on two key questions:

- What proportion of the maximum-attainable welfare can be achieved if the decision-maker adopts this rule?
- What does the investment policy implied by a simple rule look like?

The key difference from the earlier chapters is that now the investment policy has two dimensions: timing and scale.

Table 6.5 summarises the welfare performance of the same decision-making rules as in Chapters 4 and 5. The top row reports the maximum attainable present value of future welfare associated with the option to undertake the adaptation project, evaluated at the break-even level of the economic factor. That is, the entries in this row show the option value that can be attained if the decision-maker adopts the optimal investment policy. The subsequent rows report the option value if she uses various simple decision-making rules. In each case, the option value is evaluated at the break-even level of the economic factor and is expressed as a proportion of the maximum attainable option value.[4] For example, if the decision-maker uses a constant IRR threshold of 8% and the expected rate of sea-level rise is 7mm/year, then the option value is initially 96.1% of its value under the optimal policy, assuming the economic factor is currently at the break-even level.

Standard CBA

- The welfare performance is poor if the project is evaluated frequently. If standard CBA is used, then it is better to evaluate the project infrequently, perhaps every five or ten years. Even then, standard CBA, might achieve less than half of the maximum achievable welfare.

Constant BCR threshold

- The welfare performance of this rule is sensitive to the chosen level of the BCR threshold. Welfare performance first improves then worsens as the threshold increases.
- It is possible to achieve more than 60% of the maximum attainable welfare using this approach.

Constant IRR threshold

- The welfare performance of this rule is sensitive to the chosen level of the IRR threshold. Starting from a threshold of $\hat{h} = 0.05$, welfare performance first improves then worsens as the threshold increases.
- It is possible to achieve more than 80% of the maximum attainable welfare using this approach.

Approximating the delay-option value

- All three approaches typically achieve more than 97% of the maximum attainable welfare. The performance is robust over time and over changes in the climate factor.
- The performance of these approaches is superior to both rules of thumb (constant BCR and IRR thresholds).

There are two dimensions to the investment policy implied by these rules: timing and scale. Table 6.6 summarises the investment timing implied by simple alternatives to ROA that appear in Table 6.5. The top row reports the optimal threshold for the BCR for the indicated combinations of the climate factor and the current date. It is the same as the top row in Table 6.3. The subsequent rows report the BCR threshold that the decision-maker effectively adopts if she uses the indicated simple decision-making rules. For example, if the decision-maker uses a constant IRR threshold of 6% and the expected rate of sea-level rise is 7mm/year, then the effective BCR threshold at date 0 is 1.91.

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[4] Unless stated otherwise, these calculations assume that the project is evaluated every five years under the simple policies, and continuously under the optimal policy.

Table 6.6: Investment timing implied by simple rules in baseline case

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Optimal policy											
	–	–	3.08	2.33	–	4.27	2.64	2.16	–	3.67	2.58	2.21
Δt	Standard CBA											
0.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$\hat{B}$	Constant BCR threshold											
1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
$\hat{h}$	Constant IRR threshold											
0.06	2.05	1.60	1.43	1.36	1.91	1.47	1.38	1.35	1.81	1.42	1.37	1.35
0.07	–	2.32	1.91	1.73	3.41	2.03	1.81	1.71	3.14	1.93	1.77	1.71
0.08	–	3.13	2.41	2.11	5.58	2.67	2.26	2.08	5.04	2.52	2.22	2.08
0.09	–	4.00	2.93	2.50	–	3.36	2.73	2.46	7.55	3.14	2.68	2.45
0.10	–	4.92	3.46	2.89	–	4.07	3.21	2.84	–	3.80	3.16	2.83
	Approximating delay-option value											
Fixed	–	5.21	2.79	2.03	–	3.93	2.37	1.94	–	3.37	2.27	1.93
Ignore econ vol	–	–	2.85	2.04	–	3.98	2.36	1.96	–	3.39	2.30	1.91
Ignore clim vol	–	5.47	3.02	2.32	–	4.20	2.64	2.16	–	3.65	2.58	2.21

Notes. The top row reports the optimal threshold for the BCR for the indicated combinations of the climate factor and the current date. The subsequent rows report the BCR thresholds that the decision-maker effectively adopts if she uses the indicated simple decision-making rules. All parameters take their baseline values.

Standard CBA By definition, if the decision-maker uses standard CBA, then she invests whenever the project's BCR is greater than or equal to one.

Constant BCR threshold In each case, the simple rule is to invest if the project's BCR is greater than or equal to some constant threshold.

Constant IRR threshold In this case, the investment threshold is constant when expressed in terms of the project's IRR, but non-constant when expressed in terms of the BCR.

- Higher levels of the constant IRR threshold lead to higher levels of the implied BCR threshold—that is, to later investment.
- Holding the IRR threshold constant, the implied BCR threshold is greater (that is, the investment test is more demanding) if the expected rate of sea-level rise is lower.
- The implied threshold for the BCR shares some of the qualitative properties of the optimal BCR threshold. In particular, it is higher if the expected rate of sea-level rise is lower.

Table 6.7: Investment scale implied by simple rules in baseline case

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
	Optimal policy											
	–	–	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49
Δt	Standard CBA											
0.25	0.21	0.23	0.28	0.33	0.36	0.43	0.61	0.83	0.48	0.61	0.96	1.38
1	0.21	0.23	0.28	0.33	0.36	0.43	0.61	0.83	0.48	0.61	0.96	1.38
2	0.21	0.23	0.28	0.33	0.36	0.43	0.61	0.83	0.48	0.61	0.96	1.38
5	0.21	0.23	0.28	0.33	0.36	0.43	0.61	0.83	0.48	0.61	0.96	1.38
10	0.21	0.23	0.28	0.33	0.36	0.43	0.61	0.83	0.48	0.61	0.96	1.38
$\hat{B}$	Constant BCR threshold											
1.50	0.25	0.27	0.31	0.36	0.46	0.52	0.71	0.89	0.64	0.76	1.09	1.44
1.75	0.26	0.28	0.33	0.37	0.50	0.56	0.75	0.90	0.70	0.83	1.15	1.46
2.00	0.28	0.29	0.33	0.38	0.54	0.60	0.78	0.92	0.76	0.88	1.21	1.48
2.25	0.29	0.30	0.34	0.39	0.57	0.63	0.81	0.93	0.81	0.93	1.26	1.49
2.50	0.29	0.31	0.35	0.39	0.60	0.66	0.83	0.93	0.85	0.98	1.30	1.51
$\hat{h}$	Constant IRR threshold											
0.06	0.28	0.28	0.31	0.36	0.52	0.52	0.69	0.88	0.72	0.74	1.05	1.41
0.07	–	0.30	0.33	0.37	0.68	0.60	0.76	0.90	0.95	0.87	1.16	1.46
0.08	–	0.33	0.35	0.38	0.80	0.67	0.81	0.92	1.16	0.98	1.25	1.49
0.09	–	0.34	0.36	0.39	–	0.73	0.84	0.93	1.34	1.08	1.33	1.50
0.10	–	0.36	0.37	0.40	–	0.78	0.87	0.94	–	1.16	1.39	1.52
	Approximating delay-option value											
Fixed	–	0.36	0.36	0.38	–	0.77	0.82	0.92	–	1.11	1.26	1.48
Ignore econ vol	–	–	0.36	0.38	–	0.78	0.81	0.92	–	1.11	1.26	1.48
Ignore clim vol	–	0.36	0.36	0.39	–	0.79	0.84	0.92	–	1.14	1.31	1.49

Notes. The top row reports the optimal investment scale (measured in metres) for the indicated combinations of the climate factor and the current date. The subsequent rows report the scales that the decision-maker effectively adopts if she uses the indicated simple decision-making rules. All parameters take their baseline values.

Approximating the delay-option value

- All three approaches result in high BCR thresholds that are higher if the expected rate of sea-level rise is lower, and if the evaluation date is earlier.
- The fixed-date approximation implies a lower BCR threshold than the other two approaches.

The second dimension of the investment policy is the scale of investment. Table 6.7 summarises the investment scale implied by simple alternatives to ROA that appear in Table 6.5. The top row reports the optimal investment scale (measured in meters) for the indicated combinations of the climate factor and the current date. It is the same as the top row in Table 6.4. The subsequent rows report the scale the decision-maker effectively adopts if she uses the indicated simple decision-making rules. For example, if the decision-maker uses a constant IRR threshold of 6% and the expected rate of sea-level rise is 7mm/year, then the scale of investment is 0.52m if investment occurs at date 0.

Standard CBA

- If the expected rate of sea-level rise is larger when the decision-maker invests, then she will choose a larger investment scale.
- Later investment will have greater scale, especially if the expected rate of sea-level rise is larger.

Constant BCR and IRR thresholds

- The investment scale will be larger if the expected rate of sea-level rise is larger.
- Delayed investment (that is, a higher investment threshold) leads to greater investment scale, especially if the expected rate of sea-level rise is larger.

Approximating the delay-option value

- The investment scale will be larger if the expected rate of sea-level rise is larger.
- All three approaches result in similar investment scales.

6.4.2 Sensitivity analysis

This section uses sensitivity analysis to determine the robustness of the results in Section 6.4.1 and to identify situations in which these simple alternatives to ROA perform particularly well or particularly poorly. As in the previous two chapters, I focus on the welfare performance of each alternative. For each approach, I report the option value if the decision-maker uses this approach, evaluated at the break-even level of the economic factor and expressed as a proportion of the maximum attainable option value. The tables of results in this section have the same format as Table 6.2.

Standard CBA Table 6.8 reports the results for the case when the decision-maker evaluates the project using standard CBA at five-yearly intervals.

- In the short term, in most cases standard CBA achieves more than 25% of the maximum attainable welfare associated with the adaptation project.
- In the short term, welfare losses are greater when the expected rate of sea-level rise is lower, the economic factor is less volatile, the economic factor is expected to grow more quickly, and the initial height of the sea wall is greater. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

Constant BCR threshold Table 6.9 considers the case when the decision-maker uses the constant BCR threshold in equation (3.2) and evaluates the project at five-yearly intervals.

- In the short term, using this constant BCR threshold usually achieves more than 60% of the maximum attainable welfare associated with the adaptation project.
- Welfare losses are greater in the short term. In this case, the losses are greater when the expected rate of sea-level rise is lower, the economic factor is less volatile, the economic factor is expected to grow less quickly, and the initial height of the sea wall is larger. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.

Table 6.8: Welfare implications of using standard CBA

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.08	0.242	0.509	0.474	0.519	0.302	0.429	0.425	0.433	0.318	0.420	0.420	0.687
0.09	0.251	0.514	0.489	0.538	0.312	0.443	0.446	0.456	0.328	0.435	0.440	0.689
0.10	0.259	0.518	0.504	0.554	0.322	0.456	0.466	0.477	0.338	0.448	0.458	0.691
0.11	0.268	0.523	0.517	0.568	0.332	0.469	0.483	0.495	0.348	0.461	0.475	0.694
0.12	0.276	0.528	0.530	0.581	0.342	0.480	0.499	0.513	0.358	0.474	0.491	0.696
μ	Drift of economic factor											
0.010	0.280	0.606	0.617	0.658	0.363	0.556	0.569	0.662	0.388	0.563	0.649	0.668
0.015	0.269	0.558	0.548	0.650	0.347	0.506	0.517	0.569	0.356	0.505	0.563	0.523
0.020	0.259	0.518	0.504	0.554	0.322	0.456	0.466	0.477	0.338	0.448	0.458	0.691
0.025	0.249	0.473	0.469	0.550	0.295	0.394	0.403	0.617	0.299	0.387	0.355	0.566
0.030	0.244	0.428	0.440	0.448	0.283	0.360	0.363	0.575	0.266	0.306	0.488	0.418
$\hat{t}$	Noise in climate information											
30	0.313	0.454	0.498	0.560	0.325	0.440	0.456	0.475	0.336	0.457	0.459	0.692
40	0.271	0.487	0.500	0.558	0.322	0.442	0.460	0.475	0.337	0.452	0.459	0.692
50	0.259	0.518	0.504	0.554	0.322	0.456	0.466	0.477	0.338	0.448	0.458	0.691
60	0.260	0.534	0.515	0.549	0.323	0.458	0.472	0.481	0.339	0.446	0.458	0.690
70	0.266	0.531	0.518	0.549	0.324	0.460	0.478	0.485	0.341	0.447	0.457	0.688
q	Current height of seawall											
1.26	0.360	0.514	0.515	0.608	0.377	0.464	0.532	0.528	0.380	0.437	0.508	0.694
1.31	0.313	0.515	0.500	0.534	0.356	0.453	0.493	0.499	0.353	0.422	0.484	0.702
1.36	0.259	0.518	0.504	0.554	0.322	0.456	0.466	0.477	0.338	0.448	0.458	0.691
1.41	0.216	0.511	0.512	0.541	0.293	0.438	0.509	0.592	0.309	0.434	0.432	0.677
1.46	0.175	0.502	0.486	0.562	0.274	0.430	0.499	0.640	0.299	0.427	0.425	0.661

Notes. Each row reports the option value if the decision-maker uses standard CBA, for various evaluation dates and expected rates of sea-level rise. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Constant IRR threshold Table 6.10 considers the case when the decision-maker uses the constant IRR threshold in equation (3.4) and evaluates the project at five-yearly intervals.

- In most cases, using this constant IRR threshold achieves more than 85% of the maximum attainable welfare associated with the adaptation project.
- Welfare losses are greater in the short term. In this case, the losses are greater when the expected rate of sea-level rise is smaller, the economic factor is less volatile, the economic factor is expected to grow less quickly, and the initial height of the sea wall is greater. In most cases, the scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls.
- Welfare losses are smaller using the constant IRR threshold in equation (3.4) than they are using the constant BCR threshold in equation (3.2).

Approximating the option value of waiting Table 6.11 considers the case when the decision-maker approximates the value of the delay option using a fixed three-month delay. She evaluates the project at five-yearly intervals.

Table 6.9: Welfare implications of using a constant threshold for the BCR

a	$\hat{B}$	0.003				0.007				0.011			
t		0	40	80	120	0	40	80	120	0	40	80	120
σ						Volatility of economic factor							
0.08	1.89	0.647	0.895	0.980	0.982	0.756	0.947	0.988	0.973	0.787	0.961	0.988	0.983
0.09	1.94	0.660	0.906	0.981	0.977	0.771	0.953	0.988	0.975	0.802	0.965	0.989	0.977
0.10	2.00	0.673	0.915	0.984	0.976	0.786	0.959	0.988	0.977	0.816	0.969	0.988	0.966
0.11	2.06	0.686	0.923	0.984	0.973	0.800	0.963	0.987	0.973	0.830	0.972	0.987	0.971
0.12	2.12	0.698	0.929	0.985	0.972	0.813	0.966	0.986	0.966	0.842	0.974	0.987	0.974
μ						Drift of economic factor							
0.01	1.59	0.577	0.897	0.976	0.964	0.703	0.956	0.979	0.949	0.741	0.971	0.978	0.961
0.015	1.76	0.623	0.903	0.978	0.968	0.746	0.957	0.985	0.966	0.782	0.970	0.984	0.963
0.020	2.00	0.673	0.915	0.984	0.976	0.786	0.959	0.988	0.977	0.816	0.969	0.988	0.966
0.025	2.35	0.730	0.930	0.985	0.982	0.831	0.964	0.991	0.980	0.853	0.970	0.991	0.973
0.030	2.88	0.792	0.946	0.990	0.986	0.882	0.972	0.993	0.984	0.900	0.978	0.993	0.989
$\hat{t}$						Noise in climate information							
30	2.00	0.712	0.913	0.984	0.978	0.791	0.959	0.988	0.977	0.818	0.969	0.988	0.966
40	2.00	0.688	0.915	0.984	0.978	0.788	0.959	0.988	0.977	0.817	0.969	0.988	0.966
50	2.00	0.673	0.915	0.984	0.976	0.786	0.959	0.988	0.977	0.816	0.969	0.988	0.966
60	2.00	0.667	0.915	0.982	0.977	0.786	0.959	0.988	0.977	0.816	0.969	0.988	0.967
70	2.00	0.669	0.913	0.981	0.977	0.788	0.959	0.988	0.977	0.817	0.968	0.988	0.967
q						Current height of seawall							
1.26	2.00	0.846	0.969	0.988	0.970	0.872	0.975	0.988	0.969	0.876	0.977	0.988	0.963
1.31	2.00	0.763	0.950	0.987	0.973	0.833	0.969	0.988	0.973	0.850	0.974	0.988	0.964
1.36	2.00	0.673	0.915	0.984	0.976	0.786	0.959	0.988	0.977	0.816	0.969	0.988	0.966
1.41	2.00	0.589	0.866	0.972	0.979	0.740	0.946	0.987	0.978	0.784	0.963	0.987	0.969
1.46	2.00	0.527	0.802	0.952	0.981	0.697	0.927	0.984	0.971	0.752	0.955	0.987	0.971

Notes. Each row reports the option value if the decision-maker uses the constant BCR threshold in equation (3.2), for various evaluation dates and expected rates of sea-level rise. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

- In the short–medium term, using this approach achieves more than 98% of the maximum attainable welfare associated with the adaptation project.

- In the long term, welfare losses are greater when the economic factor is expected to grow less quickly. The scale of welfare losses is relatively insensitive to the speed with which climate uncertainty falls and to the initial height of the sea wall.

Tables 6.12 and 6.13 consider the case when the decision-maker ignores climatic and economic volatility, respectively, when calculating the option value of waiting. She evaluates the project at five-yearly intervals.

- In the short–medium term, using either approach achieves more than 98% of the maximum attainable welfare associated with the adaptation project. The performance of the two approaches is similar across a wide range of parameter settings.

- In the long term, welfare losses are greater when the economic factor is expected to grow less quickly.

Table 6.10: Welfare implications of using a constant threshold for the IRR

a	h	0.003				0.007				0.011			
t		0	40	80	120	0	40	80	120	0	40	80	120
σ		Volatility of economic factor											
0.08	0.0768	0.893	0.976	0.992	0.980	0.946	0.987	0.992	0.972	0.952	0.988	0.991	0.981
0.09	0.0783	0.902	0.980	0.992	0.976	0.954	0.989	0.990	0.974	0.960	0.990	0.990	0.974
0.10	0.0800	0.910	0.983	0.991	0.976	0.961	0.990	0.989	0.975	0.966	0.991	0.988	0.966
0.11	0.0818	0.917	0.986	0.990	0.972	0.967	0.991	0.987	0.971	0.972	0.991	0.986	0.970
0.12	0.0836	0.924	0.987	0.989	0.970	0.972	0.991	0.985	0.966	0.977	0.991	0.984	0.970
μ		Drift of economic factor											
0.010	0.0735	0.825	0.966	0.983	0.960	0.910	0.982	0.978	0.949	0.922	0.984	0.976	0.957
0.015	0.0766	0.867	0.975	0.987	0.966	0.938	0.987	0.984	0.965	0.946	0.988	0.983	0.963
0.020	0.0800	0.910	0.983	0.991	0.976	0.961	0.990	0.989	0.975	0.966	0.991	0.988	0.966
0.025	0.0837	0.945	0.989	0.993	0.981	0.980	0.994	0.992	0.980	0.983	0.994	0.991	0.973
0.030	0.0877	0.970	0.994	0.995	0.986	0.990	0.996	0.994	0.984	0.993	0.996	0.994	0.986
$\hat{t}$		Noise in climate information											
30	0.0800	0.941	0.984	0.991	0.976	0.962	0.990	0.989	0.975	0.967	0.991	0.988	0.966
40	0.0800	0.926	0.984	0.991	0.976	0.962	0.990	0.989	0.975	0.967	0.991	0.988	0.966
50	0.0800	0.910	0.983	0.991	0.976	0.961	0.990	0.989	0.975	0.966	0.991	0.988	0.966
60	0.0800	0.896	0.981	0.991	0.975	0.960	0.990	0.989	0.975	0.966	0.991	0.988	0.967
70	0.0800	0.888	0.979	0.990	0.975	0.961	0.990	0.989	0.975	0.967	0.991	0.988	0.967
q		Current height of seawall											
1.26	0.0800	0.959	0.991	0.988	0.970	0.977	0.992	0.987	0.969	0.977	0.992	0.987	0.963
1.31	0.0800	0.936	0.989	0.990	0.972	0.969	0.991	0.988	0.973	0.972	0.991	0.987	0.964
1.36	0.0800	0.910	0.983	0.991	0.976	0.961	0.990	0.989	0.975	0.966	0.991	0.988	0.966
1.41	0.0800	0.881	0.973	0.991	0.977	0.953	0.989	0.989	0.976	0.961	0.990	0.988	0.969
1.46	0.0800	0.875	0.959	0.988	0.980	0.945	0.986	0.990	0.971	0.955	0.989	0.989	0.971

Notes. Each row reports the option value if the decision-maker uses the constant IRR threshold in equation (3.4), for various evaluation dates and expected rates of sea-level rise. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

6.5 Conclusions

Real option values continue to be economically significant when scale flexibility is added to the timing flexibility covered in Chapters 4 and 5. Using standard CBA at fixed intervals continues to capture a substantial amount of the option value and simple rules of thumb based on constant BCR and IRR thresholds continue to be effective. Using a fixed-date approximation to estimate the option value of delaying investment is still preferred, due to its ease of use and negligible welfare losses.

Table 6.11: Welfare implications of assuming a fixed future investment date

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ					Volatility of economic factor							
0.08	0.990	0.994	0.992	0.988	0.996	0.994	0.991	0.987	0.996	0.994	0.991	0.987
0.09	0.990	0.994	0.992	0.986	0.996	0.994	0.991	0.986	0.996	0.994	0.991	0.986
0.10	0.989	0.994	0.991	0.985	0.996	0.993	0.990	0.985	0.996	0.993	0.990	0.985
0.11	0.988	0.993	0.991	0.983	0.995	0.993	0.989	0.983	0.996	0.993	0.989	0.983
0.12	0.988	0.993	0.990	0.982	0.995	0.992	0.988	0.981	0.996	0.992	0.988	0.981
μ					Drift of economic factor							
0.010	0.980	0.989	0.983	0.969	0.993	0.988	0.977	0.959	0.993	0.985	0.970	0.961
0.015	0.985	0.992	0.988	0.979	0.995	0.991	0.986	0.977	0.995	0.991	0.985	0.977
0.020	0.989	0.994	0.991	0.985	0.996	0.993	0.990	0.985	0.996	0.993	0.990	0.985
0.025	0.992	0.995	0.993	0.990	0.996	0.995	0.992	0.989	0.996	0.994	0.992	0.989
0.030	0.994	0.996	0.995	0.993	0.997	0.996	0.994	0.992	0.997	0.995	0.994	0.992
$\hat{t}$					Noise in climate information							
30	0.997	0.994	0.991	0.985	0.996	0.993	0.990	0.984	0.996	0.993	0.990	0.985
40	0.995	0.994	0.991	0.985	0.996	0.993	0.990	0.985	0.996	0.993	0.990	0.985
50	0.989	0.994	0.991	0.985	0.996	0.993	0.990	0.985	0.996	0.993	0.990	0.985
60	0.979	0.993	0.991	0.986	0.995	0.993	0.990	0.986	0.996	0.993	0.990	0.985
70	0.968	0.992	0.991	0.986	0.995	0.993	0.990	0.985	0.996	0.993	0.990	0.985
q					Current height of seawall							
1.26	0.986	0.992	0.990	0.985	0.995	0.993	0.990	0.985	0.995	0.993	0.989	0.985
1.31	0.986	0.993	0.991	0.985	0.995	0.993	0.990	0.985	0.996	0.993	0.990	0.985
1.36	0.989	0.994	0.991	0.985	0.996	0.993	0.990	0.985	0.996	0.993	0.990	0.985
1.41	0.994	0.995	0.992	0.986	0.996	0.994	0.990	0.986	0.996	0.994	0.990	0.985
1.46	0.997	0.996	0.993	0.986	0.996	0.994	0.991	0.986	0.996	0.994	0.990	0.985

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option using a fixed three-month delay, for various evaluation dates and expected rates of sea-level rise. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Table 6.12: Welfare implications of ignoring climate volatility

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ					Volatility of economic factor							
0.08	0.985	0.992	0.988	0.978	0.995	0.990	0.986	0.981	0.995	0.990	0.987	0.981
0.09	0.984	0.991	0.986	0.978	0.994	0.989	0.985	0.980	0.994	0.989	0.985	0.979
0.10	0.982	0.991	0.984	0.978	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.978
0.11	0.981	0.990	0.983	0.973	0.994	0.987	0.981	0.974	0.993	0.987	0.981	0.976
0.12	0.981	0.990	0.981	0.973	0.993	0.986	0.979	0.973	0.992	0.985	0.978	0.971
μ					Drift of economic factor							
0.010	0.975	0.986	0.972	0.959	0.992	0.978	0.968	0.961	0.990	0.976	0.968	0.958
0.015	0.978	0.989	0.979	0.965	0.993	0.984	0.977	0.967	0.992	0.983	0.977	0.972
0.020	0.982	0.991	0.984	0.978	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.978
0.025	0.985	0.993	0.987	0.983	0.995	0.991	0.987	0.984	0.994	0.991	0.987	0.985
0.030	0.989	0.995	0.992	0.988	0.996	0.993	0.991	0.989	0.996	0.993	0.991	0.988
$\hat{t}$					Noise in climate information							
30	0.996	0.990	0.984	0.972	0.994	0.988	0.982	0.975	0.994	0.988	0.983	0.980
40	0.992	0.990	0.985	0.972	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.980
50	0.982	0.991	0.984	0.978	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.978
60	0.970	0.991	0.984	0.977	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.978
70	0.959	0.991	0.984	0.977	0.994	0.988	0.982	0.977	0.994	0.988	0.983	0.978
q					Current height of seawall							
1.26	0.988	0.987	0.982	0.976	0.992	0.987	0.982	0.978	0.992	0.987	0.982	0.978
1.31	0.984	0.988	0.983	0.976	0.993	0.987	0.982	0.976	0.993	0.987	0.982	0.979
1.36	0.982	0.991	0.984	0.978	0.994	0.988	0.983	0.976	0.994	0.988	0.983	0.978
1.41	0.993	0.993	0.986	0.974	0.995	0.989	0.982	0.977	0.994	0.988	0.983	0.978
1.46	0.997	0.995	0.988	0.973	0.996	0.990	0.983	0.978	0.994	0.989	0.983	0.980

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option by ignoring climate volatility, for various evaluation dates and expected rates of sea-level rise. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Table 6.13: Welfare implications of ignoring economic volatility

a	0.003				0.007				0.011			
t	0	40	80	120	0	40	80	120	0	40	80	120
σ	Volatility of economic factor											
0.08	0.993	0.993	0.993	0.988	0.995	0.994	0.992	0.987	0.996	0.995	0.992	0.987
0.09	0.993	0.993	0.992	0.986	0.995	0.994	0.991	0.985	0.996	0.994	0.991	0.985
0.10	0.993	0.993	0.992	0.985	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
0.11	0.993	0.992	0.991	0.983	0.995	0.993	0.989	0.980	0.996	0.993	0.988	0.981
0.12	0.993	0.992	0.990	0.982	0.995	0.992	0.988	0.978	0.995	0.992	0.986	0.979
μ	Drift of economic factor											
0.010	0.987	0.988	0.983	0.963	0.992	0.987	0.973	0.945	0.993	0.984	0.966	0.955
0.015	0.991	0.991	0.987	0.979	0.994	0.991	0.985	0.973	0.994	0.990	0.983	0.974
0.020	0.993	0.993	0.992	0.985	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
0.025	0.994	0.994	0.993	0.990	0.996	0.995	0.993	0.989	0.996	0.995	0.993	0.989
0.030	0.996	0.996	0.995	0.993	0.997	0.996	0.995	0.993	0.997	0.996	0.995	0.992
$\hat{t}$	Noise in climate information											
30	0.996	0.993	0.992	0.985	0.996	0.994	0.990	0.983	0.996	0.993	0.990	0.984
40	0.994	0.993	0.992	0.985	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
50	0.993	0.993	0.992	0.985	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
60	0.991	0.992	0.991	0.986	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
70	0.990	0.992	0.990	0.986	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
q	Current height of seawall											
1.26	0.992	0.992	0.990	0.985	0.995	0.993	0.989	0.984	0.995	0.993	0.989	0.982
1.31	0.992	0.993	0.991	0.985	0.995	0.993	0.990	0.984	0.996	0.993	0.989	0.984
1.36	0.993	0.993	0.992	0.985	0.995	0.993	0.990	0.983	0.996	0.993	0.990	0.983
1.41	0.993	0.994	0.992	0.985	0.995	0.994	0.990	0.983	0.996	0.994	0.990	0.984
1.46	0.996	0.994	0.993	0.986	0.995	0.994	0.991	0.983	0.996	0.994	0.990	0.984

Notes. Each row reports the option value if the decision-maker approximates the value of the delay option by ignoring economic volatility, for various evaluation dates and expected rates of sea-level rise. The option value is evaluated at the breakeven-level of the economic factor and is expressed as a proportion of the maximum attainable option value. All parameters other than those listed take their baseline values.

Chapter

7

Insights for practitioners

7.1 Evaluating small projects

In all the cases considered in this report, the value of the flexibility embedded in the projects is economically significant. That is, welfare is much higher if the decision-maker follows a socially optimal investment policy than if she continuously monitors a project and invests the first time that its BCR is greater than one. Therefore, decision-makers should attempt to exploit this investment flexibility in ways that benefit society as a whole: investing as soon as the present value of a project's benefits exceeds its cost will lead to substantial welfare losses compared to the socially optimal benchmark.

The welfare-maximising investment-timing rule can be expressed in terms of a threshold that a project's BCR must exceed in order for investment to occur. If the decision-maker knows the level of the threshold then optimal investment is easy:

- each time a project is evaluated, calculate the project's BCR from investing immediately;
- if the BCR is greater than the threshold, then invest immediately;
- otherwise wait and reevaluate the project in the future.

Unfortunately, the results in Chapters 4–6 show the optimal threshold varies over time and over the decision-maker's assessment of the speed and magnitude of climate change. It is also sensitive to the level of parameters including the mean and standard deviation of the annual growth rate of the economic factor, as well as the current capacity of infrastructure to cope with climate change. It will not usually be economically viable to determine the precise threshold that is optimal for the relatively small projects considered in this report.

Fortunately, there are simple decision-making rules that generally lead to relatively small welfare losses.

- If standard CBA is used, then projects should be evaluated at fixed intervals. It is important that decision-makers resist the temptation to reevaluate a delayed project ahead of schedule in response to news that the project benefits have increased. Doing so will tend to lead to investment occurring much sooner than is socially optimal.

- There are superior alternatives to standard CBA that are no more difficult to implement and produce higher levels of overall welfare. The two simplest alternatives use constant thresholds for the project's BCR and its IRR. The IRR is preferred because a constant IRR threshold implies a non-constant BCR threshold with qualitative properties that tend to be similar to the welfare-maximising threshold. A constant IRR threshold seems to get reasonably close to the welfare-maximising threshold.

- The main difficulty with these approaches is calculating an appropriate (BCR or IRR) threshold. The thresholds suggested in equations (3.2) and (3.4) are simple functions of the social discount rate, the mean annual growth rate of the economic factor, and the standard deviation of this growth rate. The first two inputs should already be available from standard CBA, so it is only the third input—economic volatility—that requires extra work. The data used to estimate the mean can also provide an estimate of the standard deviation.

- In situations where this information is difficult to obtain, or where superior performance is required, decision-makers can use the fixed-date-approximation approach. This simple rule delivers small welfare losses, even though the calculation is not much more complicated than standard CBA.

    - Each time a project is evaluated, the decision-maker calculates the present values of the investment payoffs for a small set of possible fixed future investment dates.
    - She invests in the project immediately if it is better to invest immediately than to commit to invest at any of the fixed future dates.
    - Otherwise she waits and repeats the evaluation process at the next scheduled evaluation date.

    All that is required at any evaluation date is a series of straightforward CBA calculations, one for each possible fixed future evaluation date. The analysis in Chapters 4–6 suggests this approach leads to very small welfare losses.

7.2 Evaluating large projects

When analysts apply ROA to relatively large adaptation projects, for which some form of bespoke analysis might be worthwhile, they often assume the decision-maker uses only one source of information to make investment timing decisions. The decision-maker might choose when to invest based on the level of a climatic variable, or alternatively on the level of an economic variable. This can keep the analysis relatively tractable, but at the price of oversimplifying the decision-maker's problem. The analysis summarised in this report suggests that either approach will probably lead to investment behaviour that is close to optimal. Welfare losses are likely to be small with either approach.

The theoretical framework described in Chapter 2 can also be useful for evaluating larger projects using bespoke ROA. This would involve retaining the parts of the current model that specify the uncertainty surrounding future climatic and economic conditions, but enhancing the current approach to estimating the annual flow of benefits associated with investment. The analysis in Chapters 4–6 uses very stylised benefit-flow functions, but practitioner-generated benefit-flow functions could be substituted into the model with little loss of tractability. This would allow analysts to implement ROA and derive welfare-maximising investment policies in a rich model with climatic and economic volatility, the former deriving from the gradual arrival of information about the magnitude and speed of climate change. This would be suitable for relatively large or complicated adaptation projects, for which the simple rules considered in this report may not be sufficient.

7.3 A word of caution

Finally, a word of caution. The results in this report are based on extensive sensitivity analysis that shows the results hold over a wide range of situations. However, the examples analysed are only snapshots of the wide spectrum of possible adaptation projects. It is potentially dangerous to extend the results here beyond the situations in which they are obtained. For example, the fixed-date approximation of the option value of waiting works well here, but it may not work as well in other situations. In particular, we cannot be sure it will work as well with adaptation projects that have more complicated option structures. There will always be a place for bespoke ROA, such as when analysing large or complex adaptation projects.

Appendix

A

Climate-factor behaviour

A.1 Two climate scenarios

This approach assumes there are two possible climate scenarios, "good" and "bad." The decision-maker does not know which climate scenario holds. Instead, she assigns a probability to each scenario being the true one and then updates these probabilities as more information about the state of the climate arrives. Let p_t denote the date t probability that the bad climate scenario holds. The new climate information takes the form of a noisy signal of some measure of the climate (such as the average annual maximum one-day rainfall), denoted by λ_t. At any given date t, λ_t takes the values $\lambda_g(t)$ and $\lambda_b(t)$ in the good and bad scenarios, respectively. The functions λ_g and λ_b are increasing in t and satisfy $\lambda_b(t) \geq \lambda_g(t)$ for all t. The decision-maker continuously observes the noisy signal

$$h_t = \lambda_t + \theta \tilde{W}_t, \tag{A.1}$$

where θ is a constant and $\tilde{W}_t$ is white noise, independent of λ_t and ξ_t.[1]

The decision-maker's beliefs regarding which climate scenario holds evolve stochastically. If the noisy signal in equation (A.1) is greater than the decision-maker's current estimate of λ_t, then she will increase her subjective probability that the bad scenario holds, otherwise she will decrease it. The resulting process for p_t is given in the next lemma.

Lemma A.1 *The subjective probability that the bad climate holds evolves according to*

$$dp_t = \frac{p_t(1-p_t)(\lambda_b(t) - \lambda_g(t))}{\theta} d\zeta_t, \tag{A.2}$$

where ζ_t is a Wiener process uncorrelated with ξ_t.

Proof. Over the next short period of time lasting Δt years, the decision-maker observes $h = \lambda + \theta \, \Delta\eta / \Delta t$, where $\Delta\eta \sim N(0, \sqrt{\Delta t})$. If $p = \Pr[\lambda = \lambda_b]$ is the decision-maker's current

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[1] This significantly simplifies the analysis. For example, if the white noise term were correlated with the shock that influences the path of the economic factor, then the decision-maker would need to incorporate the information content of growth in the economic factor when updating her subjective probability that the bad scenario holds.

subjective probability that the bad scenario holds, then Bayes' Theorem implies that her updated subjective probability is

$$p' = \Pr\left[\lambda = \lambda_b | h\right] = \frac{f\left(h|\lambda = \lambda_b\right) \cdot p}{f\left(h|\lambda = \lambda_b\right) \cdot p + f\left(h|\lambda = \lambda_g\right) \cdot (1-p)},$$

where

$$f\left(h|\lambda\right) = \frac{1}{\theta}\sqrt{\frac{\Delta t}{2\pi}} e^{\frac{-\Delta t}{2}\left(\frac{h-\lambda}{\theta}\right)^2}$$

is the density function of h, conditional on λ. The change in the probability equals

$$\Delta p \equiv p' - p = p(1-p)\left(\frac{f\left(h|\lambda = \lambda_b\right) - f\left(h|\lambda = \lambda_g\right)}{f\left(h|\lambda = \lambda_b\right) \cdot p + f\left(h|\lambda = \lambda_g\right) \cdot (1-p)}\right).$$

Substituting in $h = \lambda + \theta\,\Delta\eta/\Delta t$ implies that

$$\Delta p = p(1-p)\left(\frac{e^{\frac{-1}{2\Delta t}\left(\left(\frac{\lambda-\lambda_b}{\theta}\right)\Delta t+\Delta\eta\right)^2} - e^{\frac{-1}{2\Delta t}\left(\left(\frac{\lambda-\lambda_g}{\theta}\right)\Delta t+\Delta\eta\right)^2}}{e^{\frac{-1}{2\Delta t}\left(\left(\frac{\lambda-\lambda_b}{\theta}\right)\Delta t+\Delta\eta\right)^2} \cdot p + e^{\frac{-1}{2\Delta t}\left(\left(\frac{\lambda-\lambda_g}{\theta}\right)\Delta t+\Delta\eta\right)^2} \cdot (1-p)}\right).$$

Taking a Taylor series expansion in $(\Delta t, \Delta\eta)$ and setting $(\Delta\eta)^2 = \Delta t$ implies that

$$\Delta p = \frac{p(1-p)(\lambda_b - \lambda_g)}{\theta}\left(\left(\frac{\lambda - (p\lambda_b + (1-p)\lambda_g)}{\theta}\right)\Delta t + \Delta\eta\right).$$

From the decision-maker's point of view, Δp has expected value zero and standard deviation $(p(1-p)(\lambda_b - \lambda_g)/\theta)\sqrt{\Delta t}$. Therefore

$$\Delta p = \frac{p(1-p)(\lambda_b - \lambda_g)}{\theta}\Delta\eta,$$

which motivates the stochastic process for p in equation (A.2). Note that $\Delta p > 0$ if and only if $h = \lambda + \theta\,\Delta\eta/\Delta t > p\lambda_b + (1-p)\lambda_g$.

A.2 Infinitely many climate scenarios

The average annual maximum sea level is initially s_0 and increases at the unknown constant rate R, so the average annual maximum sea level is $s_t = s_0 + Rt$ at date t. At date 0, the decision-maker believes R is normally distributed with mean a_0 and standard deviation b_0. She continuously observes the noisy signal

$$h_t = s_t + \theta\,\tilde{W}_t \tag{A.3}$$

of the average annual maximum sea level, where θ is a constant and $\tilde{W}_t$ is white noise. For example, in practice the decision-maker might observe the actual monthly maximum sea level and use that information to infer an estimate of the average annual maximum sea level. The decision-maker uses the information contained in this noisy signal to continuously update her beliefs regarding R. The next lemma describes how these beliefs evolve over time.

Lemma A.2 *At date t, the decision-maker believes that R is normally distributed with mean a_t and standard deviation b_t. The mean a_t evolves according to*

$$da_t = \frac{b_0^2 t}{\theta^2 + \frac{1}{3}b_0^2 t^3}\left((R - a_t)t\,dt + \theta\,d\zeta_t\right), \tag{A.4}$$

where $d\zeta_t = \tilde{W}_t\,dt$, and

$$b_t^2 = \frac{\theta^2 b_0^2}{\theta^2 + \frac{1}{3}b_0^2 t^3}. \tag{A.5}$$

Proof. This result is implied by Theorem 6.2.8 in Øksendal (1998). In terms of the notation there, let $Z_t = \int_0^t (h_{t'} - s_0)dt'$, so that $dZ_t = (h_t - s_0)dt = Rt\,dt + \theta d\zeta_t$, where ζ_t is a Wiener process. Similarly, let $X_t = R$, so that $dX_t = 0$. The situation here corresponds to the special case of Theorem 6.2.8 in which $C = 0$, $D = \theta$, $F(t) = 0$, and $G(t) = t$. The estimate's mean square error, $S(t)$, therefore satisfies

$$S'(t) = \frac{-t^2}{\theta^2}(S(t))^2, \quad S(0) = b_0^2,$$

which implies $S(t)$ equals the expression on the right-hand side of equation (A.5). The estimate itself satisfies the stochastic differential equation

$$da_t = \frac{-t^2 b_t^2}{\theta^2} a_t\,dt + \frac{t b_t^2}{\theta^2} dZ_t = \frac{t b_t^2}{\theta^2}((R - a_t)t\,dt + \theta d\zeta_t).$$

As the average annual maximum sea level equals $s_t = s_0 + Rt$ at date t, the decision-maker believes s_t is normally distributed with mean $s_0 + a_t t$ and standard deviation

$$b_t t = \frac{\theta b_0 t}{\sqrt{\theta^2 + \frac{1}{3} b_0^2 t^3}}.$$

The decision-maker's uncertainty about the contemporaneous average annual maximum sea level is initially zero, increases until date $(6\theta^2/b_0^2)^{1/3}$, and then slowly decreases to zero. There are two opposing forces at work. Each year, the sea level rises by an uncertain constant amount, so that uncertainty about the cumulative change grows over time. However, this is offset by the ongoing learning process resulting from the noisy observations of the sea level. The first effect dominates initially, but eventually the second effect dominates.

The volatility of a_t in the stochastic process given in equation (A.4) is an important determinant of the value of the option to delay investment. It is initially low, but increases until date $(3\theta^2/(2b_0^2))^{1/3}$ and then decreases to zero. The volatility of a_t is a consequence of the decision-maker learning about the rate of sea-level rise. As the rate of learning accelerates, the volatility of a_t grows. Finally, as the learning process slows down, the volatility of a_t falls.

Appendix

B

Model details

B.1 Simple timing options

This section describes the model in Chapter 4. In this model, a decision-maker is responsible for retrofitting new technology to an existing building that will enable its occupants to cope with higher outside temperatures. At each date t, the temperature-related cost incurred by the building's occupants over the next day equals $\max\{0, \tilde{h} - q_t\}x_t \, \Delta t$, where $\tilde{h}$ is the daily maximum outdoor temperature, q_t measures the building's ability to cope with high outdoor temperatures, x_t is an economic factor, and $\Delta t = 1/365$ is the amount of time corresponding to one day. The expected cost, measured at date t, therefore equals $E_t[\max\{0, \tilde{h} - q_t\}]x_t \, \Delta t$. The economic factor evolves according to the geometric Brownian motion

$$dx_t = \mu x_t \, dt + \sigma x_t \, d\xi_t,$$

where μ and σ are known constants and ξ_t is a Wiener process. The building's temperature resilience q_t is initially equal to the constant k, but the decision-maker can increase it to the constant k' at any time. This costs $c > 0$, can only happen once, and is irreversible. The decision-maker's objective is to minimise the present value of all relevant costs, including heat-related costs and the investment expenditure incurred when upgrading the building. The social discount rate is the constant r.

The initial distribution of the daily maximum outdoor temperature is chosen to match daily NIWA data for Christchurch for the period 1954–2019. Climate change shifts this distribution to the right by an amount that depends on the date and the climate scenario. There are two possible climate scenarios, "good" and "bad." The implied paths for the average daily maximum outdoor temperature are

$$\lambda_b(t) = 19.83 - 3.0e^{-0.0203t} \quad \text{and} \quad \lambda_g(t) = 17.53 - 0.7e^{-0.0869t}.$$

The subjective probability that the bad scenario holds, p_t, evolves according to the process described in Appendix A.1. I choose the value of θ so that the standard deviation of $\lambda_{t=100}$ is halved over the first fifty years, assuming that $p_0 = 0.5$.

Let $V(t, p_t, x_t)$ denote the present value of the retrofit option at date t. The function V satisfies the partial differential equation

$$\mathcal{D}V(t, p, x) - rV(t, p, x) = 0$$

Table B.1: Baseline parameter values for the model in Chapter 4

Economic factor	
Drift, μ	0.015
Volatility, σ	0.060
Climate factor	
Path in bad scenario, $\lambda_b(t)$	$19.83 - 3.0e^{-0.0203t}$
Path in good scenario, $\lambda_g(t)$	$17.53 - 0.7e^{-0.0869t}$
Noise, θ	2.072
Distribution of the daily maximum outdoor temperature	
Initial	Chosen to match daily NIWA data for Christchurch (1954–2019)
Dist. in bad scenario	Shift by $\lambda_b(t) - \lambda_b(0)$
Dist. in good scenario	Shift by $\lambda_g(t) - \lambda_g(0)$
Miscellaneous	
Pre-retrofit system capacity, k	32.8
Post-retrofit system capacity, k'	34.8
Cost of retrofit, c	1
Social discount rate, r	0.05

in the waiting region, where

$$\mathcal{D} = \frac{\partial}{\partial t} + \frac{1}{2}\left(\frac{p(1-p)(\lambda_g(t) - \lambda_b(t))}{\theta}\right)^2 \frac{\partial^2}{\partial p^2} + \frac{1}{2}\sigma^2 x^2 \frac{\partial^2}{\partial x^2} + \mu x \frac{\partial}{\partial x}.$$

In the investment region, V satisfies

$$V(t,p,x) = \big(pv_b(t) + (1-p)v_g(t)\big)\, x - c,$$

where

$$v_b(t) = \int_t^\infty e^{-(r-\mu)(s-t)} \Big(E[\max\{0, \tilde{h} + \lambda_b(s) - \lambda_b(0) - k\}] \\ - E[\max\{0, \tilde{h} + \lambda_b(s) - \lambda_b(0) - k'\}]\Big)\, ds$$

and

$$v_g(t) = \int_t^\infty e^{-(r-\mu)(s-t)} \Big(E[\max\{0, \tilde{h} + \lambda_g(s) - \lambda_g(0) - k\}] \\ - E[\max\{0, \tilde{h} + \lambda_g(s) - \lambda_g(0) - k'\}]\Big)\, ds.$$

If the upgrade policy is welfare maximising, then V satisfies

$$V(t,p,x) \geq \big(pv_b(t) + (1-p)v_g(t)\big)\, x - c$$

and

$$\mathcal{D}V(t,p,x) - rV(t,p,x) \leq 0$$

everywhere. The first condition holds with equality in the investment region and the second condition holds with equality in the waiting region.

Table B.1 reports the baseline values of the model's parameters.

B.2 Ongoing investment programmes

This section describes the model in Chapter 5. A more detailed description can be found in Guthrie (2023b). In this model, a decision-maker is responsible for upgrading an urban stormwater system. The system's capacity at any given date t equals q_t, which the decision-maker is able to increase over time by investing in system upgrades. At any point in time, she can increase capacity by any positive amount Δq by spending $c \cdot \Delta q$, for some constant $c > 0$. There is no limit to the number of times that investment can occur, but increases in capacity are irreversible. The decision-maker's objective is to minimise the present value of all relevant costs, including flooding costs and the investment expenditure incurred when upgrading the system. The social discount rate is the constant r.

There are two possible climate scenarios, "good" and "bad." The subjective probability that the bad scenario holds, denoted p_t, evolves according to the process described in Appendix A.1. At any date t, the expected cost associated with flooding over the next increment of time equals $E_t[\max\{0, R - q_t\}]x_t \, dt$, where the annual maximum one-day rainfall R is drawn from a generalised extreme value (GEV) distribution. The observable economic factor x_t evolves according to the geometric Brownian motion

$$dx_t = \mu x_t \, dt + \sigma x_t \, d\xi_t,$$

where μ and σ are known constants and ξ_t is a Wiener process. The GEV distribution's initial location, scale, and shape parameters equal 75.71, 22.54, and 0.1908, respectively, which are chosen to match the estimated distribution generated by the NIWA High Intensity Rainfall Design System (HIRDS). The location parameter increases over time in such a way that the implied paths for the average annual maximum one-day rainfall are

$$\lambda_b(t) = 132.95 - 39.03e^{-0.0083t} \quad \text{and} \quad \lambda_g(t) = 98.03 \, - 4.12e^{-0.0788t}.$$

These are consistent with the projected means of the HIRDS distributions under RCP2.6 and RCP8.5. It follows that $E_t[\max\{0, R - q_t\}]$ equals

$$\Gamma_b(q_t, t) = \int_{q_t}^{\infty} (R - q_t) F_b'(R; t) \, dR$$

and

$$\Gamma_g(q_t, t) = \int_{q_t}^{\infty} (R - q_t) F_g'(R; t) \, dR$$

in the bad and good scenarios, where $F_b(R; t)$ and $F_g(R; t)$ are the distribution functions in the bad and good scenarios.

Let $V(t, p_t, x_t; q_t)$ denote the present value of the incremental upgrade option at date t. In Guthrie (2023b), I show that V satisfies the partial differential equation

$$\mathcal{D}V(t, p, x; q) - rV(t, p, x; q) = 0$$

in the waiting region, where

$$\mathcal{D} = \frac{\partial}{\partial t} + \frac{1}{2}\left(\frac{p(1-p)(\lambda_g(t) - \lambda_b(t))}{\theta}\right)^2 \frac{\partial^2}{\partial p^2} + \frac{1}{2}\sigma^2 x^2 \frac{\partial^2}{\partial x^2} + \mu x \frac{\partial}{\partial x}.$$

In the investment region, V satisfies

$$V(t, p, x; q) = \big(p v_b(t; q) + (1-p) v_g(t; q)\big)\, x - c,$$

Table B.2: Baseline parameter values for the model in Chapter 5

Economic factor	
Drift, μ	0.015
Volatility, σ	0.070
Climate factor	
Path in bad scenario, $\lambda_b(t)$	$132.95 - 39.03e^{-0.0083t}$
Path in good scenario, $\lambda_g(t)$	$98.03 - 4.12e^{-0.0788t}$
Noise, θ	15
GEV distribution of the annual maximum one-day rainfall	
Location in bad scenario	$75.71 + \lambda_b(t) - \lambda_b(0)$
Location in good scenario	$75.71 + \lambda_g(t) - \lambda_g(0)$
Scale in both scenarios	22.54
Shape in both scenarios	0.1908
Miscellaneous	
Initial system capacity, q	175
Marginal cost of capacity, c	1
Social discount rate, r	0.05

where

$$v_b(t;q) = -\int_t^\infty e^{-(r-\mu)(s-t)} \frac{\partial \Gamma_b(q,s)}{\partial q}\,ds$$

and

$$v_g(t;q) = -\int_t^\infty e^{-(r-\mu)(s-t)} \frac{\partial \Gamma_g(q,s)}{\partial q}\,ds.$$

If the upgrade policy is welfare maximising, then V satisfies

$$V(t,p,x;q) \geq \big(pv_b(t;q) + (1-p)v_g(t;q)\big)\,x - c$$

and

$$\mathcal{D}V(t,p,x;q) - rV(t,p,x;q) \leq 0$$

everywhere. The first condition holds with equality in the investment region and the second condition holds with equality in the waiting region.

Table B.2 reports the baseline values of the model's parameters. A detailed description of how they are derived can be found in Guthrie (2023b).

B.3 One-off investments with scale and timing flexibility

This section describes the model in Chapter 6. A more detailed description can be found in Guthrie (2023a). A decision-maker has the opportunity to upgrade an existing sea wall, which initially has height q. Investment, which can begin at any time and can occur only once, is instantaneous and irreversible. Lump-sum expenditure of $f + c \cdot \Delta q$ is needed to permanently increase the sea wall's height by Δq, where f and c are positive constants and Δq is chosen by the decision-maker. Her objective is to minimise the present value of all relevant costs, including inundation costs and investment expenditure. The level of the social discount rate, r, is constant.

The expected value of the costs associated with sea-wall breaches over the next increment of time equals $E[\max\{0, s_t + \tilde{z} - q_t\}]x_t\,dt$, where s_t is the average annual maximum sea level at the current date, $\tilde{z} \sim N(0,\psi^2)$ for some constant ψ, q_t is the height of the sea wall at date t, and x_t is the contemporaneous level of an economic factor.[1] The average annual maximum sea level is initially s_0 and increases at the unknown constant rate R, so that the average annual maximum sea level is $s_t = s_0 + Rt$ at date t. The economic factor evolves according to the geometric Brownian motion

$$dx_t = \mu x_t \, dt + \sigma x_t \, d\xi_t,$$

for some constants μ and σ, where the Weiner process ξ_t is independent of the noise contained in the decision-maker's signal of the average annual maximum sea level.

The decision-maker knows the values of all the model's constant parameters except for R. At date 0, she believes that R is normally distributed with mean a_0 and standard deviation b_0. After this date, her beliefs evolve according to the process described in Appendix A.2. The properties of the rectified normal distribution imply that

$$E_t[\max\{s_t + \tilde{z} - q', 0\}] = g(t, a_t; q'),$$

where

$$\begin{aligned} g(t, a_t; q') &= (b_t^2 t^2 + \psi^2)^{1/2} \phi\left(\frac{q' - (s_0 + a_t t)}{(b_t^2 t^2 + \psi^2)^{1/2}}\right) \\ &\quad - (q' - (s_0 + a_t t))\left(1 - \Phi\left(\frac{q' - (s_0 + a_t t)}{(b_t^2 t^2 + \psi^2)^{1/2}}\right)\right), \end{aligned}$$

ϕ is the probability density function of the standard normal distribution, and Φ is the cumulative distribution function of this distribution.

Let $V(t, a_t, x_t)$ denote the present value of the investment option at date t. In Guthrie (2023a), I show that V satisfies the partial differential equation

$$\mathcal{D}V(t, a, x) - rV(t, a, x) = 0$$

in the waiting region, where

$$\mathcal{D} = \frac{\partial}{\partial t} + \frac{1}{2}\left(\frac{\theta b_0^2 t}{\theta^2 + \frac{1}{3} b_0^2 t^3}\right)^2 \frac{\partial^2}{\partial a^2} + \frac{1}{2}\sigma^2 x^2 \frac{\partial^2}{\partial x^2} + \mu x \frac{\partial}{\partial x}.$$

In the investment region, V satisfies

$$V(t, a, x) = \sup\left\{G(t, a; \Delta q)x - (f + c\,\Delta q) \middle| \Delta q > 0\right\},$$

where

$$G(t, a; \Delta q) = \int_t^\infty e^{-(r-\mu)(t'-t)} E_t[g(t', a_{t'}; q) - g(t', a_{t'}; q + \Delta q)] \, dt'.$$

If the investment policy is welfare-maximising, then the function V satisfies

$$V(t, a, x) - \sup\left\{G(t, a; \Delta q)x - (f + c\,\Delta q) \middle| \Delta q > 0\right\} \geq 0$$

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[1] It can be helpful to informally interpret $s_t + \tilde{z}$ as the actual annual maximum sea level, with actual flooding costs being proportional to the extent by which the annual maximum sea level exceeds the height of the sea wall. As time is assumed to be continuous and seasonal variations in weather conditions are ignored, this interpretation can only be informal. Nevertheless, it is a useful way to motivate the form of the cost function.

Table B.3: Baseline parameter values for the model in Chapter 6

Economic factor	
Drift, μ	0.02
Volatility, σ	0.10
Estimated rate of sea-level rise	
Initial mean, a_0	0.007
Initial standard deviation, b_0	0.003
Noise, θ	0.2165
Distribution of the annual maximum sea level	
Initial average level, s_0	1.2414
Standard deviation, ψ	0.0704
Miscellaneous	
Height of existing sea wall, q	1.36
Marginal cost of increasing sea wall's height, c	1
Fixed cost of increasing sea wall's height, f	0.5
Social discount rate, r	0.05

and

$$\mathcal{D}V(t,a,x) - rV(t,a,x) \leq 0$$

everywhere. The first condition holds with equality in the investment region and the second condition holds with equality in the waiting region.

Table B.3 reports the baseline values of the model's parameters. A detailed description of how they are derived can be found in Guthrie (2023a).

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