An economic analysis of adaptation to climate change under uncertainty

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Abstract

The changing climate increases the vulnerability of societies around the world. Besides mitigation efforts, adaptation measures are needed to counteract the impacts of climate change. However, there exist uncertainties about the impacts of climate change. Decision-makers are faced with the challenge to implement economically efficient and effective climate change policies and adaptation measures to mitigate uncertain climate change impacts. This thesis presents an economic analysis of adaptation to climate change under uncertainty. The thesis focuses on the exploration and further development of economic assessment methods to support decision-making in adaptation to climate change. The results of this thesis show that Multi-Criteria Analysis and Cost-Benefit Analysis are appropriate decision-support tools in the context of adaptation to climate change. The priority ranking of adaptation options for the Netherlands based on Multi-Criteria Analysis, through evaluation and feasibility criteria, gives an indication of the priority options for the Dutch adaptation policy. The regional case study applies Cost-Benefit Analysis for a quantitative assessment of the costs and benefits of climate proofing spatial planning at a regional level. Furthermore, the investment decision model developed in this thesis, based on Cost-Benefit Analysis under climate change uncertainty, takes into account the effect of future investment moments and the availability of new information on climate change impacts. The model analysis and case study application show that the optimal mix of structural and non-structural adaptation measures depends on the level of the damage costs, the cost structure of the measures, the discount rate and the timing of future investment moments, including the timing of partial resolution and full resolution of uncertainty.

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1. Introduction

The changing climate is a challenge for both current and future generations. Climate variability and future climate change impacts will increase the vulnerability of societies around the world. Especially in developing countries the impacts will be severe, but also those living in high risk areas in developed countries could be greatly impacted. Economic costs of impacts of climate change have been estimated to be several percentages of GDP if no measures are taken either to adapt to or mitigate the effects of climate change (Stern, 2006; Tol, 2002a). However, as there are many uncertainties in the debate (e.g. where the impacts will happen, different scenarios of what will happen, who will be affected and in what way) those in power have challenging decisions to make. In addition, due to different time scales of processes in the climate system, irreversible climate change is already taking place (Solomon et al., 2009), which makes the 2°C target difficult to reach (New et al., 2011; Stafford Smith et al., 2011). Thus, it is inevitable that besides mitigation efforts, adaptation measures are needed to counteract the impacts of climate change. Decision-makers need to plan for these impacts, through investment in mitigation and adaptation policies, with the respective aim to reduce emissions of greenhouse gases and to avoid damages of climate change. However, the uncertain future magnitude and effects of climate change make it more difficult for decision-makers to decide what economically efficient and effective climate change policies are and what measures should be implemented.

The aim of the thesis is to investigate different decision-support tools, and to incorporate uncertain climate change impacts, to support the decision-makers to reach the optimal decision in adaptation to climate change from an economic perspective. In the first two chapters of this thesis, Multi-Criteria Analysis (MCA) and Social Cost-Benefit Analysis (SCBA) are applied to rank and quantify a set of adaptation measures under existing climate change scenarios. The second part of this thesis presents a theoretical investment model that deals with investment in flood protection measures under climate change uncertainty. The investment model is applied to coastal protection in relation to uncertain sea-level rise.

This research was carried out under the Dutch National Research Programme 'Climate changes Spatial Planning'. Although the adaptation measures relate to the Dutch context of adaptation to climate change, the assessment methods presented are not site specific and they can be transferred to other regions.

This chapter continues in Section 1.1 with an overview of the historical observations of climate change and projections of future climate change. Section 1.2 defines adaptation and mitigation, as two responses to address climate change. In Section 1.3 a review of the economic analysis of adaptation to climate change is presented, including different decision-support tools. The chapter ends with the research objective, research questions and the outline of this thesis.

1.1 Climate change

Climate change relates to changes in the average weather patterns. The Forth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) defines climate change as:

"A change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity." IPCC (2007b)

The IPCC concludes that the "warming of the climate system is unequivocal" (IPCC, 2007d). Observations presented in the Physical Science Basis report of the IPCC show an increase of the global average surface temperature of $0.74 \pm 0.18°C$ over the period from 1906 to 2005 (Solomon et al., 2007). More changes in the climate system, such as global sea-level rise, changes in precipitation patterns and extreme events have been observed in the last century. They indicate that global mean sea level has risen from 1960 to 2003, with an average rate of 1.8 ± 0.5 mm per year and precipitation patterns have changed (Solomon et al., 2007). They observed long term increasing precipitation trends in eastern parts of North and South America, northern Europe and northern and central Asia from 1900 to 2005. While areas in the tropics and subtropics are affected by more intense and longer drought periods since the 1970s. In addition, they observed an increase in extreme events, such as heavy precipitation events and more frequent heat waves over the last 50 years (Solomon et al., 2007).

In addition to observations, the IPCC has made projections of future climate change effects (IPCC, 2007d), based on available scientific literature. Taking into account a range of emission scenarios and presenting different uncertainty intervals, they project a warming of about 0.2°C per decade for the next two decades. Model based projections of global average sea-level rise at the end of the 21st century are between 0.18 and 0.59 m and changing precipitation patterns are expected to result in more frequent and intense flood and drought events (Solomon et al., 2007). The IPCC climate change scenarios are used to translate the effects of climate change to different spatial scales. In the Netherlands, the Royal Netherlands Meteorological Institute developed a set of national climate scenarios for the year 2050 and 2100, based on the IPCC scenarios and own research. These scenarios consider global temperature increase for the Netherlands under different air circulation patterns (KNMI, 2003, 2006, 2009).

1.2 Mitigation and adaptation

To address climate change, two approaches have been identified that deal with the cause and effect of climate change. Mitigation focuses on the reduction of greenhouse gas emission and adaptation reduces the changes resulting from global warming. Setting international mitigation targets has been done by signing the Kyoto Protocol in 1997. The protocol mandated that by the period from 2008 to 2012, Annex I countries (developed countries and economics in transition) committed to reduce their greenhouse gas emissions by approximately 5% compared to their 1990 levels. At the European level, the European Union set a 2°C target, aimed at limiting the global average temperature increase to less than 2°C compared to pre-industrial levels (CEC, 2007). The 2009 UNFCCC Conference of the Parties in Copenhagen reached a non-binding Copenhagen Accord which recognises the scientific view "that the increase in global temperature should be below 2 degrees Celsius"(UNFCCC, 2010a). However, currently it is unclear whether the international climate negotiations concerning the follow-up of the Kyoto Protocol will reach consensus on reducing greenhouse gas emissions, and if the 2°C target of reducing emissions is sufficient to counter the most severe impacts of climate change resulting from temperature rise.

Adaptation to climate change is defined by the IPCC as the "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" (Parry et al., 2007). Adaptation involves making investment decisions to reduce potential damages of climate change and taking advantage of new opportunities. Through the implementation of adaptation measures, the adaptive capacity of the system increases and the sensitivity reduces, thereby reducing the vulnerability of a society to the impacts of climate change (Mastrandrea et al., 2010). Various types of adaptation are distinguished, including reactive, anticipatory (proactive), autonomous and planned adaptation, where anticipatory adaptation is seen as an essential part of the optimal response to climate change, as it is likely much less expensive than relying on reactive adaptation alone (Fankhauser et al., 1999). Adaptation is implemented at different spatial scales and requires an integrated response. Policymakers play an important role in taking well-considered policy decision aimed at reducing vulnerability to climate change (Klein et al., 2003). The challenge for the decision-makers is, according to the IPCC, "to find out which actions are currently appropriate and likely to be robust in the face of the many long-term uncertainties" (Klein et al., 2007). Through systematic assessment of adaptation measures policymakers are able to make well-informed choices about what measures to implement.

Estimations of the economic damage of climate change present different values. Tol (2002a) derives estimates of climate change damage, where the global average lies between -3% and 2% of global GDP. The Stern review (Stern, 2006) presents the effect of climate change on the world economy and indicates that the damages, with doubling of concentrations, will be 5-20% of global GDP. However, there has been critique on the Stern review (Byatt et al., 2006; Carter et al., 2006; Dietz et al., 2007; Mendelsohn, 2006; Nordhaus, 2007; Weitzman, 2007) which focuses on the low discount rate applied, the projected costs and benefits, overestimated climate change impacts, risk aversion, and the lack of consideration of uncertainties.

The assessment of the impacts of climate change and economic costs of adaptation in developing countries has received more attention, where the WorldBank (2009) assessed the cost to developing countries of climate change adaptation and concluded that the cost between 2010 and 2050 of adapting to approximately 2°C warmer world in 2050 would be in the range of $ 75 to $ 100 billion a year, Watkiss et al. (2010) used integrated assessment models to derive the cost of climate change for Africa, which with high uncertainty could range from 1.5-3% GDP each year. Further studies focus on the effect of climate change on different impacts, such as sea-level rise (Dasgupta et al., 2009). Furthermore, international adaptation funding is an important topic of recent UNFCCC meetings in Copenhagen (UNFCCC, 2009) and Cancun (UNFCCC, 2010b) and discussed in literature (Dellink et al., 2009; Paavola and Adger, 2006).

However, there remain uncertain climate change projections and impacts and uncertain costs and benefits of mitigation and adaptation measures, that potentially impact investments in adaptation and mitigation measures. For example, studies on the impact of climate change on flood risk in river basins show mixed results, describing in some cases upward flood trends related to extreme flows (Milly et al., 2002; Petrow and Merz, 2009) but in others varying results, with both increases, decreases and no long-term changes (Kundzewicz et al., 2005; Mudelsee et al., 2003). Studies that discuss and project future climate-induced sea-level rise, emphasize that long-term projections include uncertainties related to thermal expansion, and the contribution of glaciers and ice caps that impact the local sea-level rise (Katsman et al., 2011; Tol et al., 2008). However, Adger et al. (2009) argue that the presence of uncertain climate and impact projections should not limit investment decisions in adaptation. Wardekker (2011) investigated several approaches on how to deal with decision-making in adaptation to climate change uncertainties, however without taking into account costs and benefits of adaptation measures that affect the optimal investment decision under uncertain climate change.

1.3 Economic analysis of adaptation

Adaptation to climate change has received increasing attention in the scientific and policy debate, especially the appraisal of adaptation strategies. The scientific literature on adaptation deals with impacts, vulnerability and constraints to adaptation (Adger, 2006; Smit and Wandel, 2006; Smit et al., 2001), but only little is known about the costs and benefits of adaptation to climate change. Different economic methods have been developed with the aim to identify and evaluated options, such as Multi-Criteria Analysis and Cost-Benefit Analysis. The qualitative and quantitative assessments of adaptation options focus on specific sectors (Ebi and Burton, 2008; Rosenzweig et al., 2007) or serve as input for national adaptation strategies.

Analysis of adaptation options requires the assessment of climate change impacts, the design and selection of adaptation options in close consultation with stakeholders and experts, and the evaluation of the adaptation options based on a set of criteria. The selection of the best options is done using different decision-support tools, based on various criteria, such as effectiveness, efficiency and feasibility. Multi-Criteria Analysis (MCA) is used to evaluate the adaptation options based on a set of criteria. MCA requires the identification of all the alternatives, the selection of a set of criteria and assessment of scores, and selection of the weights of each criterion (Janssen and Van Herwijnen, 2006). With criteria weighting, each criterion is given a weight that reflects the preferences of the decision-makers and the weighted sum of the different criteria is used to rank the options. Cost-Benefit Analysis (CBA), on the other hand focuses on the quantitative evaluation of the climate impacts and allows for the estimation of the net benefits of different adaptation options. It includes the direct costs and benefits and the indirect and external effects in order to assess the total welfare effects of an adaptation option (Pearce et al., 2006). Some argue that standard CBA does not fully address all issues of adaptation to climate change, such as intra- and inter-generational equity, discounting over long periods and uncertainties related to climate change impacts and costs and benefits (Gowdy and Howarth, 2007; Pindyck, 2000; Van den Bergh, 2004; Watkiss et al., 2010). However, there remains a need to gain insight into the economics of adaptation to climate change, as there is a lack of knowledge on costs and benefits of adaptation options (Adger et al., 2007; Agrawala and Fankhauser, 2008).

Uncertainty

As future projections of climate change effects are uncertain, this requires decision-makers to make decisions about adaptation to climate change under uncertainty. Uncertainties of climate change pose new challenges for decision-makers assessing policy options (Hallegatte, 2009) and complicate decision-making tools. Uncertainties in combination with irreversible climate change effects and irreversible costs may affect the optimal choice of the policy instrument, the optimal policy intensity and the optimal timing of implementation (Pindyck, 2007). Assessments of adaptation policies to climate change need to consider key uncertainties regarding long-term costs and benefits and future climate change, and evaluate the implications for the design of climate robust adaptation options (Füssel, 2008). When the costs of adaptation options and the effects of climate change are irreversible, and when the timing of investment in adaptation measures is flexible, the decision problem is linked to the theory of investment under uncertainty (Dixit and Pindyck, 1994). Flexibility provides the possibility to postpone an investment decision until more information about the effects of climate change has become available. The application of the decision-support tool CBA is complicated by climate change uncertainties and the choice of the discount rate is not straightforward (Weitzman, 2001). The level of the discount rate determines the weight put on future costs and benefits of adaptation options, where a low discount rate puts more weight on future costs and benefits of adaptation. The decision-support tools are appropriate to apply in the context of adaptation to climate change, however further research is needed into the ability of these tools to deal with uncertainty and irreversibility, and how they incorporate flexibility.

1.4 Research objective and questions

This thesis focuses on the economic analysis of adaptation to climate change, through the use of decision-support tools, to contribute to the knowledge gap that exists on the costs and benefits of adaptation to climate change. Furthermore, this thesis incorporates decision-making under climate change uncertainty into a decision-support model to explore how climate change uncertainty, irreversible investment decisions and flexible timing affect the optimal investment decision in adaptation to climate change. Multi-Criteria Analysis (MCA) and Cost-Benefit Analysis (CBA) are applied to rank and quantify a set of adaptation measures under existing climate change scenarios, and a theoretical investment model is developed and applied that deals with investment in flood protection measures under climate change uncertainty. This thesis explores these issues in the context of the adaptation of spatial planning and flood protection to climate change impacts.

The main objective of this thesis is: "to explore and further develop economic assessment methods to support decision-making in adaptation to climate change, that take into account uncertain climate change impacts".

To achieve the objective, the following research questions are defined:

Q1: *Is Multi-Criteria Analysis an appropriate decision-support tool to be used to assess and rank adaptation options to climate change?*

The first research question deals with a qualitative assessment of potential adaptation options to respond to climate change in the Netherlands in connection to spatial planning, with the aim to rank adaptation options. To answer this research question, I will apply Multi-Criteria Analysis to rank and prioritise adaptation options, where the inventory and ranking of adaptation options is based on stakeholder analysis and expert judgement for a given climate change scenario. The adaptation options are assessed based on a set of evaluation and feasibility criteria.

Q2: *Which adaptation options are suitable, from an economic perspective, to adapt spatial planning to climate change at a regional scale?*

The second research question deals with a quantitative assessment of adaptation options to identify suitable options to adapt spatial planning to climate change. I will first identify adaptation options based on climate change scenarios and resulting climate change impacts for the Zuidplaspolder, a polder area located in the southwestern part of the Netherlands. Furthermore, I apply Cost-Benefit Analysis to assess the direct, indirect and external effects of different climate robust adaptation options.

Q3: *From a theoretical perspective, how can we model the decision to invest in flood protection measures to adapt to uncertain climate change impacts?*

The third research question focuses on how to model investment decisions in flood protection measures under uncertain climate change impacts. I will develop a discrete and continuous investment model based on decision-making under uncertainty. I will answer the following sub-questions; How does the distinction between structural and non-structural flood protection measures affect the optimal investment decision? And how does the inclusion of an intermediate decision moment, where partial resolution of uncertainty is used to adjust the investment decision, impact the optimal investment decision today? The model will provide insights into the optimal investment mix of structural and non-structural adaptation options under full resolution of climate change uncertainty. The resolution of uncertainty is modeled as a gradual process over time until full resolution is reached.

Q4: *How can the model developed under research question Q3 be applied to investment in coastal flood protection under uncertain climate change impacts?*

The fourth research question deals with the application of the investment model developed under research question Q3 to a case study on coastal adaptation in the Netherlands. I will answer the following sub-questions: How does the resolution of scientific uncertainty on climate-induced sea-level rise affect the optimal investment decision in coastal flood protection measures? And how can the model reflect stakeholders' perceptions about uncertain future sea-level rise and investment in flood protection measures? The case study is related to the coastal town of Katwijk, located along the midwestern coastal zone of the Netherlands.

1.5 Methods

To address the research questions formulated above, I focus on three decision-support tools, namely Multi-Criteria Analysis, Cost-Benefit Analysis and an investment decision model under climate change uncertainty.

Multi-Criteria Analysis

Multi-Criteria Analysis is used to evaluate options based on a set of criteria. Through stakeholder analysis and expert judgement, the options can be identified, criteria selected and weighted to derive a priority setting for alternative adaptation options. With criteria weighting each criterion is given a weight that reflects the preferences of the decision-makers and the weighted sum of the different criteria is used to rank the options. This thesis presents an innovative application of MCA to adaptation to climate change.

Cost-Benefit Analysis

Cost-Benefit Analysis focuses on the quantitative assessment of adaptation options. CBA is a social-economic evaluation method based on welfare economics (Pearce et al., 2006). The key issue is to make an inventory of the costs and benefits associated to the direct, indirect and external effects of an adaptation option. Where possible these effects are expressed in monetary terms. When the timing of the different cost and benefit elements and the discount rate is known, the net present value of these costs and benefits can be determined. The objective of a CBA is to gain insight into all costs and benefits for the society as a whole. In this thesis I apply a standard CBA to assess suitable spatial adaptation options dealing with flood risks from dike breach and extreme precipitation events. I present the net benefits of the adaptation options, however the application is not very innovative as it does not explicitly consider uncertain climate change impacts and uncertain costs and benefits.

Investment decision model

Decision making is influenced by uncertainties and irreversibilities. Several studies have focused on the implications of irreversibility and uncertainty on investment decisions (Dixit and Pindyck, 1994; Pindyck, 2002, 2007). These uncertainties might be resolved through the option value of waiting for better information or taking a precautionary approach when dealing with uncertainties. The investment model developed in Chapter 4 fits within the growing literature on decision-making under uncertainty and real options approach. The investment decision model developed in this thesis is based on Hennessy and Moschini (2006), who consider costly regulatory action under scientific uncertainty and model the probabilistic resolution of uncertainty. New elements are the extension of a discrete-state two-period model, to a continuous-state two-period and three-period model, by considering the continuous range of possible climate change impacts and associated range of possible damages. Furthermore, I distinguish between structural and non-structural flood protection and assume a continuum of structural and non-structural flood protection measures instead of a discrete investment decision. Furthermore, the resolution of climate change uncertainty is modeled as a gradual process over time until full resolution is reached. In the two-period model the initial investment decision can be updated when full resolution of uncertainty is reached at an unknown future moment in time. The three-period model allows for an intermediate investment decision under partial resolution of uncertainty before the adjustment of the investment decision under full resolution of climate change uncertainty.

Spatial scales

This thesis assesses the costs and benefits of adaptation options at different spatial scales under climate change uncertainty. In Chapter 2 adaptation measures are identified and assessed from a national perspective for different sectors that are affected by climate change (i.e. agriculture, nature, water, energy & transport, housing & infrastructure, health and recreation & tourism). In Chapter 3, the spatial focus changes from a national to a regional scale by presenting adaptation to climate change in the context of land use/spatial planning for a polder area. Chapter 4 and 5 take a local perspective on adaptation of flood protection under climate change uncertainty.

1.6 Application

This research was carried out under the Dutch 'Climate changes Spatial Planning' programme, and therefore focuses on adaptation to climate change in the Netherlands. The Netherlands is a low-lying and densely populated country. The western part of the Netherlands is located below mean sea level and locates a large proportion of the national economic activities. Together with ongoing land subsidence, this makes the Netherlands vulnerable for river and coastal flood events. Future climate change will further increase the vulnerability of the country. The aim of the research programme is to link climate change research with the economic and policy domain, stimulate involvement and input of stakeholders and experts and apply economic decision-support tools in case studies.

This thesis presents two case studies, the first case study (Chapter 3), was selected in the early stages of the research. The case study focuses on adaptation of spatial planning, and applies the existing decision-support tool Cost-Benefit Analysis, with a central climate change scenario.

The consideration of climate change impacts in spatial planning increases the adaptive capacity of a country (Parry et al., 2007). Tol et al. (2008) point out that climate change should even be considered as early as in the design phase of spatial planning, because "retrofitting existing infrastructure is more expensive than designing it to be more flexible or more robust". Within Europe, the European Commission (CEC, 2009) indicates that integrated spatial planning is needed to 'climate proof' infrastructure. Projects such as ESPACE and ADAM develop decision support tools for spatial planners to assess how spatial development might be affected by climate change in the future (ESPACE, 2008). The philosophy behind these projects is that governments play a major role in "modification of infrastructures and of spatial plans in response to climate impacts" (CEPS, 2008). In the Netherlands adaptation to climate change is closely related to spatial planning as the Netherlands is a densely populated country where adjustments of economic development policies have considerable spatial consequences. The strong link between water management and spatial planning in the Netherlands provides opportunities to adapt to climate change (De Vries, 2006). Climate robust designs that reduce the vulnerability of societies to known and uncertain impacts of climate change are needed to 'climate proof' spatial planning. Climate robust adaptation options reduce sensitivity and are robust across different climate change scenarios and related uncertainties.

The second case study was conducted in the final phase of the research (Chapter 5) and focuses on adaptation of coastal protection. The investment decision model developed in Chapter 4 is applied to analyse decision-making in coastal protection under climate change uncertainty.

Recent severe river flooding in Europe has triggered debates on future projections of flood frequency and the need for adaptive investments, such as flood protection measures. There exists uncertainty about the impact of climate change on flood risks in river basins and coastal areas, therefore the relevant question for decision-makers responsible for flood protection is how to deal with this uncertainty. Adaptation measures include both structural and non-structural measures, where structural measures have high investment costs, for example dike heightening, and non-structural measures have low investment costs, for example early warning systems. In the Netherlands, optimal investment in the heightening of dikes to protect against flooding from the height of high tide and sea-level rise has been studied in detail by Eijgenraam (2006) and Van Dantzig (1956). They optimize the investment in dike heightening in the context of changing flood probability under a given climate change scenario and increasing economic value over time. In this thesis, the optimal investment decision in flood protection is considered, however, I make a distinction between structural and non-structural flood protection measures and model the resolution of climate change uncertainty.

1.7 Outline of the thesis

The main objective of this thesis is to investigate and further explore decision-support tools in the context of adaptation to climate change. In Chapter 2, adaptation measures for the Netherlands are ranked based on evaluation and feasibility criteria with Multi-Criteria Analysis. I give an overview of a set of adaptation measures for different sectors. In Chapter 3, adaptation options for a low-lying polder area in the Netherlands are assessed with Cost-Benefit Analysis. Direct investment costs and avoided damage and nature valuation are included in the assessment. In Chapter 4, a model on investment in flood protection under climate change uncertainty is presented. In a discrete and continuous two and three period setting the effect of resolution of uncertainty on investment decisions in structural and non-structural measures is discussed. In Chapter 5, the investment decision model is applied to a coastal setting, where uncertainty to climate change relates to uncertain sea-level rise. Finally, Chapter 6 provides the main conclusions of the research, policy implications and recommendations for further research.

2. Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives*

In many countries around the world impacts of climate change are assessed and adaptation options identified. We describe an approach for a qualitative and quantitative assessment of adaptation options to respond to climate change in the Netherlands. The chapter introduces an inventory and ranking of adaptation options based on stakeholder analysis and expert judgement, and presents some estimates of incremental costs and benefits. The *qualitative* assessment focuses on ranking and prioritisation of adaptation options. Options are selected and identified and discussed by stakeholders on the basis of a sectoral approach, and assessed with respect to their importance, urgency and other characteristics by experts. The preliminary *quantitative* assessment identifies incremental costs and benefits of adaptation options. Priority ranking based on a weighted sum of criteria reveals that in the Netherlands integrated nature and water management and risk based policies rank high, followed by policies aiming at 'climate proof' housing and infrastructure.

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*This chapter is based on De Bruin et al. (2009). Adapting to climate change in the Netherlands: an inventory of climate adaptation options and ranking of alternatives. Climatic Change 95:23-45.

2.1 Introduction

Adaptation to climate change has received increased attention in the scientific and policy debate, and is seen as complementary to mitigation (UNFCCC, 1997; McCarthy et al., 2001). Adaptation can be defined as: "adjustment in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects or impacts" (Smit et al., 1999). The related concept of 'adaptive capacity' refers to the 'potential or ability of a system, region, or community to adapt to the effects or impacts of climate change' (Smit et al., 2001; Smit and Pilifosova, 2003), mostly interpreted to reflect only adjustments to moderate potential damages, not to extreme scenarios. The report 'Impacts, adaptation and vulnerability' of the Intergovernmental Panel on Climate Change (IPCC) defines adaptive capacity as: "the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences" (IPCC, 2007a). The Stern Review states that: "adaptation will be crucial in reducing vulnerability to climate change and is the only way to cope with the impacts that are inevitable over the next few decades" (Stern, 2006). Anticipatory adaptation is seen as an essential part of the optimal response to climate change, as it is likely much less expensive than relying on reactive adaptation only (Fankhauser et al., 1999). Climate change represents a complex, strategic risk, and thus robust adaptation options are required that will provide benefits under various future climate scenarios (Willows and Connell, 2003).

Adaptation assessments are developed and conducted with the aim to identify and evaluate adaptation options. They serve as input for national adaptation strategies, or focus on specific sectors, such as the water (Rosenzweig et al., 2007) and health (Ebi and Burton, 2008) sector. In many countries around the world the impacts of climate change are assessed and adaptation options identified. For example, Canada (Lemmen et al., 2008), Finland (MMM, 2005) and the United Kingdom (DEFRA, 2006) have conducted national adaptation assessments or developed national strategies to adapt to climate change. The Adaptation Policy Frameworks for Climate Change (UNDP, 2005) and the National Programmes of Action are programmes which provide a guideline for developing countries to identify priority activities that respond to their urgent and immediate needs with regard to adaptation to climate change (UNFCCC, 2007). Füssel (2007), in a review of general assessment approaches related to adaptation planning, points out that adaptation assessments are relevant in different contexts, both in climate impact and vulnerability assessments and for adaptation planning and policy-making (Burton et al., 2002; Füssel and Klein, 2006). Tol et al. (2008) states that "adaptation assessment must consider the full context in which adaptation takes place, including the factors that determine the capacity of the country or system to adapt". By involving local stakeholders and experts in the development of a national adaptation strategy the gap between the top-down and bottom-up approaches to adaptation can be bridged, thereby providing the national government the ability to reach optimal policy decisions about adaptation when considering the allocation of scarce resources.

For the Netherlands the possible consequences of climate change have been documented in various reports, including the Environmental Balance (RIVM, 2004), the Climate Policy report commissioned by the Parliament (Rooijers et al., 2004) and the Climate reports of the Royal Netherlands Meteorological Institute (KNMI, 2003, 2006). Most studies agree on the fact that climate change will take place, in spite of all mitigation efforts. Thus, mitigation alone is not sufficient to offset climate change in the Netherlands. The Ministry of Housing, Spatial Planning and the Environment initiated a programme, the 'Routeplanner project', to develop a national adaptation strategy for the Netherlands. To prepare this strategy the national research programme on climate change and spatial planning commissioned a study on adaptation options (Van Ierland et al., 2007).

The challenge for the Netherlands–as well as for other countries–is to harmonize a national adaptation policy with its spatial planning policy. The focus will be on developing more robust systems including *technical solutions* and *improved control and risk management systems*, and combine this with *improved spatial planning*. To make the Netherlands 'climate proof', a wide set of policy instruments can be used, ranging from financial instruments (e.g. taxes, subsidies or insurance arrangements) or command and control instruments (e.g. spatial planning or technology requirements) to institutional approaches (e.g. institutional reform, or education and communication). Systematic assessment of options that are technically, economically, and politically feasible could enable policymakers to make well-informed choices about different adaptation options.

The main aim of this chapter is to outline the approach that was used in the qualitative and quantitative assessment and the ranking system of identified potential adaptation options to respond to climate change in the Netherlands in connection to spatial planning. We also report on the preliminary results and discuss the strengths and weaknesses of the approach.

The assessment started with the selection of a climate change scenario relevant for the Netherlands for the period up to 2050, based on the scenarios of the Royal Meteorological Institute (KNMI, 2003, 2006). The study has the character of a "what if" setting where it is assumed that the selected scenario of the KNMI represents the characteristics of climate change for average temperature change, rainfall patterns and sea-level rise for the Netherlands. Based on this starting point the assessment includes the following aspects: (1) identification of adaptation options in the Netherlands, based on literature study and consultation of stakeholders; (2) a qualitative assessment of the characteristics of the options; (3) definition of criteria used to make a ranking of the options, based on expert judgements; (4) determining the scores of the options on the various criteria; (5) determining the weights to be used in the Multi-Criteria Analysis for the ranking of the options and (6) the actual ranking and an interpretation of the results.

In addition we looked into the institutional complexities of implementing the various adaptation options, in order to be informed about the complexities that we would face when introducing adaption options in the various sectors of society. The institutional complexity was not integrated in the Multi-Criteria Analysis because we consider the issue of institutional complexity substantially different from the questions of what adaptation options would be important to consider. By combining information on the highly ranking options and their institutional complexity it becomes possible to develop an adaptation strategy that deals with the priority options and that can focus on solving the institutional barriers that may show up in the implementation.

We also identified the available information on the order of magnitude of the costs and benefits related to the introduction of adaptation options, in order to sketch the relative size of costs and benefits. However, we observed that for many options only limited information on costs and benefits was available and therefore a complete cost-benefit analysis was not possible. We made a start with compiling a database on the available costs and benefits. In more elaborated studies more complete cost-benefit analysis can be made on the most relevant adaptation options, and this process is currently ongoing in the Netherlands. The chapter is explicitly restricted to adaptation options in the Netherlands, but with adjustment to local conditions, this approach is relevant to other countries as well.

In Section 2.2 we present the methods used to identify and assess the adaptation options including the ranking of the options based on their qualitative characteristics. We analyse the results of the assessment in Section 2.3 and in Section 2.4 we discuss results and conclude.

2.2 Method

There are many approaches to arrive at a priority setting for alternative policy options. Metroeconomica (2004) identifies a full range of decision-support tools for option appraisal and regards cost-benefit analysis as a key decision support tool (Metroeconomica, 2004). Willows and Connell (2003) discuss how to deal with the issue of uncertainty associated with decisions in a climate change context. Through Multi-Criteria Analysis (MCA) a ranking of alternative options can be derived. Janssen and Van Herwijnen (2006) provide a toolbox for multicriteria decisionmaking. The evaluation steps of the toolbox contain a clear problem definition, which includes the identification of all alternatives, selection of a set of criteria and assessment of scores. Then the scores are standardized and the weight of each criteria is determined. For the MCA method 'weighted summation' the weights represent the trade-offs between the criteria. Through sensitivity analysis uncertainties in scores and weights can be further analysed (Janssen and Van Herwijnen, 2006). MCA has been used to assess climate change policy; focused on adaptation and mitigation options (e.g. Bell et al., 2001; Brouwer and Van Ek, 2004; Ebi and Burton, 2008; Gough and Shackley, 2006).

Based on a thorough analysis of the most suitable criteria that decision-makers can adopt in their decision making, a multi-level MCA is carried out to categorize and rank promising and feasible adaptation options. The MCA was based on expert judgement, because the definition of the weights to be used in the analysis requires an overview of the various issues at stake. Stakeholders representing specific sectors in society would focus on the sector of their interest and would therefore be less able to provide an evaluation across sectors. Experts were invited from the scientific and the policy community and selected on the basis of their disciplinary and sectoral background (including economics, water management, agriculture, nature conservation, transportation, energy issues and public administration) and their capability to compare options across various sectors, which requires a broad multisectoral perspective. The list of experts and stakeholders represented in the research programme is given in Table 2.5 in Appendix 2.A. The experts involved included professors and senior scientists from leading universities and research institutes in the Netherlands, including Wageningen University, Institute of Environmental Studies Vrije Universiteit Amsterdam and Erasmus University Rotterdam.

The system that we developed for the MCA is interactive and can be used by individual policymakers or individuals or categories of stakeholders to express their views on the scores and on the weights to be used and this allows for alternative rankings that then can be discussed. In this manner the system can clarify the issues at stake and contribute to a thorough understanding of the adaptation options and the various perspectives of stakeholders in society.

Our assessment focuses on the ranking of the adaptation options under one of the scenarios of the Royal Netherlands Meteorological Institute (KNMI, 2003, 2006). The characteristics of the scenario are given in Table 2.1, we focused on the central estimate.

Table 2.1: KNMI climate change scenarios for the Netherlands for the year 2100[a]

	Low estimate	Central estimate	High estimate
Temperature ($^\circ C$)	+1	+2	+4 to +6
Average summer precipitation (%)	+1	+2	+4
Average summer evaporation (%)	+4	+8	+16
Average winter precipitation (%)	+6	+12	+25
Annual maximum of the 10-days sum of winter precipitation in the Netherlands	+10	+20	+25
Repetition of the 10-days sum which now occurs once every 100 years ($\geq$ 140 mm)(years)	47	25	9
Sea-level rise (cm)	+20	+60	+110

[a]Source: KNMI (2003)

As the assessment was done in close consultation with stakeholders we have focused on a deterministic setting in which it was assumed that the changes would indeed occur according to the central scenario. In this manner we obtained a ranking of adaptation options that would be relevant under the sketched scenario.[1]

2.2.1 Identification and categorisation of adaptation options

The adaptation options have been selected and identified on the basis of literature review and stakeholder consultation in a sectoral approach, in order to obtain the best inventory for the various sectors of the economy, see details reported in Van Ierland et al. (2007). Sectors included in the study are: agriculture, forestry, fisheries, water, energy and infrastructure. Some information is included on health, recreation and transport. Sector-specific literature on climate change and related adaptation options has been reviewed. As far as necessary and possible, this information was verified and augmented with expert knowledge from various disciplines, through individual consultations with experts, both within and outside the research team and through workshops where sectoral options were discussed in detail with stakeholders. We constructed a database to summarize the identified adaptation options and the associated effects, and to make an inventory of the institutional aspects related to their implementation. The interconnections between the adaptation options were also identified, including overlap, synergy and competition. For instance changes in water management may have important implications for nature, agriculture, recreation and safety. While there are undeniable gaps in this inventory, it

[1]In further studies it would be necessary to allow for uncertainty and to search for robust strategies that consider the uncertainty about whether climate change and its impacts will be high, medium or low. For the medium term perspective of the study (up to 2050) it was however felt that the selected scenario of the KNMI provided sufficient ground for making the inventory and ranking the options.

does reflect the state of the art knowledge and can hence be used as a guide in policy preparation and for future research.

2.2.2 Criteria for scoring adaptation options

The adaptation options have been given scores with respect to the following criteria: (i) the importance of the option in terms of the expected gross benefits that can be obtained, (ii) the urgency of the option, reflecting the need to act soon and not later (iii) the no-regret characteristics of the option (it is good to implement, irrespective of climate change) (iv) the co-benefits to other sectors and domains and (v) the effect on climate change mitigation (for instance through changes in landuse that reduce emissions of greenhouse gases as a side effect). In defining the criteria we aimed at selecting them as such that they are complete (all relevant criteria have been included), operational (each option can be judged against each criterion), mutually independent (options are independent of each other from one criterion to the next), contain no double counting and are consistent with effects occurring over time (Dodgson et al., 2000; Keeney and Raiffa, 1976).[2] However, not all criteria are completely mutually exclusive, the no-regret and co-benefit criteria are closely related to each other.[3] The scoring is based on subjective expert judgement and has been discussed in a workshop with external experts to validate the scores. We have invited experts with a broad overview of the problem of adaptation to make the ranking because the adaptation options cover many different aspects and sectors of society, and the ranking requires the capability to compare the various options across these sectors. Specialized stakeholders representing a specific sector would be less able to make this comparison across sectors, but of course they were valuable in identifying adaptation options relevant to their sector.

The *importance* (*i.e. effectiveness in avoiding damages)* of an option reflects the level of necessity to implement the option in order to avoid negative impacts. These options can reduce major damages related to climate change. In principle they generate substantial gross benefits (avoided damages), though potentially at high costs.

The *urgency* of the option relates to the need of implementing the adaptation option immediately or whether it is possible to defer action to a later point in time. Investments with a long lead time, or investments that have a long life time and conservation of the current situation require early action, and therefore potentially a long delay before

[2]Belton and Stewart (2002) give a more detailed outline of the considerations that need to be taken into account when identifying criteria, namely value relevance, understandability, measurability, non-redundancy, independence, balancing completeness and conciseness, operationality and simplicity.

[3]If cost and benefits of options would be fully available, a criterion could be 'net benefits' of the option. However, data are lacking and we therefore did not include costs or benefits explicitly in the set of criteria.

implementing the option will make it redundant, much more costly or even impossible. Note that a high score on urgency does not necessarily imply that the option deserves a very high final ranking. It indicates that postponing action may result in higher costs or irreversible damage.

In assessing the economic characteristics of various adaptation options a distinction is made between no-regret options and options with co-benefits. *No-regret* options are the adaptation options for which non-climate related benefits, such as improved air quality, will exceed the costs of implementation; hence they will be beneficial irrespective of future climate change taking place. The United Kingdom Climate Impacts Programme (Willows and Connell, 2003) has defined no-regret adaptation options (or measures) as: "options (or measures) that would be justified under all plausible future scenarios, including the absence of human-induced climate change". A no-regret option could be one that is worthwhile (in that it would yield economic and environmental benefits which exceed its cost), and will continue to be worthwhile, irrespective of any benefits of avoided climate damages. Options that score high on the criterion *co-benefit* are specifically designed to reduce climate change related vulnerability while also producing corollary benefits that are not related to climate change (Abramovitz et al., 2002). Co-benefits thus concern external effects which have a positive impact on policy goals unrelated to climate change policy (Metroeconomica, 2004).

Finally, the options are scored according to their *effect on mitigation*. Certain adaptation options will also induce a reduction of greenhouse gas emissions, and thus score very high on mitigation effect (i.e. are strengthening mitigation policies), while other adaptation options actually increase greenhouse gas emissions. Scores were attached for each of the options and for each of the criteria, ranging from 1–5, indicating very low priority (1) to very high priority (5).

In order to inform policymakers on the feasibility of the adaptation options, a separate sub-project focused on assessing their feasibility in the phase of implementation. The feasibility has been scored based on the technical, societal and institutional complexity that accompany the implementation of the proposed measures. *Technical complexity* refers to the technical difficulties and challenges which accompany the realization of the adaptation option, such as the technical facilities that have to be realized or mobilized; the technological uncertainties which accompany the implementation; the uniqueness of the operation and its risks. *Social complexity* involves the diversity of values which are at stake when the option will be implemented, the changes which are necessary in the perceptions of stakeholders, the necessity of their cooperation, etc. This complexity expresses itself in: the number of parties which have a stake at the option (or its effects); the diversity in normative views of the concerned parties; the degree to which the option is controversial and generates resistance; and the necessity to generate consensus and frame convergence. As the *institutional complexity* of implementing an adaptation grows, there are more adjustments of the official, bureaucratic organizations, existing procedures and arrangements necessary, more cooperation between institutional separated domains and thus resulting in a bigger tension with existing practices and structures. Elements of institutional complexity are: clashes between institutional rules (for example because different departments use different sets of rules or make different demands on procedures and process arrangements which can be used in implementation trajectories); the organizational consequences of the option; the cooperative relations or associations which are necessary for the implementation; and the degree of renewal of the option in relation to existing arrangements. Scores were attached from 1–5, ranging from very low (1) to very high (5) complexities.

2.2.3 Ranking adaptation options

The ranking of the adaptation options is done using Multi-Criteria Analysis (MCA), a common tool in decision analysis when there are multiple objectives. MCA uses the judgements of decision-makers or experts or stakeholders on the importance of the various criteria to make rankings of the options according to the weights attached to the various criteria. Our method is basically interactive: each individual, group of individuals or decision-maker or group of decision-makers (or experts) can express the relevant weights to be used and then the ranking will be updated.

In this chapter we report on a ranking based on criteria weighting. The ranking is based on weighted summation of the scores on the different criteria (Dodgson et al., 2000; Greening and Bernow, 2004; Munda et al., 1994), where for the results reported in this chapter, the scores and the weights are based on expert judgement in order to be able to compare across various sectors in society. In criteria weighting, weights are given to each criterion that are supposed to reflect the preferences of the decision-makers and the weighted sum of the different criteria is used to rank the options. The main problem is choosing the appropriate weights. A possible candidate is equal weights; this mirrors an unweighted summation of the scores. Another relevant weighting is to give higher weights to importance and urgency, thereby indicating that these are essential criteria. Our system allows for a wide variety of weights to be applied in an interactive manner in order to study the ranking under a wide variety of weights. By setting the weights of certain criteria to zero it is also possible to focus on a limited number of criteria.

Although we are convinced that the adopted ordering and weights in this chapter bear empirical relevance, which was confirmed by an expert workshop of September 1st 2006 with key stakeholders and scientific experts, we do not claim that these are 'objective' or can be considered final, but rather they represent a suitable starting point for further discussions and analysis. These discussions are ongoing and will continue until the national strategy for climate adaptation in the Netherlands will be presented in 2009.

2.2.4 Inventory of the incremental costs and benefits

A preliminary inventory has been made of the incremental costs and benefits of adaptation options, in order to assess the order of magnitude of these in support of decision making on adaptation and to identify the knowledge gaps in this respect. For each option, the cost and benefit items are first described *qualitatively* and second for some options monetary estimate ranges are presented in *quantitative* terms (Euros). The costs and benefits of the adaptation options are computed in preparation for a Social Cost-Benefit Analysis (SCBA), an evaluation method based on welfare economics.[4] The objective of a SCBA is to have insight into all costs and benefits for society as a whole, including external social and environmental costs and benefits. The Net Present Value of the costs of adaptation options has been calculated using a discount rate of 4%, as suggested in the guidelines of the Dutch government for SCBA.[5]

2.3 Results

In the first step of our assessment (the literature survey and the stakeholder workshops) 96 adaptation options have been identified and described which reduce the vulnerability of the Netherlands to the effects of climate change. As the options have been taken from the literature or have been suggested by a wide range of stakeholders, they include a wide variety of policy measures, technological solutions and adjustments in behaviour (see Table 2.6 in Appendix 2.B for a complete overview of the identified options). We consider this an inevitable aspect of the stakeholder approach where many different perspectives are represented, and it seems to be inherent to the adaptation issue.

2.3.1 Scoring and ranking of the adaptation options

The identified adaptation options were scored on their different characteristics: importance, urgency, no-regret characteristics, co-benefits for other domains, and mitigation

[4] A social cost-benefit analysis allows for the estimation of the net benefits of a project not only on the basis of the direct costs and benefits of such projects but also by considering the indirect or external effects in order to be able to assess the total welfare effects of public projects.

[5] Note that since the assessment of the options for this project, the official discount rate to be used in SCBA has been changed to 2.5%. A lower discount rate would result in a higher discounted stream of future costs and benefits.

effect by experts directly involved in the identification of the options and through an expert workshop in which experts with broad experience on adaptation participated. The ranking of the options is made using criteria weighting. The ranking on feasibility (technical, societal and institutional complexity) was done in a separate sub-project by experts in public administration and policy planning, in order to provide additional information in this respect.[6]

2.3.2 Ranking based on evaluation criteria

The ranking is based on a weighted summation of the scores on the criteria (i) importance (weight 40%), (ii) urgency (weight 20%), (iii) no-regret characteristics (weight 15%), (iv) co-benefits (weight 15%) and (v) mitigation effect (weight 10%).[7] From the ranking, the following adaptation options have the highest priority (see Table 2.2):

- Integrated nature and water management (nr. 34);
- Integrated coastal zone management (nr. 35);
- More space for water: a. regional water system, b. improving river capacity (nr. 40);
- Risk based allocation policy (nr. 41);
- Risk management as basic strategy (nr. 65);
- New institutional alliances (nr. 68).

These options will emerge among the highest ranked almost regardless of the way the criteria are ordered, as their score is high on all criteria. Changing the order of the criteria will only affect options that score better on some criteria than on others. For instance, Water storage on farmland (nr. 07) scores very high on no-regret and high on urgency and co-benefits, but only medium on importance and mitigation effect. Therefore, when importance has a relatively high weight, this option has a relatively low ranking, whereas it ranks just below the top when no-regret characteristics are prioritised. It will always be below the top options mentioned above, however. There are some options that score (very) low on all criteria and therefore rank very low (see Table 2.6 in Appendix 2.B).

These options are:

- Subsoil drainage of peatlands (nr. 08);
- Reclamation of (part of) southern North Sea (nr. 52);
- Abandoning of the whole of low-lying Netherlands (nr. 53);
- Self sufficiency in production of roughage (nr. 06).

[6] In principle it is possible to include feasibility directly in the list of criteria, but we considered the feasibility issues as too distinct from the criteria on importance, urgency, no regret, co-benefits and mitigation effect, and we preferred a separate listing. The ranking system however allows full integration of the feasibility criteria in ranking by weighted summation for those that prefer an integrated MCA.

[7] This ordering is in line with the expert judgement as expressed in the expert workshop of September 1st 2006, although at an individual level some discrepancies exist.

Table 2.2: The top ten options based on ranking with criteria weighting for importance, urgency, co-benefits and mitigation effects—high scores indicate high priority

Nr.	Sector*	Adaptation option	Importance (40%)	Urgency (20%)	No regret (15%)	Co-benefits (15%)	Mitigation effect (10%)	Weighted sum
34	N	Integrated nature and water management	5	5	5	5	4	4.9
35	N	Integrated coastal zone management	5	5	5	5	4	4.9
40	W	More space for water a. Regional water system b. Improving river capacity	5	5	5	5	4	4.9
41	W	Risk based allocation policy	5	5	5	5	4	4.9
65	W	Risk management as basic strategy	5	5	5	5	4	4.9
68	W	New institutional alliances	5	5	5	4	5	4.9
87	H&I	Make existing and new cities robust avoid 'heat islands', provide for sufficient cooling capacity	5	5	4	5	4	4.8
75	E&T	Construct building with less need for air-conditioning/heating	5	4	5	4	5	4.7
84	E&T	Change modes of transport and develop more intelligent infrastructure	5	5	4	4	5	4.7
28	N	Design and implementation of ecological networks the National Ecological Network	4	5	5	5	4	4.5

*N-Nature; W-Water; H&I-Housing & Infrastructure; E&T-Energy & Transport

These options have very different characteristics but are either relatively far-fetched or unnecessary or very costly (for instance abandoning low-lying Netherlands!), or not directly related to adaptation to climate change.

2.3.3 Ranking according to feasibility criteria

For the ranking according to the feasibility of the adaptation options, the following criteria weighting is used for technical complexity (20%), societal complexity (40%)and institutional complexity (40%). Table 2.3 presents the highest ranked adaptation options according to their feasibility; note that a high score reflects a high level of complexity, and hence a low level of feasibility.

Some adaptation options are technically relatively easy to implement. However, that does not say anything about the social and institutional complexity that their implementation brings about. These forms of complexity are much more difficult to handle. Implementing the adaptation options therefore requires a careful scan of the social and institutional environment in which they have to take place.

The feasibility analysis shows that many important and significant adaptation options encounter huge institutional complexities. This underlines that new, flexible and timely institutional arrangements are necessary to make an effective and smooth implementation of adaptation options possible.

There seems to be a weak relation between the feasibility of adaptation options and their ranking (in Section 2.3.2/Table 2.2).[8] We see that the top 4 options on priority show feasibility scores between 4.2 and 4.4 indicating a relatively high level of complexity. The next options on the priority list show complexity in the range of 2.6–4.2, which indicates intermediate complexities. There are numerous counterexamples: some very important and urgent options (like educational programs (38) and some more technical options) are relatively well feasible and generate little social and institutional complexity compared to some less important and urgent options (abandoning of low-lying Netherlands (53), relocation of farms (13), reclamation of (part of) southern North Sea (52)) that are very complex to implement. So, in every case a specific analysis is necessary regarding the complexity conditions for implementation.

2.3.4 Inventory of the incremental costs and benefits

Ideally a Social Cost-Benefit Analysis (SCBA) should be performed for each of the options. It has, however, been difficult to acquire detailed information on the costs and

[8] The priority ranking and the feasibility ranking is shown for all options in the last two columns in Table 2.6 in Appendix 2.B.

Table 2.3: Top ten of complex options: scoring and ranking of adaptation options regarding feasibility—high scores indicate highest complexity

Nr.	Sector*	Adaptation option	Technical complexity (20%)	Social complexity (40%)	Institutional complexity (40%)	Weighted sum
42	W	Moving power plants to coast (cooling water)	4	5	5	4.8
46	W	Widening the coastal defence area (in comb. with urbanisation and nature)	4	5	5	4.8
47	W	Re-connecting water systems in Delta area	4	5	5	4.8
53	W	Abandoning the whole of low-lying Netherlands	4	5	5	4.8
15	A	Land use change	3	5	5	4.6
43	W	Spatial planning of locations for power plants (nuclear in particular)	3	5	5	4.6
44	W	Construction of additional dikes in low-lying parts of the Netherlands	3	5	5	4.6
52	W	Reclamation of (part of) southern North Sea	3	5	5	4.6
12	A	Regional adaptation strategies for the fen meadow area	4	5	4	4.4
40	W	More space for water a. Regional water system b. Improving river capacity	4	4	5	4.4

Note: high scores indicate complexity to implement the option, i.e. low feasibility.
*W - Water; A - Agriculture

benefits related to the identified adaptation options. Much of the information that is needed for a proper SCBA of the adaptation options is not yet available; information is especially missing on the indirect and external economic and environmental effects of the options. Therefore only preliminary and incomplete estimates are presented. Detailed additional research about the economic and environmental effects is needed in order to improve the rough estimates presented in this chapter and to allow a proper quantitative assessment of adaptation priorities.

Table 2.4 presents an indication of the costs and benefits of adaptation options, as far as available. The overview shows that several prioritised adaptation policies will cost many billions of Euros in terms of net present value over the period from 2006 to 2050. Furthermore, within the field of spatial planning billions of Euros will have to be invested to reserve space, possibly to construct additional dikes in low lying parts of the country and make infrastructure climate proof.

Additionally within the private sector, investments are important to prepare the Dutch economy for the envisaged climatic changes. These investments need to fit within the ongoing investment trajectories of the different economic sectors and the costs will differ considerably between the different sectors. Also the costs and benefits depend on location, specific circumstances and the exact phasing of the measures, which require detailed SCBA in order to prioritise adaptation options for these locations. Unfortunately, several options that are prioritised in the qualitative assessment cannot yet be evaluated quantitatively, and hence these are missing from Table 2.4. This implies that Table 2.4 cannot be used as a priority list of adaptation options, nor can the costs be aggregated over the options to gain insight into the total costs of adaptation policy for the coming decades. For these analyses, more information is required.

Adaptation options involving relatively high costs are typically those for maintaining safety against flooding, but it is not easy to assess which part of the costs are required for maintenance of the existing safety standards and which part of the costs are explicitly related to changes induced by climate change. Many factors are interacting in determining sea level and river discharge and the exact role of climate change is difficult to determine, also because soil subsidence occurs in some parts of the Netherlands.

Another category involving high costs is the adaptation of housing and buildings in order to cope with higher temperatures. This will involve several tens of billions of Euros in net present value terms for the coming decades (until 2050). For the ecological network additional costs would be involved if an expansion of the network would be required to cope with the impacts of climate change.

Table 2.4: Indication of the costs and benefits of adaptation options (million €)

Nr.	Sector*	Adaptation option	Costs[a]	Benefits[b]
40	W	More space for water a. Regional water system b. Improving river capacity	19,000	N/A
41	W	Risk based allocation policy	> 7,000	N/A
87	H&I	Make existing and new cities robust avoid 'heat islands', provide for sufficient cooling capacity	54-65 €/m^2	
75	E&T	Construct building with less need for air-conditioning/heating	23,000	N/A
28	N	Design and implementation of ecological networks (the National Ecological Network)	7,000	> 7,000
31	N	Afforestation and mix of tree species	0.43/ha	> 0.43/ha
46	W	Widening the coastal defence area (in comb. with urbanisation and nature)	1,000	N/A
55	W	Re-enforcement of dikes and dams including weak spots	> 5,000	N/A
89	H&I	Water management systems revision of sewer system	3,000-5,000	N/A
37	N	Monitoring nature, interpreting changes and informing	340	> 340
51	W	Relocation of fresh water intake points	50-100	N/A
90	H&I	Water management systems options for water storage and retention in or near city areas	3,300	N/A
73	E&T	Lowering the discount factor for project appraisal	0	N/A
81	E&T	Development of cooling towers	275-550	6.6-11
07	A	Water storage on farmland	15-50	N/A
49	W	High water level IJsselmeer	> 500	N/A
54	W	Increase sand suppletions along coast	750-1,500	N/A

N/A not available
*W - Water; H&I - Housing & Infrastructure; E&T - Energy & Transport;
N - Nature; A - Agriculture
[a]Net present value: discounted stream of future costs
[b]Net present value: discounted stream of future benefits

2.4 Discussion and conclusion

In this chapter, an inventory was made of adaptation options for the Netherlands. The inventory was sector based, but the options can also be classified in several other ways. It turned out that the costs and benefits of the adaptation options can be estimated with reasonable accuracy for only a limited number of options. For the majority of the options knowledge gaps exist, data are missing or their reliability is insufficient. This means that based on our current knowledge it is impossible to evaluate the costs and benefits of the various policy alternatives and adaptation options that we presented. If we intend to use the database on adaptation options for selection of effectiveness and determination of costs, additional research is required to improve and expand the information that it contains so far. As the costs and benefits depend on location, specific circumstances and the exact phasing of the measures, detailed studies in so-called hotspot areas are indispensable. It also requires an analysis of the administrative and policy context at the level appropriate for specific adaptation options, on a local, regional, national and international level, and/or at the level of the ecosystems under study.

The strength of the MCA approach is that it provides a ranking of options that can be used in further discussions and decisions on the adaptation strategy in the Netherlands. The method is useful in communication with the stakeholders and in raising awareness about the challenges of adaptation and the various options to do so. A set of top priority options could be identified based on expert judgement and at relatively low research costs. A weakness of the approach is that it does not yet provide a full social cost-benefit analysis of the options we have identified. We suggest to further develop the database on adaptation options and to continue with obtaining better data on costs of the options and where possible the monetary estimates of the benefits. This, however, cannot be done at a general level but would require specific studies at specific hotspots. These have now been defined and research in this direction is currently ongoing in the National Research Programme on Climate Change and Spatial Planning (Climate changes Spatial Planning, 2008).

From the analysis we observe the following. Several of these options relate to water management, especially for inland and coastal areas and the nature and agriculture sector. It is necessary to carefully check whether the current institutions (for instance the waterboards or the local authorities) can handle the challenges posed by climatic change and whether they are suited to implement the identified adaptation options. Improved coping capability of institutions can be achieved through the cooperation of institutions and stakeholders in new alliances (for instance through restructuring of the institutions responsible for protection against flooding) or through embedding adaptation policies systematically into existing institutions. Problems may, however, arise when the urgency of the local and regional institutions differ from the national level. It is thus important that the national institutions have a coordinating role in the area of spatial planning, and management of water and nature.

Adaptation options dealing with security (including water management) require much attention. It is necessary to improve evacuation plans and evacuation routes and also additional dikes can be constructed in vulnerable regions in order to reduce damages. Public utilities are important, because security risks occur if electricity generation will be hampered due to a possible shortage of cooling water in periods with high temperatures and low precipitation. Moreover it is important that overhead electricity transmission poles and high-tension cables are sufficiently strong and able to resist extreme weather events. Water management needs to be adapted in order to secure safe and sufficient drinking water. For public health, heat stress is an important risk. To reduce these risks, it is important to improve air conditioning in hospitals and nursing homes and to improve provision of good information. Attention should also be paid to preventing negative effects of toxic algae and an increase of disease (like Lyme disease).

Adaptation of traffic infrastructure is necessary to reduce the number of climate related disturbances. Possibilities are measures to reduce inundation of tunnels, facilities to deal with problems related to low river water levels, or measures to reduce disturbances of public transport due to extreme weather events. Also important are adaptations in the agricultural sector, forestry and fisheries. This concerns adaptation of production systems, changes in crop and variety choice, improvements in water management, (e.g. irrigation) and risk spreading for example, by developing new insurances and improving ecosystem management in the fisheries sector. The industry sector, especially the risk prone industries (e.g. refineries, petrochemical or chemical industry), should consider changes in temperature, precipitation and weather extremes in order to avoid calamities.

In the long run, the spatial planning of the Netherlands as well as plans to build in flood prone areas should be reconsidered. In new construction and city plans it is essential to use natural cooling, to prevent so-called 'heat islands' and to provide enough green areas so that cities remain pleasant, also when temperatures are high, without the need to use air conditioning. This requires a more climate oriented design of houses and offices.

For ecology, strengthening the National Ecological Network and integrated water management remain important.

Improved harmonization and coordination between different policy making and executing institutions is needed especially in areas where fine tuning between the central government, the provinces, and other stakeholders is a prerequisite for successful implementation, e.g. in the domain of water management. It is important to strengthen existing initiatives and develop new alliances, as well as making a clear division and coordination of the different tasks. Communication and consciousness-raising is important to prepare the Dutch society to climate change. Finally, it is very important to create transparency on the responsibilities and tasks of the various authorities and stakeholders, and to make clear what the role of the various authorities, producers, consumers and other stakeholders are in dealing with the impacts of climate change.

Appendix 2.A

Table 2.5: Organisations from which experts or stakeholders were represented during the consultations

Research institutes:	
	Alterra
	KNMI (Royal Netherlands Meteorological Institute)
	MNP (Netherlands Environmental Assessment Agency)
	Plant Research International
	National Institute for Coastal and Marine Management
	Institute for Inland Water Management and WasteWater Treatment
	VU University Amsterdam Climate Centre
	WL | Delft Hydraulics; now Deltares
NGOs:	
	COS Nederland
	Foundation ‘Bomenstichting’
	Programme office Climate changes Spatial Planning
	The Climate Group
	Waddenvereniging (Wadden Sea Society)
Business:	
	Insurance company Interpolis
	Consultancy Agency Buiten
Universities:	
	Erasmus University Rotterdam
	Faculty of Earth and Life Sciences, VU University Amsterdam
	Institute for Environmental Studies, VU University Amsterdam
	Delft University of Technology
	Wageningen University
National Science Foundation:	
	NWO (The Netherlands Organisation for Scientific Research)
Ministries:	
	Ministry of Agriculture, Nature and Food Quality, DG Knowledge
	Ministry of Agriculture, Nature and Food Quality, DG Nature
	Ministry of Transport, Public Works and Water Management DG Water
	Ministry of Housing, Spatial Planning and Environment, DG Spatial Planning
Provinces:	
	Province of Flevoland

Appendix 2.B

Table 2.6: List of adaptation options based on literature survey and stakeholder consultation, ordered by sector (a)

Nr.	Sector*	Adaptation option	Weighted sum—ranking: importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking: technical social institutional complexity
1	A	Adjusting crop rotation schemes and planting and harvesting dates	3.1	3.4
2	A	Choice of crop variety and genotype	3.5	3.4
3	A	Development and growing of crops for biomass production	2.8	3.2
4	A	Soil moisture conservation practices	3.6	2.4
5	A	Irrigation	2.9	3.2
6	A	Self sufficiency in production of roughage	1.6	2.6
7	A	Water storage on farmland	3.7	3.4
8	A	Subsoil drainage of peatlands	1.2	3.6
9	A	Insurance	3.1	3.2
10	A	Changes in farming systems	3.8	3.4
11	A	Water management and agriculture	3.4	4
12	A	Regional adaptation strategies for the fen meadow area	3	4.4
13	A	Relocation or mobilization of farms	1.6	4.2
14	A	Floating greenhouses	1.9	2.8
15	A	Land use change	3.3	4.6
16	A	Adaptation strategies to salinization of agricultural land	2.6	4
17	A	Increasing genetic and species diversity in forests	4.4	2.8
18	A	Introduction of southern provenances of tree species and drought resistant species	3.9	2.2
19	A	Limiting the import of timber	1.6	3.2
20	A	Retention of winter precipitation in forests	2.6	2.2
21	A	Acceptation of changes in species composition in forests	3.9	2.4
22	A	Adjusting fishing quota	2.6	3
23	A	Adaptation of target species and fishing techniques	2.2	2.8
24	A	Introduction of ecosystem management in fishery	4.2	3.8
25	A	Eco-labelling and certification of fish	1.5	3
26	A	Reallocation of mussel nursery plots	2.3	3.2
27	A	Aquaculture on former grassland	1.8	3.4
28	N	Design and implementation of ecological networks (The National Ecological Network)	4.5	3.6

*A - Agriculture; N - Nature

Table 2.6: continued (b)

Nr.	Sector*	Adaptation option	Weighted sum—ranking importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking complexity
29	N	Establishment and management of protected areas	3.4	3.4
30	N	Artificial translocation of plant and animal	1.6	3.6
31	N	Afforestation and mix of tree species	4.3	2.8
32	N	Adjustment of forest management	3.7	2.6
33	N	Implementation of effective agri-environmental schemes	3.6	4
34	N	Integrated nature and water management	4.9	4.2
35	N	Integrated coastal zone management	4.9	4.2
36	N	Restoration of ecosystems directly depending on water quantity and quality	3.3	3.8
37	N	Monitoring nature, interpreting changes and informing	4.1	2.6
38	N	Educational programs	4.3	2
39	N	Development of financing mechanisms	2.6	4
40	W	More space for water: a. Regional water system b. Improving river capacity	4.9	4.4
41	W	Risk based allocation policy	4.9	4.4
42	W	Moving power plants to coast (cooling water)	3.2	4.8
43	W	Spatial planning of locations for power plants (nuclear in particular)	4	4.6
44	W	Construction of additional dikes in low-lying parts of the Netherlands	3.5	4.6
45	W	Allow transgression of sea in wide dune areas, allow wash over of dikes	3.4	3.8
46	W	Widening the coastal defence area - in combination with urbanisation and nature	4.2	4.8
47	W	Reconnecting water systems in Delta area (Volkerak Zoommeer and Oosterschelde)	3.3	4.8
48	W	Fresh water storage to flush brackish water out during dry periods	4.3	4
49	W	Higher water level IJsselmeer	3.6	3.4
50	W	Maintain higher water table to prevent salt water intrusion	4.3	3.8
51	W	Relocation of fresh water intake points	4	2.4
52	W	Reclamation of (part of) southern North Sea	1.4	4.6
53	W	Abandoning of the whole of low-lying Netherlands	1.3	4.8
54	W	Increase sand suppletions along coast	3.5	2.8
55	W	Re-enforcement of dikes and dams, including weak spots	4.2	2.2

*N - Nature; W - Water

Table 2.6: continued (c)

Nr.	Sector*	Adaptation option	Weighted sum—ranking importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking complexity
56	W	Adapted forms of building and construction	4	3.6
57	W	Adaptation of highways, secondary dikes to create compartments	4	4
58	W	Protection of vital objects	3.1	2.6
59	W	Protection of vital infrastructure	3.1	3.4
60	W	Enhancing capacity of sluices and weirs	3.6	2
61	W	Artificial reefs along the coastline & development nature conservation values	1.8	2.8
62	W	De-salinization	1.5	2
63	W	Reduction salt water tongue	2.8	2.8
64	W	Stimulate economic activity in other parts (eastern and northern) of the Netherlands	4	3.2
65	W	Risk management as basic strategy	4.9	3.2
66	W	Evacuation plans	4.5	4
67	W	Creating public awareness	4.2	3.2
68	W	New institutional alliances	4.9	4
69	W	Private insurances against inundations and/or drought related damages	3	3.6
70	W	Reduce wastewater discharge during drought periods	3.6	3.8
71	E&T	Adapt regulations such that a higher discharge temperature is allowed	2.3	2.8
72	E&T	Sluices	2.8	2.2
73	E&T	Lowering the discount factor for project appraisal	4	3
74	E&T	Building stronger wind turbines	2.4	2.6
75	E&T	Construct buildings less need for air-conditioning/heating	4.7	2.6
76	E&T	Constructing more stable overhead electricity transmission poles	3.7	2.2
77	E&T	Adapt to mitigation strategies	3.4	2.4
78	E&T	Use improved opportunities for generating wind energy	2.2	2.6
79	E&T	Use improved opportunities for generating solar energy	2.2	2
80	E&T	Planting of biomass crops	2.4	2.8
81	E&T	Development of cooling towers	4	2.6
82	E&T	Development of more intelligent infrastructure that can serve as early warning indicator	4.5	2.6
83	E&T	Improvement of vessels	3.7	1.6
84	E&T	Change modes of transport and develop more intelligent infrastructure	4.7	4

*W - Water; E&T - Energy & Transport

Table 2.6: continued (d)

Nr.	Sector*	Adaptation option	Weighted sum—ranking importance, urgency, no regret, co-benefits and mitigation effect	Weighted sum—ranking complexity
85	E&T	Increase standards for buildings as to make them more robust to increased wind speeds	3.9	1.8
86	H&I	Design spatial planning—construct new housing and infrastructure	4.5	4
87	H&I	Make existing and new cities robust—avoid 'heat islands', provide for sufficient cooling capacity	4.8	3
88	H&I	Design houses with good climate conditions (control)—'low energy'	4.5	2.4
89	H&I	Water management systems: revision of sewer system	4.2	2.4
90	H&I	Water management systems: options for water storage and retention in or near city areas	4	3.8
91	H&I	Water management systems: emergency systems revision for tunnels and subways	3.7	2.2
92	H&I	New design of large infrastructure	4.2	3.6
93	Health	Improved air conditioning in nursery homes or hospitals	3.4	1
94	Health	Measures for preventing climate related diseases	3.1	2.4
95	Health	Improvement of health care for climate related diseases	3.3	2.2
96	R&T	Design infrastructure for recreation and tourism—coastal areas	3.3	3.6

*E&T - Energy & Transport; H&I - Housing & Infrastructure
R&T - Recreation & Tourism

3. Costs and benefits of adapting spatial planning to climate change*

Climate change increases the vulnerability of low-lying coastal areas through sea-level rise and increased water discharge in rivers. Careful spatial planning can reduce the vulnerability of these areas, provided that decision-makers have insight into the costs and benefits of adaptation options for society. This chapter addresses the question which adaptation options are suitable, from an economic perspective, to adapt spatial planning to climate change at a regional scale. We use a project level Social Cost-Benefit Analysis approach to assess the net benefits of a number of adaptation options to deal with the impacts of climate change induced extreme events in a case study of the Zuidplaspolder. The adaptation options focus on different climate change effects and areas of the Zuidplaspolder. The Zuidplaspolder is an example of a large-scale urban development project for which adaptation options are developed. The direct, indirect and external effects of adaptation options relating to spatial planning (e.g. flood proof housing and adjusted infrastructure) are identified, and where possible quantified. Our results show that three adaptation options are not efficient investments, as the costs of investment exceed the benefits of avoided damages. When we focus on 'climate proofing' the total area of the Zuidplaspolder (particularly if the costs and benefits of all the presented adaptation options are considered together) the total package has a positive net present value.

*This chapter is based on De Bruin et al. (2010), to be submitted.

3.1 Introduction

Climatic change increases the vulnerability of societies around the world. The fourth assessment report of the IPCC (IPCC, 2007a) defines vulnerability in the context of climate change as “the degree to which a system is susceptible to and unable to cope with adverse effects of climate change, including climate variability and extremes”. The core concepts that determine the vulnerability of a system are the exposure, sensitivity and adaptive capacity of a system (Adger, 2006; Adger et al., 2005; Smit and Wandel, 2006; Swart and Raes, 2007). Implementation of adaptation measures increases the adaptive capacity, reduces the sensitivity of a system, and thereby reduces the vulnerability of a society to the impacts of climate change (Mastrandrea et al., 2010). Adaptation, in this context, is defined as “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” (IPCC, 2007a). Policymakers play an important role in taking well-considered policy decisions which are aimed at reducing vulnerability to climate change (IPCC, 2007a; Klein et al., 2003).

Consideration of climate change impacts in spatial planning increases the adaptive capacity of a country (Parry et al., 2007). Tol et al. (2008) point out that climate change should even be considered as early as in the design phase of spatial planning, because “retrofitting existing infrastructure is more expensive than designing it to be more flexible or more robust”. Within Europe, the European Commission (CEC, 2009) indicates that integrated spatial planning is needed to climate proof infrastructure. Projects such as ESPACE and ADAM develop decision support tools for spatial planners to assess how spatial development might be affected by climate change in the future (ESPACE, 2008). The philosophy behind these projects is that governments play a major role in “modification of infrastructures and of spatial plans in response to climate impacts” (CEPS, 2008).

In the Netherlands adaptation to climate change is closely related to spatial planning because the Netherlands is a densely populated country where adjustments of policies related to economic development have considerable spatial consequences. The strong link between water management and spatial planning in the Netherlands provides opportunities for adaptation to climate change (De Vries, 2006). Climate robust designs that reduce the vulnerability of societies to known and uncertain impacts of climate change are needed to ‘climate proof’ spatial planning. Climate robust adaptation options reduce sensitivity and are robust across different climate change scenarios and related uncertainties.

In this chapter we address the question which adaptation options are suitable, from an economic perspective, to adapt spatial planning to climate change at a regional scale. We assess the net benefits of different climate robust adaptation options and study how different discount rates, time horizons and changes in flood probability affect the Social Cost-Benefit Analysis (SCBA) outcomes for a specific case study in the Netherlands.[1] We use a project level SCBA approach to assess the net benefits of the adaptation strategy, a package of adaptation options, to deal with the impacts of climate induced extreme events in the Zuidplaspolder in the southwestern part of the Netherlands. The Zuidplaspolder is an example of a large scale urban development project in one of the Dutch polders. Because of its location there is a risk of flooding if the protection by dikes fails and there is a risk of inundation due to excessive precipitation leading to damages. We have identified the current and future flood probability due to a dike breach and excessive rainfall events. For both situations we have, in close consultation with stakeholders, developed adaptation options and assessed the costs and benefits of these options.

The development of an integral adaptation strategy requires the assessment of the potential impacts of climate change, the design of possible adaptation options and the evaluation of costs and benefits of the designed adaptation options. The literature presents a wide variety of frameworks and adaptation assessments that facilitate decision-makers in their decisions regarding adaptation to climate change. This includes, for example, adaptation assessments aimed at the identification and evaluation of adaptation options for specific sectors, such as the water and health sector (Ebi and Burton, 2008; Füssel, 2008; Rosenzweig et al., 2007). The United Nations Environmental Programme Handbook on Methods for Impact Assessment and Adaptation Strategies (Feenstra et al., 1998) provides a general assessment for developing countries. The UK Climate Impacts Programme presents a decision-making framework for adaptation (Willows and Connell, 2003), which focuses on a circular decision making process. Insight into the costs and benefits for society helps decision-makers to assess the effectiveness of adaptation options. So far, most cost-benefit analyses in the context of climate change have focused on mitigation policies, whereas few studies assess adaptation policies.[2]

This chapter is organised as follows. Section 3.2 discusses the main costs and benefits of spatial planning for adaptation to climate change, and introduces the use of a SCBA in the area of climate robust spatial planning. Section 3.3 introduces the study area,

[1] Note that different SCBAs are performed for the selected adaptation options that focus on different climate change effects and areas of the Zuidplaspolder. The options are not ranked based on their net benefits.

[2] Assessments of mitigation policies are presented in, for example, Bürgenmeier et al. (2006), Tol and Yohe (2007), and Hof et al. (2008). Assessments of adaptation policies are presented in, for example, Leary (1999), Dawson et al. (2009), and De Bruin et al. (2009).

and Section 3.4 presents the result of the different SCBAs of each of the four adaptation options relevant for the spatial planning of the study area, including a sensitivity analysis. Section 3.5 discusses the practical applicability of SCBA related to adaptation of spatial planning, and concludes.

3.2 Costs and benefits of adaptation in the context of spatial planning

Assessing climate change adaptation options requires an assessment framework that includes the following steps: (1) describe the reference situation; (2) identify the climate scenarios relevant for the study; (3) assess the effects of climate change under the climate scenarios; (4) identify the adaptation options; (5) assess the effects of the adaptation options; (6) perform social cost-benefit analysis; (7) discuss the results with decision-makers and stakeholders.

The first step involves a description of the reference situation, or business as usual case, for the local area and its current spatial planning. For the second step, the IPCC climate change scenarios or available national climate change scenarios are translated to the local level. The third step projects the climate scenarios onto the reference situation to determine the expected direct and indirect effects of climate change. This step requires information about the probability of extreme events such as flooding due to extreme rainfall or extreme heat (Halsnaes, 2006). Moreover, it is important to calculate the expected flood damages resulting from dike failure or excessive precipitation, for a range of conditions of increasing climate change severity. In the fourth step, adaptation options are identified in close consultation with stakeholders and decision-makers. These include local water boards, local policy-makers, nature organisations and local spatial planners. This step also requires close cooperation with climatologists in order to understand the impacts of climate change in detail. In the fifth step, the direct and indirect effects of the adaptation options are assessed and where possible quantified and monetarised. In the sixth step, SCBA is conducted for the identified costs and benefits of the identified and selected set of different adaptation options. The results of the different SCBAs are further analysed through a sensitivity analysis, to consider the effects of key parameters on the results. In the seventh and final step the results of the SCBAs and sensitivity analysis are discussed with all decision-makers and stakeholders regarding the implications on the economic efficiency of the new spatial planning and the impacts of climate change as identified in the first steps. The primary focus of the adaptation analysis is on the effects at the local level of the various adaptation options.

3.2.1 Direct and indirect effects

The economic effect of the implementation of an adaptation option is determined by comparing the benefits and costs of the option. It is important that all relevant direct and indirect effects of the adaptation option are considered. Adaptation costs are expressed in monetary terms and include investment costs (e.g. construction costs, or land purchases), operations costs and maintenance costs. Adaptation benefits include, among others, avoided damages from climate change. Two distinctions are made with regards to the effects of the adaptation options, namely tangible versus intangible effects, and direct versus indirect effects. Tangible damages are damages that have a monetary value, and intangible damages have no market price (e.g. injuries, increased stress, environmental and cultural losses) (Jonkman et al., 2008). The direct damages are caused by direct contact with water, while the indirect damages are caused by interruption and disruption of the social and economic activities that have resulted from the direct damages.

We define the avoided direct damages as the net present value of the difference between the expected value of the yearly direct damage without the investment and the expected value of the yearly direct damage with the investment. Indirect effects include changes in landscape characteristics, such as the creation of water and nature areas with increased public access. Environmental effects relate to, for example, changes in soil, water and air quality. External effects of an adaptation option include side effects of the option on another polder, region or sector, if these impacts are not expressed in the market. For instance, adaptation options may increase the probability of flooding of neighbouring areas. Another example of an external effect is when adaptation of coastal infrastructure has an effect on landscape quality. In addition, it is important to identify the synergy or competition effect between adaptation options and the effect on mitigation efforts of the adaptation options. This includes an assessment and integrated design of adaptation and mitigation options at local level.

3.2.2 Social Cost-Benefit Analysis

SCBA assesses and compares the total welfare effect of alternative projects by considering not only the direct costs and benefits but also the indirect effects of the alternatives, as well as their external effects. Its primary aim is to inform decision-makers on the costs and benefits of alternative policy options. The specification of the effects on the different stakeholders involved increases the transparency in the decision-making process (Ruijs, 2008). Given the future stream of cost and benefits, as well as the discount rate, the present value of the benefits and costs can be determined.

The net present value (NPV) is calculated by the formula

$$NPV = \sum_{t=0}^{T} \frac{B_t - C_t}{(1+r)^t} \tag{3.1}$$

where B_t denotes the benefits and C_t denotes the costs of an adaptation option in year t, r the discount rate and T the time horizon of the project. The decision rule is to go ahead with the project if its NPV is positive or, in the case of competing projects, with the project that shows the highest NPV. Because spatial planning focuses on the long term impacts of climate change, the effect of climate change on development needs to take the next 100 years into consideration.

An important choice in a SCBA is on the discount rate (r) to be used, and the time horizon (T). We assume a time horizon of 100 years with a risk free discount rate of 2.5%, as indicated by Dutch regulations for spatial planning. In 2007 the Dutch government changed the recommendation of the risk-free discount rate for SCBA from 4 to 2.5% (Ministry of Finance, 2007). In the sensitivity analysis we also consider a discount rate that declines over time, following the UK government guideline on long-term discount rates for costs and benefits accruing more than 30 years into the future (HMT, 2003).[3]

Uncertainties of climate change pose new challenges for decision-makers assessing policy options (Hallegatte, 2009), and seriously complicate cost-benefit analysis. Uncertainties in combination with irreversible effects may affect the optimal choice of the policy instrument, the optimal policy intensity and the optimal timing of implementation (Pindyck, 2007). Assessments of adaptation policies to climate change need to consider key uncertainties with regard to long-term costs and benefits, future climate change and evaluate the implications for the design of climate robust adaptation options (Füssel, 2008). For the study area considered in this chapter we focus on central projections of climate change impacts, as insufficient information is available to define probability density functions to study the effect of uncertain climate change impacts. Note that in Chapters 4 and 5 of this thesis we will incorporate uncertain climate change impacts in the assessment of adaptation options.

3.3 Application to the Zuidplaspolder, the Netherlands

The assessment framework discussed in Section 3.2 is applied to an urban development area, named the Zuidplaspolder (ZPP), located in the southwestern part of the Netherlands, partly along the river the Hollandsche IJssel. A large part of the ZPP is located

[3]Declining discount rate; from 0-30 years, 3.5%, from 31-75 years, 3% and from 76-100 years, 2.5%.

at six meters below sea level, in dike ring area 14.[4] The national spatial strategy (Nota Ruimte, 2006) selected the ZPP for urban development, focused on new residential, commercial and further agriculture development, specifically greenhouse horticulture.

The province of Zuid-Holland together with several non-governmental organisations, municipalities and the water authority of Schieland and the Krimpenerwaard made a master plan for the spatial development of the ZPP. For the period 2010 - 2020 the plan includes the construction of 15 000 - 30 000 houses, the creation of 125 hectares of commercial area, 280 hectares of greenhouse horticulture area, 500 hectares of ecological development, space for water storage and infrastructure improvements. In addition, a project was launched focusing on 'climate proofing' the new spatial development of the ZPP. The aim of 'Hotspot Zuidplaspolder' was to provide input for developing the polder in such a way that future inhabitants of the polder suffer minimal impact of the possible effects of climate change. The ZPP is protected against flooding from sea-level rise and more run off in the river systems by means of dikes.

3.3.1 Climate change

For the project the long-term effects of climate change for the province of Zuid-Holland and the ZPP were assessed. Climate change scenarios, based on IPCC (2007a) and KNMI (2006), served as input to determine the effects of climate change on the region. Table 3.1 provides more details of the estimates of the KNMI scenarios for 2050 and 2100. The scenarios vary with regard to whether the atmospheric circulation patterns will change.

Table 3.1: Description of KNMI climate change scenarios

Year	2050		2100	
Climate scenarios[a]	W	W+	W	W+
Global temperature ($^\circ C$)	+2	+2	+4	+4
Change in air circulation patterns	No	Yes	No	Yes
Winter - Average temperature change ($^\circ C$)	+1.8	+2.3	+3.6	+4.6
Winter - Average precipitation change (%)	+7	+14	+14	+28
Summer - Average temperature change ($^\circ C$)	+1.7	+2.8	+3.4	+5.6
Summer - Average precipitation change (%)	+6	-19	+12	+38
Sea level - Absolute rise (cm)	20-35	20-35	40-85	40-85

[a] KNMI climate scenarios for 2050 and 2100 (high estimates) compared with 1990, W: warming without air circulation patterns, W+: warming with more westerly winds in winter and easterly winds in summer.

[4] A dike ring area is a low-lying area protected by defenses (such as dikes, dunes and structures) or higher grounds (Jonkman et al., 2008).

Van den Berg et al. (2007) investigated the local impacts of the climate scenarios for the province of Zuid-Holland. We assume these impacts also hold for the ZPP because it is located in Zuid-Holland. The most important impacts are: the effects of flooding from sea-level rise or river discharge; the effects of inundation from precipitation; the effects of water shortages related to droughts, the effects of salinisation; and the effects of temperature rise (heat waves). We focus on the risks of flooding from sea-level rise or river discharge and inundation from excessive precipitation.

3.3.2 Climate change impacts on flooding

Climate change affects both the probability and consequences of flooding. In the Netherlands a distinction is made between the exceedance probability and the flood probability related to river systems and sea level. The exceedance probability, also named the threshold probability, is the probability that the water level exceeds the design water level or design standard, where the dike does not breach. The design standard is set by the Flood Protection Act (2006) for each dike ring. The flood probability, the failure probability of the flood defense, is the probability that the land behind the flood defense becomes flooded because the defense fails (e.g. dike breach) at one or more places (Deltacommissie, 2008; Ministry of Transport Public Works and Water Management, 2005).

In our study area, the design standard for the dike ring, under business as usual, is such that the probability that it would be exceeded is once in 10 000 years (Maaskant et al., 2009). The high design standard is due to the fact that the ZPP is part of a primary dike ring area, located near the sea and major river flows. The failure probability of the flood defense, a dike breach, is set at once in 1250 years. Anticipated climate change will increase flood probability. We follow the assumptions made by Maaskant et al. (2009) for dike ring 14. They expect that the failure probability of the flood defense increases by a factor 2.1 for the year 2050, assuming that flood protection measures are not improved during that period (e.g. the height of the dike does not change).

For inundation due to excessive precipitation, the standards are set by the National Administration Agreement for Water (NBW), where the probability of inundation due to excessive rainfall is defined for different land use functions. We focus on an extreme rainfall event with a return period of 100 years. Due to climate change the consequences of an extreme rainfall event with a return period of 100 years increase. Following the KNMI scenarios (KNMI, 2009), we assume that the downpour in 24 hours increases (on an average day), resulting in higher damage costs.

This implies that in our analysis we focus both on measures aimed at reducing flood damage if a dike breach occurs and on reducing inundation damage from excessive precipitation, resulting from an extreme rainfall event.

River flood

Climate change potentially leads to increased discharge in the river Rhine, and sea-level rise, which in turn leads to increased water levels and higher flooding probabilities in the Hollandsche IJssel. The amount of water flowing into the Hollandsche IJssel from the Rhine can be regulated by two storm surge barriers disconnecting the Hollandsche IJssel from the open connection to the North Sea. During an emergency, this enables regulation of water levels in the Hollandsche IJssel and limits the impact of river flooding in the relevant area. Hoes and Van Leeuwen (2008) simulated flood events resulting from multiple breaches of the dike along the Hollandsche IJssel, using a two-dimensional hydraulic model (SOBEK 1D/2D) to simulate water flows in the ZPP. Because only a limited volume of water will flood the ZPP in such an event, only the south eastern part of the ZPP will be flooded which results in a maximum water depth of 1.30 m.

Based on flood simulations, Jonkman et al. (2008) calculated flood damage using a model that estimates economic damage based on detailed land use statistics and population density. This information is implemented in the SCBAs in Section 3.4. In calculating potential flood damage in the ZPP, Hoes and Van Leeuwen (2008) have considered the additional development of 15 000 houses, 250 ha greenhouse horticulture development and 110 ha commercial area development.[5]

For the calculation of the NPV of the adaptation options that deal with the increase in flooding from rivers due to a dike breach, we assume that climate change will increase the current probability of dike failure from once in 1250 years to once in 600 years. Thereby we assume no investments will occur in the coming 100 years that reduce flood probability.

Excessive precipitation

The climate scenarios show that whereas average precipitation will increase during winter, it can decrease substantially during summer. In addition, evaporation will increase as well, resulting in a reduction of water resources. This may affect many different sectors, including flood protection (integrity of peat dikes), nature, agriculture, recreation, transport and urban settlement. During dry periods, river discharge and thus water levels will be lower and salty sea water will advance inland, salinifying the water in the Hollandsche IJssel. When water is allowed into the polder during dry periods this will negatively affect the agricultural crops and nature areas in the polder.

[5] We assume no additional major economic development in the area for the next 100 years.

In situations where heavy rainfall exceeds the drainage capacity of the polder, inundation can occur. De Moel (2008) studied the effect of extreme rainfall on local water levels in the polder using a hydrodynamic model of the polder. The climate scenarios of KNMI (2006) show a considerable increase in peak rainfall especially in the W-scenario. They indicate that both the averages as well as the extremes in precipitation will rise. For inundation risks, the extremes in precipitation are most relevant. De Moel (2008) assesses that urban development will enhance inundation through faster runoff of precipitation. On the other hand, the creation of additional open water increases water storage capacity through ditches, small lakes and canals. Hence, creation of open water may compensate the negative effect of urban development, even under the extreme anticipated climate change scenarios (e.g. global temperature increase of 4 degrees Celsius towards 2100).

For inundation due to rainfall events, the risk of inundation is defined by the probability of inundation times the damage caused by inundation (including the number of hectares inundated and the economic damage per hectare). This can be determined for a full range of rainfall events with increased intensity (increased water levels). A frequency-damage curve is often used to display the probability of exceedance as a function of the economic damage. The area below the curve then equals the expected value of the economic damage. In the Netherlands the standards for the frequency of inundation through rainfall are set by the National Administration Agreement for Water, which defines the probability of inundation due to excessive rainfall for different land use functions, with the probability for horticulture set at 1/50 and for urban areas at 1/100 (NBW, 2003). In this study we focus on the impact of inundation from an extreme rainfall event with a return period of 100 years (defined by the amount of downpour in 24 hours) and its corresponding damage costs.

Table 3.2 gives an overview of flood probability of the identified extreme events under the current and anticipated climate scenarios. We assume that the probability of flooding due to a dike breach and inundation resulting from extreme rainfall will increase under the anticipated climate change. In the sensitivity analysis the effect of changes in the flood probability are shown and further discussed.

3.3.3 Adaptation options

Based on the identified effects of climate change, adaptation options were designed with the aim to ‘climate proof’ the ZPP. The alternatives are strongly interlinked with the already existing development plans and master plan, namely the Interregional Development Vision (ISV, 2006), and the Inter-municipality Development Plan (ISP, 2006). Through workshops, consultations with stakeholders and design sessions with various

Table 3.2: Probability of extreme events

Extreme event	Current climate	Anticipated climate change
Rainfall inundation:		
downpour in 24 hours, return period 100 years	1/100, resulting in 79 mm downpour	1/100, resulting in 2050: G: 88mm, G+: 84 mm, W: 98 mm, W+: 88 mm[a] 2100: 120 mm[b]
River flood:		
dike breach	1/1250[c]	2050: 1/600[d]

[a]KNMI (2009), G, G+, W, W+ refer to the KNMI climate scenarios.
[b]Damage costs € 230 000 per ha, Goosen et al. (2008) based on LGN4 (2004).
[c]Maaskant et al. (2009)
[d]The flood probability increases with a factor 2.1 (Maaskant et al., 2009), which is based on data from Rijkswaterstaat (2007).

experts over 50 options were identified. This long-list of options was reduced to four concrete proposals for adapting spatial planning in specific areas within the ZPP.[6] The four adaptation options are: (1) Water storage for housing and greenhouse development in the northern part of the ZPP, (2) Climate robust ecological network (entire area ZPP), (3) Climate robust design of the residential area of Nieuwerkerk Noord, and (4) Climate robust design of a residential area of Moordrecht. Figure 3.1 shows the location of the adaptation options in the ZPP. The reference situation is the current master plan for the area. Table 3.3 presents the adaptation options, and the specific impacts of climate change which are addressed by the adaptation options.

Adaptation option 1 aims at creating areas for water storage, to prevent periodical damage to crops and property caused by heavy rainfall in the northern part of the ZPP. This area should accommodate the development of 800 houses and 280 hectares of greenhouse horticulture. An alternative was designed to overcome an inundation event by creating sufficient storage capacity for water in the urban area. The design was based on an extreme rainfall event with a return period of more than one hundred years, a cloudburst which results in a downpour of 120 mm in 24 hours.

Adaptation option 2 deals with the adaptation of the ecological network in the ZPP. The effects of climate change on nature in the polder relate to drought, more intense precipitation and an increase in the average temperature.

Adaptation option 3 focuses on the urban expansion of Nieuwerkerk Noord, which is the largest development within the ZPP. A total of 1800 houses will be constructed

[6]The selection of the adaptation options was done based on their applicability, urgency, effectiveness, and robustness characteristics (Xplorelab, 2008; Mes et al., 2008).

Figure 3.1: Location of the adaptation options in the Zuidplaspolder, for which the costs and benefits were identified in the 'Hotspot Zuidplaspolder' project (Xplorelab, 2008) Adaptation option 2 concerns the entire polder.

in the southwestern part of the polder. The planned reference situation includes the construction of the houses without flood protection measures, whereas the alternative option entails the construction of the houses with raised infrastructure, which means that the area itself is not raised but protected by a raised road, which functions as a dike.

Lastly, adaptation option 4 aims to 'climate proof' the expansion of the municipality of Moordrecht with 250 houses in one of the lowest parts of the ZPP. The design of the houses is focused on waterproof building, this includes houses with, for example, water tight glass walls or windows, or houses on top of dikes.

3.4 Results of the Social Cost-Benefit Analysis

SCBA requires that all the related costs and benefits are identified in a quantitative assessment of the adaptation options. The adaptation options were assessed and compared with the reference situation, with specific focus on investment costs, avoided damages,

Table 3.3: Adaptation options identified for the Zuidplaspolder

Nr.	Adaptation option	Specification	Climate change impacts
1.	Water storage for housing and greenhouse development in the Zuidplas Noord	Water storage in the urban area/agriculture area	Inundation and impacts on water resources
2.	Climate robust ecological network	Creation of corridors	Impacts on ecology
3.	Climate robust design of a residential area Nieuwerkerk Noord	Raised infrastructure	Flooding
4.	Climate proof housing Moordrecht Noord	Flood proof construction of houses	Flooding

and valuation of water and nature. The reference situation is the master plan for the spatial development of the ZPP without special adaptation measures.

3.4.1 Direct effects of the adaptation options

The costs of direct effects include direct costs of the adaptation options and the purchase of land to create additional water storage or nature areas. Direct benefits include avoided damages, where total avoided damage costs equal the discounted sum of the expected annually avoided damage costs over a period of 100 years. The expected annually avoided damage costs are the product of the avoided damage costs times the probability of damage each year. The probability of an extreme rainfall event is set at once per 100 years; the probability of a river flood event from a dike breach along the Hollandsche IJssel is set at once per 1250 years. The direct investment costs take place in period $t = 0$, whereas the benefits (avoided damages) are spread over a period of 100 years. For investment costs and avoided damages of the adaptation options we used the estimates of Brouwer et al. (2008), De Boer et al. (2008), Pötz and Bleuzé (2008) and Van den Dobbelsteen et al. (2008). For flood damages, including injury and fatalities, we used the estimate of Hoes and Van Leeuwen (2008).

3.4.2 Indirect effects of adaptation options

The main indirect effects of the adaptation options are effects on nature, landscape and water values associated with alternative land use types. Brander (2010) performed a large-scale survey of almost 2 500 households living in or close to the ZPP to elicit local residents' preferences for the relevant landscape characteristics. Brander's results indicate that households are on average willing to pay € 0.15 per year in additional municipal tax for an additional hectare of water rich area (Table 3.4). This value was aggregated over the total number of households in municipalities in the vicinity of the ZPP, namely Gouda, Moordrecht, Nieuwerkerk aan den IJssel, Waddinxveen, and Zevenhuizen-Moerkapelle. Together these municipalities contain 60 341 households and this gives a total annual WTP for each additional hectare of water rich area of just above € 9 000 per year. The estimated WTP for additional area of wetland (not open to the public) is lower. Average annual household WTP for an additional hectare of wetland is around € 0.11. Aggregating this across the total number of households gives a total annual WTP for each additional hectare of wetland area of just above € 6 600 per year. Average annual household WTP for open access to nature areas (water rich and wetland) is € 0.33 per hectare. On an aggregate level this is almost € 20 000 per hectare per year. Regarding public preferences to avoid raised infrastructure, average annual household WTP to avoid raised roads and railway lines is around € 10.40 per year, the total annual WTP is just below € 630 000.

Table 3.4: Willingness to pay (WTP) for landscape characteristics in the ZPP

	Annual WTP per household[a]	Total annual WTP
Water area	0.15 €/ha	9 000 €/ha
Wetland area	0.11 €/ha	6 600 €/ha
Public access	0.33 €/ha	20 000 €/ha
Avoidance of raised infrastructure	10.40 €	630 000 €

[a] Brander (2010)

3.4.3 Costs and benefits of adaptation options

For adaptation option 1 the costs and benefits were identified for the reference situation (where no additional adaptation options are proposed) and the planning alternative which considers the impacts of climate change. With the estimations of total avoided damage it is assumed that the adaptation options in the planning alternative lead to a 100% avoidance of damages due to inundation resulting from a once in 100 years extreme rainfall event. De Moel (2008) estimates that no inundation would occur with the implementation of the planning alternative. In theory, also heavier downpours can occur which might lead to inundation damage, but insufficient data was available to construct a frequency-damage curve. Therefore we assume that the adaptation option leads to full protection of the area. In a sensitivity analysis (see Table 3.10) we analyse whether this simplification leads to significant changes in the SCBA outcomes. The avoided damage costs to crops and property, the increased quality of the urban area due to presence of water and nature, and the costs of creating an additional area of water and nature in the housing area were identified. As the area created for additional water storage was developed directly alongside the houses, it is owned by the inhabitants of the area, therefore this privately owned land can be sold for half the price of the land.

For adaptation option 2 Xplorelab (2008) identified the adjustments needed for adaptation of the ecological network in the polder, which includes further development and management of nature in the polder to deal with issues such as drought and more intense precipitation. The costs of acquisition, development and management of additional nature areas for the ZPP have been calculated by experts from the Province of Zuid-Holland. The benefits of additional nature area have been estimated through the survey results of Brander (2010).

For adaptation option 3 the costs and benefits of climate robust design of the urban expansion of Nieuwerkerk Noord were calculated for the reference situation and the raised infrastructure alternative, which included avoided damage costs in case of a flood event, costs of flood protection measures (costs of raised infrastructure) and the costs and benefits of creating an additional area of water and nature in the housing area.

Adaptation option 4 included the development of the area to sustain a 1.60 m water level.[7] As this includes innovative techniques for which the construction is considered more costly than conventional building techniques. On the other hand, costs of preparing the area will be lower because raising and flattening it, as is done in the reference situation, is not necessary for option 4. Table 3.5 presents a detailed overview of the costs (year one) and benefits (annual) identified for the adaptation options. We define the avoided direct damages as the net present value of the difference between the expected value of the yearly direct damage without the investment and the expected value of the yearly direct damage with the investment.

Note that the cost per hectare of converting land to water and parks is different from the cost of land acquired for the ecological network. This difference is caused by the difference in the initial purpose of the area before land conversion. For option 2, agricultural land is acquired for the ecological network, while for option 3 a development area is converted to a water area and nature parks.

[7] This water level includes a maximum water depth of 1.30 m and an additional 0.30 m for waves resulting from strong winds.

Table 3.5: Overview of the costs and benefits of the identified adaptation options (million €)

Nr.	Costs (year one)			Benefits (annual)			
	Additional investment	Land conversion - development area to water /nature area	Land conversion - agriculture area to water /nature area	Avoided damages - in case of a flood event	Creation of additional water storage - nature quality	Creation of additional nature area (public access)	Probability of extreme flood or inundation event
1.		34.5(1)		3.22(2)	0.027(3)	0.4(4)	1/100
2.			9.3(5)			1.86(6)	
3.	11.4(7)	10.5(8)		78	0.032(9)		1/1250
4.	20(10)			12			1/1250

Note that as not all the costs and benefits indicated relate to each adaptation option, there are some blank cells in the table.

(1)23 hectare is converted with € 3 000 000 per ha which leads to a total cost of € 69 000 000 for land conversion.
Half of the costs will be returned through the prices of properties, because this area is privately owned open access nature area.
(2)A flood event results in 14 ha (Goosen et al., 2008) flooded area with estimated damage costs of € 230 000 per ha.
The maximum damage cost per ha for greenhouse horticulture is based on (LGN4, 2004).
(3)3 ha additional water/nature area; € 9 000 per ha.
(4)20 ha public area; € 20 000 per ha.
(5)93 ha land conversion; valued at € 100 000 per ha.
(6)93 ha additional public accessible nature area; € 20 000 per hectare.
(7)Additional investment costs due to raising infrastructure.
(8)3.5 ha is converted with € 3 000 000 per ha.
(9)3.5 ha additional water/nature area; € 9 000 per ha.
(10)Additional investment costs; difference between standard design and '1.60 m design' of houses.

3.4.4 Results

The result of the different SCBAs for each of the four adaptation options is summarized in Table 3.6. The numbers represent an 'order of magnitude' of the costs and benefits needed to 'climate proof' the ZPP as the quantification of some direct and indirect effects (e.g. environmental, synergy, competition or mitigation effect) was not possible.

Table 3.6: Net Present Value of the four identified adaptation options (million €)

Nr.	Adaptation option	Location	NPV[a]
1.	Water storage in residential area	Zuidplas Noord	-17.2
2.	Climate robust ecological network	Zuidplaspolder	60.7
3.	Climate robust design of a residential area	Nieuwerkerk Noord	-18.37
4.	Climate proof construction of a residential area	Moordrecht Noord	-19.64
	Adaptation strategy (sum of all adaptation options)	Zuidplaspolder	5.49

[a]Discount rate 2.5%

The NPV results of the four adaptation options (with a discount rate of 2.5%) suggest that not all adaptation options are an efficient investment, because the costs of investment exceed the benefits of the avoided damages. If we focus on 'climate proofing' the total area of the ZPP, however, the costs and benefits of all the presented adaptation options should be considered as a package (adaptation strategy), which results in a positive net present value (€ 5.49 million) for the total package. The main benefits that contribute to a positive net present value is the creation of a climate robust ecological network.

Somewhat surprisingly, the benefits from reduced flood risk and avoided damage in the case of a flood event due to a dike breach are outweighed by the costs of the adaptation measures. This is due to the very small probabilities of flood events occurring in this part of the Netherlands (even when considering the future flood probability due to a dike breach, which is in the order of once per 600 years). The damage costs of a flood event due to dike breach can be up to € 200 million for the ZPP without any adaptation options Hoes and Van Leeuwen (2008). Furthermore, the discount rate reduces the appraisal of future costs and benefits over time. A higher discount rate (4%) results in a lower discounted stream of future benefits, and therefore reduces the NPV of all adaptation options.

A discount rate that declines over time[8] results in a higher discounted stream of future benefits compared to a constant discount rate of 4%, and lower discounted stream of

[8]From 0-30 years, 3.5%, from 31-75 years, 3% and from 76-100 years, 2.5% following the UK government guideline on long-term discount rates (HMT, 2003).

future benefits up to year 75, compared to a constant discount rate of 2.5%. However, as the investment costs exceed the benefits for options 1, 3 and 4, this does not have a large effect on the overall outcomes of the SCBA (see Table 3.7).

Table 3.7: Net Present Value of the four identified adaptation options (million €)

Nr.	Adaptation option	Discount rate		
		2.5%	declining	4%
1.	Zuidplas Noord	-17.2	-19.6	-22.8
2.	Zuidplaspolder	60.7	50.9	38.14
3.	Nieuwerkerk Noord	-18.37	-18.86	-19.51
4.	Moordrecht Noord	-19.64[a]	-19.69[a]	-19.76[a]
	Adaptation strategy (sum of all options)	5.49	-7.25	-23.92

[a] Net present value is the same for both constant and declining discount rates because the high investment costs take place in period 1, while the low benefits (avoided damages) are spread over a period of 100 years.

3.4.5 Sensitivity analysis

We assessed the sensitivity of the results of the SCBA for the following key parameters: the discount rate (r), the time horizon (T), the probability of flooding, damage by flooding and the valuation of landscape characteristics. In this study costs only occur at $t = 0$ (C_0), whereas there are benefits (B) from $t = 0$ to $t = T$. Therefore, the NPV formula presented in Section 3.2 can be rewritten as

$$NPV = B \sum_{t=0}^{T} \frac{1}{(1+r)^t} - C_0 \tag{3.2}$$

This shows that the output of the function is sensitive to the value of C_0, the level of benefits from $t = 0$ to $t = T$ multiplied by the sum of the discount factor, which depends on the chosen time horizon (T) and discount rate (r). Figure 3.2 shows the sum of the discount factors for different discount rates and different time horizons (T). It shows for each time horizon (T), and specific discount rate, the sum of the discount factor over a period of T years.

Table 3.8 presents the NPV calculated for different time horizons (25, 50 and 100 years) and a constant discount rate of 2.5%. With a longer time horizon a longer stream of benefits is included in the NPV calculation, whereas the costs are only present in year $t = 0$. The net benefits are higher when taking into account a longer time horizon of benefits compared to the net costs that only occur in year $t = 0$, as is shown in Eq. 3.2.

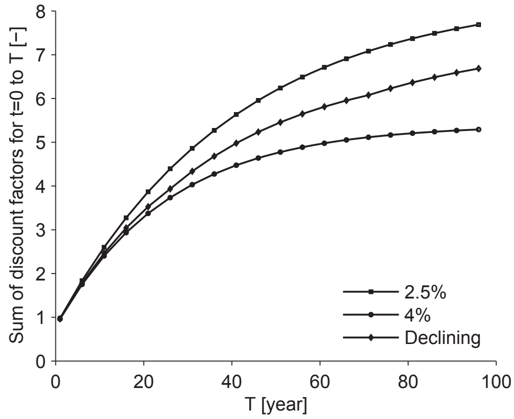


Figure 3.2: Sum of the discount factors from $t = 0$ to T (for $r = 2.5\%$, $r = 4\%$ and r declining)

Table 3.8: NPV for different time horizons (million €)

Nr.	Adaptation option	Time horizon		
		25 years	50 years	100 years
1.	Zuidplas Noord	-25.58	-21.02	-17.23
2.	Zuidplaspolder	26.83	45.31	60.66
3.	Nieuwerkerk Noord	-20.34	-19.79	-18.37
4.	Moordrecht Noord	-19.81	-19.72	-19.64

Note: probability of extreme events for flooding from dike breach 1/1250 years, for inundation from extreme rainfall event 1/100 years.

An overview of the NPV for different probabilities of flooding is presented in Table 3.9, where the sensitivity for the probability of flooding under anticipated climate change is shown. An increase of the probability of flooding results in a higher level of avoided damages when the adaptation options are implemented. For both options the NPV increases (becomes less negative) with increasing probability of flooding, but more so for adaptation option 3 (Climate robust design in Nieuwerkerk Noord) than for adaptation 4 option (Climate proof construction of a residential area in Moordrecht Noord). The net benefits (avoided damages) increase due to the increase of the probability of flooding. The NPV of adaptation 4 shows a smaller increase with increasing probability of flooding, due to very low net benefits compared to the net costs of the adaptation options. Note that, if further economic development takes place, additional investments in flood protection will be made (e.g. strengthen the dike). This will affect the probability of flooding under anticipated climate change. However, a lower probability of flooding due to investments in flood protection will have a small effect on the NPV due to the very low net benefits compared to the net cost of the adaptation options.

Table 3.9: NPV for different discount rates and different probabilities of flooding due to a dike breach (million €)

Probability of flooding	Discount rate		
	2.5%	Declining	4%
Once per 1250 years			
3. Nieuwerkerk Noord	-18.37	-18.86	-19.51
4. Moordrecht Noord	-19.64	-19.69	-19.76
Increases from year $t = 51$ onward[a]			
3. Nieuwerkerk Noord	-17.81	-18.39	-19.30
4. Moordrecht Noord	-19.55	-19.62	-19.72

[a]From $t = 0$ to $t = 50$ the flood probability is 1/1250, from $t = 51$ to $t = 100$ the flood probability is 1/600.

Table 3.10 shows the effects of increasing damage by flooding, and of a decrease and increase in landscape characteristics. We assume that damage costs of a flooding increase over a time horizon of 100 years due to increase in the number of inhabitants in the area. The results show that there is not much change in the NPV of the adaptation options as compared with the results in Table 3.6. This is due to the very low probability of flooding and the discounting effect of the benefits. An increase in the valuation of landscape characteristics including public access to newly developed water and nature areas results in higher net benefits and overall increase of the NPV (or less negative NPV), as indicated in Table 3.10B. A decrease in the valuation of landscape characteristics by households results in lower net benefits and overall decrease of the NPV, as indicated in the Table 3.10C. For adaptation 4 there is no change, as this option does not include the indirect benefits and costs related to the creating of additional nature/water areas.

Sensitivity analysis of investment costs of each of the adaptation options shows that the results of the SCBAs are sensitive to an increase or decrease of the investment costs (see Table 3.10D and 3.10E). As investment costs take place only in the first year ($t = 0$), they have a larger impact in the net costs minus the net benefits of the adaptation option, because there is no impact of the discount factor. Table 3.11 in the Appendix 3.A presents an overview of the NPV for the adaptation options, with a one-at-a-time sensitivity analysis of the input parameters.

Table 3.10: Sensitivity analysis of the NPV for different discount rates (million €)

Parameters	Discount rate 2.5%	Declining	4%
A. Damages by flooding increase by 25%			
1. Zuidplas Noord	-16.93	-19.37	-22.58
3. Nieuwerkerk Noord	-17.78	-18.35	-19.12
4. Moordrecht Noord	-19.55	-19.61	-19.69
B. Value of landscape characteristics increase by 25%			
1. Zuidplas Noord	-13.21	-16.17	-20.07
2. Zuidplaspolder	78.15	65.99	49.99
3. Nieuwerkerk Noord	-18.07	-18.60	-19.30
C. Value of landscape characteristics decrease by 25%			
1. Zuidplas Noord	-21.24	-23.09	-25.51
2. Zuidplaspolder	43.17	35.88	26.28
3. Nieuwerkerk Noord	-18.66	-19.11	-19.71
D. Investment costs increase by 25%			
1. Zuidplas Noord	-25.85	-28.25	-31.41
2. Zuidplaspolder	58.34	48.61	35.81
3. Nieuwerkerk Noord	-23.84	-24.33	-24.98
4. Moordrecht Noord	-24.64	-24.69	-24.76
E. Investment costs decrease by 25%			
1. Zuidplas Noord	-8.60	-11.00	-14.16
2. Zuidplaspolder	62.99	53.26	40.46
3. Nieuwerkerk Noord	-12.89	-13.38	-14.03
4. Moordrecht Noord	-14.64	-14.69	-14.76

Note: Probability of extreme events: flooding from dike breach 1/1250, inundation from rainfall event 1/100.

3.5 Discussion and conclusion

In this chapter we analysed adaptation of spatial planning to cope with climate change induced extreme events, specifically extreme flood events caused by dike breach and inundation caused by extreme rainfall. Furthermore, we assessed which adaptation options are suitable, from an economic perspective, to adapt spatial planning to climate change induced extreme events at a regional scale. Investment in adaptation to climate change requires the assessment of costs and benefits of adaptation options, taking into account scarce resources and climate change uncertainty. A SCBA gives insight into the economic effects of an adaptation strategy aimed at 'climate proofing' spatial planning. We assess four adaptation options including the creation of additional water retention areas, designing flood proof housing, construction of raised infrastructure to prevent flood damage and adaptation of the ecological network in the polder. Our results show that three adaptation options are not efficient investments, as the costs of investment exceed the benefits of avoided damages. When we focus on 'climate proofing' the total area of the Zuidplaspolder (particularly if the costs and benefits of all the presented adaptation options are considered together) the total package has a positive net present value.

It is important to note that the results of a SCBA are sensitive to specific issues, such as the time horizon, unknown long term costs and benefits and the discount rate. As investments concerning climate change adaptation are made for the long term (> 100 years), it is difficult to express the uncertainties about climate change in cost-benefit analysis. Through assigning probability distributions to different climate change scenarios it is possible to further analyse the sensitivity of the results. In addition, costs or benefits occurring after 50 years are difficult to quantify and the choice of the discount rate, whether constant or declining, affects the NPV outcomes. Thus, it is important that decision-makers are aware of the sensitivity of the SCBA results as they decide on adaptation of spatial planning to climate change.

The case study shows that as the climate is changing, important decisions related to spatial planning in the Netherlands need to take this into account. It is, however, impossible to assess these changes with complete certainty. By downscaling the IPCC climate scenarios to the Dutch KNMI climate scenarios, and further down to the local setting of the Zuidplaspolder, this chapter made a first step to identify the effects of climate change at a regional and local level, and to incorporate these effects in the future planning of this specific area. The spatial planning of the Zuidplaspolder needs to take into account the increased risks of flooding caused by a dike breach along the Hollandsche IJssel and the risks of inundation through increased precipitation. The net present value of four adaptation options has been calculated, using a 2.5% discount rate and a time horizon of 100 years.

The systematic application of the assessment framework presented in this chapter provided the inputs for an iterative planning process, where the active involvement of stakeholders has contributed to identification of costs and benefits of the adaptation options based on a detailed downscaling of the international climate scenarios to the local situation. The results of the cost-benefit analysis are an important starting point for further discussion and implementation of climate robust spatial planning. As the results of the case study of the Zuidplaspolder demonstrate, the SCBA results are not very sensitive to changes in flood probability. Moreover, varying the potential damage costs does not have substantial effects on the outcome of the SCBA. This is due to the low probability of flooding and the discounting effect of the benefits. Varying the value of landscape characteristics and investment costs does have significant effects on SCBA outcomes.

Our results show that investment decisions on adaptation to climate change related to urban development and infrastructure, and based on an integrated cost benefit analysis, should not only be focused on the benefits of flood protection, but also include the benefits of increasing spatial quality. The strength of the approach is that it provides direct input for decision-makers responsible for 'climate proofing' spatial planning policies. The framework can also be applied to other low-lying coastal areas around the world that face the challenges of climate change.

Appendix 3.A

Table 3.11: Overview of the NPV for different adaptation options, with one-at-a-time sensitivity analysis (million €), with a variation of +25% (+) and −25% (−)

	Adaptation option			
	1	2	3	4
Costs				
Additional investment (+)	-	-	-21.22	-24.64
Additional investment (−)	-	-	-15.52	-14.64
Land conversion:				
Development area to water/nature area (+)	-25.85	-	-20.99	-
Development area to water/nature area (−)	-8.60	-	-15.74	-
Agriculture area to water/nature area (+)	-	58.34	-	-
Agriculture area to water/nature area (−)	-	62.99	-	-
Benefits				
Additional damages (+)	-16.93	-	-17.78	-19.55
Additional damages (−)	-17.53	-	-18.95	-19.73
Creation additional water storage (+)	-16.97	-	-18.07	-
Creation additional water storage (−)	-17.48	-	-18.66	-
Creation additional nature area (public access) (+)	-13.47	78.15	-	-
Creation additional nature area (public access) (−)	-20.99	43.17	-	-

Note: Discount rate 2.5%. Probability of extreme events: flooding from dike breach 1/1250, inundation from rainfall event 1/100. Time horizon 100 years.

4. Investment in flood protection measures under climate change uncertainty*

Recent river flooding in Europe has triggered debates among scientists and policy-makers on future projections of flood frequency and the need for adaptive investments, such as flood protection measures. Because there exists uncertainty about the impact of climate change on flood risk, such investments require a careful analysis of expected benefits and costs. The objective of this chapter is to show how climate change uncertainty affects the decision to invest in flood protection measures. We develop a model that simulates optimal decision making in flood protection, it incorporates flexible timing of investment decisions and scientific uncertainty on the extent of climate change impacts. This model allows decision-makers to cope with the uncertain impacts of climate change on the frequency and damage of river flood events and minimises the risk of under- or over-investment. One of the innovative elements of our chapter is that we explicitly distinguish between structural and non-structural flood protection measures. Our results show that the optimal investment decision today depends strongly on the cost structure of the adaptation measures and the discount rate, especially the ratio of fixed and weighted annual costs of the measures. A higher level of annual flood damage and later resolution of uncertainty in time increases the optimal investment. Furthermore, the optimal investment decision today is influenced by the possibility of the decision-maker to adjust his decision at a future moment in time.

*This chapter is based on De Bruin and Ansink (2010), submitted to the journal Climate Change Economics.

4.1 Introduction

The August 2002 flood in the Elbe basin was a showcase of a flood event, with estimated damage costs of approximately US$ 12 billion (Becker and Grünewald, 2003). The Elbe flood, jointly with other severe floods in Europe, provided a stimulus to two ongoing scientific debates. The first debate takes place among hydrologists and concerns historical observations and future projections of flood frequency, and its relation to the possible impacts of climate change on river flow. The second debate takes place among river basin decision-makers and concerns the need for additional (adaptive) investments in flood protection measures. In this chapter we link the two debates in a model that assesses optimal investments in flood protection measures under uncertain climate change impacts on flood risk.

There is mixed evidence on the impact of climate change on flood risk and extreme flood events in river basins. On the one hand, Petrow and Merz (2009) analysed historical observations for different river basins in Germany for the period 1951-2002, and concluded that a large share of these basins show significant upward flood trends, and Milly et al. (2002) showed "significant trends towards more extreme flood events" in 29 basins. On the other hand, Mudelsee et al. (2003) analysed flood frequency in the Oder and Elbe rivers and concluded that "although extreme floods with return periods of 100 year and more occurred in central Europe in July 1997 (Oder) and August 2002 (Elbe), there is no evidence from the observations for recent upward trends in their occurrence rate". Kundzewicz et al. (2005) found varying results, with "increases, decreases as well as no significant long-term changes in annual extreme flows" for a sample of 195 rivers (Trenberth et al., 2007). The same ambiguity is present in projections of climate change effects on flood frequency. The frequency of flood events is influenced by, among others, precipitation intensity and the discharge regime, both of which might be affected by climate change. It is unclear, however, to what extent climate change will affect extreme peak discharges, which under normal circumstances result in flood events. Climate models generally project changes in seasonal average discharge regimes of rivers, with higher discharges in winter and lower discharges in summer (Te Linde et al., 2008). In addition, these models project an overall decrease in precipitation in Europe, although flooding may well become more frequent in summertime (Christensen and Christensen, 2003). These types of projections, however, have to be used with care as they are not supported by historic flooding trends (Helms et al., 2002; Mudelsee et al., 2003), are typically made at scales that are larger than those relevant for decision-making (Towler et al., 2010), and it remains difficult to link individual extreme weather events to a change in the climate (Kundzewicz, 2005; Trenberth et al., 2007).

Thus, there exists uncertainty about the impact of climate change on flood risk in river basins. Therefore, the relevant question for decision-makers responsible for flood protection is how to deal with this uncertainty. In response to the 2002 flood, decision-makers in the Elbe basin started to adapt their flood protection infrastructure. Relevant flood protection measures were identified, including increased storage capacity in upstream reservoirs and upgrading of the existing river dikes (De Kok and Grossmann, 2010). The implementation of these measures remains uncertain, however, most likely because this requires long-term political commitment (Petrow et al., 2006). In the Netherlands, flood events in the Meuse and Rhine basins in the 1990s resulted in a similar upgrading of the flood protection programme, although uncertainty about climate change effects remains (Silva et al., 2004).

These examples illustrate that the relation between uncertainty and the timing of investments in flood protection measures presents decision-makers with a trade-off between investing in flood protection today and postponing the decision. Because the effects of climate change are uncertain, decision-makers are reluctant to invest in additional flood protection measures, especially when the costs of these measures are irreversible. When the timing of investment in flood protection measures is flexible, the investment decisions may be postponed until more information about the effects of climate change has arrived. The presence of both irreversibility and flexibility link this decision problem to the theory of investment under uncertainty (Dixit and Pindyck, 1994).

Only few studies relate the risk of flooding in river basins to the implementation of adaptive protection measures. Fankhauser et al. (1999) assess efficient adaptation to climate change-induced extreme events. Kundzewicz (2009) identifies flood protection and flood preparedness measures to avoid adverse impacts for the Baltic Sea basin. De Bruin et al. (2009) present an inventory and ranking of adaptation options for the water sector in the Netherlands. Tol et al. (2003) discuss the impacts of climate change on flood risks in the Netherlands and conclude that structural solutions that integrate land-use planning and water management are better capable of dealing with climate change than incidental solutions. The previous studies did not consider different adaptation measures under climate change uncertainty. In this chapter we address flood risk in river basins and investment decisions in adaptation measures. We make a distinction between different types of protection measures and model the resolution of climate change uncertainty.

Our objective is to show how climate change uncertainty affects the decision to invest in flood protection measures. We develop a model of optimal investment in flood protection measures under climate change uncertainty. Such a model allows decision-makers to cope with the uncertain impacts of climate change on the frequency and damage of river flood events, while minimising the risk of under- or over-investment. Under-investment results in a flood damage probability that is higher than optimal, while over-investment leads to sunk costs and redundant flood protection capacity.

We adapt a model by Hennessy and Moschini (2006) on costly regulatory action under scientific uncertainty to the case of flood protection. Our simplest model specification is a discrete-state two-period model which provides a crude first decision-rule for investments. In subsequent sections, this model is extended to a continuous-state two-period and three-period model, which allows us to analyse the effects of various model elements on this decision-rule. One of these elements is the trade-off between investment in structural and non-structural measures, explained below. Another element is the resolution of climate change uncertainty, which is modeled as a gradual process over time until full resolution is reached. In the two-period model the initial investment decision can be updated when full resolution of uncertainty is reached at an unknown future moment in time. The three-period model allows for an intermediate investment decision under partial resolution of uncertainty before the adjustment of the investment decision under full resolution of climate change uncertainty. The motivation for studying gradual resolution of uncertainty is that over time, additional evidence adds to the overall insight into these impacts, reducing their uncertainty. Our results show that the effect of uncertainty on the investment decision depends on the cost structure of the flood protection measures under consideration. To be precise, a combination of the discount rate, climate change uncertainty, and the cost structure of structural and non-structural measures determines the optimal mix of investments in these measures. A higher level of annual flood damage and later resolution of uncertainty in time increases the optimal investment decision. Furthermore, the optimal investment decision today is influenced by the possibility of the decision-maker to adjust his decision at a future moment in time.

One of the innovative elements of our chapter is that we explicitly distinguish between two categories of protection measures, which vary in their cost structure. The first category, that we will refer to as *structural* measures, includes those measures that have high fixed costs relative to annual costs. Examples are dike improvement and relocation. The second category, that we will refer to as *non-structural* measures, includes those measures that have low fixed costs relative to annual costs. Examples are the creation of retention areas to accommodate peak flows, and programmes to raise public awareness on flood events. Note that our definition of structural and non-structural measures is slightly different from the one used by for instance Kundzewicz (2002, 2009), see Section 4.5. We will see that the inclusion of an intermediate decision moment where partial resolution is observed induces lower investments in structural measures.

The chapter is structured as follows. In Section 4.2 we introduce the basic elements of our model to establish the optimal investment decision under uncertainty in a discrete two-period model. In Section 4.3 we relax the discreteness assumption as to allow for a wide range of possible climate change impacts as well as a continuous range of investment in both structural and non-structural measures. In Section 4.4 we introduce a three-period model, in order to analyse the effect of an intermediate investment decision under partial resolution of uncertainty. The implications of the models for flood protection are discussed in Section 4.5, followed by the conclusion in Section 4.6.

4.2 Discrete-state two-period model

In this section we present a simple discrete-state, two-period model, inspired by Hennessy and Moschini (2006). We assume that the world knows two possible states α; either climate change affects flood damage ($\alpha = 1$) or it does not ($\alpha = 0$). At time $t = 0$ there is uncertainty about which of the two states is the real state. State $\alpha = 1$ has probability q, and state $\alpha = 0$ has probability $1 - q$. This uncertainty will be resolved at some unknown future time $t = \kappa > 0$, where κ is exponentially distributed with $f(\kappa) = he^{-h\kappa}$, such that $E[\kappa] = 1/h$, where h is the hazard rate. A lower value of h implies that the expected resolution of uncertainty is further away in the future. An exponential distribution is often used in the R&D literature to model the expected arrival time of new information (Choi, 1991; Malueg and Tsutsui, 1997). It is a memoryless distribution, which means that the probability of arrival of new information does not depend on the arrival of past information. Following Hennessy and Moschini (2006), we further assume that new information is free and the arrival date is considered to be exogenous to the decision-maker.

The problem faced by the decision-maker is whether or not to make an irreversible and costly investment in flood protection measures m, that suffices to prevent damage in case $\alpha = 1$. Two actions are possible: $m = 1$ denotes the decision to invest and $m = 0$ the decision not to invest. In this section, we simplify matters by assuming that investment induces a fixed and irreversible investment cost C and that the flood protection measure has an infinite lifetime. Annual costs of the flood protection measure c include for instance opportunity costs (e.g. for land used as retention area) and maintenance costs (e.g. for dike maintenance). Let D_{max} denote maximum annual damage from climate change over the period up to $t = \kappa$. Damage is for instance caused by overflow, where at a certain location peak flow exceeds the critical height of the dike.

We assume that the decision-maker chooses the value of m that minimizes expected costs. The discounted realised cost is denoted as $R(m_0, \alpha, \kappa)$, where m_0 is the selected measure at time $t = 0$, α is the realized state of nature and κ is the time at which uncertainty is resolved. Costs consist of investment (C) and annual costs (c) of the implemented measure as well as damage costs D. For simplicity, α and m are the result of the normalisation of the ratio of the increase of flood damage due to climate change (A) and decrease of flood damage due to investment in flood protection measure (M), both in monetary units, with the maximum annual flood damage (D_{max}), where $\alpha = A/D_{max}$, and $m = M/D_{max}$.

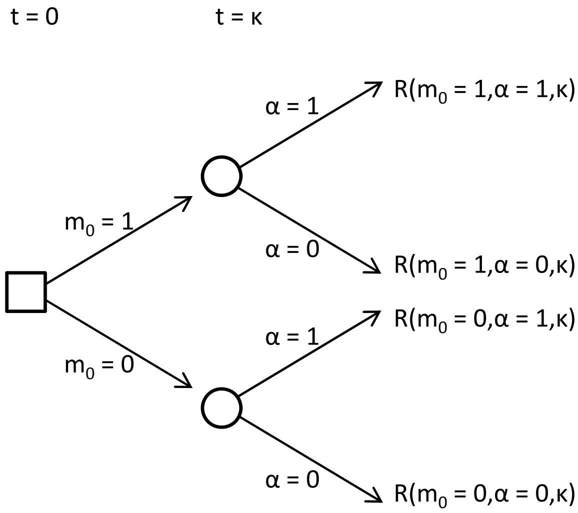


Figure 4.1: Decision tree for the discrete-state two-period model.

The decision-maker may make two erroneous decisions (Figure 4.1). First, if the decision-maker chooses $m_0 = 0$ and it turns out that at $t = \kappa$, $\alpha = 1$, he can revert his initial decision and invest $m_\kappa = 1$, while having incurred damage D over the period from $t = 0$ to $t = \kappa$. Second, if the decision-maker chooses $m_0 = 1$ and it turns out that at $t = \kappa$, $\alpha = 0$, he cannot retrieve his initial investment (i.e. C is irreversible), but saves annual costs c from time $t = \kappa$ onward.

Costs are evaluated at $t = 0$ present values, using the continuous-time discount rate r. The decision node, represented as a square in Figure 4.1, indicates the decision to invest or not to invest at $t = 0$. The information node, shown as a circle, indicates the arrival of new information, in this situation leading to the full resolution of climate change uncertainty. The outcome of each path through the decision tree is defined is the discounted stream of costs for each specific path. The discounted realised cost is a function of m_0 and the random variables α and κ. The two random variables are independent. The outcome of each path is specified as:

$$\begin{aligned}
&R(m_0 = 1, \alpha = 1, \kappa) = C + \int_0^{\infty} ce^{-rt}dt \\
&R(m_0 = 1, \alpha = 0, \kappa) = C + \int_0^{\kappa} ce^{-rt}dt \\
&R(m_0 = 0, \alpha = 1, \kappa) = \int_0^{\kappa} D_{max}e^{-rt}dt + Ce^{-r\kappa} + \int_{\kappa}^{\infty} ce^{-rt}dt \\
&R(m_0 = 0, \alpha = 0, \kappa) = 0
\end{aligned} \tag{4.1}$$

The expected cost of investing, $E[R(m_0 = 1)]$, and of not investing, $E[R(m_0 = 0)]$, can be expressed as a function of the two random variables α and κ, where α is a discrete random variable, and κ a continuous random variable.

$$\begin{aligned}
E[R(m_0 = 1)] &= \int_0^{\infty} \left[qR(m_0 = 1, \alpha = 1, \kappa) + (1-q)R(m_0 = 1, \alpha = 0, \kappa)\right] f(\kappa)d\kappa \\
&= C + q\left(\frac{c}{r}\right) + (1-q)\left(\frac{c}{r+h}\right) \\
E[R(m_0 = 0)] &= \int_0^{\infty} \left[qR(m_0 = 0, \alpha = 1, \kappa) + (1-q)R(m_0 = 0, \alpha = 0, \kappa)\right] f(\kappa)d\kappa \\
&= q\left(\frac{c}{r} + \frac{D_{max} - c + hC}{r+h}\right)
\end{aligned} \tag{4.2}$$

Comparing the expected costs, investment at $t = 0$ is optimal if $E[R(m_0 = 1)] < E[R(m_0 = 0)]$, which is equivalent to $\bar{q} < q$, where:

$$\bar{q} = \frac{c + C(r+h)}{D_{max} + Ch} \tag{4.3}$$

Because $\partial\bar{q}/\partial C > 0$ and $\partial\bar{q}/\partial c > 0$, investing at $t = 0$ is less likely if investment costs (fixed and/or annual) are higher. When the expected resolution of uncertainty moves closer in time (i.e. h increases) or the discount rate r increases, investing at $t = 0$ also becomes less likely, as the decision-maker prefers to postpone the uncertain decision until uncertainty is resolved. However, when the damage costs increase, investing at $t = 0$ becomes more likely; the decision-maker faces higher expected costs when postponing his investment decision. The results are intuitive and the model set-up is rather simple. For instance, the uncertainty of climate change impacts on flood damage α should preferably not be modeled as a draw from only two possible states of the world. Therefore, we introduce state-continuity of this impact and other model features in the next section, which also allows us to distinguish between investing in structural and non-structural measures.

4.3 Continuous-state two-period model

The continuous-state model is derived by three major adjustments to the discrete model. First, instead of the discrete set of states of nature $\alpha \in \{0, 1\}$, we now assume a continuum of states of nature $\alpha \in [0, 1]$, which has a density function $f(\alpha)$ over its domain. The interval $[0, 1]$ reflects the possible states of nature of how climate change affects expected flood damage as explained below. As before, at $t = 0$ the value of α is unknown.

Second, we introduce structural measures s and non-structural measures n. These flood protection measures serve to mitigate the increase of flood damage and thus the expected flood damage caused by climate change. Instead of the discrete investment decision $m \in \{0, 1\}$, we now assume a continuum of structural and non-structural flood protection measures with $s \in [0, 1]$ and $n \in [0, 1]$, where s and n are the result of normalisation such that $s = 0$ or $n = 0$ reflects no investment while $s = 1$ or $n = 1$ reflects maximum investment. We assume that each combination of measures suffices to adapt to the impacts of climate change if $s + n \geq \alpha$. This assumption implies that structural and non-structural measures are additive, as in the case where dike heightening (structural measure) is accompanied by an early-warning system (non-structural).

The variables α, s and n are the result of normalisation based on the variable A that denotes the increase in potential flood damage due to climate change, and S and N that denote the decrease of flood damage due to investment in structural and non-structural measures, all defined in monetary units. These variables have been normalised by taking ratios using the maximum annual flood damage (D_{max}), which leads to $s = S/D_{max}$, $n = N/D_{max}$, and $\alpha = A/D_{max}$. Thus the inequality $S + N \geq A$ is normalised by taking ratios using the maximum annual flood damage, leading to $s + n \geq \alpha$.

Costs of the measures reflect the differences between structural and non-structural measures as discussed in Section 4.1. Structural measures have irreversible fixed costs $C_s s$ and annual costs $c_s s$. Similarly, non-structural measures have irreversible fixed costs $C_n n$ and annual costs $c_n n$. We assume $C_s > C_n$ but $c_s < c_n$. Structural measures have high fixed costs but low annual costs relative to non-structural measures. From this cost structure we can derive that, in absence of uncertainty and for sufficiently low discounting, structural measures are preferred over non-structural measures. Under uncertainty, however, a decision-maker may want to diversify between structural and non-structural measures in order to minimise total expected costs.

Third, instead of the fixed damage parameter D_{max}, we now assume a damage function $\mathcal{D}(\alpha, s, n)$ that maps damage as a function of uncertain climate change impact α, mitigated by flood protection measures $s+n$. Recall that we assumed that each combination of measures suffices to adapt to the impacts of climate change if $s+n \geq \alpha$, which leads to zero damage costs. This assumption allows us to use the difference between α and $s+n$ in order to account for the mitigating effect of flood protection measures on damage.

These three adjustments to the discrete model allow us to model the decision-maker's decision in a similar way as was done for the discrete case described in Section 4.2. Again, the decision-maker may make two erroneous decisions: First, if it turns out that at $t = \kappa$ the decision-maker has under-invested (i.e. $s_0 + n_0 < \alpha$),[1] he can upgrade his initially implemented measures to the optimal level (i.e. to $s_0+n_0+s_\kappa+n_\kappa = \alpha$), while incurring the possible additional fixed costs $C_s s_\kappa$ or $C_n n_\kappa$, and increase of annual costs by $c_s s_\kappa$ or $c_n n_\kappa$. Obviously, damage is incurred over the period from $t = 0$ to $t = \kappa$. Second, if it turns out that at $t = \kappa$ the decision-maker has over-invested (i.e. $s_0+n_0 > \alpha$), he cannot retrieve his initial investment (i.e. $C_s s_0$ and $C_n n_0$ are irreversible), but he can reduce his annual costs such that $s_0 + n_0 + s_\kappa + n_\kappa = \alpha$ from time $t = \kappa$ onward. The interval range for s_0 and n_0 is from $[0, 1]$, and the interval range for s_κ and n_κ is from $[-s_0, 1]$ and $[-n_0, 1]$. The constraints $s_\kappa \geq -s_0$ and $n_\kappa \geq -n_0$ are imposed on the interval range of s_κ and n_κ to indicate that in the case of over-investment at $t = 0$, a reduction of the annual costs at $t = \kappa$ cannot exceed the initial investment made at $t = 0$.

Figure 4.2 shows the decision tree for the continuous-state two-period model. The decision problem is solved backward. The decision node (square) on the right indicates the decision for s_κ and n_κ at $t = \kappa$ when a combination of s_0 and n_0 has been chosen and α is known (represented by the circular information node). We assume the optimal adjustment of the investment decision under full resolution of uncertainty at $t = \kappa$, where

$$s_\kappa + n_\kappa = \alpha - s_0 - n_0 \tag{4.4}$$

We first define the adjustment decision for the level of s_κ and then, given this choice, the investment level of n_κ, where

$$n_\kappa = \alpha - s_0 - n_0 - s_\kappa \tag{4.5}$$

is set. This allows us to substitute n_κ by $\alpha - s_\kappa - s_0 - n_0$, and therefore leave out the

[1] Where necessary, we add a subscript t ($t = 0$ or $t = \kappa$) to s or n, in order to clarify the timing of the investment.

term n_κ in the decision tree and continuation of the model description. First, we solve the decision-maker's problem to choose s_κ at time $t = \kappa$, when s_0 and n_0 have been chosen and α is known. The decision for s_κ is based on the minimisation over all possible values of s_κ (represented by a range of possible values from 1 to M) given the constraint $s_\kappa \geq -s_0$. Second, given the choice at $t = \kappa$, the optimal levels of s_0 and n_0 are selected at $t = 0$. As we evaluate the costs from a $t = 0$ perspective, we consider a continuum of α, as at $t = 0$ we do not know the exact value of α at $t = \kappa$. The continuum over α is represented in Figure 4.2 by different regions to indicate how the combination of s_0 and n_0 and the value of α affects the optimal choice at $t = \kappa$ (see Figure 4.2).

The decision node on the left represents the objective of the decision-maker to choose the combination of s_0 and n_0 in order to minimise the path outcome of the decision tree, the discounted realised cost $R(s_0, n_0, s_\kappa, \kappa, \alpha)$ that consists of damage, fixed and annual costs of the flood protection measures. For each combination of s_0 and n_0 and associated choice at $t = \kappa$, the discounted realised cost is derived. The superscripts in Figure 4.2 and further equations indicate over which set of choices the discounted realised cost is derived; the set of $\{s_0, n_0\}$ combinations is defined from 1 to N. The set of $\{s_0, n_0\}$ combinations includes all combinations based on the interval range of s_0 and n_0. The set for $\{s_\kappa\}$ ranges from 1 to M, and is based on the interval $[-s_0, \alpha - s_0]$. The lower and upper bound of the interval are based on the constraint $s_\kappa \geq -s_0$ and $n_\kappa \geq -n_0$, where the latter constraint can be rewritten in the following way. Note that $n_\kappa \geq -n_0$, by substituting n_κ by Eq. 4.5, can be written as $\alpha - s_0 - s_\kappa \geq 0$, which is equal to $\alpha - s_0 \geq s_\kappa$, and presents the upper-bound of the interval for s_κ.

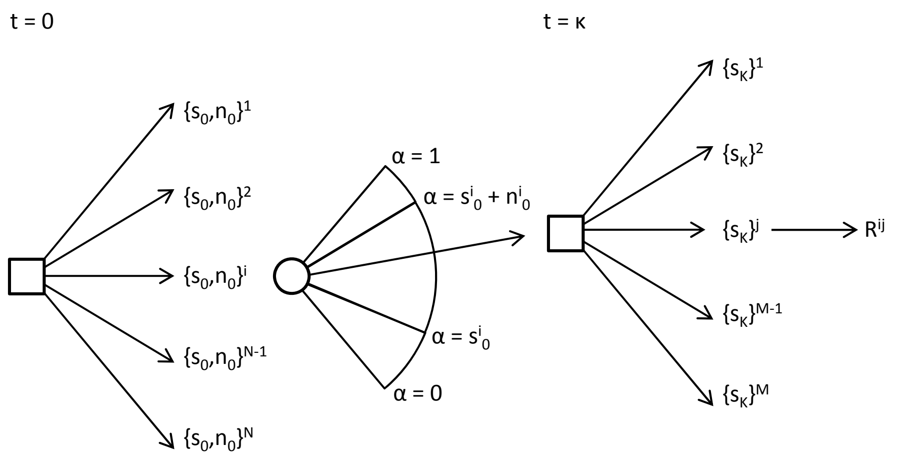


FIGURE 4.2: Decision tree for continuous-state two-period model.

4.3.1 Specific decision path

We now highlight a specific path of the decision tree that leads to the outcome R^{ij} to indicate how the discounted realised cost is derived. The stream of costs is discounted for a specific $\{s_0, n_0\}^i$, $\{s_\kappa\}^j$, α and κ. The discounted realised cost R^{ij} is defined as

$$R^{ij} = I_0^i + D_0^i + I_\kappa^{ij} \tag{4.6}$$

which includes the discounted investment cost and discounted damage cost for the period starting at $t = 0$ (I_0^i and D_0^i) and the discounted adjustment cost for the period starting at $t = \kappa$ (I_κ^{ij}).[2] The damage cost from $t = \kappa$ onwards is zero as we assume optimal investment adjustment at $t = \kappa$. The discounted investment cost I_0^i is a function of a combination of $\{s_0, n_0\}^i$ and random variable κ:

$$\begin{aligned} I_0^i &= C_s s_0^i + C_n n_0^i + \int_0^\kappa \Big(c_s s_0^i + c_n n_0^i \Big) e^{-rt} dt \\ &= C_s s_0^i + C_n n_0^i + \left(\frac{c_s s_0^i + c_n n_0^i}{r} \right) (1 - e^{-r\kappa}) \end{aligned} \tag{4.7}$$

The discounted damage cost D_0^i is a function of a combination of $\{s_0, n_0\}^i$ and random variables κ and α:

$$\begin{aligned} D_0^i &= \int_0^\kappa \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) e^{-rt} dt \\ &= \frac{\mathcal{D}\big(\alpha, s_0^i, n_0^i\big)}{r} (1 - e^{-r\kappa}) \end{aligned} \tag{4.8}$$

The discounted adjustment cost I_κ^{ij} is a function of $\{s_0, n_0\}^i$, $\{s_\kappa\}^j$ and random variables κ and α:

$$\begin{aligned} I_\kappa^{ij} &= \Big(C_s \max\big\{0, s_\kappa^j\big\} + C_n \max\big\{0, \alpha - s_0^i - n_0^i - s_\kappa^j\big\} \Big) e^{-r\kappa} \\ &\quad + \int_\kappa^\infty \Big(c_s \big(s_0^i + s_\kappa^j\big) + c_n \big(\alpha - s_0^i - s_\kappa^j\big) \Big) e^{-rt} dt \\ &= \Big(C_s \max\big\{0, s_\kappa^j\big\} + C_n \max\big\{0, \alpha - s_0^i - n_0^i - s_\kappa^j\big\} \Big) e^{-r\kappa} \\ &\quad + \Big(\frac{c_s}{r} (s_0^i + s_\kappa^j) + \frac{c_n}{r} \big(\alpha - s_0^i - s_\kappa^j\big) \Big) e^{-r\kappa} \end{aligned} \tag{4.9}$$

Note that $s_0^i + s_\kappa^j \geq 0$ and $n_0^i + n_\kappa^j \geq 0$.

[2] The superscript ij refers to a combination of $\{s_0, n_0\}^i$ and $\{s_\kappa\}^j$ to calculate the discounted adjustment cost for the period starting at $t = \kappa$.

4.3.2 Optimal adjustment at $t = \kappa$

As we follow a backward procedure, the focus is first on the optimal adjustment decision at $t = \kappa$, denoted as $\{s_\kappa, n_\kappa\}^{j_{min}}$, which is defined as the decision where the discounted adjustment cost is minimum, i.e. $I_\kappa^{ij_{min}}$. Therefore, I_κ^{ij} is minimised over all possible values of $\{s_\kappa\}^j$ for a given $\{s_0, n_0\}^i$ and α.

We rewrite Eq. 4.9 as $I_\kappa^{ij} = A_\kappa^{ij} e^{-r\kappa}$, where A_κ^{ij} represents the flow of fixed and annual costs and is defined as

$$\begin{aligned} A_\kappa^{ij} &= C_s \max\left\{0, s_\kappa^j\right\} + C_n \max\left\{0, \alpha - s_0^i - n_0^i - s_\kappa^j\right\} \\ &\quad + \frac{c_s}{r}(s_0^i + s_\kappa^j) + \frac{c_n}{r}(\alpha - s_0^i - s_\kappa^j) \end{aligned} \tag{4.10}$$

The minimum A_κ^{ij} can be written as a function of $\mathcal{C}_1$ and $\mathcal{C}_2$, where $\mathcal{C}_1$ and $\mathcal{C}_2$ are defined as:

$$\begin{aligned} \mathcal{C}_1 &= C_s + \frac{c_s}{r} - \frac{c_n}{r} \\ \mathcal{C}_2 &= C_s + \frac{c_s}{r} - C_n - \frac{c_n}{r} \end{aligned} \tag{4.11}$$

The magnitudes of $\mathcal{C}_1$ and $\mathcal{C}_2$ are determined by the value and ratio of the fixed and annual cost elements between the structural and non-structural measure and the level of the discount rate r.[3]

There are three possible combinations for $\mathcal{C}_1$ and $\mathcal{C}_2$, namely: (1) $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$, (2) $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$ and (3) $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$. Note that the combination $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 \geq 0$ is not valid, as $\mathcal{C}_2$ cannot be positive if $\mathcal{C}_1$ is negative, given that $C_n > 0$.

For each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$, the minimum A_κ^{ij} is defined by how the level of α relates to the investment decision made at $t = 0$, $\{s_0, n_0\}^i$, i.e. if the decision-maker has over- or under-invested. This can be summarized as follows:

1. $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$

$$A_\kappa^{ij_{min}} = \begin{cases} \frac{c_s}{r}\alpha & 0 \leq \alpha \leq s_0^i \\ C_s(\alpha - s_0^i) + \frac{c_s}{r}\alpha & s_0^i < \alpha \leq s_0^i + n_0^i \\ C_s(\alpha - s_0^i) + \frac{c_s}{r}\alpha & s_0^i + n_0^i < \alpha \leq 1 \end{cases} \tag{4.12}$$

[3] We define $C_s + c_s/r$ as the fixed plus weighted annual cost. The weighted annual cost is the present value of the infinite stream of annual costs.

2. $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$

$$A_{\kappa}^{ij_{min}} = \begin{cases} \frac{c_s}{r}\alpha & 0 \leq \alpha \leq s_0^i \\ \frac{c_s}{r}s_0^i + \frac{c_n}{r}(\alpha - s_0^i) & s_0^i < \alpha \leq s_0^i + n_0^i \\ C_s(\alpha - s_0^i - n_0^i) + \frac{c_s}{r}(\alpha - n_0^i) + \frac{c_n}{r}n_0^i & s_0^i + n_0^i < \alpha \leq 1 \end{cases} \tag{4.13}$$

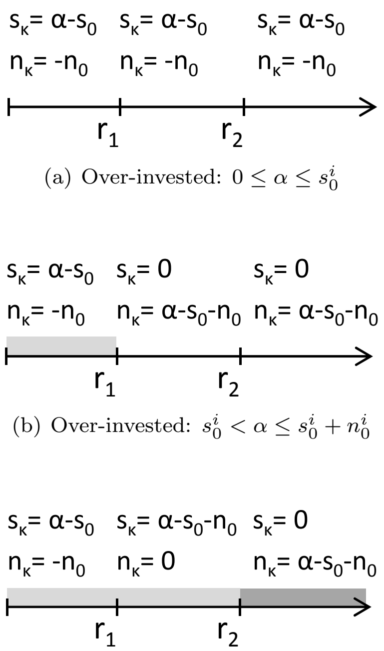
3. $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$

$$A_{\kappa}^{ij_{min}} = \begin{cases} \frac{c_s}{r}\alpha & 0 \leq \alpha \leq s_0^i \\ \frac{c_s}{r}s_0^i + \frac{c_n}{r}(\alpha - s_0^i) & s_0^i < \alpha \leq s_0^i + n_0^i \\ C_n(\alpha - s_0^i - n_0^i) + \frac{c_s}{r}s_0^i + \frac{c_n}{r}(\alpha - n_0^i) & s_0^i + n_0^i < \alpha \leq 1 \end{cases} \tag{4.14}$$

Each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$ marks a different adjustment strategy. Since $\mathcal{C}_1$ and $\mathcal{C}_2$ are a function of the discount rate (r), three regions of adjustment types can be defined along the discount rate axis. This is shown in Figure 4.3 for the cases where the decision-maker has over- and under-invested. r_1 denotes the discount rate where $\mathcal{C}_1 = 0$, and thus if $r < r_1$ then $\mathcal{C}_1 < 0$. r_2 denotes the discount rate where $\mathcal{C}_2 = 0$, and thus if $r < r_2$ then $\mathcal{C}_2 < 0$. Investments in structural measures are indicated with a light gray bar, and non-structural measures with a dark gray bar.

If $\mathcal{C}_1 < 0$ then $C_s + \frac{c_s}{r} < \frac{c_n}{r}$, i.e. the fixed cost plus the present value of an infinite stream of the annual costs of the structural measure is smaller than the present value of an infinite stream of the annual cost of the non-structural measure. Moreover, if $\mathcal{C}_2 < 0$ then $C_s + \frac{c_s}{r} < C_n + \frac{c_n}{r}$, i.e. the fixed plus weighted annual cost of the structural measure is smaller than the fixed plus weighted annual cost of the non-structural measure. $\mathcal{C}_2$ determines the choice between structural and non-structural measures if the decision-maker has under-invested at $t = 0$ and therefore an additional investment is required at $t = \kappa$. $\mathcal{C}_1$ determines whether the non-structural measures are reduced if the decision-maker has over-invested at $t = 0$ or if they are replaced by an investment in structural measures.

For example, if $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$ then the optimal adjustment decision at $t = \kappa$ is to reduce the investment in the non-structural measures as much as possible, i.e. $n_{\kappa}^j = -n_0^i$. Moreover, if $0 \leq \alpha \leq s_0^i$, the decision-maker has over-invested at $t = 0$. Even after reducing the non-structural measures at $t = \kappa$, there is still an over-investment. The structural measures are therefore reduced: $s_{\kappa}^j = \alpha - s_0^i$. Reducing structural measures leads to a reduction in the annual costs, but it does not imply that the initial investment is removed. If $s_0^i < \alpha \leq s_0^i + n_0^i$, the decision-maker has over-invested at $t = 0$. After reducing the non-structural measures, an additional investment is however required to avoid damages. He will invest in structural measures $s_{\kappa}^j = \alpha - s_0^i$. On the other hand, if $s_0^i + n_0^i < \alpha \leq 1$ the decision-maker has under-invested, there are damages incurred up to $t = \kappa$. He will further invest only in structural measures $s_\kappa^j = \alpha - s_0^i$. Inserting these conditions in Eq. 4.10 gives Eq. 4.12.



(a) Over-invested: $0 \leq \alpha \leq s_0^i$

(b) Over-invested: $s_0^i < \alpha \leq s_0^i + n_0^i$

(c) Under-invested $s_0^i + n_0^i < \alpha \leq 1$

FIGURE 4.3: Three regions of adjustment types along the discount rate axis defined by $\mathcal{C}_1$ and $\mathcal{C}_2$ for the cases where the decision-maker has over- and under-invested.

4.3.3 Optimal decision at $t = 0$

With the optimal adjustment decision at $t = \kappa$ known, the discounted realised cost in Eq. 4.6 is rewritten as

$$R^i = I_0^i + D_0^i + I_\kappa^{ij_{min}} \tag{4.15}$$

The discounted realised cost is a random variable as it is a function of the random variables κ and α. To derive the optimal investment decision $t = 0$ we need to first determine the expected value of R^i, which is defined as

$$E[R^i] = E[I_0^i] + E[D_0^i] + E[I_\kappa^{ij_{min}}] \tag{4.16}$$

We solve Eq. 4.16 for the defined exponential distribution of κ, however we do not yet solve for the probability distribution of α, as this probability density function may have different shapes depending on the focus of the climate change impact (i.e. peak discharge, sea-level rise, etc.). As we consider the random variables κ and α to be independent random variables, the joint probability distribution of κ and α can be written as the product of the probability distribution of κ and α ($f(\kappa,\alpha) = f(\kappa)f(\alpha)$).

The expected discounted investment cost ($E[I_0^i]$) is a function of $\{s_0, n_0\}^i$:

$$\begin{aligned} E[I_0^i] &= \int_0^\infty I_0^i f(\kappa) d\kappa \\ &= C_s s_0^i + C_n n_0^i + \left(\frac{1}{h+r}\right)(c_s s_0^i + c_n n_0^i) \end{aligned} \tag{4.17}$$

The expected discounted damage cost ($E[D_0^i]$) is a function of $\{s_0, n_0\}^i$:

$$\begin{aligned} E[D_0^i] &= \int_0^1 \int_0^\infty D_0^i f(\kappa) f(\alpha) d\kappa d\alpha \\ &= \left(\frac{1}{h+r}\right) \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha) d\alpha \end{aligned} \tag{4.18}$$

The expected optimal discounted adjustment cost ($E[I_\kappa^{ij_{min}}]$) is a function of $\{s_0, n_0\}^i$ and the combination of $\mathcal{C}_1$ and $\mathcal{C}_2$:

$$\begin{aligned} E[I_\kappa^{ij_{min}}] &= \int_0^1 \int_0^\infty A_\kappa^{ij_{min}} e^{-r\kappa} f(\kappa) f(\alpha) d\kappa d\alpha \\ &= \left(\frac{h}{h+r}\right) \int_0^1 A_\kappa^{ij_{min}} \ f(\alpha) d\alpha \end{aligned} \tag{4.19}$$

With Eq. 4.17 to 4.19, we can derive the optimal investment decision at $t = 0$ for a given C_s, c_s, C_n, c_n, r, h, $\mathcal{D}$ and $f(\alpha)$. The optimal investment decision at $t = 0$ is denoted as $\{s_0, n_0\}^{i_{min}}$, and is defined as the minimisation of the expected discounted realised costs, i.e. $E[R^{i_{min}}]$,

$$E[R^{i_{min}}] = min\left\{E[R^1], ..., E[R^i], ..., E[R^N]\right\} \tag{4.20}$$

The decision maker will prefer an investment in structural measures to minimise the expected discounted investment costs at $t = 0$ ($E[I_0^i]$), if $\mathcal{C}_2^h < 0$, which is defined as

$$\mathcal{C}_2^h = C_s + \frac{c_s}{h+r} - C_n - \frac{c_n}{h+r} \tag{4.21}$$

If $\mathcal{C}_2^h < 0$, then the fixed cost plus present value of the annual costs up to the expected waiting time for resolution of uncertainty is smaller for structural measures than for non-structural measures. If the expected waiting time for resolution of uncertainty $(1/h)$ approaches infinity than, $\mathcal{C}_2^h$ approaches $\mathcal{C}_2$, defined in Eq. 4.11. Since $\mathcal{C}_2^h$ is a function of the discount rate (r) and the expected waiting time for resolution of uncertainty $(1/h)$, two regions of investment types at $t = 0$ that minimise $E[I_0^i]$ can be defined in the plane spanned by r and $1/h$. This is shown in Figure 4.4. If $1/h = 0$, only the fixed costs are relevant. Since $C_s > C_n$, non-structural measures are preferred. As $1/h$ increases, the contribution of the annual costs increases. Since $c_n > c_s$, non-structural measures become less preferable.

The optimal investment decision at $t = 0$ that minimise $E[R^i]$ will relate to the regions defined by $\mathcal{C}_2^h$ in Figure 4.4 and by $\mathcal{C}_1$ and $\mathcal{C}_2$ in Figure 4.3. This will be illustrated by numerical examples in the next section.

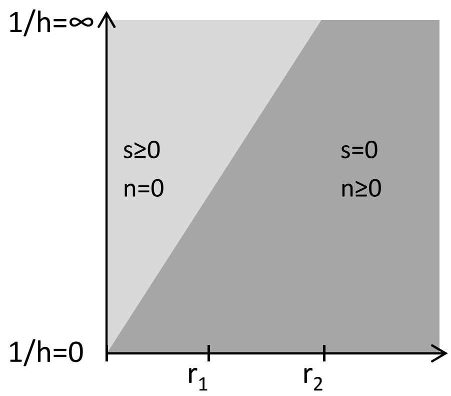


Figure 4.4: Two regions of investment types at $t = 0$ that minimise $E[I_0^i]$. Defined by $\mathcal{C}_2^h$ in the plane spanned by the discount rate (r) and the expected waiting time for resolution of uncertainty $(1/h)$.

4.3.4 Numerical examples

In this section we further illustrate the continuous-state two-period model. A uniform probability distribution for α and an increasing and concave damage function are applied. The damage function is given by:

$$\mathcal{D}(\alpha, s_0, n_0) = \begin{cases} D_{max}\sqrt{\alpha - s_0 - n_0} & \alpha - s_0 - n_0 > 0 \\ 0 & \alpha - s_0 - n_0 \leq 0 \end{cases}$$

If $\alpha > s_0 + n_0$, the decision-maker has under-invested and there are damage costs. A motivation for this functional form is provided in Appendix 4.A. The resulting expressions for the expected discounted realised cost (Eq. 4.16, 4.17, 4.18 and 4.19) are programmed in MATLAB, and minimised for a range of $\{s_0, n_0\}^i$, given the constraints $0 \leq s_0^i \leq 1$, $0 \leq n_0^i \leq 1$ and $0 \leq s_0^i + n_0^i \leq 1$.

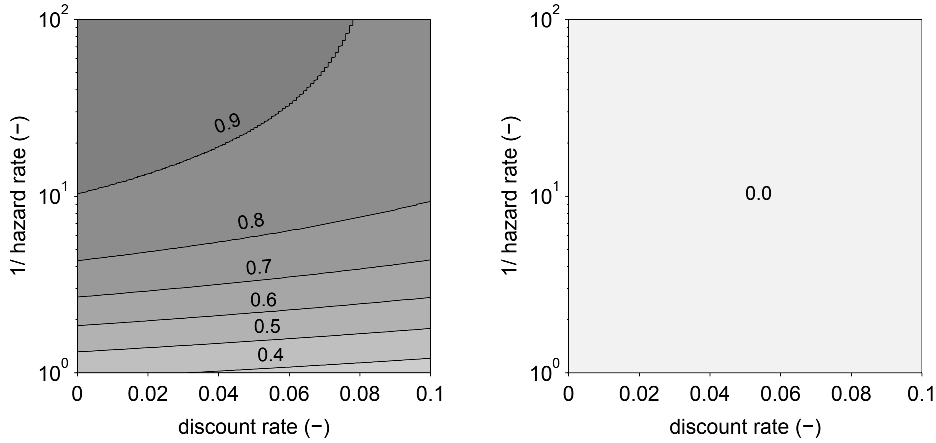
Three examples will be presented to illustrate how the combination of $\mathcal{C}_1$ and $\mathcal{C}_2$ influences the optimal investment decision at $t = 0$. The absolute value of the cost function parameters (C_s, C_n, c_s, c_n and D_{max}) used in these examples are not important. It is their relation that is of interest for this illustration. The optimal investment decision at $t = 0$ will be presented for a range of plausible parameter values for r and h. Specifically, we assess results for the intervals $r \in (0, 0.1]$ and $h \in [0.01, 1]$. The interval for r implies that we check solutions for non-negative discount rates up to 10%. The interval for h implies that we check solutions where the expected waiting time for resolution of uncertainty is between 1 year and 100 years.

Example 1.

In the first example the cost function parameters are selected such that $\mathcal{C}_1 < 0$ (and thus $\mathcal{C}_2 < 0$) for the complete range of r. For illustration, we chose the following values, $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ € and $c_n = 250$ €. We consider two values of D_{max}, namely 750 € and 1500 €, to demonstrate the effect of increasing maximum annual flood damage on the optimal decision. Figure 4.5 and 4.6 present the resulting optimal investment decision at $t = 0$ as function of r and h.

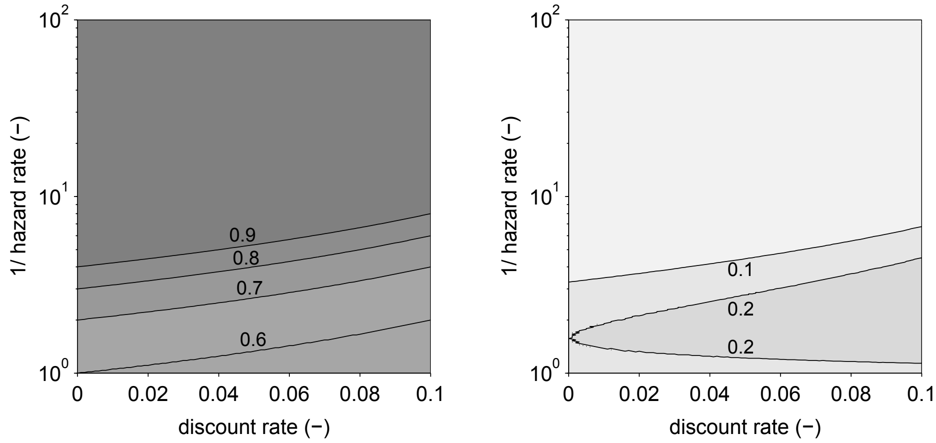
Since $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$, the focus of the optimal decision at $t = 0$ will be on structural measures. This can be seen in Figure 4.5. No investment in non-structural measures is made at $t = 0$. Investing in non-structural measures becomes more desirable as damage costs increase, as shown by Figure 4.6. The relatively high non-structural costs become justifiable when the damages increase. The damage costs will be set to zero at the moment uncertainty is resolved ($t = \kappa$).

Moreover the results demonstrate that if $1/h$ increases the investment in structural measures increases. When $1/h$ increases the expected waiting time for resolution of uncertainty is longer, and accordingly the period of possible damages is longer. Therefore, the investment in structural measures will increase to avoid a long period of possible damages. This effect becomes smaller when the discount rate increases. If the discount rate increases, future costs receive less weight, therefore the stream of damage costs receives less weight, and the investment in structural measures will increase less. Investment in structural measures increases stronger with lower discount rates and longer expected waiting time for resolution of uncertainty.



Structural measures | Non-structural measures

Figure 4.5: Example 1. Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 250$ € and $D_{max} = 750$ €. (Calculation based on step-size 0.001 for interval α.)



Structural measures | Non-structural measures

Figure 4.6: Example 1. Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 250$ € and $D_{max} = 1500$ €. (Calculation based on step-size 0.001 for interval α.)

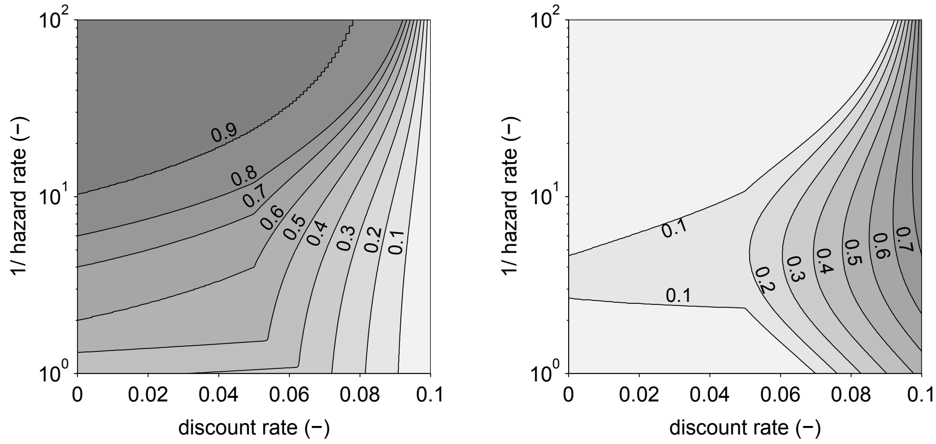
The non-structural measures, on the other hand, increase first and then decrease again if $1/h$ increases. This is related to the period of possible damages and the fact that non-structural measures become optimal to minimize $E[I_0^i]$ for small $1/h$. As the period of possible damage increases, the relatively high non-structural annual costs become justifiable. However, if this period further increases, the relative high annual non-structural costs are no longer justifiable. It is better to increase the structural measures. If the damages costs decreases it is not justifiable to invest first in non-structural measures - although it is optimal to minimize $E[I_0^i]$ for small $1/h$ - as they will be reduced at the moment uncertainty is resolved. This is reflected in Figure 4.5 and 4.6.

Example 2.

In the second example the cost function parameters are selected such that $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$ for $r \in (0, 0.05]$, defined as region 1 and $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$ for $r \in [0.05, 0.1]$, defined as region 2. For illustration, we chose the following values, $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ € and $c_n = 200$ €. Two values of D_{max} are considered: 750 € and 1500 €. Figure 4.7 and 4.8 present the resulting optimal investment decision at $t = 0$ as function of r and h.

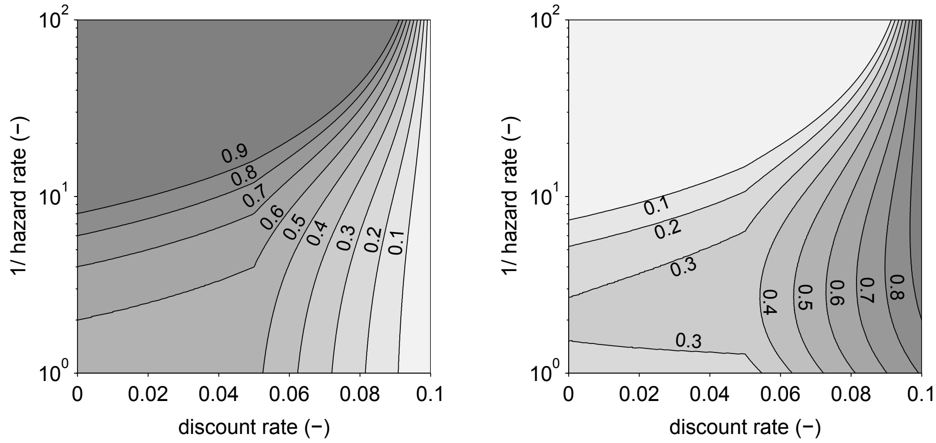
The results demonstrate that the optimal investment decision at $t = 0$ is differently related to r and h for the two regions. Similar characteristics as discussed in the first example, are present for $r \in (0, 0.05]$. For $r \in [0.05, 0.1]$, it can be observed that it becomes more favorable to invest in non-structural measures as r increases. Moreover, the optimal investment decision at $t = 0$ depends less on the $1/h$ as r increases.

If $\mathcal{C}_1 \geq 0$ then $C_s + \frac{c_s}{r} \geq \frac{c_n}{r}$, i.e. the fixed plus weighted annual costs of structural measures are greater than or equal to the weighted annual costs of non-structural measures. If $\mathcal{C}_2 < 0$ then $C_s + \frac{c_s}{r} < C_n + \frac{c_n}{r}$, i.e. the fixed plus weighted annual costs of structural measures are smaller than those of non-structural measures. For the optimal decision at $t = 0$, these conditions imply that it is still favorable to invest in structural measures. However, as the discount rate increases, the difference between the fixed plus weighted annual costs of the structural and non-structural measures becomes smaller, making non-structural measures justifiable to reduce the damages. Especially for shorter periods of possible damages (smaller $1/h$) this becomes justifiable (see Figure 4.4). If the decision-maker has over-invested, the best is to reduce the non-structural measures (as $c_n > c_s$) and let the structural measures unchanged (see Figure 4.3). Therefore, non-structural measures at $t = 0$ are justifiable if the damage costs increase and the period of possible damages is smaller, such that the annual costs can be limited. The second region can be considered as a transition zone. This is illustrated by the next example.



Structural measures Non-structural measures

Figure 4.7: Example 2. Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ € and $D_{max} = 750$ €. (Calculation based on step-size 0.001 for interval α.)



Structural measures Non-structural measures

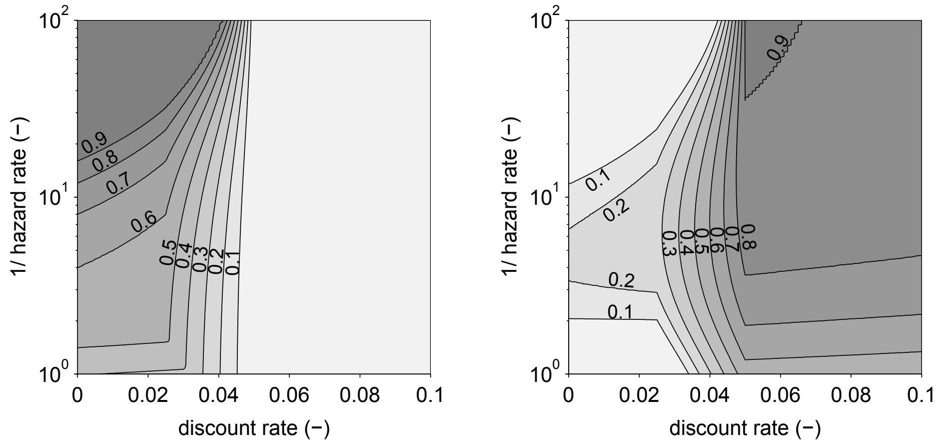
Figure 4.8: Example 2. Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ € and $D_{max} = 1500$ €. (Calculation based on step-size 0.001 for interval α.)

Example 3.

In the third example the cost function parameters are selected such that $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$ for $r \in (0, 0.025]$ (region 1), $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$ for $r \in [0.025, 0.05]$ (region 2) and $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$ for $r \in [0.05, 0.1]$ (region 3). For illustration, we chose the following values, $C_s = 1000$ €, $C_n = 500$ €, $c_s = 175$ € and $c_n = 200$ €. Two values of D_{max} are considered: 750 € and 1500 €. Figure 4.9 and 4.10 present the resulting optimal investment decision at $t = 0$ as function of r and h.

The results demonstrate that the optimal investment decision at $t = 0$ is different related to r and h for these three regions. Similar characteristics discussed in the first and second example, are present for $r \in (0, 0.025]$ and $r \in [0.025, 0.05]$, respectively. For $r \in [0.05, 0.1]$, it can be observed that it is favorable to invest in non-structural measures.

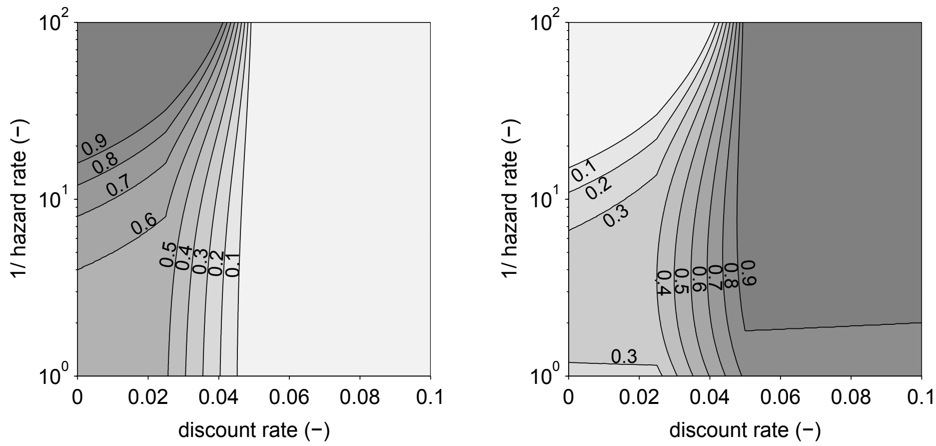
If $\mathcal{C}_1 \geq 0$ then $C_s + \frac{c_s}{r} \geq \frac{c_n}{r}$, i.e. the fixed plus weighted annual costs of structural measures are greater than or equal to the weighted annual costs of non-structural measures. If $\mathcal{C}_2 \geq 0$ then $C_s + \frac{c_s}{r} \geq C_n + \frac{c_n}{r}$, i.e. the fixed plus weighted annual costs of structural measures are greater than or equal to those of non-structural measures. For the optimal decision at $t = 0$, these conditions imply that it is favorable to invest in non-structural measures. The relatively high structural costs become unjustifiable. If the damages increase, the non-structural measures will further increase.



Structural measures

Non-structural measures

FIGURE 4.9: Example 3. Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 175$ €, $c_n = 200$ € and $D_{max} = 750$ €. (Calculation based on step-size 0.001 for interval α.)



Structural measures

Non-structural measures

FIGURE 4.10: Example 3. Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 175$ €, $c_n = 200$ € and $D_{max} = 1500$ €. (Calculation based on step-size 0.001 for interval α.)

4.4 Continuous-state three-period model

In this section we expand upon the two-period model by considering an intermediate decision moment at which there is partial resolution of climate change uncertainty. This is a natural extension of our analysis given that the resolution of the uncertainty of climate change impacts on river flow is a gradual process and the decision-maker will have additional opportunities to adjust his initial investment decision. For the three-period model, an investment decision is made at $t = 0$ and an adjustment decision, under full resolution of climate change uncertainty, is made at an unknown future time $t = \kappa$. This unknown future moment is equal to the full resolution moment in the continuous-state two-period model, therefore κ has the same probability distribution, i.e. an exponentially distributed with $f(\kappa) = he^{-h\kappa}$, such that $E[\kappa] = 1/h$, where h is denoted as the hazard rate. At an intermediate decision moment, defined as $t = x\kappa$ partial resolution of uncertainty is used to make an additional investment decision. Note that x is a fraction, where $x \in (0, 1)$. From todays perspective, this moment is unknown as also $t = \kappa$ is unknown. The decision-maker defines his investment strategy based on the expected value $t = \kappa$ and thus $t = x\kappa$, i.e. $1/h$ and x/h, respectively. If the decision-maker sets x equal to 0.2 today, he will use the information about the partial resolution of climate change uncertainty at 20% of the expected waiting time of full resolution $1/h$. Therefore, this model focuses on the effect of the use of intermediate information.[4]

Figure 4.11 shows the decision tree for the continuous-state three-period model. The decision problem is solved backward. The decision node on the far right indicates the decision for s_κ and n_κ at $t = \kappa$ when a combination of s_0, n_0, $s_{x\kappa}$ and $n_{x\kappa}$ has been chosen and α is known, based on the reduced range of α resulting from partial resolution of uncertainty (circular information node on the right). The decision node in the middle of the decision tree indicates the decision for $s_{x\kappa}$ and $n_{x\kappa}$ at $t = x\kappa$ when a combination of s_0 and n_0 has been chosen and the probability distribution of α is updated based on the received evidence range w (indicated by the two circular information nodes on the left). The decision node on the left represents the objective of the decision-maker to choose the combination of s_0 and n_0 in order to minimise the path outcome of the decision tree.

In the following subsections, we will present a specific decision path of the decision tree following a backward procedure. This includes the optimal adjustment at $t = \kappa$, the optimal decision at $t = x\kappa$ and the optimal decision at $t = 0$. Next, the process of gradual resolution of uncertainty that leads to an update of the prior distribution of

[4]Note that the intermediate information is not used to update the expected time of full resolution.

α for partial resolution of climate change uncertainty is explained. Furthermore, we show that the continuous-state two-period model is a special case of the continuous-state three-period model and present numerical examples.

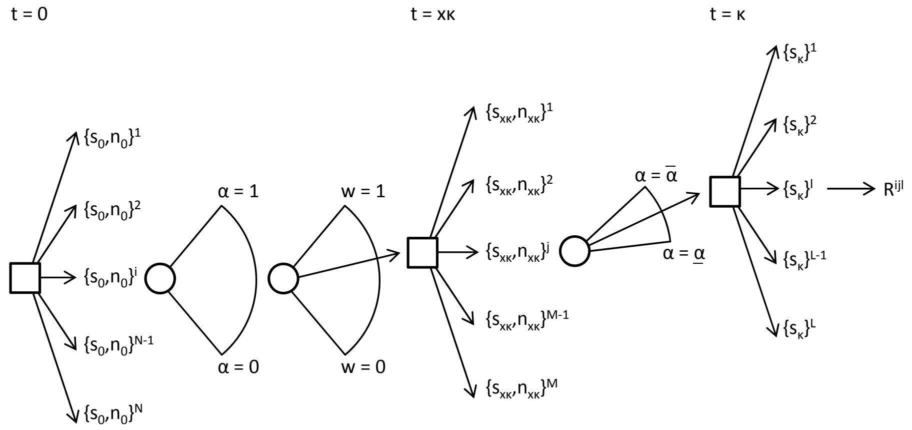


Figure 4.11: Decision tree for continuous-state three-period model.

4.4.1 Specific decision path

We now highlight a specific path of the decision tree that leads to the outcome R^{ijl} to indicate how the discounted realised cost is derived. The stream of costs is discounted for a specific $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$, $\{s_\kappa\}^l$, α, x and κ. The discounted realised cost R^{ijl} is defined as

$$R^{ijl} = I_0^i + D_0^i + I_{x\kappa}^{ij} + D_{x\kappa}^{ij} + I_\kappa^{ijl} \tag{4.22}$$

which includes the discounted investment and damage cost from $t = 0$ up to $t = x\kappa$ (I_0^i and D_0^i), the discounted adjustment and damage cost from $t = x\kappa$ up to $t = \kappa$ ($I_{x\kappa}^{ij}$ and $D_{x\kappa}^{ij}$). Further, it includes the discounted adjustment cost for the period starting at $t = \kappa$ (I_κ^{ijl}). The damage cost from $t = \kappa$ onwards is zero as we assume optimal adjustment at $t = \kappa$.

The discounted investment cost I_0^i is a function of $\{s_0, n_0\}^i$ and the random variable κ:

$$\begin{aligned} I_0^i &= C_s s_0^i + C_n n_0^i + \int_0^{x\kappa} \left(c_s s_0^i + c_n n_0^i \right) e^{-rt} dt \\ &= C_s s_0^i + C_n n_0^i + \left(\frac{c_s s_0^i + c_n n_0^i}{r} \right) (1 - e^{-rx\kappa}) \end{aligned} \tag{4.23}$$

The discounted damage cost D_0^i is a function of $\{s_0, n_0\}^i$ and the random variables κ and α:

$$\begin{aligned} D_0^i &= \int_0^{x\kappa} \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) e^{-rt} dt \\ &= \frac{\mathcal{D}\big(\alpha, s_0^i, n_0^i\big)}{r}(1 - e^{-rx\kappa}) \end{aligned} \tag{4.24}$$

The discounted adjustment cost $I_{x\kappa}^{ij}$ is a function of $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$ and the random variable κ:

$$\begin{aligned} I_{x\kappa}^{ij} &= \Big(C_s \max\big\{0, s_{x\kappa}^j\big\} + C_n \max\big\{0, n_{x\kappa}^j\big\}\Big) e^{-rx\kappa} \\ &+ \int_{x\kappa}^{\kappa} \Big(c_s(s_0^i + s_{x\kappa}^j) + c_n(n_0^i + n_{x\kappa}^j)\Big) e^{-rt} dt \\ &= \Big(C_s \max\big\{0, s_{x\kappa}^j\big\} + C_n \max\big\{0, n_{x\kappa}^j\big\}\Big) e^{-rx\kappa} \\ &+ \Big(\frac{c_s}{r}(s_0^i + s_{x\kappa}^j) + \frac{c_n}{r}(n_0^i + n_{x\kappa}^j)\Big)(e^{-rx\kappa} - e^{-r\kappa}) \end{aligned} \tag{4.25}$$

Note that $s_0^i + s_{x\kappa}^j \geq 0$ and $n_0^i + n_{x\kappa}^j \geq 0$. The discounted damage cost $D_{x\kappa}^{ij}$ is a function of $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$ and the random variables κ and α:

$$\begin{aligned} D_{x\kappa}^{ij} &= \int_{x\kappa}^{\kappa} \mathcal{D}\big(\alpha, s_0^i, n_0^i, s_{x\kappa}^j, n_{x\kappa}^j\big) e^{-rt} dt \\ &= \frac{\mathcal{D}\big(\alpha, s_0^i, n_0^i, s_{x\kappa}^j, n_{x\kappa}^j\big)}{r}(e^{-rx\kappa} - e^{-r\kappa}) \end{aligned} \tag{4.26}$$

Finally, the discounted adjustment cost I_κ^{ijl} is a function of $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$, $\{s_\kappa\}^l$ and the random variables κ and α:

$$\begin{aligned} I_\kappa^{ijl} &= \Big(C_s \max\big\{0, s_\kappa^l\big\} + C_n \max\big\{0, n_\kappa^l\big\}\Big) e^{-r\kappa} \\ &+ \int_\kappa^\infty \Big(c_s\big(s_0^i + s_{x\kappa}^j + s_\kappa^l\big) + c_n\big(n_0^i + n_{x\kappa}^j + n_\kappa^l\big)\Big) e^{-rt} dt \\ &= \Big(C_s \max\big\{0, s_\kappa^l\big\} + C_n \max\big\{0, \alpha - s_0^i - n_0^i - s_{x\kappa}^j - n_{x\kappa}^j - s_\kappa^l\big\}\Big) e^{-r\kappa} \\ &+ \Big(\frac{c_s}{r}\big(s_0^i + s_{x\kappa}^j + s_\kappa^l\big) + \frac{c_n}{r}\big(\alpha - s_0^i - s_{x\kappa}^j - s_\kappa^l\big)\Big) e^{-r\kappa} \end{aligned} \tag{4.27}$$

Note that $s_0^i + s_{x\kappa}^j + s_\kappa^l \geq 0$ and $n_0^i + n_{x\kappa}^j + n_\kappa^l \geq 0$.

4.4.2 Optimal adjustment at $t = \kappa$

As we follow a backward procedure, similar to the continuous-state two-period model, the focus is first on the optimal decision at $t = \kappa$, denoted as $\{s_\kappa\}^{l_{min}}$ and is defined as the minimisation of the discounted adjustment cost, i.e. $I_\kappa^{ijl_{min}}$. Therefore, I_κ^{ijl} is minimised over all possible values of $\{s_\kappa\}^l$ for a given $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$ and α.

Eq. 4.27 is rewritten as $I_\kappa^{ijl} = A_\kappa^{ijl} e^{-r\kappa}$, where A_κ^{ijl} is a function of $\mathcal{C}_1 = C_s + \frac{c_s}{r} - \frac{c_n}{r}$ and $\mathcal{C}_2 = C_s + \frac{c_s}{r} - C_n - \frac{c_n}{r}$. For each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$, the minimum A_κ^{ijl} is defined by how the level of α relates to the investment decision made at $t = 0$ and $t = x\kappa$, $\{s_0 + s_{x\kappa}, n_0 + n_{x\kappa}\}^{ij}$, i.e. if the decision-maker has over- or under-invested. This can be summarized as follows:

1. $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$

$$A_\kappa^{ijl_{min}} = \begin{cases} \frac{c_s}{r}\alpha & 0 \le \alpha \le s^{ij} \\ C_s(\alpha - s^{ij}) + \frac{c_s}{r}\alpha & s^{ij} < \alpha \le s^{ij} + n^{ij} \\ C_s(\alpha - s^{ij}) + \frac{c_s}{r}\alpha & s^{ij} + n^{ij} < \alpha \le 1 \end{cases} \tag{4.28}$$

2. $\mathcal{C}_1 \ge 0$ and $\mathcal{C}_2 < 0$

$$A_\kappa^{ijl_{min}} = \begin{cases} \frac{c_s}{r}\alpha & 0 \le \alpha \le s^{ij} \\ \frac{c_s}{r}s^{ij} + \frac{c_n}{r}(\alpha - s^{ij}) & s^{ij} < \alpha \le s^{ij} + n^{ij} \\ C_s(\alpha - s^{ij} - n^{ij}) + \frac{c_s}{r}(\alpha - n^{ij}) + \frac{c_n}{r}n^{ij} & s^{ij} + n^{ij} < \alpha \le 1 \end{cases} \tag{4.29}$$

3. $\mathcal{C}_1 \ge 0$ and $\mathcal{C}_2 \ge 0$

$$A_\kappa^{ijl_{min}} = \begin{cases} \frac{c_s}{r}\alpha & 0 \le \alpha \le s^{ij} \\ \frac{c_s}{r}s^{ij} + \frac{c_n}{r}(\alpha - s^{ij}) & s^{ij} < \alpha \le s^{ij} + n^{ij} \\ C_n(\alpha - s^{ij} - n^{ij}) + \frac{c_s}{r}s^{ij} + \frac{c_n}{r}(\alpha - n^{ij}) & s^{ij} + n^{ij} < \alpha \le 1 \end{cases} \tag{4.30}$$

where $s^{ij} = s_0^i + s_{x\kappa}^j$ and $n^{ij} = n_0^i + n_{x\kappa}^j$

If $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$ then the optimal adjustment decision at $t = \kappa$ is to reduce the investment in the non-structural measures as much as possible, i.e. $n_\kappa^l = -n^{ij}$ and invest only in structural measures. Moreover, if $0 \le \alpha \le s^{ij}$ the decision-maker has over-invested and the structural measures are therefore reduced: $s_\kappa^l = \alpha - s^{ij}$. Reducing structural measures leads to a reduction in the annual costs, but, it does not imply that the initial investment is removed. On the other hand, if $s^{ij} < \alpha \le 1$ the decision-maker has under-invested, there are damages incurred and at $t = \kappa$, he will further invest only in structural measures $s_\kappa^l = \alpha - s^{ij}$. Note that in all cases it is required that $-s^{ij} \le s_\kappa^l \le \alpha - s^{ij}$ because $s^{ij} + s_\kappa^l \ge 0$ and $n^{ij} + n_\kappa^l \ge 0$.

4.4.3 Optimal decision at $t = x\kappa$

With the optimal adjustment decision at $t = \kappa$ known, the discounted realised cost in Eq. 4.22 is rewritten as

$$\begin{aligned} R^{ij} &= I_0^i + D_0^i + I_{x\kappa}^{ij} + D_{x\kappa}^{ij} + I_\kappa^{ijl_{min}} \\ &= I_0^i + D_0^i + R^{j|i} \end{aligned} \quad (4.31)$$

The focus is now on the optimal discounted cost at $t = x\kappa$ ($R^{j|i}$), which is a random variable as it is a function of the random variables κ and α. To derive the optimal investment decision $t = x\kappa$ we need to first determine the expected value of $R^{j|i}$, which is defined as

$$E[R^{j|i}] = E[I_{x\kappa}^{ij}] + E[D_{x\kappa}^{ij}] + E[I_\kappa^{ijl_{min}}] \quad (4.32)$$

We consider the random variables κ and α to be independent random variable. The random variable α is conditioned on evidence for α, i.e. w. The joint probability function of $R^{j|i}$ is therefore given by: $f(\kappa, \alpha|w) = f(\kappa)f(\alpha|w)$.

The expected discounted investment cost ($E[I_{x\kappa}^{ij}]$) is a function of $\{s_0, n_0\}^i$ and $\{s_{x\kappa}, n_{x\kappa}\}^j$:

$$\begin{aligned} E[I_{x\kappa}^{ij}] &= \int_0^\infty I_{x\kappa}^{ij} f(\kappa) d\kappa \\ &= \frac{h}{(h+xr)}\Big(C_s \max\{0, s_{x\kappa}^j\} + C_n \max\{0, n_{x\kappa}^j\}\Big) \\ &+ \frac{(1-x)h}{(h+xr)(h+r)}\Big(c_s(s_0^i + s_{x\kappa}^j) + c_n(n_0^i + n_{x\kappa}^j)\Big) \end{aligned} \quad (4.33)$$

The expected discounted damage cost ($E[D_{x\kappa}^{ij}]$) is a function of $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$ and evidence for α, i.e. w:

$$\begin{aligned} E[D_{x\kappa}^{ij}] &= \int_0^1 \int_0^\infty D_{x\kappa}^{ij} f(\kappa) f(\alpha|w) d\kappa d\alpha \\ &= \frac{(1-x)h}{(h+xr)(h+r)} \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i, s_{x\kappa}^j, n_{x\kappa}^j\big) f(\alpha|w) d\alpha \end{aligned} \quad (4.34)$$

The expected optimal discounted adjustment cost ($E[I_\kappa^{ijl_{min}}]$) is a function of $\{s_0, n_0\}^i$, $\{s_{x\kappa}, n_{x\kappa}\}^j$, evidence for α, i.e. w, and the combination of $\mathcal{C}_1$ and $\mathcal{C}_2$:

$$E[I_\kappa^{ijl_{min}}] = \int_0^1 \int_0^\infty A_\kappa^{ijl_{min}} e^{-r\kappa} f(\kappa) f(\alpha|w) d\kappa d\alpha$$

$$= \frac{h}{h+r} \int_0^1 A_\kappa^{ijl_{min}} f(\alpha|w) d\alpha \tag{4.35}$$

With Eq. 4.33 to 4.35, we can derive the optimal adjustment decision at $t = x\kappa$ for a given $\{s_0, n_0\}^i$, C_s, c_s, C_n, c_n, r, h, $\mathcal{D}$, x, w and $f(\alpha|w)$. The optimal adjustment decision at $t = x\kappa$ is denoted as $\{s_{x\kappa}, n_{x\kappa}\}^{ij_{min}}$, and is defined as the minimisation of the expected discounted costs at $t = x\kappa$, i.e. $E[R^{j_{min}|i}]$,

$$E[R^{j_{min}|i}] = min\Big\{E[R^{1|i}], ..., E[R^{j|i}], ..., E[R^{M|i}]\Big\} \tag{4.36}$$

4.4.4 Optimal decision at $t = 0$

With the optimal decisions at $t = \kappa$ and $t = x\kappa$ known, the discounted realised cost in Eq. 4.31 is rewritten as

$$R^i = I_0^i + D_0^i + E[R^{j_{min}|i}] \tag{4.37}$$

The discounted realised costs is a random variable as I_0^i is a function of the random variable $x\kappa$, D_0^i is a function of the random variables $x\kappa$ and α and $E[R^{j_{min}|i}]$ is a function of the random variable w, as there is not one evidence, but a range of evidence of α at $t = x\kappa$ possible. To derive the optimal investment decision $t = 0$, we first determine the expected value of R^i, which is defined as:

$$E[R^i] = E[I_0^i] + E[D_0^i] + E\Big[E[R^{j_{min}|i}]\Big] \tag{4.38}$$

The expected discounted investment cost ($E[I_0^i]$) is a function of $\{s_0, n_0\}^i$:

$$\begin{aligned} E[I_0^i] &= \int_0^\infty I_0^i f(\kappa) d\kappa \\ &= C_s s_0^i + C_n n_0^i + \frac{x}{h+xr}(c_s s_0^i + c_n n_0^i) \end{aligned} \tag{4.39}$$

The expected discounted damage cost ($E[D_0^i]$) is a function of $\{s_0, n_0\}^i$:

$$\begin{aligned} E[D_0^i] &= \int_0^1 \int_0^\infty D_0^i f(\kappa) f(\alpha) d\kappa d\alpha \\ &= \frac{x}{h+xr} \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha) d\alpha \end{aligned} \tag{4.40}$$

The expected value of the minimum expected discounted costs at $t = x\kappa$ is a function of $\{s_0, n_0\}^i$:

$$E\Big[E[R^{j_{min}|i}]\Big] = \int_0^1 E[R^{j_{min}|i}]f(w)dw \tag{4.41}$$

With Eq. 4.39 to 4.41, we can derive the optimal investment decision at $t = 0$ for a given C_s, c_s, C_n, c_n, r, h, $\mathcal{D}$, x, $f(w)$ and $f(\alpha)$. The decision is denoted as $\{s_0, n_0\}^{i_{min}}$, and is defined as the minimisation of the expected discounted costs at $t = 0$, i.e. $E[R^{i_{min}}]$,

$$E[R^{i_{min}}] = min\left\{E[R^1], ..., E[R^i], ..., E[R^N]\right\} \tag{4.42}$$

4.4.5 Gradual resolution of uncertainty

We further examine the probability functions $f(\alpha)$, $f(w)$ and $f(\alpha|w)$, which are required to define the optimal investment at $t = 0$. The conditional function of α, given a specific value for the evidence w equals:

$$f(\alpha|w) = \frac{f(\alpha, w)}{f(w)} \text{ , where } \alpha \in [0, 1] \text{ and } w \text{ is a constant} \tag{4.43}$$

The conditional probability is proportional to the joint probability function of α and w, where evidence w is fixed to a specific value. Given this evidence w, α is more likely to occur, i.e. the universe is reduced. Therefore the joint probability function is divided by $f(w)$, the probability of this specific evidence. $f(w)$, also denoted as the marginal distribution, is found by integrating the joint probability function over the whole range of α:

$$f(w) = \int_0^1 f(\alpha, w)d\alpha \tag{4.44}$$

We could reverse the role of α and w in Eq. 4.43. The conditional probability of w given a specific value of α would be

$$f(w|\alpha) = \frac{f(\alpha, w)}{f(\alpha)}$$

$$\text{which can be rewritten as: } f(\alpha, w) = f(w|\alpha)f(\alpha) \tag{4.45}$$

Substituting Eq. 4.44 and 4.45 into the definition of the conditional function of α, given a specific value for evidence w, gives:

$$f(\alpha|w) = \frac{f(w|\alpha)f(\alpha)}{\int_0^1 f(w|\alpha)f(\alpha)d\alpha} \text{ , } \alpha \in [0, 1] \text{ and } w \text{ is a constant} \tag{4.46}$$

Eq. 4.46 is known as Bayes' theorem (Bolstad, 2007). Bayes' theorem is used to revise our beliefs of α on the basis of evidence w. $f(\alpha)$ is the prior distribution for α. It gives the weight we attach to each value of α from our prior belief. $f(w|\alpha)$ is the likelihood for α and is the conditional probability that a specific evidence w has occurred given each value of α. Finally, $f(\alpha|w)$ is the posterior distribution for α. It gives the weight we attach to each value of α after we have observed a specific evidence w. The posterior thus combines our prior beliefs with the evidence given by the occurrence of w:

$$posterior = \frac{likelihood \times prior}{\int (likelihood \times prior)} \tag{4.47}$$

Likelihood

The likelihood function that needs to be defined in a Bayesian framework, is based upon an understanding of the evidence-generating process (Patwardhan and Small, 1992). We need to evaluate the likelihood of a stream of evidence of climate induced annual flood damages given a true state of climate induced annual flood damages. In general, we do not directly obtain the stream of evidence of increased annual flood damages, because we make associated observations, for example the annual peak discharges measured at different measuring stations along rivers. The relationship between the associated observations and climate induced annual flood damages is defined by parametric models, as shown in Figure 4.12. These parameters reflect the true state of the climate. Patwardhan and Small (1992) explain the case of sea-level rise, where a relation is defined between the long-term variation in global mean sea level change relative to a base year and observations of relative sea level at different tide gauges stations around the world.

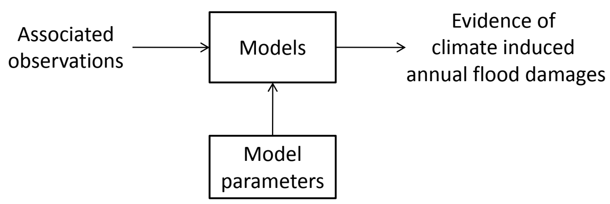


Figure 4.12: Relationship between the associated observations and climate induced annual flood damages

If such models were formulated, the likelihood of a stream of evidence of climate induced annual flood damages given a true state of climate induced annual flood damages would be defined by a Monte Carlo simulation of the model while varying the model parameters for each possible true state of the climate.

For simplification we assume that the stream of evidence of climate induced annual flood damages can directly be determined. The associated observations and the models are therefore omitted. We denote the yearly determined evidence of climate induced annual flood damages as y_ρ. This evidence has a normal distribution with mean α (the true state) and variance σ^2, i.e.

$$f(y_\rho|\alpha) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2\sigma^2}(y_\rho-\alpha)^2} \tag{4.48}$$

The variance reflects the degree to which we are able to determine climate induced annual flood damage. This variance is in expected terms proportional to the expected arrival time of full information, i.e. $1/h$, and can be compared to a measurement error of an instrument. The smaller the variance, the more accurate the instrument. Likewise, the better our capabilities to determine the climate induced annual flood damage, the shorter the expected arrival time of full information. Through investment in research we can enhance our capabilities to reduce the variance, however in this model the variance is constant thus no additional research costs are specified.

Every year we determine evidence of climate induced annual flood damages in a similar way, but independently from each other. This results in a sample (database) $y_1, \ldots, y_P$, after P years. Each evidence has the same normal distribution with mean α and variance σ^2, because the true state and our capabilities to determine evidence are considered to be constant over time. The joint likelihood of this sample after P years is the product of the individual likelihoods, because each evidence is independent of the other evidence. Using Eq. 4.48 and introducing the mean of the sample $\bar{y} = \frac{1}{P}\sum_{\rho=1}^{P} y_\rho$, gives:

$$\begin{aligned} f(y_1, \ldots, y_P|\alpha) &= \frac{1}{\left(\sqrt{2\pi}\sigma\right)^P} \prod_{\rho=1}^{P} e^{-\frac{1}{2\sigma^2}(y_\rho-\alpha)^2} \\ &= \frac{1}{\left(\sqrt{2\pi}\sigma\right)^P} e^{-\frac{P}{2\sigma^2}(\frac{1}{P}\sum y_\rho^2-\bar{y}^2)} e^{-\frac{P}{2\sigma^2}(\alpha-\bar{y})^2} \\ &= K(y_1, \ldots, y_P) e^{-\frac{P}{2\sigma^2}(\bar{y}-\alpha)^2} \end{aligned} \tag{4.49}$$

The posterior of α given the stream of evidence $y_1, \ldots, y_P$, is accordingly (see Eq. 4.47):

$$f(\alpha|y_1, \ldots, y_P) = \frac{e^{-\frac{P}{2\sigma^2}(\bar{y}-\alpha)^2} f(\alpha)}{\int_0^1 e^{-\frac{P}{2\sigma^2}(\bar{y}-\alpha)^2} f(\alpha) d\alpha} \tag{4.50}$$

Note that the constant K drops out of the equation. Further, it is noted that the likelihood of α is proportional to the distribution of the sample mean ($\bar{y}$). The sample mean (the sum of P independent normal distribution with mean α and variance σ^2) itself has a normal distribution with mean α but with variance $\tilde{\sigma}^2 = \frac{\sigma^2}{P}$. Therefore, the posterior of α given the evidence $\bar{y}$ after P years follows the same equation as the posterior of α given the stream of evidence $y_1, \ldots, y_P$.

Finally, the sample mean after $x\kappa$ years is denoted as w. Therefore, Eq. 4.46 becomes:

$$f(\alpha|w) = \frac{e^{-\frac{1}{2\tilde{\sigma}^2}(w-\alpha)^2} f(\alpha)}{\int_0^1 e^{-\frac{1}{2\tilde{\sigma}^2}(w-\alpha)^2} f(\alpha) d\alpha} \text{ , } \alpha \in [0,1] \text{ and } w \text{ is a constant} \tag{4.51}$$

Full resolution of uncertainty is obtained when $\tilde{\sigma}^2 \mapsto 0$. This would happen when we determine evidence for infinity, $P \mapsto \infty$. However, it is considered that at $t = \kappa$, $\tilde{\sigma}$ becomes small enough in order to be considered as full resolution. This threshold is indicated by δ, thus at $t = \kappa$, $\tilde{\sigma} = \delta$. The variance of the sample mean after $x\kappa$ years, can therefore be defined as

$$\begin{aligned} \tilde{\sigma}^2 &= \frac{\sigma^2}{x\kappa} \\ &= \frac{\delta^2 \kappa}{x\kappa} \text{ , } x \in [0,1] \end{aligned} \tag{4.52}$$

As mentioned before, the variance of the evidence determined in year ρ, is proportional to the year in which full resolution is considered (up to δ), i.e. $\sigma^2 \propto \kappa$. In expected terms this implies that $E[\sigma^2] \propto E[\kappa]$, which equals $1/h$. This reflects the degree to which we are able to determine evidence of climate induced annual flood damage.

The posterior of α as function of three different observation moments $x\kappa$ is illustrated in Figure 4.13 for evidence $w = 0.3$. Note that the prior of α is uniformly distributed, where no value is favored over any other. The posterior is shown for $x = 0.1$, $x = 0.5$ and $x = 0.9$, and $\delta = 0.025$. It shows that the posterior of α gradually reduces. For example, if the expected arrival time of full information ($1/h$) is set at 50 years, then already after 5 years there is a considerable reduction in uncertainty. In the decision tree (Figure 4.11) this reduced area is indicated by $\alpha \in [\underline{\alpha}, \overline{\alpha}]$.

In this study, one intermediate decision moment, $t = x\kappa$ is considered where $0 < x < 1$. At $t = 0$, the distribution of α is given by the prior. At $t = \kappa$, the distribution of α is not given by the posterior defined in Eq. 4.51 because full resolution is assumed in the model. This is represented by the assumption that $n_\kappa = \alpha - s_0 - n_0 - s_{x\kappa} - n_{x\kappa} - s_\kappa$ at full resolution of uncertainty. The posterior formulated in Eq. 4.51 is therefore only used for the intermediate decision moment. As a consequence δ can be increased in order to obtain a posterior with higher variance at $t = x\kappa$, without affecting the distribution of

α at $t = \kappa$.

The evidence w at $t = x\kappa$ is used to update our prior belief about α and to make an intermediate adjustment decision. This procedure at $t = x\kappa$ is called a posterior analysis. However, from the viewpoint at $t = 0$ different observations are possible at $t = x\kappa$. Therefore, $E[R^{j_{min}|i}]$ becomes a random variable as w becomes a random variable from our viewpoint $t = 0$. This procedure at $t = 0$ is called the pre-posterior analysis.

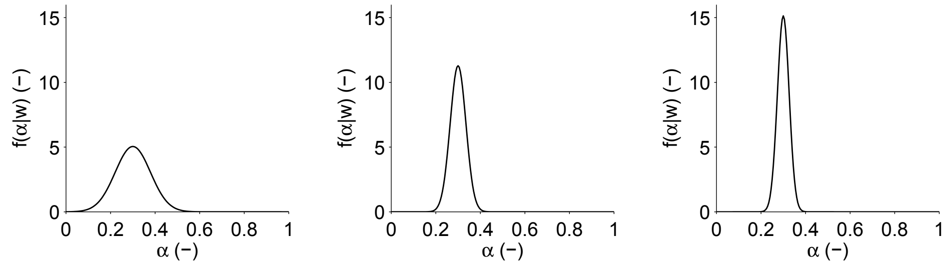


Figure 4.13: Posterior of α as function of three observation moments $x\kappa$ for evidence $w = 0.3$

The continuous-state two-period model, a special case

There is a gradual resolution of uncertainty both in the two-period and the three-period model. The difference between the two models is that in case of the three-period model, we make use of the partial resolution of uncertainty at $t = x\kappa$ to adjust the investment decision. Therefore, forcing $\{s_{x\kappa} = 0, n_{x\kappa} = 0\}$ in the three-period model, i.e. making no investment at $t = x\kappa$, should result in the same optimal investment at $t = 0$ as for the two-period model. This can be shown in the following way.

It is shown that Eq. 4.38 equals Eq. 4.16 if $\{s_{x\kappa} = 0, n_{x\kappa} = 0\}$. The expected value of the minimum expected discounted cost at $t = x\kappa$ is first specified using Eq. 4.41, 4.33, 4.34 and 4.35. Note that superscript j_0 indicates that no investment is made at $t = x\kappa$.

$$\begin{aligned} E\Big[E[R^{j_{min}|i}]\Big] &= \int_0^1 \Big(E[I_{x\kappa}^{ij_0}] + E[D_{x\kappa}^{ij_0}] + E[I_\kappa^{ij_0l_{min}}]\Big) f(w)dw \\ &= \frac{(1-x)h}{(h+xr)(h+r)} \Big(c_s s_0^i + c_n n_0^i\Big) \int_0^1 f(w)dw \\ &+ \frac{(1-x)h}{(h+xr)(h+r)} \int_0^1 \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha|w) f(w) d\alpha dw \\ &+ \frac{h}{h+r} \int_0^1 \int_0^1 A_\kappa^{ij_0l_{min}} f(\alpha|w) f(w) d\alpha dw \end{aligned} \tag{4.53}$$

Next we change the order of integration in Eq. 4.53. First we integrate to w for a fixed α, resulting in the marginal distribution of α i.e.

$$\int_0^1 \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha|w) f(w) d\alpha dw = \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) \int_0^1 f(\alpha|w) f(w) dw d\alpha$$
$$= \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha) d\alpha$$

Further, note that $\int_0^1 f(w)dw = 1$ and that $A_\kappa^{ij_0 l_{min}}$ is equal to $A_\kappa^{ij_{min}}$ in Eq. 4.12 to 4.14 of the two-period model. Therefore, Eq. 4.53 becomes:

$$\begin{aligned} E\Big[E[R^{j_{min}|i}]\Big] &= \frac{(1-x)h}{(h+xr)(h+r)}\Big(c_s s_0^i + c_n n_0^i\Big) \\ &+ \frac{(1-x)h}{(h+xr)(h+r)} \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha) d\alpha \\ &+ \frac{h}{h+r} \int_0^1 A_\kappa^{ij_{min}} f(\alpha) d\alpha \end{aligned} \tag{4.54}$$

Substituting this back in Eq. 4.38 and combining this with Eq. 4.39 and 4.40, gives the following equation for the expected discounted realised cost R^i:

$$\begin{aligned} E[R^i] = C_s s_0^i + C_n n_0^i &+ \Big(\frac{x}{h+xr} + \frac{(1-x)h}{(h+xr)(h+r)}\Big)\Big(c_s s_0^i + c_n n_0^i\Big) \\ &+ \Big(\frac{x}{h+xr} + \frac{(1-x)h}{(h+xr)(h+r)}\Big) \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha) d\alpha \\ &+ \frac{h}{h+r} \int_0^1 A_\kappa^{ij_{min}} f(\alpha) d\alpha \end{aligned} \tag{4.55}$$

As $\frac{x}{h+xr} + \frac{(1-x)h}{(h+xr)(h+r)} = \frac{1}{h+r}$, the expected discounted realised cost in the three-period model with $\{s_{x\kappa} = 0, n_{x\kappa} = 0\}$, is equal to the expected discounted realised cost in two-period model, given in Eq. 4.16 with Eq. 4.17, 4.18 and 4.19.

4.4.6 Numerical examples

We illustrate the three-period model using the same cost function parameters as in example 2 in Section 4.3.4 (Figure 4.7 and 4.8), where $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ € and two values of D_{max}, 750 € and 1500 €. Due to the similar cost structure, similar regions are present in Figure 4.14 to 4.17, where $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$ for $r \in (0, 0.05]$ is defined as region 1 and $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$ for $r \in [0.05, 0.1]$ is defined as region 2. For region 1, this implies that structural measures are preferred over non-structural measures. The non-structural measures first increase and then decrease if $1/h$ increases. As the period of possible damages increases, the relatively high annual non-structural costs become justifiable. However, as this period further increases, the relative high annual non-structural costs are no longer justifiable. It is better to increase the structural measures. In region 2 it is still favorable to invest in structural measures. However, non-structural measures are justifiable to reduce the damages if the discount rate increases. The optimal investment decision depends less on the $1/h$ as r increases.

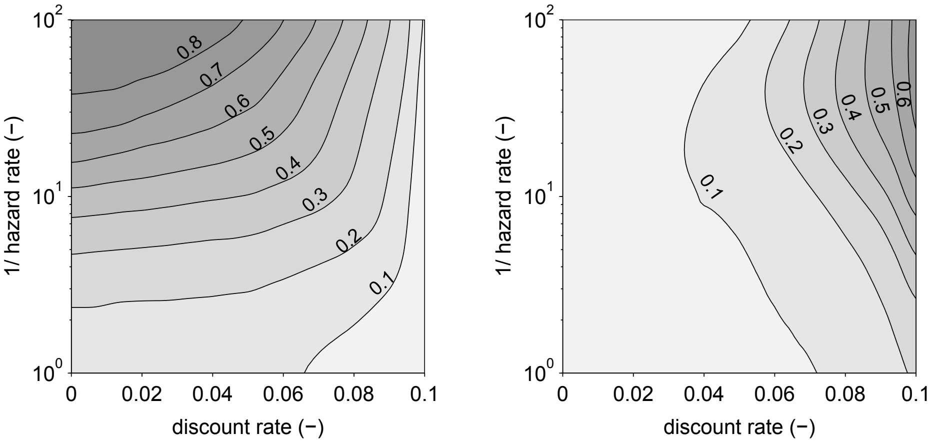
In the three-period model we introduce an intermediate decision moment ($t = x\kappa$), where partial resolution of uncertainty is used. The decision-maker sets the fraction x, which sets the moment at which partial resolution is used, relative to the moment of full resolution of uncertainty. We illustrate two different intermediate decision moments, namely $x = 0.1$ and $x = 0.5$ for a given expected value of the variance σ^2, i.e. δ^2/h. The variance reflects the capacity to collect evidence to reduce the domain of the prior distribution and is therefore proportional to the moment of full resolution of uncertainty. With $x = 0.1$ the moment at which partial resolution of uncertainty is used, is set at 10% of full resolution of uncertainty and with $x = 0.5$ at 50%. Figure 4.13 shows the posterior distribution of α as a function of three different observation moments with $\delta = 0.025$ for a constant evidence w. From the $t = 0$ perspective we consider a continuum of w, as at $t = 0$ we do not know the exact value of the evidence that will be made at this future time instant.

Figure 4.14 and 4.15 present the resulting optimal investment decision at $t = 0$, for $x = 0.1$ as function of r and h. When compared to Figure 4.7 and 4.8 of the two-period model it is noted that the total investment in structural and non-structural measures decreases. The intermediate adjustment of the initial investment decision based on reduced area $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, reduces the stream of possible future damages, therefore at $t = 0$ with full uncertainty, there is no need to over-invest as in the near future information becomes available. With low discount rates and smaller $1/h$, there is less investment in non-structural measures as future annual costs receive more weight. With high discount rates and larger $1/h$, investment in non-structural measures increases and structural measures decreases. This is due to the high fixed investment costs of the structural measures compared to the non-structural fixed investment costs, and future annual costs receive less weight, which makes investment in non-structural measures more justifiable.

When the damage costs increase, with a low discount rate structural measures are still preferred over non-structural measures. However, when the expected resolution of uncertainty increases, investment in non-structural measures becomes justifiable as the period of possible damage increases. When the period of possible damages further increases (larger $1/h$), the high annual costs of the non-structural measures receive more weight, this leads to a reduction of non-structural measures and an increase in investment in structural measures. When the damage costs increase, the transition of investment in non-structural measures, at low discount rates, shifts upwards as the level of damages does not justify investment in non-structural measures.

When we consider the intermediate decision moment at $t = 0.5\kappa$, and compare Figure 4.16 and 4.17 with Figure 4.7 and 4.8, there is considerably less difference. With $x = 0.5$ partial resolution of uncertainty is used at 50% of the expected full resolution of uncertainty. At this intermediate time instant we have a posterior distribution that has a smaller reduced area $\alpha \in [\underline{\alpha}, \overline{\alpha}]$, indicating less uncertainty, thus we have a more optimal adjustment of the initial investment decision than when $x = 0.1$. However, we only benefit from this adjustment for a short period, the period of reduced damages is shorter. Figure 4.16 and 4.17 show that the latter effect dominates, as the shrinking domain is less important than the moment at which the partial resolution of uncertainty is used. The time to the moment at which the partial resolution is used, is much longer, therefore the initial investment decision does not differ much from the initial investment decision in the two-period model. For a given σ (and thus δ and $1/h$), which relates to the capacity to collect evidence to reduce the domain of the prior distribution, the decision-maker can influence the timing of the intermediate investment decision through the selection of x. This choice impacts the level of reduced damages, which depends on the timing of the intermediate decision and associated level of partial resolution. When the decision-maker can influence the level of σ through additional research, there is a trade-off between the cost of additional research and the level of reduced damages.

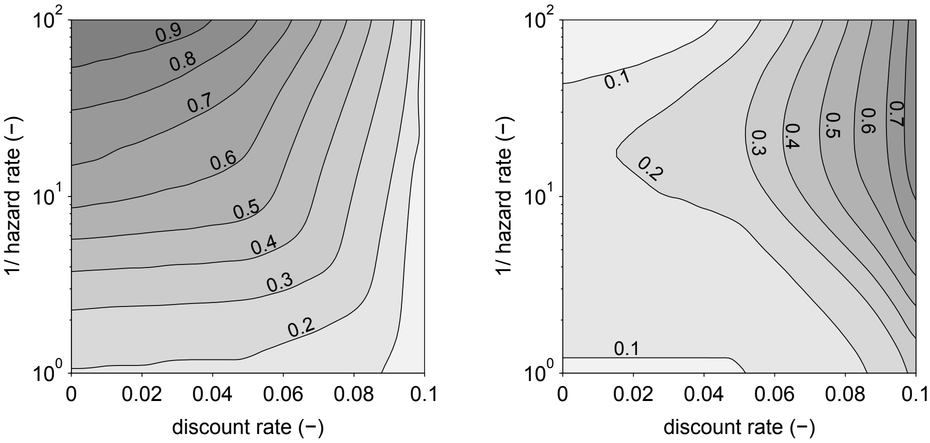
In this particular illustration we note that using the partial resolution at 10% of $1/h$ already leads to a considerable reduced domain $\alpha \in [\underline{\alpha}, \overline{\alpha}]$. This is due to the value of δ, where $\delta = 0.025$ means that already at 10% of $1/h$ a large part of uncertainty is resolved. This is shown in Figure 4.13, where the prior distribution of α is uniformly distributed and the posterior of α for $x = 0.1$ already has a considerable reduced domain.



Structural measures

Non-structural measures

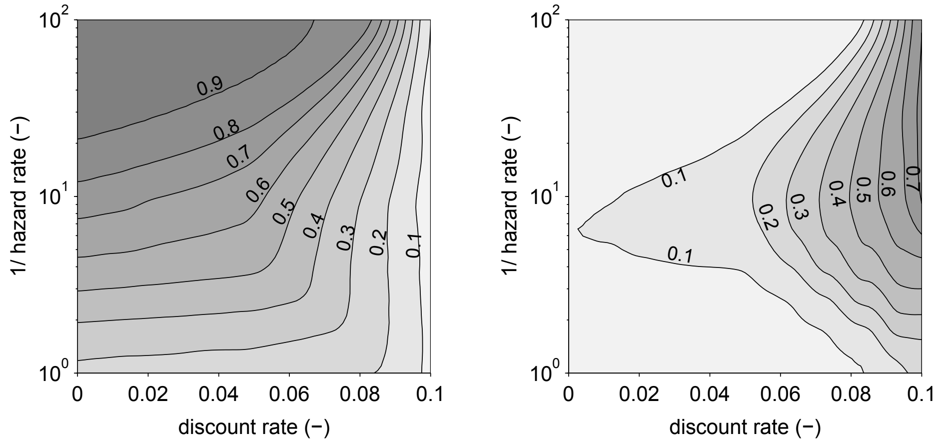
Figure 4.14: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ €, $D_{max} = 750$ € and $x = 0.1$, the calculation is based on step-size 0.01 for interval α.



Structural measures

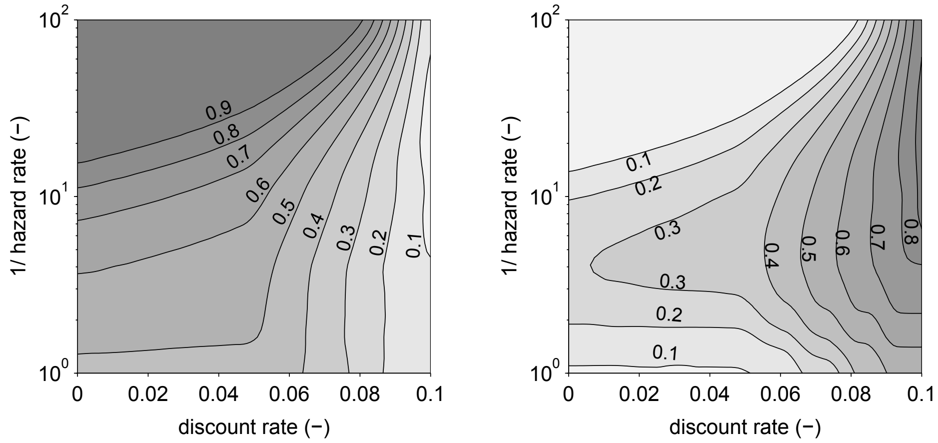
Non-structural measures

Figure 4.15: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ €, $D_{max} = 1500$ € and $x = 0.1$, the calculation is based on step-size 0.01 for interval α.)



Structural measures Non-structural measures

Figure 4.16: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ €, $D_{max} = 750$ € and $x = 0.5$, the calculation is based on step-size 0.01 for interval α.



Structural measures Non-structural measures

Figure 4.17: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. $C_s = 1000$ €, $C_n = 500$ €, $c_s = 150$ €, $c_n = 200$ €, $D_{max} = 1500$ € and $x = 0.5$, the calculation is based on step-size 0.01 for interval α.

4.5 Implications for flood management

In this section we discuss the implications of the model outcome for decision-making in flood management. We first relate our model results to real-world decision making in flood protection. In the second part of this section we discuss four biases that could occur in flood protection decision-making and show their implications in the context of our model results.

4.5.1 Decision-making

Our definition of structural and non-structural measures—based on their ratio of fixed costs relative to annual costs—is slightly different from the one used by for instance Kundzewicz (2002, 2009). In this more general interpretation structural measures refer to engineering solutions (e.g. dikes, dams, reservoirs, diversions, channels, flood-ways), while non-structural measures refer to legislation, regulatory, and institutional solutions (e.g. watershed and landscape management, laws and regulations, zoning, economic instruments, and early warning systems). Although engineering solutions often induce relatively large fixed costs, this may not hold for all engineering solutions. A similar observation can be made with respect to regulatory and institutional solutions. Hence, while largely overlapping, the two definitions are not identical. Our definition of structural measures makes it possible to rank any set of measures according to their cost structure, where one engineering solution can be considered more structural than another (implying that it has a higher fixed-to-annual-costs ratio).

Over the last decades, flood management has shown a shift from structural to non-structural approaches. In many cases, decision-makers have decided to invest in a mix of both structural and non-structural measures. In the UK case, for instance, Penning-Rowsell et al. (2006) discuss such a gradual shift in flood management policy through the 20^{th} century. This shift from structural flood defense to flood risk management was stimulated by two major flood events in 1998 and 2000 (Tunstall et al., 2009). Although it is impossible to foresee future policy changes, Penning-Rowsell et al. (2006) predict a “greater reliance on a location-specific mix of non-structural and people-centred flood mitigation actions, and lessening of the influence of traditional approaches”.

A similar shift has occurred in many other countries and basins, of which we mention two. In Germany, after the 2002 floods in the Elbe, new concepts for flood protection measures were developed, which included a combination of structural and non-structural measures. These non-structural measures were said to focus on the prevention and mitigation of the impact of floods (Petrow et al., 2006). In Canada, flood management reform was also triggered by major flood events. In this context, De Loë (2000) states that "responses to the flooding problem have evolved in Canada from an emphasis on controlling 'water out of place' through structural measures such as dams and dikes, to managing human behaviour using zoning to keep development away from hazardous areas."

The model shows that if climate change uncertainty is present, then non-structural measures become a more attractive option for flood protection. This shift in flood management is ongoing in many countries. There is increasing attention for non-structural measures in flood protection policy. Non-structural measures are often more flexible, less committing, and more sustainable (Kundzewicz, 2002). These characteristics are important, especially in the current context of uncertain impacts of climate change on flood damage, as discussed in Section 4.1. Both the flexibility and the commitment argument put forward by Kundzewicz (2002) show up as the key factors for investment decisions in our model setting. In the examples listed above (Germany, UK, Canada), the effects of climate change have entered the discussion on flood protection decision-making.

In conventional analyses of decision-making on flood protection, the role of uncertainty has often been ignored. Brouwer and Van Ek (2004), for instance, analyse several flood protection options in the context of a Dutch case study. They assess the trade-offs between costs and benefits of three policy measures (dike heightening, land use change and floodplain restoration), and conclude that the preference for one of these measures depends on the value attached to future ecological and socio-economic benefits. They do not, however, consider how uncertainty would affect the attractiveness of these measures. Current Dutch flood protection policies encompass a mix of structural and non-structural measures, and the public debate on protection from flood events revolves around the uncertainty of future flood events due to climate change. Without a doubt this uncertainty affects the optimal investment decision. Rosenberg et al. (2010) argue that for investments in storm-water infrastructure "the range of predicted change...is much too large to provide a basis for engineering design". This statement implies that when the impacts of climate change are uncertain, no sound investment decision in flood protection can be made. The results from our model, however, show that in the presence of uncertainty about the range of predicted climate change, it is possible to determine the optimal investment decision, where the prior distribution of α represents the prior knowledge of the decision-maker. A uniform distribution was implemented to indicate that no value is favored over any other. Furthermore, waiting for new information about climate change impacts, which reduces uncertainty, does not imply a complete postponement of the investment decision today. Depending on the level of uncertainty, though, structural or non-structural measures may be preferred. Specifically, our model results show that the decision-maker's preference for structural and non-structural measures depends on the combination of the cost structure of these measures, the level of the discount rate and uncertainty due to climate change.

An additional factor that may lead to a preference for non-structural measures is the short horizon of decision-makers in many institutional contexts. There is a disincentive to invest in structural measures if most benefits of these investments will only occur over a very long time horizon. Non-structural measures are more profitable in the short run, in terms of lower investment costs and may therefore provide a politically feasible alternative to structural measures.

4.5.2 Possible biases of decision-makers

The results of the three models developed in Sections 4.2–4.4 suggest that decision-makers may be biased in four ways. A first bias is that decision-makers could mistakenly assume a discrete set of states of nature (true or false) and ignore the continuous character of these impacts. The consequences of this bias can be analysed using the models of Sections 4.2 and 4.3. Clearly, if climate change is either true or false, this implies that the decision-maker assumes that either $\alpha = 0$ or $\alpha = 1$, while in fact the full range of values $\alpha \in [0, 1]$ is possible. This constraint on values of α gives more weight to the two extreme values in the initial decision to invest. Due to concavity of the damage function this leads to lower expected damages. Hence, this bias causes decision-makers to under-invest.

A second bias is related to the damage function and is discussed by Petrow et al. (2006) in the context of flood protection in the Elbe basin. They find that decision-makers in the Elbe basin have focused too much on one possible flood scenario, corresponding to the area affected by a 100-year return period flood. In the context of our model, decision-makers may assume one damage estimate corresponding to one particular value of α, instead of considering the full range of possible damage depending on the full range of possible climate change impacts. The result of this bias is similar; it leads to under-investment in flood protection measures.

A third bias occurs when decision-makers consider only one measure instead of a set of possible structural and non-structural measures. Each combination of the discount rate and climate change uncertainty implies a different optimal investment combination, as can be seen from the continuous models in Sections 4.3 and 4.4. Ignoring one (or more) measures would yield a sub-optimal investment decision. Whether this implies too much or too little investment in structural or non-structural measures depends on the set of measures considered, as well as their cost structure. Our model results show that ignoring one or more measures distorts the interplay between structural and non-structural measures that is required for optimal investment.

A fourth and last bias is the incorrect assumption that uncertainty will be resolved at once at a future date, while in reality this resolution is likely to be gradual. The difference in results between Sections 4.3 and 4.4 illustrates the implications of this bias. The optimal mix of structural and non-structural measures is affected by this bias. The option of adjusting the investment decision when more information arrives induces lower initial investments, however this depends on the timing of the intermediate investment moment and the level of partial resolution revealed.

4.6 Conclusion

Climate change uncertainty affects the decision to invest in flood protection measures. The model developed in this chapter shows how an optimal investment strategy in flood protection measures reduces the risk of under- or over-investment to the decision-maker. Our results confirm the argument of Kundzewicz et al. (2010), who state that "flood preparedness (adaptation) measures should consist of an optimal, site-specific, mix from the menu of structural and non-structural measures". We provide a theoretical foundation for this argument using a model of decision-making under uncertainty. A combination of the discount rate, climate change uncertainty, and the cost structure of structural and non-structural measures determines the optimal mix of investments in these measures. Our model results predict that if climate change uncertainty is present, then non-structural measures become a more attractive option for flood protection.

The results from our continuous-state two-period model show that the level of the optimal mix of the structural and non-structural measures is affected by the level of the maximum annual flood damage and the expected arrival time of full resolution. If maximum annual flood damage and the expected arrival time of full resolution of uncertainty increases, this leads to longer periods of possible damages, which increases the level of the optimal mix of flood protection measures. The proportion of structural and non-structural measures in the optimal policy is affected by the cost structure, discount rate and expected arrival time of full resolution of climate change uncertainty. If the discount rate increases, this puts less weight on future costs, which decreases the investment in structural measures and increases in non-structural measures.

In the three-period model, the inclusion of an intermediate decision moment, where partial resolution of uncertainty is observed, leads to lower investments in structural and non-structural measures. However, the level of reduced damages is impacted by the timing of the intermediate investment moment and the level of partial resolution revealed. If the intermediate investment decision is in the near future, only little evidence is collected to update the prior distribution, thus only little knowledge about the true state is revealed. Still the investment decision can be updated to reduce the stream of possible future damages, therefore the initial investment decision is lower in anticipation of the intermediate decision moment. If the intermediate investment decision is later in time, more evidence is collected and the posterior distribution has a smaller range, which comes closer to full resolution of uncertainty. However, as the period between the initial investment moment and the intermediate moment is longer, the period of possible damages is longer, thus a higher level of initial investment will be justified compared to early partial resolution of uncertainty. When the decision-maker is able to increase the capacity to reduce climate change uncertainty through additional research, there is a trade-off between the cost of research and the level of reduced damages.

Thus, we conclude that the optimal investment decision today depends strongly on the cost structure of the adaptation measures and the discount rate, especially the ratio of fixed and weighted annual costs of the measures. We define the optimal investment decision today as a specific mix of measures that minimizes the total expected net cost. A higher level of annual flood damage and later resolution of uncertainty in time increases the optimal investment decision. Furthermore, the optimal investment decision today is influenced by the possibility of the decision-maker to adjust his decision at a future moment in time.

Although we have used river flooding as our motivating example, the results of this chapter may apply more widely. A relevant application is coastal areas where climate change induces uncertain sea-level rise and related flood events. Again, different types of measures can be considered, that vary in their cost structure. Examples are dike heightening, beach nourishment, and restrictions on development and land use.

One possible extension to our model relates to the distinction between structural and non-structural flood protection measures. In this chapter, we distinguished between the two based on their cost structure only, so that the measures are perfect substitutes. Alternatively, the measures can be modeled as imperfect substitutes or as partly complementary, so that the interplay between the two measures is taken into account.

Appendix 4.A

A motivation for the functional form of the function $\mathcal{D}(\alpha, s, n)$, introduced in Section 4.3 is the following. Consider the capacity of existing flood protection measures to be based on a known Gumbel distribution for peak flow discharge. The Gumbel distribution is a commonly used distribution for the modeling of peak river flow. Its probability density function is

$$g(w; \mu, \beta) = \frac{z \exp(-z)}{\beta} \quad \text{with} \quad z = \exp\left[\frac{w - \mu}{\beta}\right], \tag{4.56}$$

where w denotes peak discharge, β is the scale parameter and μ is the location parameter. Without loss of generality, we assume that climate change affects the scale parameter only, by scaling β by $(1 + \alpha\gamma)$, with $\gamma > 0$, such that $(1 + \alpha\gamma)\beta \geq \beta$.[5] Climate change leads to an increase of the scale parameter, implying 'fatter tails' in the distribution of peak discharge. This corresponds to evidence on increased variance of peak river flow (IPCC, 2007a). The maximum increase in the scale parameter depends on the level of γ, i.e. if $\gamma = 1$ the scale parameter is doubled at maximum. We assume that there is at maximum one flood per year, correlating to that year's peak discharge. In year t, peak discharge w causes a flood if $w > \overline{w}$, where $\overline{w}$ denotes the maximum capacity provided by current protection measures. Damage from floods is increasing and concave in $w - \overline{w}$, so that we have the following damage function:

$$h(w, \overline{w}) = \begin{cases} \lambda(w - \overline{w}) & \text{if } w > \overline{w} \ , \\ 0 & \text{otherwise,} \end{cases}$$

where $\lambda(w - \overline{w})$ is increasing and concave. Expected damage D in a given year can now be calculated as the integral of the damage function over the Gumbel distribution of w (whose scale parameter is affected by α):

$$D = \int_0^\infty [h(w, \overline{w})] \ g(w) dw. \tag{4.57}$$

[5] Alternatively we could have modified the location parameter μ so that average peak discharge increases and thereby the probability of extreme peak discharges. Under our model assumptions, both methods lead to a similar—concave—relation between α and D.

Recall that we assumed that each combination of measures suffices to adapt to the impacts of climate change if $s+n \geq \alpha$. This assumption allows us to use the difference of α and $s+n$ in order to account for the mitigating effect of flood protection measures on damage. Hence we summarise the relation between climate change impact α, flood protection measures $s+n$, and expected damage D in the function $\mathcal{D}(\alpha, s, n) = D_{max}\sqrt{\alpha - s - n}$, that is increasing and concave in $(\alpha - s - n)$, with $\mathcal{D}(\alpha - s - n \leq 0) = 0$.[6]

[6]This requires that the damage function $\lambda(w - \overline{w})$ is sufficiently concave.

5. Local coastal adaptation to climate change uncertainty: application of an investment decision model*

Climate change impacts low-lying coastal areas around the world. Local adaptation to climate change through the implementation of coastal flood protection measures reduces the vulnerability of coastal areas. Uncertainty about climate-induced sea-level rise and the existence of different types of flood protection measures requires careful analysis of the expected costs and benefits of investment measures. We make a distinction between structural and non-structural coastal flood protection measures. The objective of this chapter is to show how climate change uncertainty affects the decision to invest in coastal flood protection measures when local costs and benefits are taken into account. We use an investment model, developed in Chapter 4, that incorporates flexible timing of investment decisions and scientific uncertainty on the extent of climate change impacts related to sea-level rise to derive the optimal investment combination of a structural and non-structural flood protection measure. The model allows decision-makers to cope with the uncertain impacts of climate change on the probability of a flood event and its associated flood damage. The model aims to minimise the risk of under- or over-investment in coastal flood protection, and is applied to a coastal area in the midwestern part of the Netherlands. Based on stakeholder perceptions, we adjust the model to consider a more integrated coastal management approach. Results show that the optimal investment decision today depends strongly on the cost structure of the adaptation measures and the level of the included ancillary benefits.

*This chapter is based on De Bruin et al. (2011), to be submitted.

5.1 Introduction

Future climate change impacts, such as sea-level rise, increased precipitation and more extreme weather events (IPCC, 2007c), will further increase the vulnerability of low-lying coastal areas around the world, and challenge coastal managers to plan for these impacts (Tompkins et al., 2008). Especially the uncertain magnitudes and effects of sea-level rise on coastal areas (Hunter, 2010; Ng and Mendelsohn, 2005; Nicholls and Cazenave, 2010; Oude Essink et al., 2010) puts pressure on coastal management to implement long-term coastal protection policies. Nicholls and Cazenave (2010) discuss the impact of sea-level rise on coastal zones, and indicate that global sea-level rises "will almost certainly accelerate through the 21st century and beyond because of global warming, but their magnitudes remains uncertain". Katsman et al. (2008) present sea-level rise ranges for the northeast Atlantic Ocean, emphasising that due to large uncertainties in estimating all separate contributions to sea-level rise, it is not possible to present single values. In more recent work, Katsman et al. (2011) consider high-end scenarios for local sea-level rise along the Dutch coast. They first update the projection of global mean sea-level rise on the basis of different elements such as global mean thermal expansion, and the contribution of glaciers, ice caps and ice sheets and then consider more local contributions to sea-level rise, with local variations due to ocean circulation changes as well as the elasto-gravity effects. For the year 2100 Katsman et al. (2011) give "a plausible high-end scenario of 0.40 to 1.05 m rise" for the Dutch coast, however the projections do include uncertainties for long-term projections. According to Lowe and Gregory (2010) "sea level rise is likely to continue, but the rise by 2100 is almost certain to be below two meters". For the implication of sea-level rise for Europe's coasts, Tol et al. (2008) argue that "the details about future sea-level rise and climate change, which matter a great deal to adaptation, are highly uncertain. Decision making about adaptation needs to take account of this uncertainty." Irreversible investment costs, and the cost of postponing investment decisions, strengthen the effect of climate change uncertainty on investment in adaptation measures. Thus there is a need to inform the decision-maker about the optimal investment decision in adaptation, through explicitly modeling uncertainty, flexible timing of the investment decision, the effect of gradual resolution of uncertainty, and irreversible and reversible costs and benefits of adaptation measures.

We use an investment decision model, developed in Chapter 4, that takes into account uncertain climate change impacts, aimed at reducing the risk of over- and under-investment. We adjust the model to include stakeholder perspectives into the decision model, as these perspectives are very important when considering the effect of climate change on a local scale. Through including the costs and benefits of local adaptation options that are able to deal with the uncertain impacts of climate change, we provide input for the challenges faced by coastal management decision-makers.

Existing studies that focus on decision-making and coastal protection against the effects of climate change deal with the costs and benefits of protection versus inundation. For example, Ng and Mendelsohn (2005) study whether coastal sites in Singapore should be protected, under different sea-level rise scenarios, given the protection costs and the value of the possible inundated land. Yohe and Neumann (1997) analyse different market-based adaptation options for coastal protection in the United States, and discuss how uncertain long term future sea-level rise may affect the evaluations done by coastal planners based on cost-benefit evaluation. They conclude that cost-benefit evaluation is an appropriate assessment tool, but that regular impact assessment of the coastal area should take place, based on updated information regarding sea-level rise projections, the local development planning and costs of protection. Anthoff et al. (2010) study the regional economic impact of three sea-level rise scenarios, focused on protection or retreat of coastal areas. They use an integrated assessment model to show that in densely populated coastal areas, the optimal response to sea-level rise, taking into account damage and protection costs, is protection of the coastal areas. Yohe et al. (2011) argue that the definition of a baseline is essential when comparing the costs and benefits of adaptation options, especially when benefits are avoided damages due to the implementation of these adaptation options. They compare the effect of a baseline with perfect foresight and one with no-foresight on the policy response towards coastal storm events and sea-level rise scenarios. Van Vuren et al. (2004) present the economic, spatial and ecological consequences of coastal policies for the Netherlands. These existing studies, however, do not explicitly model climate change uncertainty combined with the effect of gradual resolution of uncertainty, take into account the effects on local communities or make a distinction between different types of flood protection measures.

The objective of this chapter is to show how climate change uncertainty affects the decision to invest in coastal flood protection measures. We apply a model that incorporates flexible timing of investment decisions and scientific uncertainty on the extent of climate change impacts related to sea-level rise to derive the optimal investment combination of a structural and non-structural flood protection measure. In addition, based on stakeholder perceptions we adjust the model to consider a more integrated coastal management approach, by taking into account the effects of investment in coastal adaptation on the recreational and nature sector. The investment decision model is applied to a coastal area in the midwestern part of the Netherlands.

We make a distinction between structural and non-structural flood protection measures. We define structural and non-structural coastal flood protection measures based on their ratio of fixed costs relative to annual costs. A structural measure has high fixed investment cost and low annual costs, where as a non-structural measure has no or very low fixed investment cost and high annual costs. Note that this definition is slightly different from the one used by for example Kundzewicz (2002, 2009), where in a more general interpretation structural measures refer to engineering solutions (e.g. dikes, dams, reservoirs, channels, floodways), while non-structural measures refer to legislation, regulatory and institutional solutions (e.g. watershed and landscape management, laws and regulations, zoning, economics instruments, and early warning systems). Although engineering solutions often induce relatively large fixed investment costs, this may not hold for all engineering solutions. A similar observation can be made with respect to regulatory and institutional solutions. Hence, while largely overlapping the two definitions are not identical. We assume that uncertain impacts of climate change may require a combination of structural and non-structural measures, as a dike construction or beach nourishment alone might not be a sufficient coastal protection measure to deal with uncertain future climate change impacts on coastal areas.

Implementation of local adaptation measures to climate change directly affects people living and working in coastal communities, and as Few et al. (2007) point out "climate change impacts might conceivably have wider socioeconomic repercussions for local communities, such as loss of key infrastructure, impacts on tourism revenue and disruption of business". It is therefore important to incorporate the local indirect effects of implementation of coastal protection measures, and include stakeholder perceptions into the investment decision model. Only a few studies combine decision support tools with stakeholder perceptions to adapt to climate change. Few et al. (2007) and Tompkins et al. (2008) present a scenario-based stakeholder engagement method for coastal planning in the UK, which brings together coastal stakeholder preferences, climate change and long term coastal planning. They point out that the challenge in coastal management "relates to the trade-offs between risks faced and costs experienced...but that successful implementation of coastal management decisions can only be reached with support of stakeholders."(Few et al., 2007; Tompkins et al., 2008) They applied the method to two case studies on coastal planning in the UK and conducted participatory research workshops with stakeholders, focusing especially on questions of timing and scale of adaptive decision-making to long-term climate risks. It is important that decision-makers understand and take into account stakeholder perceptions towards climate change uncertainty and adaptation options in their long term investment decisions in coastal flood protection.

In this chapter we use and adjust the investment decision model developed in Chapter 4 to analyse the optimal investment decision for coastal flood protection, given the uncertainty about the future effects of climate change for the coastal town Katwijk, located along the midwestern coastal zone of the Netherlands. As local adaptation requires the involvement of local stakeholders, we adjust the model specification by including additional benefit categories, based on the discussion with the stakeholders on a more integrated coastal management approach. Such an integrated coastal management considers not only the direct aim of coastal management related to flood protection, but also local objectives related to improvement of the recreational, nature and spatial quality of the area. We identify the direct and indirect costs and benefits of a structural and non-structural flood protection measure, and further discuss the implications of the results of the investment decision model and the stakeholder perception on the optimal investment combination of a structural and a non-structural flood protection measure.

The chapter is structured as follows. In Section 5.2 we describe the model to establish the optimal investment decision under uncertainty. In Section 5.3 we apply the model to a case study of coastal flood protection in the Netherlands, which includes a qualitative assessment of the stakeholder perceptions related to the case study. The implications of the model are discussed in Section 5.4, followed by the conclusion.

5.2 Investment decision model

In this section we present a model that incorporates flexible timing of investment decisions and scientific uncertainty related to climate change impacts on a coastal area, in a continuous-state two period setting based on Chapter 4. The model allows decision-makers to cope with the uncertain impacts of climate change on flood damage from climate-induced sea-level rise. The model aims to minimise the risk of under- or over-investment.

The probability and damage of a sea flood event depend on the height of the high tide and sea-level rise. The height of the high tide is uncertain, and depends on a combination of wind direction, wind speed, storm surge, and tidal effects. In this chapter we use the expression of the probability of a flood and for simplification we assume that the probability of a flood event is the probability that the height of the high tide exceeds the dike height (e.g. Eijgenraam, 2006; Van Dantzig, 1956).[1] Flood damage occurs when the height of the high tide exceeds the capacity of the current flood protection measures.

[1] In the Netherlands a distinction is made between exceedance probability and flood probability. The exceedance probability, also named the threshold probability, is the probability that the water level exceeds the design water level or design standard, where the dike does not breach. The design standard is set by the national government. The flood probability, the failure probability of the flood defense, is the probability that the land behind the flood defense becomes inundated because the defense fails.

When sea level rises, the probability of a flood event rises and the level of flood damage increases. The additional flood damage resulting from sea-level rise can be mitigated by implementing additional flood protection measures. In our model we assume that there is uncertainty about the exact level of climate-induced sea-level rise, which will be resolved over time. The decision-maker invests in additional flood protection measures to reduce the additional damage. This, however, does not mean that with additional investments no flood damage occurs as the height of high tide still remains uncertain. When the height of the high tide in combination with sea-level rise exceeds the updated capacity of the flood protection measures, this may result in even higher damages, as the area flooded is larger and the inundation level is higher. In this chapter we solely focus on mitigating the additional flood damage resulting from uncertain climate-induced sea-level rise and for the moment will not consider the additional flood damage resulting from uncertainty about the height of the high tide.

The model focuses on the direct costs of flood protection measures, where the costs of protection relate to the construction (fixed investment cost) and maintenance (annual costs) of the protection measures. The fixed investment cost, a one-off irreversible cost, depends on the scale of the protection measure. The annual costs are reversible, in the sense that when the decision-maker has over-invested in flood protection, there may be no need to continue with high annual protection costs (such as costs related to beach nourishment or dike maintenance), because a lower level of protection offered by the flood protection in place is sufficient. A part of the annual activities then can be stopped and their costs will no longer be made. The annual costs depend on the scale of the protection measure. The measures reduce the expected flood damage due to climate change. Flood damage costs occur if the area is inundated; implementing flood protection measures reduces the flood damage costs. In addition, indirect costs and benefits related to, for example, the effect on tourism revenues or the ecological improvement as a result of the implementation of a protection measure are included in the model.

In this chapter we define structural and non-structural coastal flood protection measures by their ratio of fixed costs relative to annual costs. Where a structural measure constitutes a hard-engineering solution, with high fixed investment cost and low annual costs, a non-structural coastal flood protection measure is defined as a soft-engineering solution solely based on, for example, a sand construction, which is less committing and more flexible than a structural measure (Klein et al., 2001; Kundzewicz, 2002). The optimal combination of structural and non-structural flood protection measures, is that which minimises expected total costs, where total costs include investment and damage costs. The investment decision is influenced by the discount rate and the timing of the resolution of uncertainty, where a short-term resolution of climate change uncertainty may lead to postponing the investment decision.

For the damage costs of a flood event, we distinguish between direct and indirect damages. We follow the definition of Jonkman et al. (2008), where "the direct damages are caused by direct contact with water, while the indirect damages are caused by interruption and disruption of the social and economic activities that have resulted from the direct damages". The direct damage costs include direct material damage (e.g. damage to households, businesses, infrastructure, environment, etc.) and direct immaterial damage related to fatalities, injuries and evacuations resulting from a flood event. To take into account the immaterial damages, a monetary value can be attached to a human victim in the context of a flood event, based on the value of a statistical life (Bočkarjova et al., 2011). Indirect flood damages are, for example, damage for businesses outside the flooded area, and societal disruption (Jonkman et al., 2008).

Other indirect costs and benefits relate to local effects on tourism revenue, nature and spatial quality. The implementation of coastal flood protection measures will negatively affect the tourism sector during construction. After implementation it may benefit the tourism sector as additional recreational facilities, such as cycle and walking paths, are constructed.[2] The spatial quality of the town related to the direct link between the coastal town and the sea decreases due to the implementation of the coastal flood protection measures; the actual distance between the town and sea will increase and there is a restriction of the 'panoramic view' toward the sea from the town. The implementation of the structural and non-structural protection measures will have a positive effect on the ecological value of the area, as the measures will entail an increase of highly valued nature area. Note, that in our model setting the indirect benefits will be defined as negative costs.

The total costs of the investment in coastal flood protection measures include: fixed and annual costs, flood damage costs, costs due to negative temporary tourism effect and spatial quality, and negative costs (benefits) due to recreational and nature improvements. The objective of the decision-maker is to minimize expected total costs of coastal flood protection under climate change uncertainty. As the timing of investment in flood protection measures is flexible, the investment decision may be postponed until more information about the effects of climate change on flood damage becomes available.

[2]Note that from a national point of view there may be no effect for the tourism sector as the tourists might go to other coastal areas. As this model takes a local focus on the implementation of coastal flood protection, we therefore take into account local and regional costs and benefits.

5.2.1 Model specification and structure

The key variables of the model are the level of climate change impacts that affect the potential level of flood damage and the structural and non-structural flood protection measures that reduce flood damage. The variables α, s and n are the result of normalisation based on the variable A that denotes the increase in potential flood damage due to climate change, and S and N that denote the decrease of flood damage due to investment in structural and non-structural measures, all defined in monetary units. These variables have been normalised by taking ratios using the maximum annual flood damage (D_{max}), which leads to $s = S/D_{max}$, $n = N/D_{max}$, and $\alpha = A/D_{max}$.

Thus, the effect of climate change on flood damage is reflected by an interval that represents a continuum of states of nature for sea-level rise, $\alpha \in [0, 1]$, with a specified probability distribution $f(\alpha)$ on the interval $[0, 1]$. In the two-period model, at $t = 0$ the value of α is unknown, whereas at $t = \kappa$ the true value of α is revealed.[3]

The decision variables of the model, the structural (s) and non-structural (n) flood protection measures, serve to stem the increase of flood damage and thus the expected flood damage caused by climate change. We assume a continuum of structural and non-structural measures with $s \in [0, 1]$ and $n \in [0, 1]$, where each set of a structural and a non-structural measure does not exceed $s + n \leq 1$. Note that s and n are normalised and dimensionless such that for example $s = 0$ reflects no investment in structural measure while $s = 1$ reflects an investment that would be sufficient to prevent the largest possible flood damage. When the true value of α is revealed, the optimal combination of measures suffices to adapt to the impacts of climate change if the decrease of flood damage due to investment in structural and non-structural measures is equal to or larger than the increase in flood damage due to climate change ($s + n \geq \alpha$). We assume that structural and non-structural measures are additive, for example strengthening of the current defense with a dike construction (structural measure) is accompanied by a sand construction (non-structural measure).

Flood damage function

The flood damage function for the model is based on the relation between α, s and n, and the maximum annual flood damage and enables us to express the decrease of flood damage due to investment in flood protection measures in monetary terms. The variable α represents the climate change effect on flood damage, where the climate change effect is solely based on the climate-induced sea-level rise, thus when $\alpha = 0$ this means

[3]When the true value of α is revealed, there still remains uncertainty about the height of the high tide. In this chapter we focus on the resolution of climate change uncertainty and how this impacts the investment decision to mitigate the additional flood damage from climate-induced sea-level rise.

that is no additional flood damage occurs due to zero climate-induced sea-level rise, when $\alpha = 1$ this implies that sea levels rise so severely that they induce the maximum damage that can reasonably be expected. A combination of structural and non-structural flood protection measures suffices to adapt to the impacts on flood damage due to climate change. We assume that there is at maximum one flood event per year, that occurs when the height of high tide and sea-level rise exceed the capacity of the current protection measures. The damage function is assumed to be linear, following Tol (2002b) and Anthoff et al. (2010) who define that dryland loss is a linear function of sea-level rise.

We assume a linear damage function $\mathcal{D}(\alpha, s, n)$, specified as

$$\mathcal{D}(\alpha, s, n) = \begin{cases} D_{max}(\alpha - s - n) & \text{if } \alpha - s - n > 0 \ , \\ 0 & \text{if } \alpha - s - n \leq 0, \end{cases}$$

When $\alpha - s - n \leq 0$, investment in flood protection is equal to or exceeds climate-induced flood damage, which implies that the damage costs are zero. If the impact of climate change on flood damage is maximum ($\alpha = 1$), and no structural and non-structural measures have been implemented ($s + n = 0$), $\mathcal{D}(\alpha, s, n) = D_{max}$.

Uncertainty

There is uncertainty about the level of impact of climate change on potential flood damage, where the parameter α denotes the level of climate-induced sea-level rise. In the model we consider gradual resolution of climate change uncertainty, however there is no intermediate investment decision where partial resolution of uncertainty is revealed before full resolution is reached at $t = \kappa$. In Chapter 4 we regarded the prior distribution of α within a Bayesian framework, where we assumed no prior knowledge except the boundary conditions of the distribution. This implied that the prior α is uniformly distributed, where no value is favored over any other.

With the range of possible climate-induced sea-level rise some authors consider a uniform distribution as they are reluctant to link any likelihood to the range of sea-level rise (Nicholls et al., 2011). However, we consider that we have some prior knowledge about the level of climate-induced sea-level rise, that affects the shape of our prior distribution. A trapezium distribution would allow for low weights on the tails of the range, with an equal weight over the central range. However, our prior belief puts more emphasis on the central value of the prior distribution. This is implemented with a symmetric triangular distribution.[4]

[4]Note that a truncated normal distribution can also be used, which gives an additional degree of freedom, to present our prior belief.

The uncertainty about the impact of climate change on flood damage is resolved at a future moment in time $t = \kappa > 0$, where κ is exponentially distributed with $f(\kappa) = he^{-h\kappa}$ (cf. Choi, 1991; Malueg and Tsutsui, 1997; Taylor and Karlin, 2002), such that $E[\kappa] = 1/h$, where h is the hazard rate. A lower value of h implies that the expected resolution of uncertainty is further away in time. An exponentially distributed arrival time is often used in the R&D literature, as this distribution is considered memoryless, which means that the probability of arrival of new information does not depend on the arrival of past information. Following Hennessy and Moschini (2006), we further assume that the new information is free and the arrival date is exogenous to the decision-maker.

Stakeholder perceptions

It is important to understand stakeholders' perceptions towards climate change uncertainty and adaptation options when considering long term investment decisions in coastal flood protection, as decisions in coastal flood protection directly affect the livelihoods of local stakeholders. Based on the stakeholder analysis, presented in Section 5.3.3, we adjust the investment model to consider a more local integrated coastal management approach that includes the effects of the adaptation measures on the recreational and nature sector in the case study.

5.2.2 Specification for the continuous-state two-period model

The investment and annual maintenance costs of the measures reflect the differences between structural and non-structural measures. Structural measures have irreversible fixed investment cost $C_s s$ and annual costs $c_s s$, and non-structural measures have irreversible fixed investment cost $C_n n$ and annual costs $c_n n$. We assume $C_s > C_n$ but $c_s < c_n$.[5] We assume all costs are linear in the scale of the measures (see Figure 5.1 for a graphical illustration). Note the intercept of the investment costs in Figure 5.1, which implies that there is a cost component to the measures that is incurred regardless of their scale. We denote this cost component by K_s for the structural measures and K_n for the non-structural measures.

The implementation of the structural and non-structural measure has two effects on the tourism revenues. The first effect is a temporary cost, T, which is incurred in the year of implementation of the measure, and is independent of the scale of the flood protection measure. Due to the construction of the flood protection measure, the tourism revenues will be affected, as less tourists will come to the coastal area. The second effect is that flood protection measures result in annual benefits related to tourism revenues and nature

[5] Structural measures have high fixed investment cost but low annual costs relative to non-structural measures.

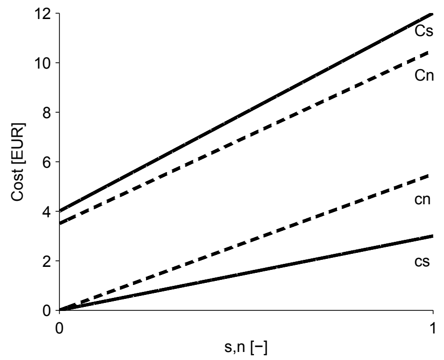


Figure 5.1: Shape of costs function structural and non-structural measures. Fixed investment cost function for a structural measure: $K_s + C_s s$ (−−), and annual cost function for a structural measure $c_s s$ (−).

quality, as the construction of the measures increases the recreational and nature quality of the area and compensates the decrease in spatial quality. We assume that the positive effects depend on the scale of the measures. Due to the modeling framework, we define the annual benefits as negative annual costs. Structural measures have tourism benefits $P_s s$ and nature benefits $N_s s$, and non-structural measures have tourism benefits $P_n n$ and nature benefits $N_n n$.

The decision-maker may make two erroneous decisions in the two-period model, with regards to the level of investment made at $t = 0$. First, it may turn out at $t = \kappa$ that the decision-maker has under-invested (i.e. $s_0 + n_0 < \alpha$). In that case he can upgrade his initially implemented measures to the optimal level (i.e. to $s_0 + n_0 + s_\kappa + n_\kappa = \alpha$), while incurring the possible additional fixed costs $C_s s_\kappa$ or $C_n n_\kappa$, and increase of annual costs by $c_s s_\kappa$ or $c_n n_\kappa$. Obviously, excessive risk is experienced over the period from $t = 0$ to $t = \kappa$. Second, it may turn out at $t = \kappa$ that the decision-maker has over-invested (i.e. $s_0 + n_0 > \alpha$). In that case he cannot retrieve his initial investment (i.e. $C_s s_0$ and $C_n n_0$ are irreversible), but he can reduce his annual costs such that $s_0 + n_0 + s_\kappa + n_\kappa = \alpha$ from time $t = \kappa$ onward.

The decision-maker's objective is to choose s_0 and n_0 in order to minimise the discounted expected realised cost $R^i(s_0, n_0, s_\kappa, \kappa, \alpha)$ that consists of fixed and annual costs, damage costs, tourism and nature benefits of the flood protection measures, using a continuous time discount rate r. Note that κ and α are independent random variables. First, we solve the decision-maker's problem to choose s_κ and n_κ at time $t = \kappa$ as a function of the s_0 and n_0 chosen at $t = 0$ and the α revealed at $t = \kappa$. Second, given this choice at $t = \kappa$, the optimal levels of s_0 and n_0 are selected at $t = 0$. The problem is expressed as a minimisation of a stream of expected costs:

$$E[R^{i_{min}}] = min\left\{E[R^1], ..., E[R^i], ..., E[R^N]\right\} \tag{5.1}$$

When we consider a specific combination of s_0 and n_0, denoted as $\{s_0, n_0\}^i$, we are able to derive the $E[R^i]$, which is defined as

$$E[R^i] = E[I_0^i] + E[D_0^i] + E[I_\kappa^{ij_{min}}] \tag{5.2}$$

This includes the expected investment cost, $E[I_0^i]$, and expected damage cost, $E[D_0^i]$ for the period starting at $t = 0$, and the expected adjustment cost, $E[I_\kappa^{ij_{min}}]$ [6], for the period starting at $t = \kappa$. Based on the discussion above, we exclude any damage costs from time κ onward, because we assume optimal adjustment at time $t = \kappa$. We now further specify each element of the expected investment $E[R^i]$, where we follow Chapter 4, and solve for the exponential distribution of κ and substitute the constraint $n_\kappa = \alpha - s_0 - n_0 - s_\kappa$ to obtain the expected investment and damage functions as a function of the random variable α. First the discounted cost stream is defined, followed by the expected discounted stream based on the probability distribution for κ and α.

Investment cost starting at $t = 0$

The expected investment function includes investment costs, specified for planning costs, implementation costs, annual costs and costs for the tourism and nature sector and is a function of $\{s_0, n_0\}^i$ and random variable κ.

$$\begin{aligned} I_0^i &= K_s + K_n + T + C_s s_0^i + C_n n_0^i \\ &\quad + \int_0^\kappa \left(c_s s_0^i + c_n n_0^i + (P_s + N_s) s_0^i + (P_n + N_n) n_0^i \right) e^{-rt} dt \\ &= K_s + K_n + T + C_s s_0^i + C_n n_0^i \\ &\quad + \left(\frac{c_s s_0^i + c_n n_0^i + (P_s + N_s) s_0^i + (P_n + N_n) n_0^i}{r} \right) (1 - e^{-r\kappa}) \end{aligned} \tag{5.3}$$

$$\begin{aligned} E[I_0^i] &= \int_0^\infty I_0^i f(\kappa) d\kappa \\ &= K_s + K_n + T + C_s s_0^i + C_n n_0^i \\ &\quad + \left(\frac{1}{h + r} \right) (c_s s_0^i + c_n n_0^i + (P_s + N_s) s_0^i + (P_n + N_n) n_0^i) \end{aligned} \tag{5.4}$$

[6] Superscript ij_{min} indicates the minimisation over a range of $\{s_\kappa, n_\kappa\}$ values at $t = \kappa$ given $\{s_0, n_0\}^i$.

Damage cost starting at $t = 0$

The expected damage function includes the discounted stream of damage costs, and is a function of $\{s_0, n_0\}^i$ and random variables κ and α.

$$\begin{aligned} D_0^i &= \int_0^\kappa \mathcal{D}\big(\alpha, s_0^i, n_0^i\big)e^{-rt}dt \\ &= \frac{\mathcal{D}\big(\alpha, s_0^i, n_0^i\big)}{r}(1 - e^{-r\kappa}) \end{aligned} \tag{5.5}$$

$$\begin{aligned} E[D_0^i] &= \int_0^1 \int_0^\infty D_0^i f(\kappa) f(\alpha) d\kappa d\alpha \\ &= \left(\frac{1}{h+r}\right) \int_0^1 \mathcal{D}\big(\alpha, s_0^i, n_0^i\big) f(\alpha) d\alpha \end{aligned} \tag{5.6}$$

Adjustment cost starting at $t = \kappa$

The expected adjustment function includes investment costs, specified for planning costs, implementation costs, annual costs and costs for the tourism and nature sector and is a function of $\{s_0, n_0\}^i$, $\{s_\kappa\}^j$, and random variables κ and α. $I_\kappa^{ij_{min}}$ is derived by taking the minimisation of the set $\big\{I_\kappa^{i1}, ..., I_\kappa^{ij}, ..., I_\kappa^{iM}\big\}$, over the range of $\{s_\kappa\}^j$ values that ranges from 1 to M, and is based on the interval $[-s_0, \alpha - s_0]$. The lower and upper bound of the interval are based on the constraint $s_\kappa \geq -s_0$ and $n_\kappa \geq -n_0$, where the latter constraint can be rewritten in the following way. Note that $n_\kappa \geq -n_0$, is the same as $n_0 + n_\kappa \geq 0$, which can be written as $\alpha - s_0 - s_\kappa \geq 0$, which is equal to $\alpha - s_0 \geq s_\kappa$, and presents the upper-bound of the interval for s_κ. As the constraint $\alpha - s_0 - s_\kappa \geq 0$ applies, there is no need to add a maximum constraint to the c_n, P_n and N_n part of the function.

$$\begin{aligned} I_\kappa^{ij} = &\Big(K_s + K_n + T + C_s \max\big\{0, s_\kappa^j\big\} + C_n \max\big\{0, \alpha - s_0^i - n_0^i - s_\kappa^j\big\}\Big)e^{-r\kappa} \\ &+ \int_\kappa^\infty \Big(c_s\big(s_0^i + s_\kappa^j\big) + c_n\big(\alpha - s_0^i - s_\kappa^j\big) + P_s\big(s_0^i + s_\kappa^j\big) + N_s\big(s_0^i + s_\kappa^j\big) \\ &\quad + P_n\big(\alpha - s_0^i - s_\kappa^j\big) + N_n\big(\alpha - s_0^i - s_\kappa^j\big)\Big)e^{-rt}dt \\ = &\Big(K_s + K_n + T + C_s \max\big\{0, s_\kappa^j\big\} + C_n \max\big\{0, \alpha - s_0^i - n_0^i - s_\kappa^j\big\}\Big)e^{-r\kappa} \\ &+ \Big(\frac{c_s}{r}(s_0^i + s_\kappa^j) + \frac{c_n}{r}\big(\alpha - s_0^i - s_\kappa^j\big) + \frac{P_s}{r}(s_0^i + s_\kappa^j) + \frac{N_s}{r}(s_0^i + s_\kappa^j) \\ &\quad + \frac{P_n}{r}\big(\alpha - s_0^i - s_\kappa^j\big) + \frac{N_n}{r}\big(\alpha - s_0^i - s_\kappa^j\big)\Big)e^{-r\kappa} \end{aligned} \tag{5.7}$$

From Eq. 5.7 we define A_κ^{ij}:

$$\begin{aligned} A_\kappa^{ij} &= K_s + K_n + T + C_s \max\left\{0, s_\kappa^j\right\} + C_n \max\left\{0, \alpha - s_0^i - n_0^i - s_\kappa^j\right\} \\ &\quad + \left(\frac{c_s}{r} + \frac{P_s}{r} + \frac{N_s}{r}\right)(s_0^i + s_\kappa^j) + \left(\frac{c_n}{r} + \frac{P_n}{r} + \frac{N_n}{r}\right)(\alpha - s_0^i - s_\kappa^j) \end{aligned} \tag{5.8}$$

Note that the parameters K_s, K_n and T are only taken into account in the year that a structural and/or non-structural measure is implemented at $t = 0$ and/or $t = \kappa$; thus for K_s this is when $s_0 > 0$ and/or $s_\kappa > 0$, for K_n when $n_0 > 0$ and/or $n_\kappa > 0$ and for T when $s_0 + n_0 > 0$ and/or $s_\kappa + n_\kappa > 0$.

The expected optimal discounted adjustment cost is defined as:

$$\begin{aligned} E[I_\kappa^{ij_{min}}] &= \int_0^1 \int_0^\infty A_\kappa^{ij_{min}} e^{-r\kappa} f(\kappa) f(\alpha) d\kappa d\alpha \\ &= \left(\frac{h}{h+r}\right) \int_0^1 A_\kappa^{ij_{min}}\ f(\alpha) d\alpha \end{aligned} \tag{5.9}$$

The minimum A_κ^{ij} can be written as a function of $\mathcal{C}_0$, $\mathcal{C}_1$, $\mathcal{C}_2$ and $\mathcal{C}_3$ which are defined as:

$$\begin{aligned} \mathcal{C}_0 &= \frac{c_s + P_s + N_s}{r} - \frac{c_n + P_n + N_n}{r} \\ \mathcal{C}_1 &= C_s + \frac{c_s + P_s + N_s}{r} - \frac{c_n + P_n + N_n}{r} \\ \mathcal{C}_2 &= C_s + \frac{c_s + P_s + N_s}{r} - C_n - \frac{c_n + P_n + N_n}{r} \\ \mathcal{C}_3 &= -C_n + \frac{c_s + P_s + N_s}{r} - \frac{c_n + P_n + N_n}{r} \end{aligned} \tag{5.10}$$

$\mathcal{C}_0$, $\mathcal{C}_1$, $\mathcal{C}_2$ and $\mathcal{C}_3$ are thus determined by the fixed investment cost, the annual costs and the tourism and nature benefits of the structural and non-structural measures. The present value of an infinite stream of annual costs is considered.

Table 5.1 presents the three possible combinations for $\mathcal{C}_1$ and $\mathcal{C}_2$ given that $\mathcal{C}_0 < 0$, namely: (1) $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$, (2) $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$ and (3) $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$. It is apparent that $\mathcal{C}_3$ does not introduce an additional combination in Table 5.1, because if $\mathcal{C}_0 < 0$ than $\mathcal{C}_3 < 0$, given that $C_n > 0$. Furthermore, the combination $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 \geq 0$ is not valid, as $\mathcal{C}_2$ cannot be positive if $\mathcal{C}_1$ is negative, given that $C_n > 0$. A similar overview can be presented for $\mathcal{C}_0 \geq 0$, however we do not consider this possibility and only focus on examples where $\mathcal{C}_0 < 0$.

For each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$, the minimum A_κ^{ij} is defined by how the level of α relates to the decision made at $t = 0$, $\{s_0, n_0\}^i$, i.e. if the decision-maker has over-or under-invested. There are three intervals: (1) $0 \leq \alpha \leq s_0^i$, (2) $s_0^i < \alpha \leq s_0^i + n_0^i$ and (3) $s_0^i + n_0^i < \alpha \leq 1$. The first and second interval represent over-investment, the third interval represents under-investment at $t = 0$. $\mathcal{C}_2$ determines the choice between structural and non-structural measures if the decision-maker has under-invested at $t = 0$ and therefore additional investment is required at $t = \kappa$. $\mathcal{C}_1$ determines whether the non-structural measures are reduced if the decision-maker has over-invested at $t = 0$ or if they are replaced by an investment in structural measures.

Furthermore, the minimum A_κ^{ij} is related to three additional parameters, namely $\mathcal{C}_4$, $\mathcal{C}_5$ and $\mathcal{C}_6$ which are defined in Eq. 5.11. In contrast to the parameters $\mathcal{C}_0$, $\mathcal{C}_1$, $\mathcal{C}_2$ and $\mathcal{C}_3$, these parameters are also related to α and the investment decision made at $t = 0$, $\{s_0, n_0\}^i$. The resulting minimum A_κ^{ij} given in Table 5.1, i.e. $A_{\kappa-1}^{ij_{min}}$ to $A_{\kappa-7}^{ij_{min}}$ are formulated in Eq. 5.12.

TABLE 5.1: Minimum A_κ^{ij} as a function of possible combinations $\mathcal{C}_1$ and $\mathcal{C}_2$ for $\mathcal{C}_0 < 0$ (Eq. 5.10). $A_{\kappa-1}^{ij_{min}}$ to $A_{\kappa-7}^{ij_{min}}$ are defined in Eq. 5.12; and $\mathcal{C}_4$, $\mathcal{C}_5$ and $\mathcal{C}_6$ in Eq. 5.11

	Combination 1 $\mathcal{C}_1 < 0$ $\mathcal{C}_2 < 0$	**Combination 2** $\mathcal{C}_1 \geq 0$ $\mathcal{C}_2 < 0$	**Combination 3** $\mathcal{C}_1 \geq 0$ $\mathcal{C}_2 \geq 0$
$0 \leq \alpha \leq s_0^i$	$A_{\kappa-1}^{ij_{min}}$	$A_{\kappa-1}^{ij_{min}}$	$A_{\kappa-1}^{ij_{min}}$
$s_0^i < \alpha \leq s_0^i + n_0^i$	$A_{\kappa-2}^{ij_{min}}$ if $\mathcal{C}_4 < 0$ $A_{\kappa-3}^{ij_{min}}$ if $\mathcal{C}_4 \geq 0$	$A_{\kappa-4}^{ij_{min}}$	$A_{\kappa-4}^{ij_{min}}$
$s_0^i + n_0^i < \alpha \leq 1$	$A_{\kappa-5}^{ij_{min}}$ if $\mathcal{C}_5 < 0$ $A_{\kappa-6}^{ij_{min}}$ if $\mathcal{C}_5 \geq 0$	$A_{\kappa-7}^{ij_{min}}$ if $\mathcal{C}_6 < 0$ $A_{\kappa-6}^{ij_{min}}$ if $\mathcal{C}_6 \geq 0$	$A_{\kappa-7}^{ij_{min}}$ if $\mathcal{C}_6 < 0$ $A_{\kappa-6}^{ij_{min}}$ if $\mathcal{C}_6 \geq 0$

$$\begin{aligned}
\mathcal{C}_4 &= K_s - K_n + \mathcal{C}_2(\alpha - s_0^i) + \mathcal{C}_0 n_0^i \\
\mathcal{C}_5 &= K_s - K_n + \mathcal{C}_2(\alpha - s_0^i) + C_n n_0^i \\
\mathcal{C}_6 &= K_s - K_n + \mathcal{C}_2(\alpha - s_0^i - n_0^i)
\end{aligned} \tag{5.11}$$

$$\begin{aligned}
A_{\kappa-1}^{ij_{min}} &= \frac{c_s + P_s + N_s}{r}\alpha \\
A_{\kappa-2}^{ij_{min}} &= K_s + C_s(\alpha - s_0^i) + \frac{c_s + P_s + N_s}{r}\alpha \\
A_{\kappa-3}^{ij_{min}} &= K_n + C_n(\alpha - s_0^i) + \frac{c_s + P_s + N_s}{r}(s_0^i - n_0^i) \\
&+ \frac{c_n + P_n + N_n}{r}(\alpha - s_0^i + n_0^i)
\end{aligned}$$

$$
\begin{aligned}
A_{\kappa-4}^{ij_{min}} &= \frac{c_s + P_s + N_s}{r} s_0^i + \frac{c_n + P_n + N_n}{r}(\alpha - s_0^i) \\
A_{\kappa-5}^{ij_{min}} &= K_s + T + C_s(\alpha - s_0^i) + \frac{c_s + P_s + N_s}{r}\alpha \\
A_{\kappa-6}^{ij_{min}} &= K_n + T + C_n(\alpha - s_0^i - n_0^i) + \frac{c_s + P_s + N_s}{r} s_0^i \\
&+ \frac{c_n + P_n + N_n}{r}(\alpha - s_0^i) \\
A_{\kappa-7}^{ij_{min}} &= K_s + T + C_s(\alpha - s_0^i - n_0^i) + \frac{c_s + P_s + N_s}{r}(\alpha - n_0^i) \\
&+ \frac{c_n + P_n + N_n}{r} n_0^i
\end{aligned}
\tag{5.12}
$$

There is only one expression for the minimum A_κ^{ij} per combination of $\mathcal{C}_1$ and $\mathcal{C}_2$ and the interval of α, if $K_s - K_n = 0$. In such a case where the structural and non-structural start-up costs are zero or equal to each other, $\mathcal{C}_4$ and $\mathcal{C}_5$ will always be negative and $\mathcal{C}_6 < 0$ if $\mathcal{C}_2 < 0$ and $\mathcal{C}_6 \geq 0$ if $\mathcal{C}_2 \geq 0$ (see Eq. 5.11).

A special case of Table 5.1 is given in Chapter 4 (Eq. 4.12 to 4.14) where K_s, K_n, T, P_s P_n, N_s and N_n are all set equal to zero. For each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$ there is only one expression for the minimum A_κ^{ij} per interval of α in Table 5.1. These expressions are equal to Eq. 4.12 to 4.14.

Each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$ marks a different adjustment strategy, if $K_s - K_n = 0$. Since $\mathcal{C}_1$ and $\mathcal{C}_2$ are a function of the discount rate (r), three regions of adjustment types can be defined along the discount rate axis. These regions were shown in Figure 4.3. For example, if the decision-maker has under-invested at $t = 0$ ($s_0^i + n_0^i < \alpha \leq 1$), he will make one of the following adjustments at $t = \kappa$:

1. The decision-maker will reduce all non-structural measures taken at $t = 0$ and adjust his investment decision with structural measures, when $\mathcal{C}_1 < 0$ and $\mathcal{C}_2 < 0$.

2. The decision-maker will resolve the under-investment gap with investment in structural measures and retain the same level of non-structural measures, when $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$.

3. The decision-maker will resolve the under-investment gap with investment in non-structural measures and retain the same level of structural measures, when $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$.

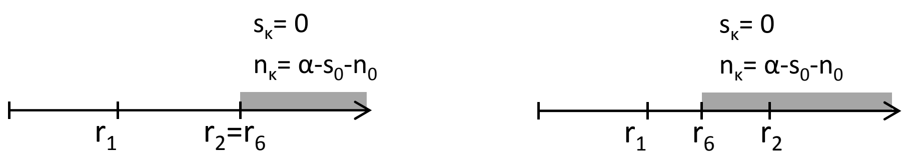
The decision-maker's preference to resolve the under-investment gap with investment in structural measures and retain the same level of non-structural measures when $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$, might change if the structural start-up costs (K_s) are higher than the non-structural start-up costs (K_n). This will occur when $\mathcal{C}_6$ becomes positive although $\mathcal{C}_2$ is negative (see Table 5.1). The decision-maker will then investment in non-structural measures and retain the same level of structural measures. As a consequence, the decision at $t = \kappa$ for combination 2 ($\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$) will equal the decision for combination 3 ($\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$) for those conditions where $\mathcal{C}_6$ becomes positive.

On the other hand, the decision-maker's preference to resolve the under-investment gap with investment in non-structural measures and retain the same level of structural measures when $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$, might change if the structural start-up costs (K_s) are lower than the non-structural start-up costs (K_n). This will occur when $\mathcal{C}_6$ becomes negative although $\mathcal{C}_2$ is positive (see Table 5.1). The decision-maker will then investment in structural measures and retain the same level of non-structural measures. As a consequence, the decision at $t = \kappa$ for combination 3 will equal the decision for combination 2 for those conditions where $\mathcal{C}_6$ becomes negative.

Thus, if $K_s - K_n \neq 0$, each combination of $\mathcal{C}_1$ and $\mathcal{C}_2$ does no longer mark a region of adjustment type along the discount rate axis. The regions will however be defined by the values of $\mathcal{C}_4$, $\mathcal{C}_5$ and $\mathcal{C}_6$. For example, the previous region formed by $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$ enlarges as the discount rate where $\mathcal{C}_6 = 0$ decreases, i.e. r_6 decreases. A schematic representation is given in Figure 5.2. r_6 is given by

$$r_6 = \frac{\Big((c_n + P_n + N_n) - (c_s + P_s + N_s)\Big)(\alpha - s_0^i - n_0^i)}{K_s - K_n + (C_s - C_n)(\alpha - s_0^i - n_0^i)} \tag{5.13}$$

Therefore, r_6 decreases if the structural start-up costs (K_s) increases with respect to the non-structural start-up costs (K_n), and if the gap between α and the investment at $t = 0$ decreases.



(a) $K_s - K_n = 0$

(b) $K_s - K_n \geq 0$

FIGURE 5.2: Schematic representation of the region of adjustment type along the discount rate axis for $s_0^i + n_0^i < \alpha \leq 1$ and $\mathcal{C}_6 \geq 0$ if (a) $K_s - K_n = 0$ and (b) $K_s - K_n \geq 0$.

The structural and non-structural start-up costs have a similar effect on the investment at $t = 0$ that minimise $E[I_0^i]$. The two regions of investment types at $t = 0$ that minimise $E[I_0^i]$ were given in Figure 4.4 for $K_s - K_n = 0$. The regions were defined in the plane spanned by the discount rate (r) and the expected waiting time for resolution of uncertainty ($1/h$). If $K_s - K_n \geq 0$ then the region of non-structural measures will cover a larger area. The intersection line will move to the left. This effect will however be less for higher values of $1/h$, as the total annual costs[7] will outweigh the fixed and start-up costs. This implies that the choice between structural and non-structural measures is set by $\mathcal{C}_0$ and therefore structural measures are preferred. The optimal investment decision at $t = 0$ that minimise $E[R^i]$ will relate to the regions defined by $\mathcal{C}_4$, $\mathcal{C}_5$ and $\mathcal{C}_6$ at the moment of full resolution of uncertainty and by the regions at $t = 0$.

5.3 Case study

In this section we introduce a case study of coastal flood protection in the coastal town Katwijk, to demonstrate the model described in Section 5.2 along with an analysis of the perceptions of key stakeholders that are directly impacted by uncertain impacts of climate change and the implementation of coastal flood protection measures. The case study presents a coastal town in the Netherlands, where the current coastal defense system needs to be updated to deal with current high water levels and future impacts of climate change.[8] The data used in the model application is based on preliminary data from a cost-benefit analysis of coastal flood protection measures for Katwijk that was conducted by ARCADIS (2010). The preliminary data was collected during the early phase of the planning process to update the current coastal defense system in Katwijk.

5.3.1 Introduction

The coastal zone of the Netherlands is vulnerable to the future effects of climate change, as the western part of the Netherlands is located below mean sea level and locates a large proportion of the national economic activities and population. Flood protection measures have been implemented and safety standards against flooding have been set after the southwestern part of the Netherlands was flooded in 1953. The Flood Protection Act regulates the responsibility of maintaining the safety standard against flooding and the division of tasks between government and regional authorities. In the Netherlands different institutes can be identified that have the primary responsibility or shared responsibility for the coordination, implementation and financing of coastal management. The national government is primarily responsible for updating the national coastal defense system, and upholding the safety standards for flood protection. Together with

[7]Total annual costs are the sum of the maintenance costs and the negative costs for the tourism and nature sector.

[8]Note that we only focus on the change of the sea-level as a future impact of climate change, we do not consider the impact of climate change on wind, wave and storm intensity as there is, at this moment, too much uncertainty to estimate the impact of climate change on these parameters (KNMI, 2009).

the regional Water Control Board, Province and local municipality the coordination and implementation of coastal management takes place. The national government is responsible for the direct financing of the coastal measures focused on maintaining the safety standards. The financial responsibility for any additional investment related to, for example improvement of spatial quality, construction of car parks, or development of nature areas, as part of integrated coastal management and development plans in addition to the protection measures, lies with regional and or local institutions.

For the Netherlands the possible consequences of climate change on coastal areas, specifically related to sea-level rise have been documented by the Commissie Waterbeheer 21^e eeuw (2000), the Royal Netherlands Meteorological Institute KNMI (2006, 2009) and the Deltacommissie (2008). A technical advisory committee on water defense (TAW, 2002) has developed official guidelines for the design of coastal flood protection measures that follow the sea-level rise scenarios documented by the Commissie Waterbeheer 21^e eeuw.

The implementation of coastal flood protection measures is primarily based on climate change scenarios of the Commissie Waterbeheer 21^e eeuw (2000), which indicates that relative sea-level rise (including subsiding land) will be between 10 and 45 cm by 2050 and between 20 and 110 cm by 2100. Updated scenarios from KNMI and Deltacommittee present sea-level rise for the Dutch coast excluding land subsidence. The KNMI study (KNMI, 2006, 2009) yields sea-level rise between 15 and 35 cm by 2050 and between 35 and 84 cm by 2100, which includes the insights from IPCC (2007c). The Deltacommissie (2008) estimated that based on a temperature increase of 6 degrees Celsius, regional sea-level rise between 55 and 120 cm by 2100 may be expected[9] and between 200 and 400 cm by 2200 for the Dutch coastal area, however due to large uncertainties this last range is very indicative. The reports indicate that for the Dutch coasts there is currently no evidence that shows intensification and higher frequency of storm surges due to climate change. Katsman et al. (2011) confirm that even though wind speeds are expected to increase along the Dutch coast, the "local extreme surge heights are largely unaffected by the increase in wind speed" as south-westerly winds increase due to climate change, and extreme surge heights are caused by north-westerly winds along the Dutch coast.

The case study presented in this chapter focuses on the coastal town Katwijk, located along the midwestern coastal zone of the Netherlands. The current coastal defense system in this town needs to be upgraded to ensure that the national safety standards for the area behind the coastal defense system remains intact. The uncertain future climate change impacts on sea-level rise, storm surges and precipitation complicate the

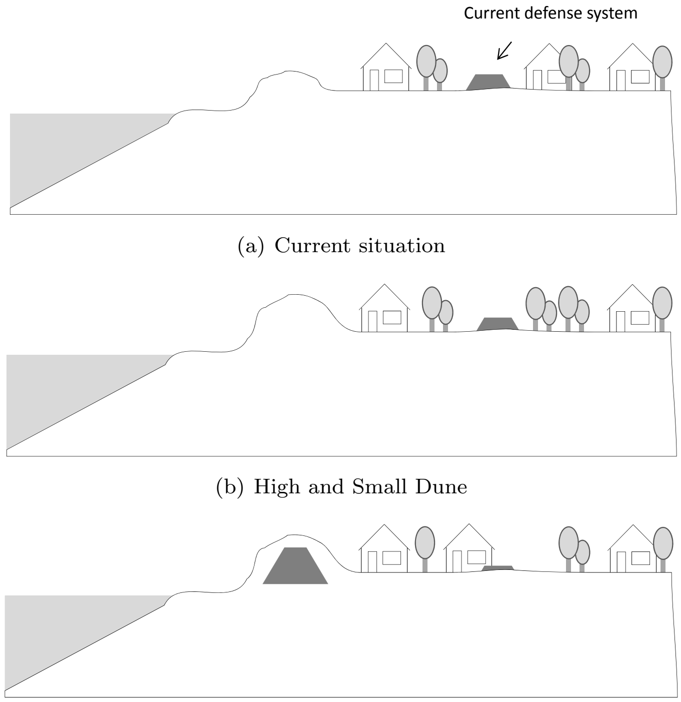
[9] When including mean land subsidence of over 10 cm in 2100, they indicate that relative sea-level rise will be between 65 and 130 cm by 2100, Deltacommissie (2008), p. 25.

investment decision in flood protection to maintain the safety level for this area. ARCADIS (2010) made an inventory of possible coastal flood protection measures that are able to withstand a wide range of future sea-level rise. Decision-makers responsible for coastal management need to decide on the optimal timing, mix and scale of the measures implemented for coastal protection in this area.

Monetary costs and benefits for the case study are the direct costs (investment and annual costs), direct and indirect flood damage costs, and indirect costs and benefits related to tourism revenue and nature quality of the area. Issues that are important for this case study, but not included in the model application due to lack of monetary values, are the indirect effects related to the *spatial quality* of the area. The implementation of the structural measure provides opportunities for further spatial development in the coastal town, as currently a part of the town is located between the coastal protection and the sea. As a result of the implementation of the measures this area will become located behind the coastal protection, which means that regulations that prevented further spatial development in this area will be lifted. However, the spatial quality related to the direct link of the coastal town with the sea decreases due to the implementation of the flood protection measures, the actual distance increases and there is restriction of the view towards the sea. An additional effect relates to *nuisance* during the implementation of structural measures, such as noise, reduced air quality and visual obstruction that occurs during construction of the measures.

5.3.2 Coastal protection measures

Different coastal flood protection measures are identified as appropriate measures for the application of the investment model to this case study. Figure 5.3 gives a graphical representation of the current situation (Figure 5.3a) and the flood protection measures. The non-structural coastal flood protection measure is a soft-engineering solution solely based on a sand construction and is considered to be less committing and more flexible than the structural measure. The implementation of a dike in a dune is considered to be the structural measure, as it is a hard-engineering solution with high fixed investment cost and lower annual costs. The measures are differentiated by the fixed-to-annual costs ratio. The construction of the *high and small dune* (Figure 5.3b) entails large amounts of sand placed directly along the town—sea line, restricting the panoramic view of the coastline. The measure will increase the distance between town and sea slightly and creates additional dune nature areas. The *dike in dune high* (Figure 5.3c) measure involves the construction of a dike in a dune, which is lower than the high and small dune alternative, thus maintaining part of the panoramic view. In addition it provides the opportunity to combine local development plans with the measure, where it is possible to construct an underground parking garage in front of the dike.



(a) Current situation

(b) High and Small Dune

(c) Dike in Dune High

Figure 5.3: A graphical illustration of the current situation (a), non-structural coastal flood protection measure (b) and structural coastal flood protection measure (c).

5.3.3 Stakeholder perceptions

Understanding stakeholders' perceptions towards climate change uncertainty and adaptation options is important when considering long term investment decisions in coastal flood protection. Decisions on coastal flood protection are made by indirect stakeholders[10], although they directly affect the livelihoods of direct stakeholders living and working in the coastal area. Based on the qualitative assessment we incorporate the perceptions of stakeholders into our investment model to increase the effectiveness of coastal flood protection investments.

We used a qualitative approach to gain insight into stakeholders' attitude toward the future impacts of climate change and coastal flood protection measures for the case study

[10]Stakeholders with a stake in decision-making related to coastal management.

of the coastal town described above. We organised two workshops to understand how key stakeholders in coastal management perceive climate change impacts and coastal flood protection measures. Two groups of key stakeholders were identified, stakeholders with direct personal stake in coastal impacts, living and working in the coastal area (direct stakeholders), and stakeholders with a stake in decision-making related to coastal management (indirect stakeholders). The aim of the workshops was to use the obtained insights towards uncertain climate change impacts as input for the investment decision model presented in Section 5.2. The workshops included presentations, general discussions and group discussions. During the workshop, the individual perceptions were identified through questionnaires. Two questionnaires recorded individual attitudes to, and perceptions of climate change, future climate change impacts, investment in coastal flood protection and preferences for a specific coastal flood protection measure. Questions concerning climate change and coastal flood protection were given before the group activities, and questions regarding their concerns about the costs and benefits that determined their preference for a specific coastal flood protection measure after the group activities. Participants ranked statements in terms of agreement and disagreement using a five point Likert scale (strong disagree, disagree, neither agree nor disagree, agree, strongly agree).

Taking into account uncertainty about climate change impacts, the direct stakeholders prefer to implement the coastal measures in steps, as they are currently sceptical towards information about flood probabilities and long term predictions of climate change impacts. They prefer to update the coastal measures when new information about the impacts of climate change on sea-level rise becomes available. The stakeholders living and working in the coastal town have a strong connection with the beach and sea, and prefer measures that keep this link intact (distance from the town to the sea and view). They prefer an 'integrated approach', where upholding safety levels is combined with improvement of the spatial quality.

Both direct and indirect stakeholders acknowledge that climate change is occurring, however the direct stakeholders state that they believe the issue has been blown out of proportions.

The indirect stakeholders agree that the Netherlands will experience negative consequences of climate change, where future climate change impacts (sea-level rise, extreme precipitation and storm surges) will increase flood risks along the coastal areas in the Netherlands, resulting in local flood events. The direct stakeholders are more sceptical towards the future climate change impacts for the Netherlands, especially relating to local flood events resulting from extreme precipitation and storm surges. The indirect stakeholders also agree with the statement that the Netherlands will, besides negative consequences, also experience positive consequences from climate change.

The indirect stakeholders disagree with the statement that the currently identified options for coastal flood protection will provide protection up to 2050 or even up to 2100, they believe that additional protection will be required related to possible sea-level rise. The direct stakeholders agree with the statement that the current protection measures provide protection up to 2100 and that no additional measures will be required to deal with future sea-level rise. One direct stakeholder states that there is a need for additional research on the level of future sea-level rise.

The stakeholders ranked reasons for implementing a specific coastal protection measure. The indirect stakeholders regarded 'safety (reduction of flood risk)', 'flexibility of protection measure' and 'future climate change' as the most important aims of implementing a coastal protection measure. The direct stakeholders ranked 'safety (reduction of flood risk)', together with 'tourism', 'spatial quality' and 'parking space' as important reasons for the implementation of a coastal protection measure. The ranking of the important reasons for implementation is different between the two groups. The indirect stakeholders are involved in the coastal management primarily for the upgrading of the current safety standard, and prefer flexible options that can be adapted to future climate change. The direct stakeholders question if the future ranges of sea-level rise are correct. Their primary concern with regard to the implementation of a coastal protection measure is a combination of safety and the integration of the measure within the development plans for the town, including spatial quality and parking problems, and the possible effect on tourism revenues. The direct stakeholders focus on a local integrated coastal management plan, integrating safety requirements with local development plans.

The stakeholders also ranked the most relevant costs and benefits that influence the choice for a specific coastal protection measure. Both groups indicated that 'investment costs', 'maintenance costs' and 'safety benefits' are the most important costs and benefits. Direct stakeholders prefer a more 'integrated' approach, a combination of upholding the safety levels measure with spatial issues, such as improved recreational and nature quality. It should be noted that one of the major differences between the direct and indirect stakeholders is that the indirect stakeholders have a political and administrative responsibility for upholding the safety levels along the coast, whereas for direct stakeholders, their living environmental is directly impacted by climate change impacts and investment in coastal protection measures.

5.3.4 Application of investment decision model

In order to apply the model described in the previous section we need to define a number of parameter values. Furthermore, we include the preference of the stakeholders for a more integrated coastal management approach by including costs and benefits of local effects related to the implementation of coastal flood protection.

Flood damage function

The starting point to define the damage function is to select a climate change scenario for the Dutch coastal area. In this chapter we focus on a 4 degrees Celsius rise in global mean atmospheric temperature as starting point, as we assume that the current mitigation efforts and delayed atmospheric effects of the already emitted greenhouse gases will not be sufficient to limit the increase of the global temperature to 2 degrees Celsius, which has been defined in the Cancun 2010 climate change agreements.

The climate change scenarios for the Netherlands are defined by the Royal Netherlands Meteorological Institute (Katsman et al., 2008; KNMI, 2006), and project a range of sea-level rise under the moderate (2 degrees Celsius) and warm (4 degrees Celsius) scenario for 2100. We have selected the warm (4 degrees Celsius) climate change scenario, with a projected range of 0.30 to 0.80 m, where this projected range is the relative sea-level rise at the Dutch coast, corrected for land subsidence. We assume a triangular shaped distribution with mean of 0.5 m.

In addition we need to determine the maximum annual flood damage (D_{max}). The parameter value for flood damage resulting from inundation as a result of a flood event. The value of this parameter is based on Deltares (2010), which estimates a monetary value for the damage from a flood event resulting from different levels of sea-level rise for the coastal town Katwijk. Different levels of sea-level rise were used to estimate flood damage for the coastal area Katwijk, where the case study presented in this chapter is situated. We assume a linear relation between the water level and the resulting damage. A flood event, with the current flood protection measures in place and no climate-induced sea-level rise, has an expected monetary damage of € 3200 million and an expected casualty number of 283 flood victims (Deltares, 2010). When climate-induced sea-level rise is 1.30 m, and the flood protection measures are updated with the full knowledge of the level of sea-level rise, a flood event has an expected monetary damage of € 8200 million and an expected casualty number of 1079 flood victims (Deltares, 2010). The reason for such high values of flood damage is the location of the coastal town along the midwestern coastal zone of the Netherlands, where a flood event affects an economically important and densely populated area.

When we do not update the flood protection measure, but climate-induced sea-level rise is expected to rise to 130 cm, we assume that total flood damage will have tripled.[11] This implies that the total amount of flood damage is € 9600 million. As the amount of flood damage with updated flood protection measured is € 8200 million, the difference (€ 1400 million), is the additional flood damage from sea-level rise. Investing the maximum amount in flood protection measures mitigates this additional flood damage. In our model we regard 1.0 m as the maximum level of climate-induced sea-level rise, but for illustrative purposes have decided to use this difference for the D_{max} parameter value in the model. In the results section we will discuss the sensitivity of the results to the level of D_{max}. Because we focus on the additional damage resulting from climate-induced sea-level rise we assume that sea-level rise will always result in additional damage costs, where a flood event with 1.0 m sea-level rise results in € 1400 million additional damages.

The flood damage function $\mathcal{D}(\alpha, s, n)$ maps damage as a function of uncertain climate change impact α, mitigated by flood protection measures $s + n$. We assume that each combination of measures suffices to adapt to the impacts of climate change if $s + n \geq \alpha$. This assumption allows us to use the difference between α and $s + n$ in order to account for the mitigating effect of flood protection measures on damage. We assume that the function $\mathcal{D}(\alpha, s, n) = D_{max}(\alpha - s - n)$ is linear in $(\alpha - s - n)$, with $D(\alpha - s - n \leq 0) = 0$, and where $D_{max} =$ € 1400 million.

Additional parameter values

The values of the additional parameter are based on ARCADIS (2010), which are preliminary results of a cost-benefit analysis of coastal protection for Katwijk, and consider the design of the coastal flood protection measures in relation to a climate-induced sea-level rise of 0.30 m. In the model we have normalised the parameters, in such a way that we assume that a structural measure of 0.3 mitigates the damages resulting from a sea-level rise of 0.30 m. We furthermore assume that the maximum annual flood damage relates to sea-level rise of 1.0 m. These assumptions, and a linear relation, lead to the parameter values for the start-up costs (K_n, K_s), investment cost (C_s, C_n), and maintenance costs (c_s, c_n) of both the structural and non-structural measures, and the temporary (T) and permanent effect (P_s, P_n) for the tourism sector and the effect on nature improvement (N_s, N_n) for both the structural and non-structural measures. Table 5.2 presents the preliminary values from ARCADIS (2010) and Table 5.3 presents the adjusted param-

[11] This factor is based on a report that discusses flood risk for the unembanked areas of the city of Rotterdam, where they estimate that under a 1.30 m sea-level rise scenario potential flood damage increases by approximately a factor 4 (Veerbeek et al., 2010). As our case study area is less densely populated we have assumed a factor 3. In Section 5.3.5 the sensitivity of the level of flood damage will be further discussed.

eter values for the model calculation. We assume that 20% of the investment costs is reserved as start-up cost. We use a triangular distribution for $f(\alpha)$, with a minimum value of 0 m, a mean of 0.5 m and a maximum value of 1.0 m sea-level rise.

Table 5.2: Preliminary costs of coastal flood protection measures based on ARCADIS (2010) (1000 €)

	High & small dune (non-structural)	Dike in dune high (structural)
Costs		
Fixed investment cost	29458	38320
Annual costs	48	36
Cost tourism sector during implementation	473	473
Annual negative costs (benefits)		
Tourism revenues	-620	-1250
Extra nature (per ha)	-45	-29

When at $t = \kappa$, it is optimal to implement additional investments, this requires the removal of the constructed spatial infrastructure (such as cycle and walking paths) that was part of the investment made at $t = 0$. Currently, we do not explicitly include these additional costs in the model, as their exact magnitude is unclear. Table 5.2 shows a substantial difference for permanent tourism effect of the implementation of structural or non-structural flood protection measures. The difference is due to dimensions of the measures, the height of the non-structural measure exceeds the height of the structural measure, therefore with the implementation of the non-structural measure the link between the town and the sea is disrupted which reduces the benefits for the tourism sector. We furthermore include a constraint that sets a minimum investment scale for the structural and/or non-structural flood protection combination, this fulfills the requirement of achieving the minimum national safety standards for this particular coastal town with regard to coastal protection. We have set the constraint at $s_0 + n_0 \geq 0.2$ to incorporate this requirement.

5.3.5 Results

Based on values given in Table 5.3 we present the optimal initial investment (s_0 and n_0) for the intervals $r \in (0, 0.1]$ and $h \in [0.01, 1]$. The interval for r implies that we check solutions for non-negative discount rates up to 10%. The interval for h implies that we check solutions for $E[\kappa]$ between 1 and 100 years (recall that $E[\kappa] = 1/h$). In addition, the effect of an over-estimation of the damage costs is presented, by reducing the maximum additional annual flood damage with related to 1.0 m climate-induced sea-

Table 5.3: Costs of coastal flood protection measures (1000 €)

Parameter	Description	Value[a]
D_{max}	Maximum additional annual flood damage with 1.0 m climate-induced sea-level rise	1400000[b]
K_s	Start-up cost structural, independent of the scale of s, but only if $s > 0$	7664
C_s	Investment structural dependent on level s	102187
c_s	Annual structural dependent on level s	120
K_n	Start-up cost non-structural, independent of the scale of n, but only if $n > 0$	5891
C_n	Investment cost non-structural dependent on level n	78553
c_n	Annual non-structural dependent on level n	160
T	Tourism - temporary effect, independent of the scale of s or n, but only if $s + n > 0$	473
P_s	Tourism - permanent effect, dependent on level s	-4167[c]
P_n	Tourism - permanent effect, dependent on level n	-2067[c]
N_s	Nature quality improvement, dependent on level s	-97[c]
N_n	Nature quality improvement, dependent on level n	-150[c]

[a] Values are based on own calculations using ARCADIS (2010) as a starting point.
[b] Based on Deltares (2010)
[c] Negative cost (benefit)

level rise, with a factor 10. The minimisation of expected costs is solved using MATLAB. The results are presented in the surface plots of Figures 5.4 to 5.7.

Costs

First, only the investment, maintenance and damage costs of the structural and non-structural flood protection measures are considered. This implies that K_s, K_n, T, P_s P_n, N_s and N_n are all set equal to zero. The combinations of $\mathcal{C}_1$ and $\mathcal{C}_2$, defined in Eq. 5.10, mark different investment strategies because $K_s - K_n = 0$. r_1, defined as the discount rate where $\mathcal{C}_1 = 0$, equals 0.4×10^{-3} and r_2, defined as the discount rate where $\mathcal{C}_2 = 0$, equals 1.7×10^{-3}. As a consequence, $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 \geq 0$ covers the main part, i.e. $r \in (1.7 \times 10^{-3}, 0.1]$.

If $\mathcal{C}_1 \geq 0$ then the fixed plus weighted total annual costs of structural measures are greater than or equal to the weighted total annual costs of non-structural measures. If $\mathcal{C}_2 \geq 0$ then the fixed plus weighted total annual costs of structural measures are greater than or equal to the non-structural measures. As a consequence, the optimal investment is to invest in non-structural measures. Structural measures are not justifiable. Moreover, the investment in non-structural measures will increase if the expected waiting time for resolution of uncertainty $(1/h)$ increases because the period of possible damages increases. The type of investment does not change if the damage costs change, because they have no effect on the values of $\mathcal{C}_1$ and $\mathcal{C}_2$. Only the amount of non-structural measures is affected.

Figures 5.4 and 5.5 present the resulting optimal investment decision at $t = 0$ as function of r and h, for flood damages of € 140 million and € 1400 million. It is apparent that even for shorter periods of possible damages, i.e. shorter expected waiting times for resolution of uncertainty $(1/h)$, the decision-maker invests at a high level in non-structural measures. The costs of over-investment do not outweigh the high damage costs. This effect reduces as the damage costs decrease.

Costs and benefits

Next, the additional effects of the flood protection measures on the tourism and nature sector are included following the stakeholder perspectives. r_1, defined as the discount rate where $\mathcal{C}_1 = 0$, becomes 0.02 and r_2, defined as the discount rate where $\mathcal{C}_2 = 0$, becomes 0.09. Therefore, three combinations of $\mathcal{C}_1$ and $\mathcal{C}_2$ are possible over the range of $r \in (0, 0.1]$, which was similar for Example 3 of Chapter 4. However, as we also include the structural and non-structural start-up costs, $\mathcal{C}_1$ and $\mathcal{C}_2$ do no longer mark regions of different investment strategies. The regions will be defined by the values of $\mathcal{C}_4$, $\mathcal{C}_5$ and $\mathcal{C}_6$, see Eq. 5.11.

The difference between K_s and K_n is € 1.8 million, and thus $K_s - K_n > 0$. As a consequence $\mathcal{C}_6 \geq 0$ for $\mathcal{C}_2 \geq 0$. This implies that for $r \in (r_2, 0.1]$ it is only optimal to invest in non-structural measures. Moreover, this region of investment in non-structural measures expands towards lower values of the discount rate since $K_s - K_n > 0$. The expansion is towards the previous region formed by $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$. This can be observed in Figures 5.6 and 5.7, which present the resulting optimal investment decision at $t = 0$ as function of r and h, for flood damages of € 140 million and € 1400 million. However, the effect of the higher structural start-up costs reduces as the expected waiting time for resolution of uncertainty $(1/h)$ increases. The total annual costs will outweigh the fixed and start-up costs. Therefore, the extension towards lower discount rates is less for higher $1/h$.

For smaller discount rates, the total annual costs outweigh the fixed and start-up costs ($\mathcal{C}_3 < 0$ and $\mathcal{C}_5 < 0$). The total annual structural costs are mainly reduced due to the relative high benefits for the tourism sector related to the implementation the structural measures. Therefore, investment in structural measures becomes preferable, even for higher discount ranges, i.e. towards the previous region formed by $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$. The transition between structural and non-structural measures does not take place as the two regions have moved toward each other on the account of the start-up costs and relative high total annual non-structural costs.

Finally, the decision-maker will try to further reduce the possible damages due to under-investment at $t = 0$ if the damage costs increases. Therefore, the investment increases as the damage costs increases. The intersection line in the previous region formed by $\mathcal{C}_1 \geq 0$ and $\mathcal{C}_2 < 0$, is a function of the possible gap between α and the investment at $t = 0$ (see Eq. 5.13). The region of non-structural measures will therefore move towards lower discount rates if the damages increases.

If we only include the investment and maintenance costs of the structural and non-structural measures the results show investment in non-structural measures and none in structural measures. As the annual damage costs for this case study are high the investment level of the decision at $t = 0$ of the flood protection measures is high, even when the resolution of uncertainty is in the near future. Investing to prevent the high damage costs dominates the investment decision at $t = 0$. With the inclusion of the local adaptation costs related to the tourism and nature sector investment, the preference shifts to an investment structure similar to Example 3 of Chapter 4. For low discount rates, structural measures are optimal, for high discount rates non-structural measures are optimal, separated by a transition zone. If, moreover, the structural start-up costs are taken into account that exceed the non-structural start-up costs, the region of optimal investment in structural measures expands to higher discount rates, whereas the region of optimal investment in non-structural measures expands to lower discount rates. This intersection line is a function of the possible gap between α and the investments. If the damage costs increase, it becomes optimal to invest as much as possible. Therefore the intersection line moves as a function of the damage costs. Given the present cost structure, the intersection line moves globally towards lower discount rates if the damage costs increase. These results show that it is important to consider the local adaptation costs and benefits, as they impact the optimal investment decision at $t = 0$.

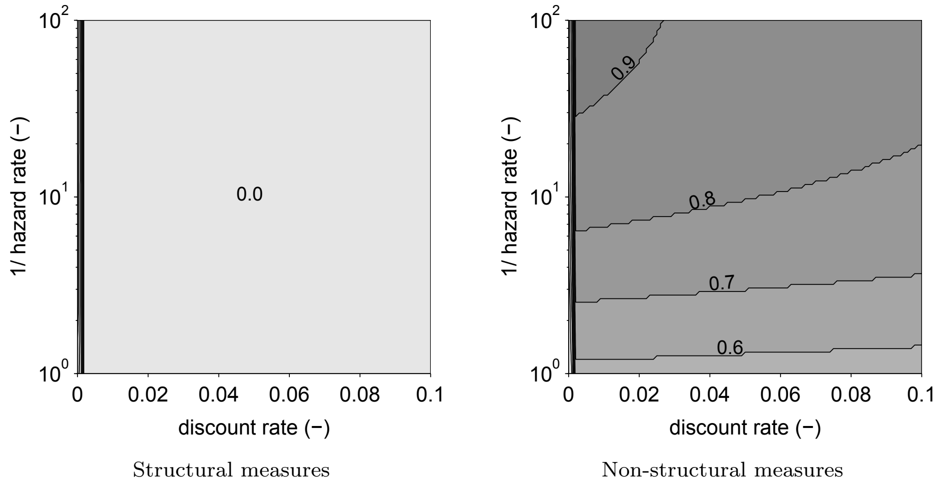


Figure 5.4: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. C_s = 102187 €, C_n = 78553 €, c_s = 120 €, c_n = 160 € and D_{max} = 140000 €. (x 1000) (Calculation based on step-size 0.01 for interval α.)

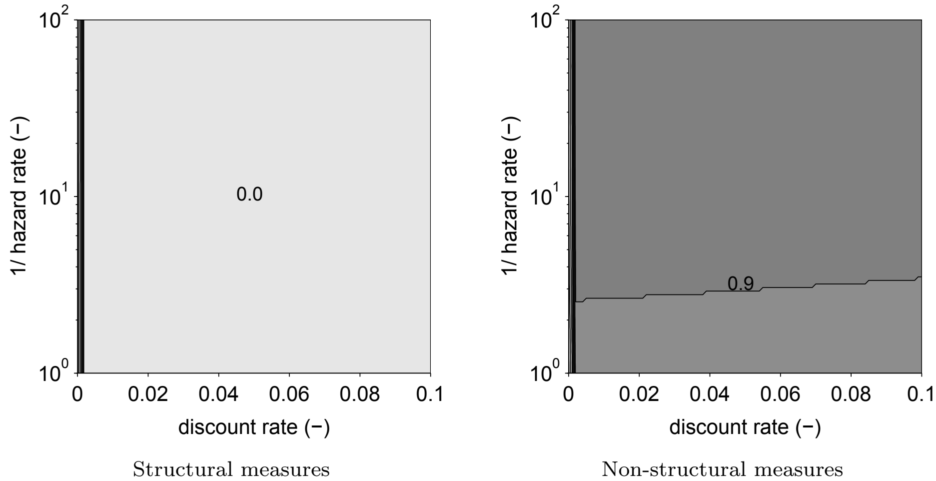
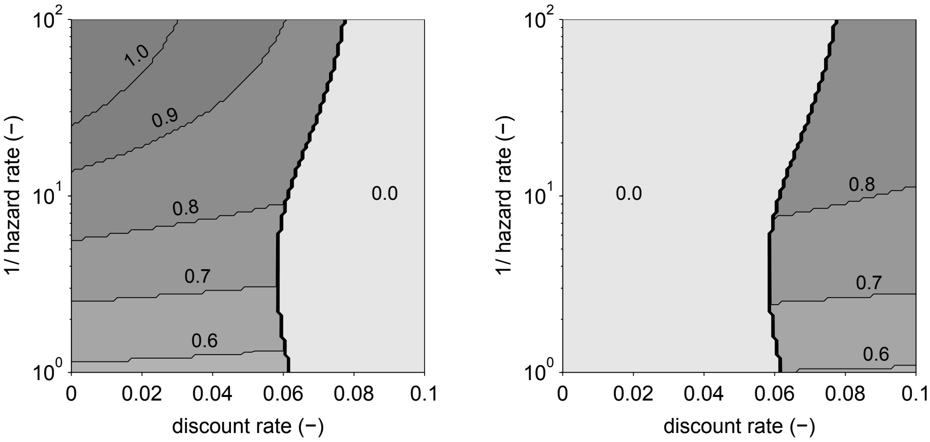
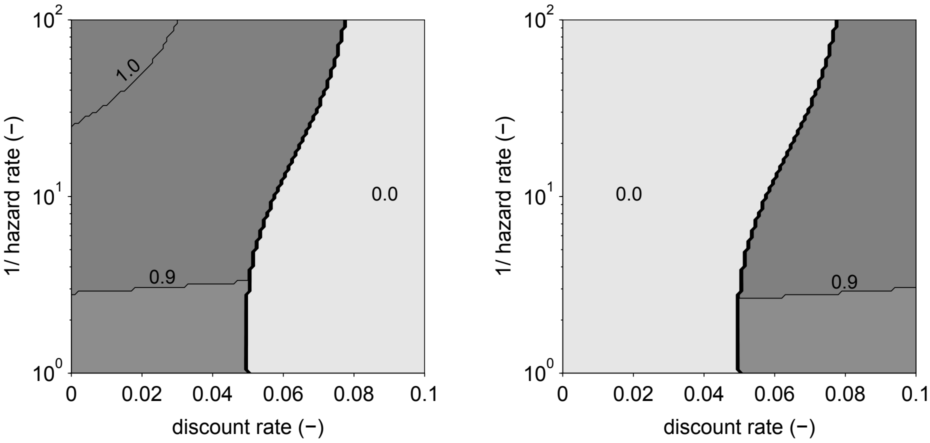


Figure 5.5: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. C_s = 102187 €, C_n = 78553 €, c_s = 120 €, c_n = 160 € and D_{max} = 1400000 €. (x 1000) (Calculation based on step-size 0.01 for interval α.)



Structural measures | Non-structural measures

Figure 5.6: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. All cost parameter functions from Table 5.3 are included, with $D_{max} = 140000$ €. (x 1000) (Calculation based on step-size 0.01 for interval α.)



Structural measures | Non-structural measures

Figure 5.7: Optimal investment decision at $t = 0$ as a function of discount rate r and hazard rate $(1/h)$. All cost parameter functions from Table 5.3 are included, with $D_{max} = 1400000$ €. (x 1000) (Calculation based on step-size 0.01 for interval α.)

5.4 Discussion and conclusion

Decisions on coastal flood protection are complicated by the long time horizon, the uncertainty associated with the distribution of impacts (Tompkins et al., 2008) and local impacts of the investment measures. The investment model presented in this chapter and adjusted to the local case study on adaptation to climate-induced sea-level rise shows how an optimal investment strategy in flood protection measures reduces the risk of under- or over-investment to the decision-maker. The combination of the discount rate, climate change uncertainty, the cost structure of structural and non-structural measures and the inclusion of local costs determines the optimal mix in investment in these measures. Our results show that if climate change uncertainty is present, the ratio of costs determines the optimal investment decision with a strong emphasis on either structural or non-structural measures.

When we consider the guidelines in the Netherlands regarding the selection of the discount rate for Cost-Benefit Analysis, the risk-free rate is set at 2.5% (Ministry of Finance, 2007) and the risk premium of 1.5% when irreversible effects related to costs and benefits are evaluated to take into account long term benefits (Ministry of Finance, 2009). The results show that with a discount rate r equal to 4% when only direct investment, maintenance and damage cost are considered, the optimal investment decision at $t = 0$ is in non-structural measures. The fixed cost of structural measures outweigh the fixed cost of the non-structural measures. When ancillary benefits related to the tourism and nature sector are included, investment in structural measures is preferred over non-structural measures. This shift is due to the inclusion of the annual ancillary benefits. The total annual costs outweigh the fixed and start-up costs, the total annual structural costs are mainly reduced due to the relative high benefits for the tourism sector related to the implementation the structural measures.

Thus, we conclude that the optimal investment decision today depends strongly on the cost structure of the adaptation measures and the discount rate, especially the ratio of fixed and weighted total annual costs of the measures. We define the optimal investment decision today as a specific mix of measures that minimizes the total expected net cost. A higher level of annual flood damage and later resolution of uncertainty in time increases the optimal investment decision. Furthermore, the ancillary benefits, related to the tourism and nature sector, have an effect on the optimal investment decision today and therefore affect the optimal mix of structural and non-structural measures.

The coastal setting, preferences of the local stakeholders and the decision-makers responsible for coastal protection have a strong impact on the preferred investment measure in coastal protection under climate change uncertainty. As the national government is responsible for the primary maintenance of the flood protection measures and upholding the flood safety standards, they are less concerned with the effects of the implementation of the coastal flood protection measures on the local stakeholders that live and work in the region. Through including the perceptions of the regional and local governmental organisations and stakeholders working and living in the area in the decision-making process, the impacts on local development of both climate change itself but also of the construction of coastal protection measures is taken into account. In this case study the impacts of the measures on the tourism sector have a high weight in the optimal investment decision. However, for this particular coastal town, at some point the benefits for the tourism sector might decrease when additional investments are made, as the effect of the disconnection between the town and the sea outweighs additional spatial benefits of the options, which is due to the unique historical link of the town with the sea. Further integrated coastal management with local development plans could also entail for example the combination of the flood protection measure with an underground parking garage.

The investment model can be applied more widely, to other coastal or river settings where different types of flood protection measures and climate change impacts can be considered, as the uncertainty with regard to climate change impacts is not likely to disappear or might even increase over time. A possible extension of the chapter would be to set up a multi-period model, to explore in more detail the effect of intermediate decision moments, where we model that over time partial resolution of climate change uncertainty is revealed. It would be expected that an intermediate decision moment leads to lower investments in structural and non-structural measures. However, there is a trade-off between the timing of the intermediate investment moment and the level of partial resolution revealed. An additional extension of the model framework, would be to include more specifically the uncertainty related to the different climate change effects, that impact the Dutch coastal area, such as sea-level rise, storm surge heights and peak river discharge, as these impacts can have a strong effect on coastal areas.

6. Conclusions

This thesis presents an economic analysis of adaptation to climate change, it explores and further develops economic assessment methods to support decision-making in adaptation to climate change that take into account uncertain climate change impacts. In this chapter I will first answer the research questions presented in Chapter 1. In Section 6.2 I will discuss the decision-support tools used in this thesis, and in Section 6.3 I will draw overall modeling and policy conclusions. Section 6.4 provides recommendations for further research.

6.1 Answers to the research questions

Q1: *Is Multi-Criteria Analysis an appropriate decision-support tool to be used to assess and rank adaptation options to climate change?*

In Chapter 2 I present an assessment framework for the priority setting of alternative adaptation options. The adaptation options are assessed based on a set of evaluation criteria (importance, urgency, co-benefits, effect on mitigation, no-regret characteristics) and feasibility criteria (technical, social and institutional complexity) using Multi-Criteria Analysis. Stakeholders and experts were involved in the identification and ranking of the adaptation options. The options were identified based on a sectoral approach with the aim to rank options that are available to 'climate proof' the Netherlands.

The qualitative assessment started with the selection of a climate change scenario and the identification of adaptation options based on literature study and consultation of stakeholders. The options were scored and ranked for a set of criteria based on expert judgement. The ranking was based on a weighted sum of the evaluation criteria. Data was lacking on the costs and benefits to perform a quantitative assessment of the adaptation.

Multi-Criteria Analysis is an appropriate decision-support tool as it provides a ranking of options. This ranking can be used in further discussions and decisions on an adaptation strategy, is useful in communication with stakeholders and in awareness raising about the challenges of adaptation to climate change. The study showed that integrated nature and water management and risk-based policies have the highest priority, followed by policies aiming at 'climate proof' housing and infrastructure. However, we also observed that many important and significant adaptation options ranked high on institutional complexities.

Q2: *Which adaptation options are suitable, from an economic perspective, to adapt spatial planning to climate change at a regional scale?*

In Chapter 3 I present a quantitative assessment of adaptation options, to identify suitable options to adapt spatial planning to climate change at a regional level. Identified adaptation options related to spatial planning include the creation of additional water retention areas, designing flood proof housing, construction of raised infrastructure to prevent flood damage and adaptation of an ecological network. I apply Cost-Benefit Analysis (CBA) to assess the direct, indirect and external effects of the different climate robust adaptation options. Furthermore, I examine how different discount rates, time horizons and changes in flood probability affect the CBA outcomes for a case study in the Zuidplaspolder. The Zuidplaspolder is an example of a large-scale urban development project in the south-western part of the Netherlands, where a large part of the area is located at six meters below sea level. Different CBAs are performed for the selected adaptation options that focus on different climate change effects and areas of the Zuidplaspolder. I aggregate the net benefits to gain insight into the total net benefits of an adaptation strategy to 'climate proof' the Zuidplaspolder for the coming decades.

The spatial planning of the Zuidplaspolder needs to take into account the increased risks of flooding caused by a dike breach and risks of inundation through increased precipitation. The Cost-Benefit Analysis included the investment costs, the benefits of reducing vulnerability (avoided damages in case of flood event) and benefits of improved spatial quality. Due to the low probability of the flood event and high investment costs, the net benefits of three of the four adaptation options are negative, with the exception of the climate robust ecological network. When all options are implemented, the overall adaptation strategy to make the Zuidplaspolder less vulnerable to climate change still has a positive net benefit (with a discount rate of 2.5%).

Although a full uncertainty analysis would have been preferred, probability distributions were not available for the uncertain local impacts of climate change for the Zuidplaspolder. Therefore the analysis was restricted to a deterministic setting, in which I assumed that climate change will occur according to the selected climate change scenarios of the Royal Netherlands Meteorological Institute.

Cost-Benefit Analysis is used to assess the costs and benefits of adaptation options. As there is a lack of Cost-Benefit Analysis studies of climate change adaptation, this chapter contributes to the knowledge gap that exists on the costs and benefits of adaptation options. However, the decision-maker needs to be aware of the sensitivity of the results to the discount rate, time horizon, the data requirement on the downscaling of the climate change impacts, the monetary estimates of the all relevant costs and benefits and the climate scenarios selected. CBA under uncertainty requires more insight into the probability distributions of future climate change impacts. There clearly is a challenge to economists and natural scientists to provide more insight into these probabilities. This will then provide better assessment of the need and degree of adaptation for specific case studies.

Q3: *From a theoretical perspective, how can we model the decision to invest in flood protection measures to adapt to uncertain climate change impacts?*

In Chapter 4 I develop an investment decision model. The model simulates optimal decision-making in flood protection, incorporating flexible timing of investment decisions and scientific uncertainty on the extent of climate change impacts. Flexibility provides the possibility to postpone an investment decision until more information about the impact of climate change has become available. I distinguish between structural and non-structural protection measures, where structural measures have high fixed costs but low annual costs relative to non-structural measures. Under climate change uncertainty the decision-maker may want to diversify between structural and non-structural measures in order to minimise the total expected net cost, including the avoided damages. I identify the probability distributions to describe the probability of the random variables, uncertain climate change impacts and uncertain timing of the resolution of climate change uncertainty, that affect the investment decision.

The resolution of uncertainty is modeled as a gradual process over time until full resolution is reached. I include a two-period and three-period model, where the three-period model includes an intermediate investment moment at which the initial investment decision can be adjusted based on partial resolution of uncertain climate change impacts. Thus, an additional investment decision can be made before full resolution is reached. In the two-period model the initial investment decision can be updated only after full resolution of uncertainty. The intermediate resolution of climate change uncertainty in the three-period model is presented in a Bayesian framework, where our belief of uncertain climate change impact is revised based on evidence that partly, but not fully, resolves the uncertainty. The prior distribution of random variable α attaches a weight on each value of α from our prior belief. The prior distribution is updated after evidence is obtained. This gives the posterior probability of α which gives a weight to each value of α after information is obtained.

The distinction made in the model between structural and non-structural flood protection makes it possible to identify the optimal mix of flood protection measures given the cost structure of the different measures. The fixed investment cost is a one-off irreversible cost, whereas the annual costs are reversible. When the decision-maker over-invests in flood protection there may be no need to continue with high annual protection costs (such as costs related to beach nourishment or dike maintenance), because a lower level of protection offered by the flood protection in place is sufficient. A part of the annual activities then can be stopped and these costs will no longer be made.

The results of the continuous-state two-period investment model show that the level of the optimal mix of the structural and non-structural measures is affected by the level of the maximum annual flood damage and the expected arrival time of full resolution. If maximum annual flood damage and the arrival time of full resolution of uncertainty increases, this leads to longer period of possible damages, which increases the level of the optimal mix of flood protection measures. The proportion of structural and non-structural measures in the optimal policy is affected by the cost structure, discount rate and expected arrival time of full resolution of climate change uncertainty. If the discount rate increases, this puts less weight on future costs, which decreases the investment in structural measures and increases expenditures for non-structural measures. In the three-period model, the inclusion of an intermediate decision moment, where partial resolution of uncertainty is used to adjust the investment, leads to lower investments in structural and non-structural measures. However, there is a trade-off between the timing of the intermediate investment moment and the level of partial resolution used. If the intermediate investment decision is in the near future, only little evidence is collected to update the prior distribution, thus only little knowledge about the true state can be used. Still the investment decision can be updated to reduce the stream of possible future damages, therefore the initial investment decision is lower in anticipation of the intermediate decision moment. If the intermediate investment decision is later in time, more evidence is collected and the posterior distribution has a smaller range, which comes closer to full resolution of uncertainty. However, as the period between the initial investment moment and the intermediate moment is longer, the period of possible damages is longer, thus a higher level of initial investment will be justified compared to early partial resolution of uncertainty.

Q4: *How can the model developed under research question Q3 be applied to investment in coastal flood protection under uncertain climate change impacts?*

In Chapter 5 I apply the investment decision model developed in Chapter 4 to a case study on coastal adaptation in the Netherlands. I examine the impact of flexible timing of the investment decision and the resolution of scientific uncertainty on climate-induced sea-level rise. Furthermore I include the preferences of the direct and indirect stakeholders which were derived from two workshops organised in the coastal town of Katwijk. The stakeholders prefer a more integrated coastal management approach, therefore I include costs and benefits of local effects related to the implementation of coastal flood protection. In this case study this relates to the effects on the recreational and nature sector. The model supports coastal management decision-makers to implement economically efficient and effective climate change adaptation options by taking into account the local effects.

The distinction between structural and non-structural coastal flood protection measures is based on the cost ratio, where structural measures have high fixed costs but low annual costs relative to non-structural measures. The implementation of a dike in dune is the structural measure, as it is a hard-engineering solution with high fixed investment cost and low annual costs. The non-structural coastal flood protection measure, a high and small dune, is a soft-engineering solution solely based on a sand construction and is considered to be less committing and more flexible than the structural measure.

The results of the continuous-state two-period model show that if I only consider the direct investment, maintenance and damage costs, investment in the non-structural coastal flood protection measures is preferred over a mix of the structural and non-structural measure, irrespective of the maximum annual flood damage, the discount rate or the expected arrival time of full resolution of uncertainty. This is due to the cost structure of the measures, where the investment costs of the structural measure outweigh the investment costs of the non-structural measure, and there is little difference between the annual costs of the two measures. Furthermore, the high maximum annual flood damage results in maximum investment in the non-structural measure. When the additional local effects of the flood protection measures on the tourism and nature sector are included, the optimal initial investment decision is a combination of the structural and non-structural measure. The level of the tourism benefits and the discount rate determine the preference for structural or non-structural measure. The annual tourism benefits are higher for the structural measure. If the discount rate is low, more weight is put on the tourism benefits, thus the structural measure is preferred. However, when the discount rate increases, the fixed investment cost receives more weight which leads to the preference for the non-structural measure over the structural measure. In addition, when the maximum annual flood damage increases and the expected arrival time of full resolution of uncertainty is further away in time, the level of the initial investment increases.

6.2 Discussion

This thesis explores several decision-support tools in the context of adaptation to climate change. Chapter 2 focuses on a qualitative assessment of national-level adaptation options for the Netherlands, through the use of Multi-Criteria Analysis. Chapter 3 presents a quantitative assessment of regional-level adaptation using Cost-Benefit Analysis and in Chapter 4, an investment model is developed that focuses on the minimisation of total expected net costs to reach an optimal investment mix of structural and non-structural adaptation options.

In this thesis climate change impact is incorporated in a deterministic and stochastic setting. In Chapters 2 and 3 the qualitative and quantitative assessments focus on the ranking and evaluation of adaptation options and use one of the climate change scenarios of the Royal Netherlands Meteorological Institute (KNMI, 2003, 2006, 2009). In these chapters, the focus is on a deterministic setting in which it is assumed that climate change will occur according to the selected climate change scenario. Therefore, the obtained ranking and evaluation of adaptation options are relevant under the assumed climate change scenario. In Chapters 4 and 5 a stochastic setting is introduced, where uncertain climate change impacts are incorporated, modeled as a random variable representing a continuous range of possible climate change impacts resulting in flood damage. Based on this assumption, an investment decision model is developed to determine a robust and cost effective adaptation strategy that considers the uncertain climate change impacts.

Multi-Criteria Analysis as presented in Chapter 2, is an appropriate decision-support tool to assess and rank adaptation options, especially when there is lack of data on the costs and benefits of the adaptation options. There are however some critical points that need to be taken into account when considering the assessment of adaptation options based on Multi-Criteria Analysis. First, it is important to present clear definitions of the set of criteria to improve the transferability of the method. Second, even when there is lack of information on costs and benefits, it is important to include indicators on the costs and economic feasibility to provide insight into both the benefits and costs of adaptation options. Thirdly, careful analysis of institutions and distribution of tasks and responsibilities with regard to policy making and execution of policies is very important to achieve successful implementation of adaptation options (Smith et al., 2009). As the assessment framework includes the involvement of stakeholders and experts it is essential to also indicate the sensitivity of the results to their involvement, for example to the expert-based ranking of the adaptation options. Furthermore, as Füssel (2009) indicates, it is essential to gain insight into the distribution of the costs and benefits and the residual damages of the adaptation options among regions, sectors and groups in a society, especially in vulnerable countries where fairness in adaptation to climate change is important.

The usefulness of Cost-Benefit Analysis in adaptation to climate change, presented in Chapter 3, depends strongly on the availability of data on the costs and benefits of adaptation options. The application of Cost-Benefit Analysis in the context of climate change has been widely discussed (Weitzman, 2001). With mitigation investments there is a debate about the appropriate discount rate to be used. Appropriate discount rates could be, for example a declining discount rate (HMT, 2003) or a relatively low discount rate (Stern, 2006) which both put more emphasis on future generations than a standard discount rate. With adaptation investments, which are more standard investment projects, the use of the traditional CBA and discount rate are more justifiable. There is, however, discussion about the exact level of the discount rate and the risk premium. In the Netherlands, guidelines are set regarding the selection of the discount rate for Cost-Benefit Analysis. The risk-free rate is set at 2.5% (Ministry of Finance, 2007) and the standard risk premium at 3%. However, a working group discussing the long term discount rate concluded in 2009 that when there are irreversible effects of climate change related to the costs and benefits, the risk premium should be set at 1.5%, to take into account long term benefits (Ministry of Finance, 2009). Besides, the appropriate level of the discount rate, uncertain climate change impacts make the applicability of CBA more complicated. Through the explicit incorporation of climate change uncertainty in decision-support tools and continued research to reduce the uncertainties, it is possible to support decision-makers in their analysis of what economically efficient and effective climate change policies are and what measures should be implemented.

The investment model developed in Chapter 4 fits within the growing literature on the implications of irreversibility and uncertainty on investment decisions (Dixit and Pindyck, 1994; Hennessy and Moschini, 2006; Pindyck, 2007). Modeling uncertainty, irreversible investment costs and flexibility in investment timing links the model to the real options approach. The real options approach aims to find the optimal timing of an irreversible investment given that the value of the investment project follows a geometric brownian motion. It is however difficult to follow the real option approach in detail as water levels cannot be assumed to follow a brownian motion. The main contributions of the model are the consideration of the full range of possible climate change impacts and associated full range of possible damages, the set of adaptation measures and the gradual resolution of uncertainty. Limitations of the analysis are the restricted definition of the structural and non-structural measures based on their cost structure, subjective probability distribution of uncertain climate change impacts, and the exogenous defined technological change.

6.3 Conclusions

The changing climate increases the vulnerability of societies around the world and challenges decision-makers to decide what the economically efficient and effective adaptation decisions are. This thesis contributes to the challenge of decision-makers to make the optimal investment decisions by presenting an economic analysis of adaptation to climate change under uncertainty and draws the following modeling and policy conclusions.

6.3.1 Modeling conclusions

With regard to the Multi-Criteria method presented in Chapter 2, I conclude that consultation of experts and the ranking by means of Multi-Criteria Analysis is useful to obtain a first ranking of adaptation options, but these options need to be further analysed in detailed Cost-Benefits Analysis under uncertainty.

For local adaptation measures, such as the measures identified for the Zuidplaspolder in Chapter 3, a simple Cost-Benefit Analysis can be applied under various climate and economic scenarios if the costs and benefits of these measures are assessed. This "what if approach", where it is assumed that the selected scenarios represent the characteristics of climate change and economic development for the Zuidplaspolder, provides insight into the net benefits of adaptation measures. However such a simple method does not deal with the complexity of a full uncertainty analysis and therefore runs the risk of over- or under-investment. The method assumes that the decision to investment can only be made once, whereas in reality it is possible to adjust the investment decision at a future moment in time based on the arrival of new information.

On the basis of the theoretical model in Chapter 4 I conclude that the optimal investment decision today depends strongly on the cost structure, especially the ratio of fixed and weighted annual costs for both structural and non-structural measures, the discount rate and the expected arrival time of the resolution of uncertainty. The level of the optimal investment decision increases with a higher level of the annual flood damage as well as with later resolution of uncertainty in time. Furthermore, the optimal investment decision today is influenced by the possibility of decision-makers to adjust their decision at a future moment in time. This implies that flexibility has a value.

On the basis of the application of the model in the case study in Chapter 5, I conclude that ancillary benefits have a substantial effect on the optimal investment decision today and therefore affect the optimal mix of structural and non-structural measures.

The probability distributions that I used for the independent random variables of the investment decision model (e.g. the uncertain climate change impact and uncertain future moment when uncertainty is resolved) impact the optimal investment decision today. These probability distributions can be updated, by improvements in climate models and by monitoring to collect real-life data on climate change impacts.

6.3.2 Policy conclusions

If policy-makers aim to identify the economically optimal investment decision in adaptation to climate change, this thesis concludes that the following five steps should be taken.

First, the most appropriate economic decision-support tool should be selected. This thesis shows that Multi-Criteria Analysis is a suitable tool for a first ranking of adaptation options when there is lack of monetary data. Cost-Benefit Analysis is an appropriate tool when there is data on the costs and benefits of the adaptation options, and if there is sufficient certainty about the expected future developments. The investment decision model developed in Chapter 4 of this thesis is appropriate when policy-makers need to take into account uncertain climate change impacts, and minimises the total expected net costs of the adaptation measures, including the avoided damages and the obtained ancillary benefits.

Second, the decision-support tool is adjusted to the local circumstances related to the spatial and temporal scale of the context of the investment decision, which relates to the selection of relevant climate change and socio-economic scenarios. This includes the identification of probability distributions to describe the probability of random variables affecting the investment decision (e.g. uncertain climate change impacts and uncertain timing of the resolution of climate change uncertainty) and the selection of relevant adaptation options. In the identification and selection of adaptation options, local stakeholders and experts can play an important role. Downscaling of climate scenarios is important, but the required information of local climate change impacts may not be available. This introduces additional uncertainties.

Third, the cost and benefit criteria need to be defined, through the identification of cost and benefit parameters relevant for the context and where possible the parameters are quantified.

Fourth, additional criteria can be defined that affect the optimal investment decision, such as the importance, urgency, equity and feasibility characteristics of the adaptation options that impact the economic optimal investment decision.

Fifth, a study of the sensitivity of the selected criteria and assumptions made will improve the understanding of the influence of the parameters on the economic optimal investment decision in adaptation to climate change.

In addition, although this has not been the focus of the research in this thesis it is important to analyse the lead times in the investment planning and, the possible tipping points that require to shift to a different regime of protection. Furthermore, the decision-support tools can be extended with increasing complexity, giving more insight into the sensitivity of the parameters that might play an important role in the decision on adaptation to climate change.

6.4 Recommendations for further research

My recommendations for further research relate to: (1) additional uncertainties; (2) additional criteria; (3) technological change.

In this thesis I consider only one uncertain climate change impact. An extension of the analysis is to incorporate additional uncertainties and irreversibilities related to extreme events with low probabilities and high impacts, tipping points and rapid climate change. This is a limitation of this thesis as I consider only one uncertain climate change impact.

The qualitative assessment of adaptation options can be further improved by considering additional criteria on the costs and economic feasibility of adaptation options. Furthermore, detailed analysis of institutional perspectives of national, regional and local institutions on the distribution of costs and benefits of adaptation options will improve optimal investment decisions.

An extension of the investment model is to include the ability to invest in research to enhance technological change and to speed up the expected arrival time of full information on the impact of climate change. The current model considers the choice of the available structural and non-structural adaptation options exogenous to the decision-maker. However, technological change may provide a new range of possible adaptation options over time, therefore the decision-support tools should take into account the costs of investment in research and development.

Availability of costs and benefits is an important part of assessing adaptation options. Decision-support tools are essential in providing directions for the decision-makers to reach optimal policy decisions about adaptation to climate change when considering the allocation of scarce resources. Research should be stimulated to reduce the knowledge gap on the costs and benefits of adaptation options. In addition, through investment in improving climate models and monitoring climate change impacts additional evidence can be collected which can be used to update probability distributions of uncertain climate change variables.

Summary

The issue of climatic change is a challenge for both current and future generations. Climate variability and future climate change impacts will increase the vulnerability of societies around the world. Especially in developing countries the impacts will be severe, but also those living in high risk areas in developed countries could be greatly impacted. Decision-makers need to plan for climate change impacts through investment in mitigation and adaptation policies, with the aim to reduce emissions of greenhouse gases and to avoid damages of climate change. However, the uncertain future magnitude and effects of climate change make it more difficult for decision-makers to decide what economically efficient and effective climate change policies are and what measures should be implemented. This thesis focuses on the economic analysis of adaptation to climate under uncertainty and explores and further develops economic assessment methods to support decision-making in adaptation to climate change.

In Chapter 2, a qualitative assessment approach based on Multi-Criteria Analysis to assess adaptation options is developed. The assessment is applied to respond to climate change in Netherlands. The chapter introduces an inventory and ranking of adaptation options based on stakeholder analysis and expert judgement, and presents some estimates of incremental costs and benefits. The qualitative assessment focuses on ranking and prioritisation of adaptation options. Options are selected and identified and discussed by stakeholders on the basis of a sectoral approach, and assessed based on a set of evaluation criteria (importance, urgency, co-benefits, effect on mitigation and no-regret characteristics) and feasibility criteria (technical, social and institutional complexity) by experts. Priority ranking based on a weighted sum of criteria reveals that in the Netherlands integrated nature and water management and risk based policies rank high, followed by policies aiming at 'climate proof' housing and infrastructure.

In Chapter 3, a quantitative assessment is presented that analyses which adaptation options are suitable, from an economic perspective, to adapt spatial planning to climate change at a regional scale. Careful spatial planning can reduce the vulnerability of these areas, provided that decision-makers have insight into the costs and benefits of adaptation options for society. Social Cost-Benefit Analysis (SCBA) is used to assess the net benefits of a number of adaptation options for dealing with the impacts of climate change induced extreme events in a case study of the Zuidplaspolder. The adaptation options focus on different climate change effects and areas of the Zuidplaspolder. The Zuidplaspolder

is an example of a large-scale urban development project for which adaptation options are developed. The direct, indirect and external effects of adaptation options relating to spatial planning (e.g. flood proof housing and adjusted infrastructure) are identified, and where possible quantified. Our results show that when we focus on 'climate proofing' the total area of the Zuidplaspolder (particularly if the costs and benefits of all the presented adaptation options are considered together) and consider a 2.5% discount rate, the total package has a positive net present value.

In Chapter 4, an investment decision model is developed that simulates optimal decision-making in flood protection, incorporating flexible timing of investment decision and scientific uncertainty on the extent of climate change impacts. Recent severe river flooding in Europe triggered debates among scientists and policy-makers on future projections of flood frequency and the need for adaptive investments, such as flood protection measures. Because there exists uncertainty about the impact of climate change on flood risk, such investments require a careful analysis of expected benefits and costs. The objective of this chapter is to show how climate change uncertainty affects the decision to invest in flood protection measures. The model aims to minimise the risk of under- or over-investment. Gradual resolution of uncertain climate change is modeled within a Bayesian framework. A distinction is made between structural and non-structural flood protection measures. Results show that the optimal investment decision today depends strongly on the cost structure of the adaptation measures, the discount rate and the possibility to adjust the investment decision at a future moment in time.

In Chapter 5, the investment decision model developed in Chapter 4 is applied to a case study on investment in coastal adaptation to uncertain climate-induced sea-level rise in Katwijk, a coastal town in midwestern part of the Netherlands. As climate change impacts low-lying coastal areas around the world, local adaptation to climate change through the implementation of coastal flood protection measures reduces the vulnerability of coastal areas. Uncertainty about climate-induced sea-level rise and the existence of different types of flood protection measures requires careful analysis of the expected costs and benefits of investment measures. A distinction between structural and non-structural coastal flood protection measures is made. The objective of this chapter is to show how climate change uncertainty affects the decision to invest in coastal flood protection measures and how the incorporation of stakeholder perceptions changes the optimal investment decision. The optimal initial investment depends on the expected waiting time for resolution of uncertainty, the discount rate, the cost structure of the measures, and the inclusion of start-up costs, and tourism and nature benefits.

This thesis concludes that a policymaker who aims to derive the economically optimal investment decision in adaptation to climate change, should first, select the most appropriate economic decision-support tool, where Multi-Criteria Analysis is suitable tool for a first ranking of adaptation options, Cost-Benefit Analysis is an appropriate tool when there is data on the costs and benefits of adaptation options and if there is sufficient certainty about the expected future developments. The investment decision model developed in this thesis is an appropriate tool when policymakers need to take into account uncertain climate change impacts. Second, the policymakers should adjust the decision-support tool to the local circumstances related to the spatial and temporal context of the investment decision. Third, the cost and benefit criteria need to defined and where possible quantified. Fourth, additional criteria, such as urgency, equity or feasibility can be defined that affect the optimal investment decision. Fifth, through sensitivity analysis of the selected criteria and assumptions made, further understanding of the influence of the parameters on the economic optimal investment decision in adaptation to climate change is derived.

Samenvatting

Klimaatverandering is een uitdaging voor zowel de huidige als de toekomstige generaties. De verandering van het klimaat en de toekomstige gevolgen van klimaatverandering vergroten de kwetsbaarheid van samenlevingen. Ontwikkelingslanden zullen hard worden getroffen door de gevolgen van klimaatverandering en gebieden in laaggelegen delta's over de hele wereld zijn kwetsbaar. Beleidsmakers kunnen de effecten van klimaatverandering reduceren door te investeren in mitigatiemaatregelen, die tot doel hebben de uitstoot van broeikasgassen terug te dringen, en adaptatiemaatregelen, die tot doel hebben de schade van klimaatverandering te vermijden en beperken. Echter, onzekerheid over de gevolgen en de omvang van klimaatverandering maakt het voor de beleidsmakers lastig om economisch efficint en effectief klimaatbeleid te formuleren en concrete maatregelen te implementeren. Dit proefschrift presenteert een economische analyse van klimaatadaptatie onder onzekerheid. Verschillende economische evaluatiemethoden worden toegepast en verder ontwikkeld om besluitvorming op het gebied van klimaatadaptatie te ondersteunen.

Hoofdstuk 2 bevat een kwalitatieve evaluatie van potentiële klimaatadaptatieopties voor Nederland. De kwalitatieve ordening van de adaptatieopties is gebaseerd op multicriteria-analyse. De identificatie en ordening van de adaptatieopties is gedaan op basis van het raadplegen van belanghebbenden en een workshop met deskundigen. Verder worden enkele schattingen van de kosten en baten van de opties gepresenteerd. De kwalitatieve ordening van de adaptatieopties is gebaseerd op vijf gewogen evaluatiecriteria: belang, urgentie, no-regret karakteristieken, niet-klimaat baten en het effect van de optie op mitigatie. Daarnaast zijn de opties geordend op basis van drie haalbaarheidscriteria; de technische, maatschappelijke en institutionele complexiteit van de implementatie van de opties. De scores en gewichten zijn gebaseerd op oordelen van deskundigen en gevalideerd door consultatie met belanghebbenden en experts. De opties *geïntegreerd natuur- en waterbeleid* en *risico management als basis strategie* krijgen de hoogste prioriteit, gevolgd door de implementatie van beleid gericht op klimaatbestendig ontwerp van gebouwen en infrastructuur.

Hoofdstuk 3 bevat een kwantitatieve evaluatie van adaptatieopties voor de klimaatbestendige ruimtelijke inrichting van de Zuidplaspolder. De Zuidplaspolder is een voorbeeld van een grootschalig stedelijk ontwikkelingsproject in Nederland. De kwetsbaarheid van de polder kan worden gereduceerd door te investeren in adaptatieopties, waarbij het van

belang is dat beleidsmakers inzicht hebben in de kosten en baten van de verschillende opties. Een maatschappelijke kosten-batenanalyse wordt toegepast om de kosten en baten te evalueren van de adaptatieopties voor de Zuidplaspolder. De opties zijn gericht op het beperken van de verschillende gevolgen van klimaatverandering. Wateroverlast, als gevolg van extreme hoeveelheid neerslag, wordt bijvoorbeeld beperkt door het klimaatbestendig ontwerp van huizen en aangepaste aanleg van infrastructuur. De directe, indirecte en externe effecten van de opties zijn beschreven en waar mogelijke gekwantificeerd. De maatschappelijke kosten-batenanalyse —toegepast op het totaal pakket aan klimaatbestendige inrichtingsopties voor Zuidplaspolder— laat een positieve uitkomst zien: de netto contante waarde is positief. De contante waarde van alle toekomstige baten van de inrichtingsopties (vermeden schade) is groter dan de contante waarde van alle toekomstige kosten (investeringskosten) bij een 2.5% discontovoet.

Hoofdstuk 4 beschrijft een economisch investeringsmodel dat de optimale investeringsbeslissing in klimaatrobuuste bescherming tegen overstromingen simuleert. De onzekerheid over de omvang van de gevolgen van klimaatverandering, de geleidelijke afname van onzekerheid in de tijd en flexibele investeringsmomenten worden gemodelleerd. Recente overstromingen van rivieren in Europa hebben geleid tot discussies tussen wetenschappers en beleidsmakers over de toekomstige frequentie en omvang van overstromingen en de onzekere invloed van klimaatverandering op het overstromingsrisico. Om de noodzaak en de omvang van investeringen te bepalen is het belangrijk om de verwachte kosten en baten van de beschermingsmaatregelen te analyseren. Het investeringsmodel geeft inzicht in het effect van onzekerheid over klimaatverandering op de investeringsbeslissing om de gevolgen van een overstroming te beperken. Uitgangspunt van het model is het minimaliseren van de totale verwachte kosten van de maatregelen en het beperken van het risico van over- of onderinvesteren. Een Bayesiaans raamwerk wordt gebruikt om het effect van de geleidelijke afname van onzekerheid over klimaatverandering te modeleren. Er wordt onderscheid gemaakt tussen structurele en niet-structurele beschermingsmaatregelen. De resultaten van het model laten zien dat de optimale investeringsbeslissing die vandaag wordt genomen afhankelijk is van de kosten structuur van de twee type maatregelen, de hoogte van de discontovoet, en de mogelijkheid om de investeringsbeslissing aan te passen in de toekomst op de momenten waarop tussentijdse en volledige informatie beschikbaar is over het effect van klimaatverandering.

Hoofdstuk 5 beschrijft een toepassing van het investeringsmodel ontwikkeld in hoofdstuk 4 op een case study gericht op klimaatrobuuste kustversterking. Investering in adaptatie is noodzakelijk om de gevolgen van klimaatverandering op het Nederlandse kustgebied te beperken. De investeringsbeslissing in kustversterking wordt beïnvloed door onzekerheid over de precieze zeespiegelstijging als gevolg van klimaatverandering. Katwijk, een kustplaats langs de Nederlandse kust, is de locatie van de case study. Onzekerheid over de precieze zeespiegelstijging en het bestaan van verschillende kustversterkingsmaatregelen, vereist een zorgvuldige analyse van de verwachte kosten en baten van kustversterkingsmaatregelen. In het investeringsmodel wordt een onderscheid gemaakt tussen structurele en niet-structurele kustversterkingsmaatregelen. De case study geeft eerst inzicht in de optimale investeringsbeslissing in kustbescherming onder onzekerheid over klimaatverandering uitgaande van de directe kosten en baten. Op basis van inzichten verkregen via een stakeholderanalyse worden er additionele parameters, de indirecte effecten van kustversterking voor recreatie en natuur, aan het model toegevoegd. De toepassing van het investeringsmodel laat zien dat de optimale investeringsbeslissing sterk afhangt van de directe en indirecte kosten en baten van de opties, naast de hoogte van de discontovoet en de mogelijkheid om de investeringsbeslissing in de toekomst aan passen.

Dit proefschrift presenteert een economische analyse van klimaatadaptatie onder onzekerheid. De economische evaluatiemethoden, multi-criteria analyse en kosten-batenanalyse worden toegepast. Een investeringsmodel gebaseerd op kosten-batenanalyse onder onzekerheid is ontwikkeld om de besluitvorming op het gebied van klimaatadaptatie te analyseren en te ondersteunen. De beleidsconclusie van dit proefschrift geeft een vijfstappenplan aan voor beleidsmakers die verantwoordelijk zijn voor het nemen van optimale investeringbeslissingen in klimaatadaptatie. De eerste stap is de keuze van het meest geschikte economisch beslissingsondersteunend instrument. Multicriteria-analyse is een geschikt instrument voor een eerste rangschikking van adaptatie opties, kostenbatenanalyse is een geschikt instrument wanneer kwantitatieve informatie beschikbaar is over de kosten en baten van de adaptatieopties en er voldoende zekerheid bestaat over de verwachte toekomstige ontwikkelingen. Het investeringsmodel, ontwikkeld in dit proefschrift, is een geschikt instrument wanneer de beleidsmaker rekening moet houden met onzekere gevolgen van klimaatverandering. Ten tweede dient het beslissingsondersteunend instrument aangepast te worden aan de lokale setting van de investering in klimaatadaptatie, waarbij met name de ruimtelijke en temporele schalen van belang zijn. Ten derde moeten de kosten- en batencriteria (directe, indirecte en externe effecten) worden gedefinieerd en waar mogelijk gekwantificeerd. Ten vierde is het van belang om de additionele criteria die van invloed zijn op de optimale investeringsbeslissing te identificeren, zoals bijvoorbeeld urgentie en haalbaarheidscriteria. Na het evalueren van de klimaatadaptaties op basis van de bovenstaande stappen is het van belang om ten vijfde met behulp van een gevoeligheidsanalyse van de geselecteerde criteria en gemaakte aannames inzicht te verkrijgen in de invloed van de model parameters op de economische optimale investeringsbeslissing in klimaatadaptatie.

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Karianne

About the Author

Karianne de Bruin was born on August 9^{th} 1978 in Delft, the Netherlands. In 1998, after completing secondary school at St. Vitus College in Bussum, she started her study 'Agricultural and Environmental Economics' at Wageningen University where in 2004 she received her MSc degree in Environmental Economics. During her study, she spent six months as an exchange student at Pennsylvania State University in State College, United States. Her major MSc thesis focused on the link between the rate of time preference, poverty and resource degradation. For her minor MSc thesis she investigated the payments for environmental services system for small landowners in Costa Rica for which she spent six months at the International Center of Economic Policy for Sustainable Development (CINPE) in Heredia, Costa Rica.

In 2005 she was selected for a one year Advanced Master 'Policy and Practice in International Development' at the Centre for International Development Issues Nijmegen (CIDIN), Radboud University Nijmegen, and worked at the same time as Assistant Programme Coordinator at CARE Nederland in The Hague. Her thesis focused on the role of CARE Nederland in relation to the reform of the European Commission and the changing role of northern NGOs.

From mid 2006 she worked as a researcher at the Environmental Economics and Natural Resources (ENR) Group of Wageningen University for the Routeplanner project on the assessment of adaptation options for the Netherlands. At the end of 2006 she started her PhD research on the costs and benefits of adaptation to climate change at the ENR Group of Wageningen University, as part of the Dutch National Research Programme 'Climate changes Spatial Planning'. She successfully completed the training program of the graduate school SENSE. During her PhD research she presented her work at international conferences and published in peer-reviewed journals. She is currently employed as Research Fellow at the Center for International Climate and Environmental Research-Oslo (CICERO) in Oslo, Norway.

Training and Supervision Plan

SENSE PhD courses

- Environmental Research in Context
- Research Context Activity: Participating in and reporting on the 9^{th} International NCCR Climate Summer School (29 August - 3 September 2010, Grindelwald, Switzerland)
- Uncertainty Analysis

Other PhD and MSc courses

- Advanced Econometrics
- Advanced Macro Economics
- Microeconomics
- Irreversibilities, uncertainties and real option values
- Techniques for writing and presenting a scientific paper
- Project and time management
- Effective communication

Other activities

- Co-organsiation of two workshops concerning coastal flood protection at a coastal town in the Netherlands, May-June 2010

Oral Presentations

- Netherlands national adaptation strategy: options and related costs, Climate changes Spatial Planning Conference, September 2007, The Hague, the Netherlands
- Sink or swim? Adapting to climate change six meters below sea level, 7^{th} European Conference on Applied Climatology, October 2008, Amsterdam, the Netherlands
- Adapting to climate change in the Netherlands, Symposium on emerging issues and future challenges in Environmental Science (SENSE-EPCEM symposium), October 2008, Wageningen, the Netherlands
- Costs and benefits of adapting to climate change at six meters below sea level, 17^{th} Annual Conference of the European Association of Environmental and Resource Economists, June 2009, Amsterdam, the Netherlands
- Effectiveness of adaptation to climate change in the Netherlands, International Climate Adaptation Futures Conference, June 2010, Gold Coast, Australia
- Investment in flood protection measures under climate change uncertainty, Deltas in times of climate change conference, September 2010, Rotterdam, the Netherlands
- Investment in flood protection measures under climate change uncertainty, 18^{th} Annual Conference of the European Association of Environmental and Resource Economists, June 2011, Rome, Italy

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