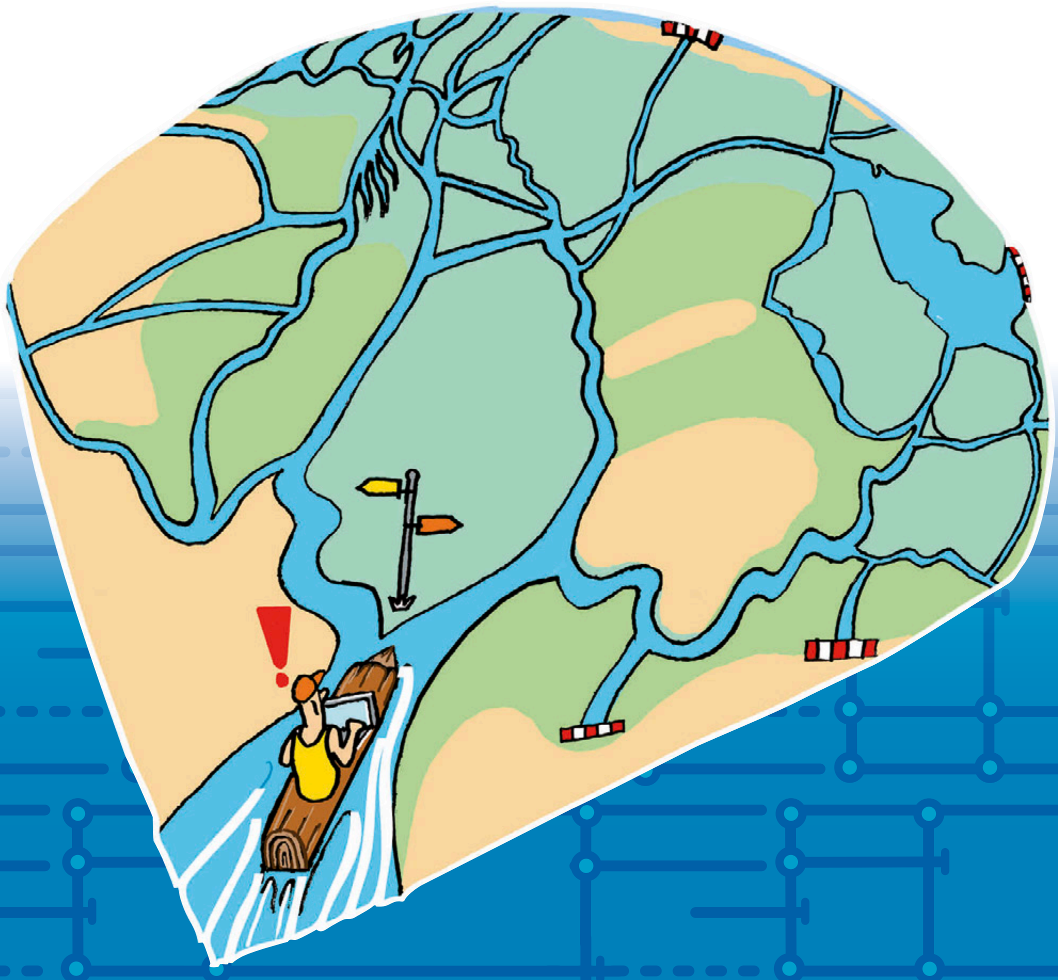
Anticipating Change

Sustainable Water Policy Pathways for an Uncertain Future



Marjolijn Haasnoot

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SUSTAINABLE WATER POLICY PATHWAYS FOR AN UNCERTAIN FUTURE

Marjolijn Haasnoot

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PROEFSCHRIFT

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SUMMARY

Water management should preferably bring solutions that sustain even if conditions change. However, relevant future changes, such as climate change, sea level rise and population growth, are impossible to predict. Moreover, policy response to change and events, will affect societal developments (e.g. urbanisation, values) and (thereby) the need and availability of future policy options. Interactions between the water system and society are, therefore, an essential component of the uncertainty about the future.

In anticipating change, a sustainable plan should not only achieve economic, environmental, and social targets, but it should also be robust to uncertainty and able to be adapted over time to (unforeseen) future conditions. Present long-term water management planning studies often ignore the dynamic aspect of adaptation as they are based on a specific end-point in the future. Exploring adaptation pathways is an alternative approach.In this research, the central question is: *How can we explore adaptation pathways to support a sustainable water management plan for river deltas taking into account uncertainties about the future?*

The research approach consists of three elements: 1) the development of a method consisting of a conceptual and technological framework for exploring adaptation pathways; the method, 2) testing and elaborating this method in two case studies, and 3) evaluation of the results.

Before developing a new method, a reflection on six decades of scenario use in water policy studies for the Rhine-Meuse delta in the Netherlands, and recommendations for future studies were provided (chapter 2). Based on two criteria, 'Decision robustness' and 'Learning success', the following was concluded 1) the possibilities for robust decision making increased through a paradigm shift from *predicting* to *exploring* futures, yet the scenario method has not been fully exploited for supporting decision making under uncertainty; and 2) scenarios enabled learning of the possible impacts of future changes and the effectiveness of policy options.

A preliminary conceptual framework was developed based on a straightforward stepwise policy analysis approach (chapter 3). This preliminary framework focuses on a perspective-based evaluation of the system using transient scenarios in which we consider time series of trends, events and policy responses. The technological framework was set up to analyse the performance of policy actions for a large set of transient scenarios, and consists of an Integrated Assessment

MetaModel (IAMM) that describes the system with simple cause-effect relations.

In a hypothetical case, called the Waas, the approach was tested and elaborated (chapter 4). The case was inspired by a real-world river stretch (Waal) in the Rhine delta in the Netherlands. Following the steps of the conceptual framework, the performance of policy actions was assessed over time with the Waas-IAMM for an ensemble of transient scenarios. At each time-step, the impacts of pressures on the system were assessed. A new action is activated once the previous no longer meets threshold values of acceptable performance and thus reaches its 'adaptation tipping point'. For each transient scenario, the timing of a tipping point ('sell-by-date') was assessed for each policy action, using acceptability threshold values for different perspectives. Pathways were constructed by exploring all possible routes with all available actions after an adaptation tipping point. However, some actions may exclude others, and some sequences of actions may be nonsensical. An overview of pathways is presented in an adaptation pathways map (see e.g. figure 21). Every route satisfies a pre-specified minimum performance level, such as a safety norm (a threshold that determines whether results are acceptable or not), but can have different costs and benefits.

Based on the Waas experiment, the conceptual framework was improved and combined with elements of the approach of Adaptive Policy Making that complemented the method with a planning process and signposts to monitor if adaptation is required (chapter 5). The integrated approach, called 'Dynamic Adaptive Policy Pathways', consists of a number of steps (figure 26). First, the system and targets are described. This is followed by a problem analysis in the current and future situation that should not only identify the current policy's vulnerabilities but also opportunities. To address the vulnerabilities and opportunities, policy actions are defined. A rich set of actions is assembled by considering different types of actions, such as actions to reduce adverse effects or actions that seize opportunities, or by addressing the problem from different perspectives. In an iterative approach, promising actions are selected and their sell-by date is assessed under a wide variety of plausible futures. Promising actions are building blocks for the construction of pathways. Pathways are evaluated and improved. Based on the improved pathways, an adaptive plan is constructed. The plan describes which robust and flexible actions should be taken *now* to anticipate change, while keeping options open for future adaptation, if necessary. Signposts and triggers are used to monitor, if actions should be implemented earlier or later, or if reassessment of the plan is needed.

The proof of the pudding is in the eating; the method was finally tested in a real-world case inspired by a decision problem the Dutch

National Government is currently working on. This so-called Delta Programme aims to develop the 'Delta Plan' for the 21st century in order to keep the Netherlands safe and attractive, now and in the future with an effectively organised flood risk management and fresh water supplies.

An IAMM was developed to explore pathways for the Rhine delta, as no appropriate model was available (chapter 6). This model needed to allow for an integrative assessment of the whole system including relevant feedbacks, and to simulate dominant processes and natural variability adequately within limited computation time; a fast, integrated model. For building the model, we defined the boundaries of the model, the drivers, the outcome indicators and the policy actions that are needed to be able to support the decision making. A useful approach for this is an iterative process, wherein (potential) end-users reflect upon the model and its results, which is used to adapt the model. For the evaluation of the model, not only the traditional modeller's criterion - model accuracy in terms of the extent to which historical data are reproduced - was used, but also the model's ability to simulate a variety of scenarios and policy actions, and the calculation speed.

For the Rhine delta, pathways were explored for multiple scenarios using the Rhine IAMM and expert judgment in discussions with water managers (chapter 7). Promising pathways were checked for consistency across multiple policy objectives. The case study showed that the approach can be applied to a real-world decision making problem. Notably, in situations where the occurrence of an adaptation tipping point is affected by slowly developing processes rather than by events, the approach was considered to be useful and promising. The results were received with great interest by potential end-users. The fast, integrated model was found to be fit for the purpose of screening and ranking of policy options over time in order to build adaptation pathways and support strategic decision making under uncertainty. A more complex detailed model can subsequently be used to obtain more detailed information about the performance of the most promising options and most troublesome scenarios or periods of interest arising from the exploration with the fast, integrated model.

The approach, presented here, supports the development of a sustainable plan by presenting different adaptation pathways for achieving water management targets. Decision makers or stakeholders may have a preference for certain pathways, since costs and benefits may differ. Decisive moments can be identified based on the moment of the adaptation tipping points, the required implementation time of actions, and the points in time where preferred pathways start to diverge. Based on their preferences and the decisive moments, decision makers are able to specify both 1) short-term actions for mitigating adverse impacts while keeping adaptation options, and 2) triggers for monitoring if adaptation or reassessment of the plan is needed.

Concluding, the research presented in this thesis resulted in two main products: 1) A stepwise policy analysis framework for the development of a sustainable plan that can cope with changing conditions. The key principles of this framework are: the use of transient scenarios representing a variety of relevant uncertain changing conditions over time; the exploration of adaptation pathways after an adaptation tipping point; and an adaptation map showing the set of most promising adaptation pathways and options for transferring from one pathway to another in the format of a metro-map, and 2) A fast, Integrated Assessment MetaModel (IAMM) that allows for exploring many policy pathways under a multiplicity of transient scenarios, and helps to assess when a policy's tipping point might occur at earliest and at latest (time-span). The approach proved to be valuable for informed decision making on a sustainable water management plan, and has been adopted in the concept of adaptive delta management of the Delta Programme.

SAMENVATTING (DUTCH SUMMARY)

Waterbeheer moet bij voorkeur oplossingen brengen die duurzaam zijn, ook als de omstandigheden veranderen. Echter, veranderingen in de toekomst, zoals klimaatverandering, zeespiegelstijging en bevolkingsgroei zijn niet te voorspellen. Bovendien beïnvloeden maatregelen die genomen worden in reactie op veranderingen en gebeurtenissen, de toekomstige maatschappelijke ontwikkelingen (urbanisatie en waarden) en (daarmee) beschikbaarheid van toekomstige maatregelen. Interacties tussen het water systeem en de maatschappij zijn, daarom, een essentiële component van de onzekerheid over de toekomst.

Anticiperen op verandering betekent dat een duurzaam plan niet alleen effectief is voor economische, milieu en maatschappelijke doelen, maar ook robuust is voor onzekerheid en zich kan aanpassen aan (onvoorziene) toekomstige condities. Huidige, lange-termijn waterbeheerstudies negeren vaak deze dynamische kant van adaptatie, doordat ze zijn gebaseerd op een specifiek eindpunt in de toekomst. Het verkennen van adaptatiepaden is daarvoor een alternatief. De centrale vraag in dit onderzoek is: *Hoe kunnen we adaptatiepaden verkennen om zodoende een duurzaam waterbeheerplan te maken voor rivierdelta's, daarbij rekening houdend met de onzekerheden over de toekomst?*

Het onderzoek bestaat uit drie onderdelen: 1) het ontwikkelen van een conceptueel raamwerk en een technologisch raamwerk voor het verkennen van adaptatiepaden: de methode, 2) het testen en verder ontwikkelen van deze methode voor twee case studies, en 3) het evalueren van de resultaten.

Voordat een nieuwe methode is ontwikkeld, is op basis van een reflectie op het gebruik van scenario's in waterbeheerstudies voor de Rijn-Maas delta in Nederland, een aantal aanbevelingen gedaan (hoofdstuk 2). Gebaseerd op twee criteria, te weten 'beslis robuustheid' en 'leersucces', is het volgende geconcludeerd: 1) de mogelijkheden voor robuust beslissen zijn toegenomen door een verschuiving van het *voorspellen* van de toekomst naar het *verkennen* van de toekomst. Echter, de scenariomethode is nog niet volledig uitgebuit voor het ondersteunen van besluitvorming onder onzekerheid; en 2) scenario's hebben het mogelijk gemaakt om potentiële effecten van toekomstige veranderingen en de effectiviteit van maatregelen in te schatten.

Een eerste versie van het conceptuele raamwerk was ontwikkeld op basis van een rechttoe rechtaan stapsgewijze beleidsanalyse (hoofdstuk 3). Deze versie van het raamwerk focust op een perspectivistische evaluatie van het system met transient scenario's waarin tijdseries van trends, events en beleidsmaatregelen zijn meegenomen. Het technologisch raamwerk is opgezet om de effectiviteit van maatregelen voor een groot aantal transient scenario's in te schatten, en bestaat uit een integraal meta effectmodel (iamm) dat het system beschrijft met simpele oorzaak-gevolg relaties.

In een case over de denkbeeldige rivier de Waas, is de methode getest en verder ontwikkeld (hoofdstuk 4). De case is gebaseerd op een bestaand stuk rivier in de Rijndelta in Nederland (de Waal). Op basis van de stappen uit het conceptuele raamwerk is de effectiviteit van maatregelen over de tijd geschat met behulp van het Waas-iamm voor een ensemble van mogelijke toekomsten. In iedere tijdstap zijn de effecten van externe veranderingen op het water systeem geschat. Een nieuwe maatregel werd geactiveerd als zijn voorganger niet langer voldeed aan een grenswaarde die bepaald of de resultaten acceptabel zijn of niet en of daarmee dus zijn 'adaptatieknikpunt' is bereikt. Voor elk transient scenario is het moment waarop een knikpunt plaats vindt (de houdbaarheidsdatum) geschat voor elke maatregel met grenswaarden voor verschillende perspectieven. De paden zijn gemaakt door alle mogelijke routes met alle beschikbare maatregelen na een knikpunt te verkennen. Echter, sommige maatregelen sluiten andere maatregelen uit, en sommige volgordes van maatregelen zijn onlogisch. Een overzicht van mogelijke paden is weergegeven in een adaptatiepadenkaart (zie bijvoorbeeld figuur 21). Elke route voldoet aan een vooraf gedefinieerd minimum resultaat, zoals de veiligheidsnorm (een grenswaarde die bepaalt of het resultaat acceptabel is of niet), maar kan verschillende kosten en baten hebben.

Op basis van de ervaringen met de Waas case, is het conceptuele raamwerk verbeterd en gecombineerd met elementen uit de methode voor het maken van adaptief beleid. Hiermee is het raamwerk uitgebreid met een stapsgewijze planningsmethode en indicatoren om te monitoren of aanpassing nodig is (hoofdstuk 5). De gecombineerde methode, genaamd 'Dynamic Adaptive Policy Pathways', bestaat uit een aantal stappen (figuur 26). De eerste stap omvat het beschrijven van het systeem en de doelen. Dit wordt gevolgd door een analyse van het probleem in de huidige en toekomstige situatie. Hierbij moeten niet alleen de potentiële negatieve gevolgen (de kwetsbaarheden) worden bekeken, maar ook de kansen. Maatregelen worden geïdentificeerd om de kwetsbaarheden en kansen aan te pakken. Een rijke set aan maatregelen wordt samengesteld door verschillende typen maatregelen te bekijken, zoals maatregelen om negatieve gevolgen te beperken of om kansen te verzilveren, of door het probleem vanuit verschillende perspectieven te bekijken. Een selectie van veelbelovende maatregelen is het resultaat van een iteratief proces. Hun houdbaarheidsdatum is geschat voor een breed palet aan mogelijke toekomsten. De veelbelovende maatregelen zijn de bouwstenen voor de adaptatiepaden. Vervolgens worden de paden geëvalueerd en verbeterd. Op basis van de verbeterde paden, wordt een adaptief plan gemaakt. Het plan beschrijft welke robuuste en flexibele maatregelen *nu* genomen moeten worden om te anticiperen op verandering, terwijl opties voor toekomstige aanpassingen mogelijk blijven. Indicatoren en triggers worden gebruikt om te meten of maatregelen eerder of later geïmplementeerd moeten worden, en of een aanpassing van het plan nodig is.

Om een methode te testen moet je de proef op de som nemen. Dat is gedaan in een case gebaseerd op een beslisprobleem waar de Nederlandse overheid op dit moment aan werkt. Dit zogenaamde Delta Programma heeft tot doel het 'Delta Plan' voor de 21e eeuw te maken om Nederland veilig en aantrekkelijk te houden, nu en in de toekomst, met een effectieve bescherming tegen overstromingen en aanvoer van zoetwater.

Een IAMM is ontwikkeld om adaptatiepaden te verkennen voor de Rijndelta, omdat er geen geschikt model beschikbaar was is (hoofdstuk 6). Dit model moest het mogelijk maken om een integrale effectbepaling van het hele systeem (inclusief terugkoppelingen) te doen, en de dominante processen en natuurlijke variabiliteit adequate te simuleren binnen met een beperkte rekentijd; een snel, integraal model dus. Voor het maken van het model zijn de grenzen van het model, de relevante ontwikkelingen, de uitkomst variabelen en de maatregelen die nodig zijn voor het ondersteunen van de besluitvorming gedefinieerd. Een bruikbare methode hiervoor is een iteratief proces, waarbinnen (potentiële) eindgebruikers reflecteren op het model en de modelresultaten wat weer gebruikt is voor het aanpassen van het model. Voor het evalueren van het model, zijn niet alleen traditionele criteria gebruikt, zoals de modelnauwkeurigheid in termen van de mate waar het model het verleden kan reproduceren, maar ook of het model in staat was om verschillende scenario's en maatregelen te simuleren binnen een beperkte rekentijd.

Voor de Rijndelta zijn paden verkend voor een veelheid aan scenario's met behulp van het IAMM voor de Rijn en expert judgement in overleg met waterbeheerders (hoofdstuk 7). Veelbelovende maatregelen zijn geëvalueerd voor meerdere beleidsdoelen. De case studie heeft geleerd dat de methode ook op een pratijkvoorbeeld toegepast kan worden. Met name in situaties waar de aanwezigheid van een adaptatieknikpunt wordt beïnvloed door geleidelijke ontwikkelingen in plaats van event, bleek de methode waardevol en veelbelovend. Het snelle integrale model bleek geschikt voor het screenen en ordenen van maatregelen over de tijd om vervolgens adaptatiepaden te maken en daarmee strategische besluitvorming te ondersteunen. Een complex gedetailleerd model kan vervolgens gebruikt worden om gedetailleerdere informatie te krijgen over de effectiviteit van de veelbelovende maatregelen en de interessante scenario's en periodes die zijn geïdentificeerd met het snelle, integrale model.

De hier gepresenteerde methode ondersteunt het maken van een duurzaam plan door verschillende adaptatiepaden voor het behalen van waterbeheerdoelen te presenteren. Beleidsmakers en betrokkenen kunnen een voorkeur hebben voor bepaalde paden, omdat kosten en baten verschillen. Het moment om een beslissing te nemen kan worden bepaald op basis van adaptatieknikpunten, de benodigde tijd om maatregelen te implementeren, en het moment waarop voorkeurspaden uit elkaar gaan lopen. Op basis van hun voorkeur en de beslismomenten kunnen beleidsmakers specificeren welke korte-termijn maatregelen nodig zijn voor het beperken van negatieve effecten en tegelijkertijd aanpassingen en opties open te houden, en welke indicatoren nodig zijn om te monitoren of maatregelen geïmplementeerd moeten worden of dat aanpassing van het plan nodig is.

Concluderend, het onderzoek gepresenteerd in dit proefschrift heeft geresulteerd in twee hoofdproducten: 1) Een stappenplan voor een beleidsanalyse om een duurzaam plan te maken dat kan omgaan met veranderende omstandigheden. De basisprincipes van dit stappenplan zijn: het gebruik van transient scenario's die een bandbreedte van relevante onzekere veranderingen over de tijd beschrijven; het verkennen van adaptatiepaden na een adapatieknikpunt; en een adaptatiekaart die een set van veelbelovende adaptatiepaden en opties voor het overstappen van het ene pad naar het andere pad weergegeven als een metrokaart, en 2) een snel integraal meta effectmodel (IAMM) voor het verkennen van veel verschillende adaptatiepaden voor een veelheid van transient scenario's en het inschatten van wanneer een adaptatieknikpunt op z'n vroegst en op z'n laatst kan voorkomen. De methode is waardevol gebleken voor geïnformeerde besluitvorming over een duurzaam plan, en is omarmd in het concept van adaptief deltamanagement van het Delta Programma.

CONTENTS

1

INTRODUCTION

1.1 SUSTAINABLE WATER MANAGEMENT UNDER AN UNCERTAIN FUTURE

Water management in river deltas has always adapted to changing conditions. Drivers to adapt were events or gradual shifts in either water availability, water demand, or both. Over time, adaptation resulted in finely tuned water systems. However, these water management strategies may not be sustainable. For example, intensive drainage and withdrawal of groundwater has led to land subsidence (Syvitski et al., 2009), in turn requiring more intensive drainage.

Future changes in social, economic, and environmental conditions are further challenging the sustainability of present water management. Technology is evolving, life-style and values are changing, and human populations are growing and increasingly moving to expanding urban areas, such as delta cities. Consequently, land cover and water demands are changing, and more people are living in flood prone areas. Also, spatial claims for urban developments may compete with the available room for water. Potential future climate change and sea level rise will influence the amount and quality of the available water (IPCC, 2007a). Changes in precipitation and evaporation are expected to result in an increase of the magnitude and frequency of floods and droughts. Without proper adaptation or planning for change, millions of people will be at greater risk for water scarcity and flooding (WWAP, 2012). Therefore, new strategies are needed for sustainable water management.

Increasingly, people believe that the world's present development path is not sustainable and that tipping points can exist (e.g. Meadows et al., 1972; Rockstrom et al., 2009; WWAP, 2012; Club of Rome, online). Efforts to meet the needs of a growing population and welfare standards in an interconnected but unequal and human-dominated world are undermining the earth's systems. Recently, at the United Nations Rio+20 summit, governments committed to create a set of sustainable development goals (Griggs et al., 2013).

Extreme water related events in the last decades and an increased awareness about potential future climate change and sea level rise have further intensified questions about the sustainability of water management in low-lying densely populated deltas. Examples of these events are the almost floods and evacuation of large number of people in 1995 along the river Rhine, floods along the river Elbe and Danube in 2002, drought conditions in many European countries in 2003, Hurricane Katrina that resulted in many life-losses in the Mississippi delta in 2005, and the 2012 storm Sandy that flooded New York city. *'Europe must adapt now'*, is the main message of the EU in the Green Paper on adapting to climate change (EEA, 2005). If no adaptation measures are taken, we may be forced into sudden unplanned actions which are far more costly (Stern, 2007).

Water management decisions should bring solutions that will sustain for several decades, as the investments involved have a long lifetime (50-200 years) and may have large societal impacts. This implies that such decisions should be adequate even in case of changing conditions. With the inherent uncertainties about the future and the increasing pressures on deltas, this is not an easy task. Uncertainties arise not only from external factors, such as climate change, population growth, and economic developments, but also from the interactions between society and the environment. Over the course of time we experience, learn and adapt to changes and events, making policy responses part of a plausible future, and thereby an essential component of the total uncertainty. These policy responses may influence societal developments (e.g. urbanisation) and (consequently) the need and availability of policy options. Moreover, world-views and societal values may change, often in response to changes in the environment. This myriad of severe uncertainties is sometimes referred to as *deep uncertainty* (Lempert et al., 2003; Hallegatte et al., 2012).

Despite severe uncertainties decisions, need to be taken, because impacts may be significant, implementation of policies takes time, and some actions may be feasible today but not in the future. The question that arises is then (see also figure 1):

> *What is, given the uncertainties about the future, a sustainable water management plan?*

Many present scenario studies on long-term water management consider (semi-)static 'end-point' situations using a few 'best estimates' of the future for one or two projection years based on central estimates of climate change and extrapolations of current socio-economic and water system trends. Such an approach might be feasible for well-understood problems, but not for complex problems with severe uncertainty (Lempert and Schlesinger, 2000), such as long-term water management under changing conditions. There are three main limitations of this traditional approach.

First of all, underlying this approach is an assumption that uncertainty results from lack of information and that we can reduce uncertainty through further data collection and processing, improvement of climate models, and/or reducing the range of possible changes into a set of (probabilistic) scenarios. Notwithstanding the usefulness of

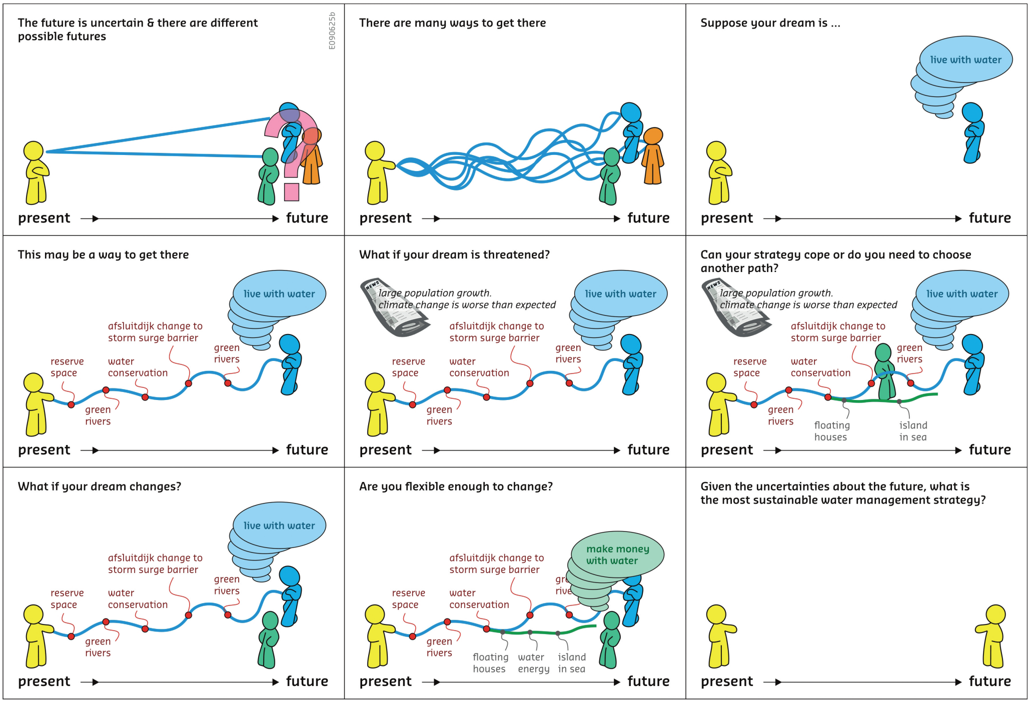


Figure 1: A sustainable water management plan involves taking into account the future uncertainties about the water and social system. A sustainable strategy is robust and/or flexible.

these actions, uncertainties remain and need to be accepted. Moreover, detection of climate change is difficult within the time scales of decision making, especially when it comes to extreme events (Diermanse et al., 2010; Wilby, 2006), and even if it were possible then it may be too late for adaptation.

A second limitation is that most approaches are based on the assumption that the system is stationary. However, under uncertain global changes, continuing the assumption of stationarity in designing strategic plans under uncertain global changes is no longer practical or defensible (Milly et al., 2008; NRC, 2011).

Thirdly, most present studies ignore pathways towards the endpoint and the possibility that events and disasters may change such pathways drastically, and may even change cultural perspectives on what is deemed as a desirable final situation. In other words the existing scenario methods neglect the dynamic aspect of adaptation and the non-linear behaviour of both the social and water system, such as tipping points, destabilisation, acceleration and inertia.

To support the development of a sustainable plan under uncertain change, an alternative method is needed (Gober et al., 2010). This method should acknowledge the complexity of a dynamic system arising from uncertain changes, natural variability and the interaction between the water system and society. Exploring pathways into the uncertain future could be a more adequate approach for supporting sustainable water management.

1.2 WHY EXPLORE PATHWAYS FOR SUSTAINABLE MANAGEMENT IN RIVER DELTAS?

The three main reasons to look for new approaches to support sustainable management of river deltas under uncertain changing conditions are:

1. *River deltas are unique with high economic, social and ecological value.* Many deltas are among the most densely populated areas in the world, with a concentration of agriculture, cities, industry, and infrastructure (Van der Most et al., 2009). This is the result of their fertile soils and the connection between sea, rivers and the hinterland, which provide ways of transport and trade. Deltas also comprise large wetland areas of high ecological value due to a diverse range of habitats with salt, brackish and fresh water zones in aquatic and terrestrial species. It is expected that in the future the spatial claims within the delta regions will increase. Consequently, these valuable areas should be managed carefully and in a sustainable way (Van der Most et al., 2009).

2. *River management of deltas faces major challenges to cope with uncertain global developments and their potential large impacts.* Population increase, economic development and changing life-styles may result in

increasing spatial and water claims for industry, agriculture, housing and infrastructure. Climate change, sea level rise and soil subsidence may threaten water availability. These developments are surrounded with uncertainties arising from both natural uncertainties (e.g. climate variability and change) and social uncertainties (e.g. future values and perceptions). Worldwide, decision makers from governments, NGOs and businesses are becoming aware that adaptation actions to counteract the potential impacts of climate change are unavoidable. However, as the need to act is recognised, attention shifts to the question of how, how much and when investments should be made, given the very large uncertainties that are generally associated with projections of future. What actions are needed in the short term and what actions can be postponed? Given that infrastructure investments are being made now, with potential for lock-in and stranded assets, how should decisions be modified to cope with a changing climate? Therefore, in addition to the traditional *climate services*, that strongly focus on understanding the changing system Earth by monitoring and modelling, scientists need to provide *decision services*, such as adaptation pathways, to enable decisions about investments under uncertain change. Recently, climate services are considered broader; e.g. the provision of climate information in such a way as to assist decision-making (Hewitt et al., 2012). Here, a shift is observed towards what we mean with decision services.

3. *Extreme weather and social events and trends (and their impacts) are important triggers for adaptive delta management.* Society has the capability to learn from experience, which may lead to adaptation of the water system (Van der Brugge et al., 2005; Offermans and Cörvers, 2012). Such adaptation actions may influence societal developments (e.g. urbanisation) and available future policy options. For example, in the Netherlands the 1953 flood of Zeeland resulted in the adoption of a new, probabilistic flood defense approach, while the near-flood disasters along the Rhine and Meuse rivers in 1993 and 1995 stimulated the start of the 'Room for the River' project (Silva et al., 2000; Van Heezik, 2012). If no reservations are made in the floodplains, 'room for the river' actions for coping with future climate change may be impossible or very costly with high societal impact, thus leaving a limited set of remaining policy options. An example, of a societal event is that increasing societal awareness of cultural heritage and nature values of the Rhine delta led in the late 1980s to a shift in river management from straightforward dike rising to integrating flood protection with nature development and preserving landscape values (Van der Brugge et al., 2005). This demonstrates the need to acknowledge pathways towards the future by considering the interaction between the water system and society.

Summarising, in order to support sustainable water management in river deltas we need to consider the uncertainties arising from the complex dynamic world we live in nowadays: uncertain climatic and socio-economic changes and uncertain policy responses to flood and drought events. Exploring adaptation pathways could be an approach to do this.

1.3 OBJECTIVE AND RESEARCH QUESTIONS

Based on the above consideration the focus of this research is on providing knowledge and tools for pathways exploration. The objective of this Ph.D. research is to develop and test a method for exploring adaptation pathways for sustainable water management in river deltas into an uncertain future. The central research question of this research is:

> *How can we explore adaptation pathways to support a sustainable water management plan for river deltas taking into account uncertainties about the future?*

To answer this central question, several sub questions need to be answered, namely:

> *1. What is meant by 'a sustainable water management plan'?*

The motivation for this research question is that sustainability is an ambiguous term. Since its introduction, sustainability has been used in different contexts and operationalised in different ways. In order to develop an approach that can support the making of a sustainable water management plan, we need a clear definition of sustainability and criteria to evaluate the sustainability of the plan. By answering this question we aim to make transparent what we mean by a sustainable water management plan.

> *2. How can we develop pathways?*

Addressing this question should result in a conceptual framework that can be used as a stepwise approach to generate and evaluate adaptation pathways that will be part of a sustainable plan. Such a policy analysis framework is thus tailored to managing uncertainties about the future in a sustainable plan. We will build upon and extend existing scenario and policy analysis approaches. The framework will explicitly consider the dynamic aspects of a policy that arise e.g. from natural variability and the interaction between the water system and society. Pathways can be generated a) qualitatively (descriptively) based on expert judgement or on storylines developed together with stakeholders, or b) quantitatively using a computational model. In this research, we focus on the model-based development of pathways. To answer this research question, we need to define what pathways look like, what information and tools we need to generate pathways, and how to evaluate and extract from many possible pathways those pathways that lead to a sustainable plan.

> *3. How can we build and evaluate a computational model for exploring adaptation pathways?*

Once we have a model-based policy framework for exploring pathways, we need a computer model that is appropriate to support such analysis. Most existing numerical models aim at simulating reality in as much detail as possible. As a result, they are computationally demanding, and, therefore, are not appropriate for pathways development. The aim of addressing this question is to develop a technological framework for building a computational model that is appropriate for exploring adaptation pathways. For this purpose, we first need to define the requirements of such a model. Next, we need metrics to evaluate the performance of the model, to assess whether it is fit for purpose. The model should be able to provide the information needed to generate and evaluate pathways, as defined in question 2. When evaluating a model, we need to address for what kind of questions, systems and policy actions such a model should be used.

> *4. How can the generated pathways support the development of a sustainable plan?*

The potential future pathways that have been generated using the conceptual framework from question 2 and the computational model from question 3 need to be translated into a sustainable plan. For the evaluation of pathways, we can build upon the criteria of question 1. Some actions and pathways may be more preferred than others. Some paths may result in lock-ins or have unwanted path-dependencies. Identifying causes of failure or success of a pathway can help to strengthen the sustainability of a plan.

> *5. What is the value of the approach, and for which situations is the approach appropriate?*

This question aims at evaluating the proposed method by identifying its strengths and weaknesses. More specifically, it aims to test whether the method is able to support the development of a sustainable water management plan. The approach may work well for some water systems and/or decision problems, and may be less appropriate for others.

1.4 DEFINITIONS AND FOCUS

Long-term water management of lowland rivers and their deltas is a key-subject in this research. Water management generally aims at providing adequate amounts of water of proper quality for the various water-related services. Long-term water management observes the water system and its use at a time scale of 50 to 100 years. This study focuses mainly on water quantity, i.e. too much water (floods) and too little water (droughts). Floods and droughts have their own implications for water management due to differences in frequency, impact and strategies, and manifest themselves differently over time. Although flood and drought strategies are often analysed separately, they interact and should thus be considered together for the development of a sustainable water management plan.

The classic definition of *sustainable development* is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). In practice, this definition of sustainability has often been summarised as meeting economic, environmental, and social objectives now and in the future. Given the uncertain changing conditions many decision makers are facing nowadays to enable future generations to meet their own needs, a *sustainable water management plan* should also be *robust*, meaning that it performs satisfactorily under a wide variety of futures, and *flexible*, meaning that it can be adapted to changing (unforeseen) future conditions. In addition to the economic, environmental, and social objectives often used, we thus add two other characteristics to sustainability: *Robustness*, the degree to which a decision or policy performs well under a range of conditions (Lempert et al., 2003); and *flexibility*, the ability of a system or policy to adapt to substantial, uncertain, and fast-occurring changes that have a meaningful impact on the system or policy performance (Kwakkel et al., 2011).

What is considered as 'effective' or 'acceptable' performance of a policy depends on people's values and perceptions (perspective). A future generation may have different values and thus different needs. Therefore, regarding future conditions, not only should a wide range of developments in climate and land use be considered, but also (changes in) social perspectives (perceptions). Offermans (2012) makes this explicit and considers, therefore the *social-robustness* of policies. She uses Van Asselt's (2000) definition of a perspective: "a perceptual screen through which people interpret the world and which guides them in action". Although I also consider social-robustness, the main focus of this research is on the physical-robustness of policies (environmental conditions).

Under changing conditions, such as climate change, adaptation is needed. *Adaptation* is the modification of ecological and social systems to accommodate changes so that these systems can persist over time (modified from Barnett 2001). An *adaptation pathway* describes a sequence of policy actions that can be used for adapting to changing conditions. A set of pathways can be summarised and presented in an

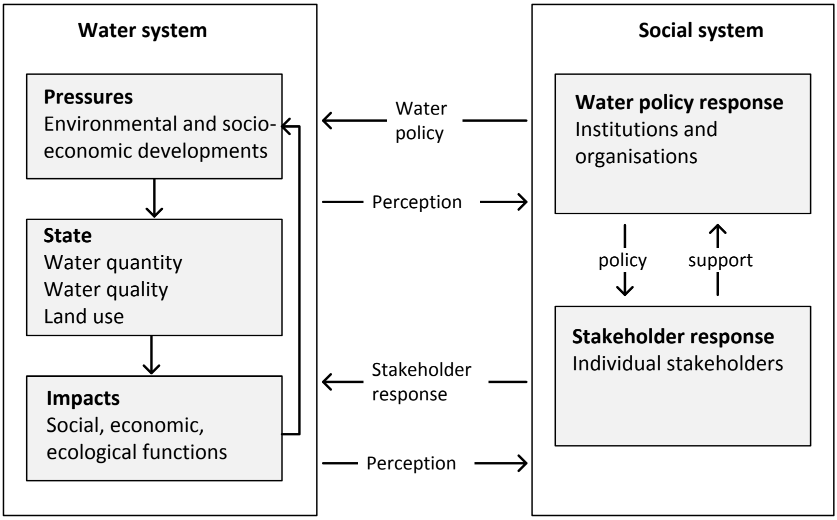


Figure 2: The PSIR framework which provides a simplified overview on the interactions between the water system and the social system (adapted from Valkering et al. (2008b)). For the original PSIR diagram applied to water management see Hoekstra (1998).

adaptation (pathways) map. Such a map can be used to identify (a set of) robust and flexible actions, and thus a sustainable strategy.

The method developed in this research can be considered as a scenario method. *Scenarios* are coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present and future developments, which can serve as a basis for action (Van Notten, 2005). When I speak of scenarios, I mean *external context* scenarios describing developments that can not be influenced and are thus policy-free. *Transient scenarios* are time-series into the future. *Storylines* describe a story of a possible future over time, and include both natural and socio economic events (e.g. floods, droughts; economic crisis), trends (e.g. climate change; changing public perception of safety or nature) and interactions between the water system and society (e.g. flood impacts; flood mitigation measures). In contrast to (transient) scenarios, storylines are not policy free.

The concept underlying the interactions between the physical and social subsystems in this project is the PSIR framework (Pressure, State, Impact, and Response; OECD 1993; Rotmans and De Vries 1997; Figure 2). The PSIR framework helps to describe the interactions between the water system and the social system, and thus links the different parts of the project. Environmental pressures, such as climate change and land use changes, influence the water availability. Socio-economic pressures determine the water demand and spatial claims. Both pressures influence the system state, including the water state (quantity and quality)

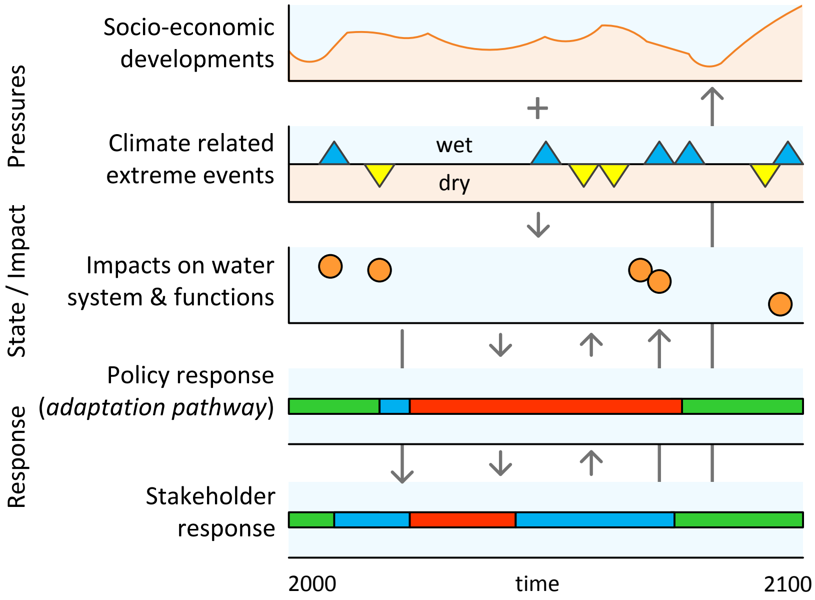


Figure 3: The PSIR framework, with focus on the dynamics of the system.

and land use state (like land use, infrastructure). The state has an impact on social, economic and ecological services, such as drinking water supply, agriculture and habitats. The effects may lead to a response which involves a societal response of water and land use, a change in perception and valuation of the environment and water system, and an inherent policy-driven water management response.

The effect-chain and social-water system interactions as described in the PSIR framework, are actually dynamic and change over time. A representation of these interactions over time is presented in Figure 3. Over time, pressures change, influencing the water system and sometime resulting in adverse impact that trigger a policy or stakeholder response. This figure also shows how a set of policy responses resulting from these interactions form an adaptation pathway. Due to uncertainties about the pressures, impacts and responses a multitude of pressures, impacts and responses are possible in the future. To describe the (change of) pressures over time, we use transient scenarios. In the research described in this thesis, the social system is a black box; we consider policy response and do not try to describe and simulate the policy arena.

Policy response (if at all, and what kind of action) depends on people's perspectives. We use the Perspectives method (Offermans, 2012) to describe this. The method originates from cultural theory (Douglas, 1970; Thompson et al., 1990) and has been developed further by Van

Asselt (1995), Rotmans and De Vries (1997), Hoekstra (1998) and Middelkoop et al. (2000). In the 'Perspectives in IWRM' project, the Perspectives method was elaborated by addressing perspective change over time and using the method for socially robustness as part of sustainable water management (Offermans, 2012). Perspectives can be used to capture uncertainty arising from different perceptual screens – values important for the policy response due to beliefs about the future, impacts of strategies, and evaluation of the impacts.

1.5 RESEARCH CONTEXT AND APPROACH

This research is part of the project 'Perspectives in Integrated Water Resources Management in River Deltas' that was initiated by Deltares, Utrecht University, ICIS Maastricht, KNMI, Carthago Consultancy and Pantopicon, and supported financially by Deltares. The 'Perspectives in IWRM' project was financially supported by Deltares, NWO and ICIS. This project was one in a row of related projects on climate change and water in the Rhine basin. The first projects used natural science to assess potential impacts of climate change on hydrology (Kwadijk, 1993; Middelkoop et al., 2001). Later, this was extended to water related services (Middelkoop et al., 2000). Next, concepts and models from the natural and social sciences were combined to develop a scenario method for evaluating the robustness of water management strategies under different plausible futures (Van Asselt et al., 2001; Middelkoop et al., 2004). That research added uncertainties arising from different perspectives that people can have, but still focused on end-point situations in the future. After a short pilot that resulted in the first ideas on transient scenarios and responses of society to events and developments, and associated changes in the water system over time (Valkering et al., 2008b), the 'Perspectives in IWRM' project started.

The overall aim of the 'Perspectives in IWRM' project was to integrate insights from the social and natural sciences to develop a method to explore the sustainability of different water management strategies under an uncertain future. For this purpose, an interdisciplinary team of researchers and practitioners (ranging from hydrologists, climatologist and modellers, to social scientists and governance experts) worked closely together and each person added his or her own piece of the puzzle, which would, in the end, support a method for sustainable water management. The 'Perspectives in IWRM' project comprised two Ph.D. projects: one focusing on socially robustness of water management and perspective change (Offermans, 2012), and one focusing on the natural system and exploring pathways (this thesis). Later, the 'Perspectives in IWRM' project was strengthened by two post-doctoral researchers, one of which focussed on describing governance aspects of sustainable water policies and one on modelling interactions between water system and policy to generate pathways computationally. A key tool in integrating the research results was the development of the game 'Sustainable Delta' (Van Deursen et al., 2010; Valkering et al., 2012) which was used to develop different possible futures in order to understand the interactions the between water system and society.

The research described in this thesis focuses on the water system and comprises three parts: 1) developing a conceptual and technological framework to identify adaptation pathways for sustainable water management, 2) testing this method in case studies, and 3) evaluating the results. The research framework of this Ph.D. research is presented in figure 4.

First, the ideas on the method were further elaborated by analysing literature on existing methods and applications, and using the results from previous studies of this research group. The literature research focused on adaptation strategies, uncertainty analysis, scenario applications and repro or other simplified computational models. This resulted in a conceptual framework and a technological framework. The conceptual framework describes the theoretical concepts and a general procedure that can be followed to derive sustainable pathways. This involves also assessment criteria to evaluate a strategy. The technological framework comprised an Integrated Assessment MetaModel (IAMM) and its description. Model criteria were derived from the conceptual framework and literature, and describe what the IAMM should be able to do. The next step was to apply and test both frameworks in an experiment for a hypothetical case. Based on this experience we improved the frameworks, which we then applied and tested in a real-world case: the Rhine delta. Finally, the results of the cases were used to reflect on the method and to analyse the value of this method.

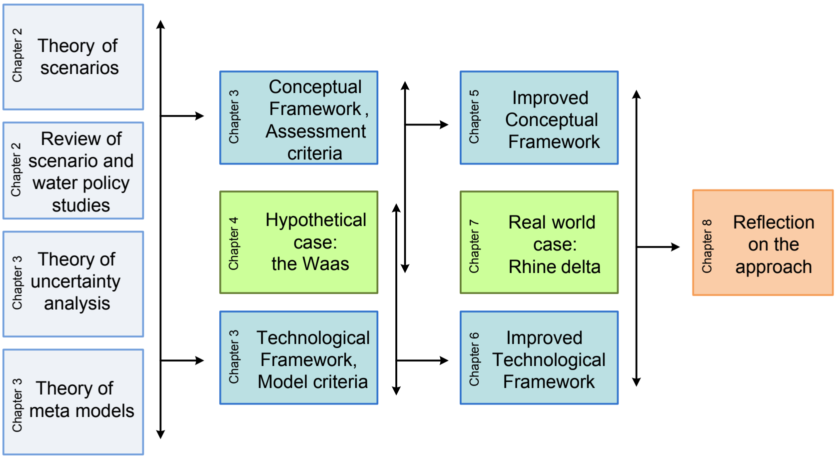


Figure 4: Overall picture of the research framework.

1.6 OUTLINE

The main part of this thesis consists of six papers that have been published, are forthcoming or have been submitted to a scientific peer-reviewed journal. As a result there is some overlap in the content between the chapters (papers). Each chapter (paper) addresses (part of) one of the research questions (see figure 4).

Chapter 2 reflects on six decades of scenario use for the Rhine-Meuse delta in the Netherlands, and provides recommendations for future water policy studies. The first versions of the conceptual and technological frameworks are presented in chapter 3. Chapter 4 describes the application and test of these frameworks for a hypothetical case, a river reach called the Waas. Based on this experience we improved and combined the approach with the concept of adaptive policy making, and illustrate this new approach for a real-world decision problem currently faced by the Dutch National Government in the Delta Programme (chapter 5). Chapter 6 describes how we developed and evaluated an Integrated Assessment Metamodel for the Rhine delta in the Netherlands, which we then used to apply the new approach to a real-world case of the Delta Programme (chapter 7). Chapter 8 answers the research questions and reflects on the research by discussing the contributions to future water policy studies.

2

A HISTORY OF FUTURES IN WATER POLICY STUDIES IN THE NETHERLANDS

ABSTRACT

The future of human life in the world's river deltas depends on the success of water management. To deal with uncertainties about the future, policy makers have used scenarios to develop water management strategies. In this chapter, we reflect on six decades of scenario use for the Rhine-Meuse delta in the Netherlands, and provide recommendations for future studies. Based on two criteria, 'Decision robustness' and 'Learning success', we conclude that 1) the possibilities for robust decision making increased through a paradigm shift from predicting to exploring futures, but the scenario method is not yet fully exploited for decision making under uncertainty; and 2) the scenarios enabled learning about possible impacts of developments and effectiveness of policy options. New scenario approaches are emerging to deal with the deep uncertainties water managers are currently facing.

This chapter has been published as Haasnoot, M., Middelkoop, H., 2012. A history of futures: A review of scenario use in water policy studies in the Netherlands. Environmental Science & Policy 19, 108–120, DOI: 10.1016/j.envsci.2012.03.002

2.1 INTRODUCTION

The world's river deltas are increasingly vulnerable due to pressures from climate change, relative sea level rise and population growth (Syvitski et al., 2009; Vörösmarty, 2009). Therefore, densely populated deltas such as the Netherlands require well-designed water management for flood protection and for coping with varying water demands and availability.

Water management decisions should bring solutions that will sustain for several decades, implying that they should be adequate even in case of changes in pressures. However, uncertainties about the future make decision making less straightforward. Therefore, policy makers increasingly use *robustness* as indicator in decision making. A robust strategy performs relatively well across wide range of possible futures (Lempert et al., 2006) and other uncertainties. Water management faces uncertainties arising from 1) natural uncertainties such as trends and extreme weather events; 2) social uncertainties due to shifts in human response and values and 3) technological uncertainties through modelling future states and impact (e.g. Chapter 3).

Scenario analysis is a method for dealing with uncertainties, and aims to assess possible impacts and to design policies (e.g. Carter et al. 2007). Scenarios are coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present and future developments, which can serve as a basis for action (Van Notten, 2005). Since its first use in military planning in the 1950s (Kahn and Wiener, 1967; Brown, 1968; Bradfield et al., 2005), scenario analysis has been applied in a variety of areas, such as business development (Wack, 1985; Bradfield et al., 2005; Van der Heijden, 1996), environmental planning (Alcamo, 2001; Peterson et al., 2003; Alcamo, 2009) and climate change mitigation and adaptation (Wigley et al., 1980; IPCC, 2000; Hulme and Dessai, 2008a; Rosentrater, 2010). Scenarios have also been used for robust decision making in case of complex problems with deep uncertainty, such as long-term water management under changing conditions (e.g. Dewar et al. 1993; Lempert and Schlesinger 2000; Lempert et al. 2003, 2006; Groves 2006; Kwakkel et al. 2010b or Van Asselt and Rotmans 2002; Middelkoop et al. 2004; Dessai and Hulme 2007 for examples related to water management).

To enable life in a low-lying delta, the Dutch have had a long history of controlling and maintaining the water system. In the Netherlands, scenarios have been used since the 1950s to prepare water management for the future. After six decades of experience, we reflect on scenario use in water management in the Netherlands, and identify possible improvements for future studies. This evaluation provides more insight in policy making on water management in river deltas under uncertainty to support the current development of the next generation scenarios for climate adaptation studies.

This chapter provides a review of scenario use in water management studies on the Rhine-Meuse delta in the Netherlands, and evaluates the lessons that can be derived from this experience. We seek to answer the following questions: What was the evolution of scenario use in water management? Did the scenarios provide prospect for robust decision making? Did the scenarios enable learning for policy makers and/or scientists? After giving a historical perspective, we evaluate the scenario use based on two criteria: 'Decision robustness' and 'Learning success'. We end the chapter with conclusions and recommendations for future water management studies.

2.2 APPROACH FOR EVALUATING THE SCENARIO USE

For our chronology on scenario use in water management in the Netherlands we reviewed all national water policy documents, the key research studies on climate and water, and related climate scenario studies. In addition, we used our own experience, based on participation in several water policy studies since the 1990s, and the experience of several colleagues, who were involved in earlier water policy studies or climate scenario studies. We present the studies from the Netherlands against the (inter)national context (see Figure 5 for overview and Appendix A for more characteristics).

For our analysis we adopted two criteria used by Hulme and Dessai (2008b) in a framework for climate scenario evaluation, which we further refer to as the 'Decision robustness' and the 'Learning success'.

The 'Decision robustness' criterion can be addressed with the following question: *'do the scenarios contain a sufficient representation of relevant knowable uncertainties to offer the prospect that decisions taken with support of the scenarios will be robust?'* Robustness is an important criterion for good decisions under uncertainty (Rosenhead et al., 1972; Metz et al., 2001), especially by policy makers facing deep uncertainty (Lempert et al., 2006; Groves and Lempert, 2007). By including uncertainties in decision making it is possible to identify strategies that perform relatively well under various different possible futures (robust strategies), or to make a well-thought-out decision on whether or not to adapt a strategy in view of a specific uncertainty. Assessing the robustness of decisions is relevant, because decisions involve large high-cost investments, and can have large implications for society. Therefore, water management decisions should be cost-effective for several decades, even if the future turns out to be different from what was anticipated.

Intuitively, one might consider the following question as a criterion for evaluating the 'Decision robustness' (in retrospect): *'was the decision taken a 'good' decision?'* However, there are some fundamental problems in answering this question. Firstly, major water management decisions have often a long implementation time, or involve strategies with a considerable life-time (e.g. tens of years). Yet, for many studies the time passed has been too short to decide whether decisions have turned out to be successful. Secondly, and more important, we can only evaluate decisions against the single past we had, which is only one realisation of all possible futures that could have evolved after the decision was taken. For example, due to inherent climate variability and the stochastic nature of the occurrence of extremes, prolonged periods can pass without extreme events, even in the case of climate change. If it was decided that anticipatory strategies were not needed, this decision would have been evaluated as 'good', as a result of the fortuitous absence of extreme events. In other - equally likely - realisations of the future, in which some extreme events occurred, this decision would have been judged as 'bad'. So, judging a decision against a single past does not provide a sound indication of its robustness or potential success; such evaluation requires confronting the result to a range of realisations of the future. In this chapter, therefore, we focus on whether the decision process - based on the scenarios considered - provided *prospects for robust decisions*.

Indicators for the 'Decision robustness' criterion should, therefore, reflect whether relevant uncertainties are sufficiently represented. *Relevant* uncertainties have significant and distinguished impact on the outcomes, and consequently the decision making (cf. IPCC 2001). For water management this involves uncertainties in both water *demand* and *availability*. This means that scenarios should include uncertainties in climate, sea level and river discharges, that all affect water availability, as well as uncertainties in socio-economic and social developments (e.g. land use and the accepted flood damage), that determine societal requirements and thus the water demand. A different kind of relevant uncertainty arises from interactions between the water system, society and water management. For example, floods and droughts may raise the need for additional or new measures, or more profoundly, it may influence societal perspective (e.g. how we evaluate system and our expectations of the future), and may trigger a water policy response which may then affect the water system. The resulting water management response will then affect the water system and its future response to extremes. Uncertainty in the policy response further adds to the total uncertainty on the water system in the future. In retrospective, water management in the Netherlands has indeed strongly been driven by both floods (e.g. in 1993 and 1995) and drought events (e.g. the summer of 1976), and socio-economic trends (e.g. increasing valuation of nature and cultural heritage). For robust decision making scenarios should, therefore, consider the dynamic interactions among climate, society and water management as these evolve in the course of time and influence the performance of policy options.

To determine whether uncertainties were *sufficiently* represented for robust decision making, we analysed the *range* and *diversity* of the considered scenarios using the following indicators: the number of scenarios, the variety in the range of outcomes encompassed, the variety in alternatives, and the temporal and dynamic nature of the scenarios.

Using the range of a scenario as indicator for 'Decision robustness' does not mean that decision making should be based only on the extremes nor that a broader range in itself is better. Instead, several alternative scenarios should be considered that encompass a relevant and plausible range of futures. Alternative scenarios go beyond the frequently used 'business as usual' scenarios derived by extrapolation of ongoing trends, and comprise changes in developments in the course of time. Regarding the temporal nature of a scenarios, scenarios can be 'snapshots' describing a moment in the future, or 'transient' scenarios describing the evolvement to a certain point in the future (Van Notten, 2005).

The dynamic nature of a scenario refers to whether a scenario is essentially based on a gradual extrapolation of trends, or whether it encompasses events, discontinuities, or even surprises which change gradual developments abruptly (Van Notten, 2005).

What is considered 'plausible' or 'relevant' is subject to different interpretations, and depends on one's expectations about the future and understanding of the system. A way of dealing with this type of uncertainty - often referred to as perspective-based uncertainty - is including such different perspectives in the scenarios (cf. Van Asselt et al. 2001; Middelkoop et al. 2004).

The 'Learning success' criterion refers to the question: *did the scenarios enable learning for policy makers and scientists?* Answering this question is relevant to indicate the value of scenario analysis, and to improve future scenario use in water management studies. Although there are many definitions of learning, most theorists agree that learning is a change in knowledge or behaviour as a result of experience (e.g. Kolb 1984; Driscoll 1994). Although we could not provide quantitative measures, we determined indications of the learning effect from reflection and underpinnings indicated in the reports. We give some examples: 1) A policy report that mentions results of a scientific long-term water policy study as a starting point of their study (*'Scenario studies show that climate change will have an impact on the hydrological water system.'*). 2) A policy document mentioning a contextual development or event as a reason to adapt a policy or a scenario (*'Event x raised awareness that a new scenario/approach is needed.'*). 3) A research study stating that *previous results showed* 'X', *but* 'Y' *is unclear, and will be studied*. Therefore, we analysed the evolution of the scenario content and use, the study's subject, and the science-policy interaction, and use this information in combination with our experience and the experience of our colleagues, to estimate the 'Learning success'.

2.3 HISTORICAL PERSPECTIVE ON SCENARIO USE IN WATER POLICY STUDIES

The Emergence of Concepts

The emergence of concept of anthropogenic global warming has been characterised by different milestones (e.g. Peterson et al., 2008; Weart, 2010). Mid-19th century, Tyndall suggested that atmospheric changes could explain ice ages (Tyndall, 1861). Arrhenius was the first to quantify the contribution of CO_2 to the greenhouse effect (Arrhenius, 1896). In the 1950s, progress in understanding of climate cycles resulted in the Milankovitch theory, explaining cycles at glacial-interglacial time scales (Milankovitch, 1930). After 1950, tools became available for measuring greenhouse gases. Keeling (1960) showed a faster CO_2 increase than Arrhenius' estimate. Together with available data on the global temperature this led to the idea that increasing CO_2 could result in marked climate change (Revelle et al., 1965). In the 1970s, climate models were developed and used to study the combined effect of cooling through aerosols and warming through CO_2. After warming trends, reported in the 1940s, a multidecade cooling was observed (Mitchell, 1963). Although scientific articles described both potential future warming and cooling, the media (e.g. Gwynne, 1975) mainly covered a future cooler world (Peterson et al., 2008). In the mid-1970s, the discussion in the media became dichotomous: the climate could become warmer or cooler (Mathews, 1976).

The scenario concept originates from the 1950s and is ascribed to Herman Kahn at that time working at the RAND Corporation (Van Asselt et al., 2010b). He demonstrated with scenarios that US military planning was based on 'wishful thinking' instead of 'reasonable expectations' (Bradfield et al., 2005). In the 1970s, scenarios were used to explore the sustainability of natural resources. 'The limits to growth' of the Club of Rome is a well-known example (Meadows et al., 1972). Using scenarios and the World3 computermodel the study showed that a long-term perspective can identify problems in current policies (Van Asselt et al., 2010a). In business development, Shell Oil is considered the first to use scenario planning (Van der Heijden, 1996; Wack, 1985).

Towards First Scenarios in Water Management (1953 - 1988)

After a millennium of adaptation in response to (flood) events, the Dutch shifted to anticipatory water management in the course of the twentieth century. The 1916 storm flood along the Zuiderzee initiated the implementation of existing plans for the Afsluitdijk, a large defence structure separating the Zuiderzee from the sea. The 1953 storm surge, which killed 1835 and affected 750,000 people, triggered a paradigm shift. policy makers learned that the deterministic approach was inadequate. From the perspective that *'this should never happen again'*, they stated that the probability of occurrence of such an event should be very small. Accordingly, an a-priori accepted exceedance probability and corresponding water level were determined, resulting in design conditions for the Delta Works (Delta Committee, 1960), the large defense structures in the southwest delta. This was the first use of future conditions. A relative sea level rise based on extrapolation of measurements was included in the design of the defense structures, because of its lifetime (100 to 200 years) (Rijkswaterstaat, 2008). However, a potentially accelerated sea level rise due to climate change was not considered. This probabilistic approach was adopted for all primary flood defences.

Along with the Delta Works the Dutch government decided for developing a national policy on water management, and to document this in a National Policy Memorandum on Water Management (PWM). As safety was ensured with the Delta Works and the Afsluitdijk, the 1st PWM focused on fresh water supply (Rijkswaterstaat, 1968). Although climate change and sea level rise were mentioned, assessments considered only an increase in water demand. Uncertainties about future developments were acknowledged, but no bandwidth was given. The document stated that *'the influence of these developments (climate change and upstream water use) on the total water availability is considered to be small. It is however important to keep monitoring these developments.'* (Rijkswaterstaat, 1968, page 137).

In the 1980s, scenarios became mainstream in futures research (Moss et al., 2010). Also, in the Netherlands scenario analysis emerged. This was probably supported by the cooperation with the RAND Corporation for the PAWN-study (Policy Analysis for the Water management of the Netherlands) (Goeller et al., 1983; Rijkswaterstaat, 1985) that provided the scientific support for the 2nd PWM (Rijkswaterstaat, 1984).

In the 2nd PWM, the government stated that revision of the 1st PWM was needed due to: *'societal developments, changes in insight and stakeholders of the water system. For example, the prognoses for the future water demands for agriculture and drinking and industry water need to be revised and the importance of sectors like industry, shipping and nature has been acknowledged'* (Rijkswaterstaat, 1984, page 7). The 2nd PWM emphasised improving water management from a cost-benefit perspective. This was a paradigm shift; instead of ensuring water for all users, policy was now only implemented if the benefits were larger than the costs. Trends in water use were considered for agriculture, drinking and industry

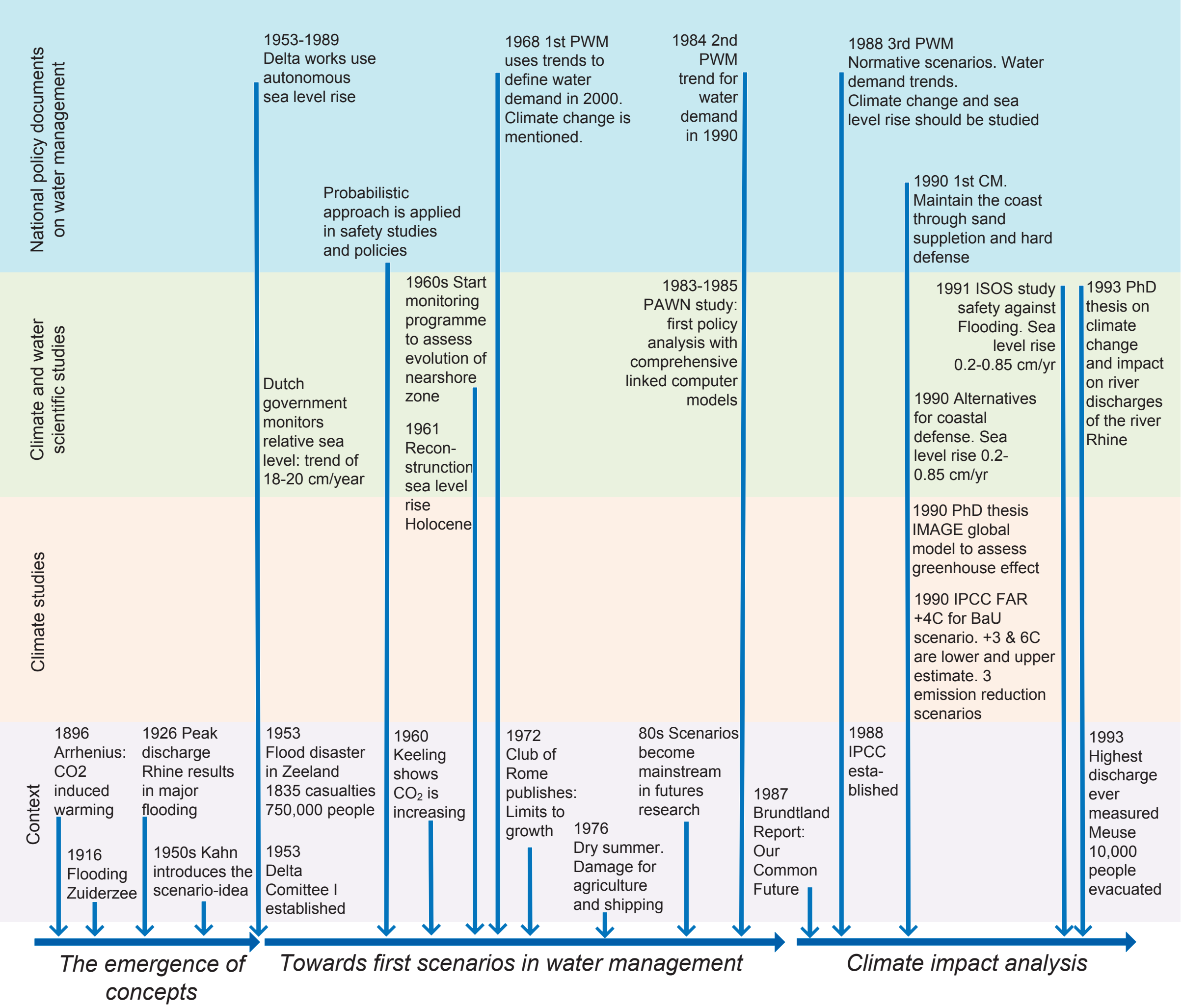
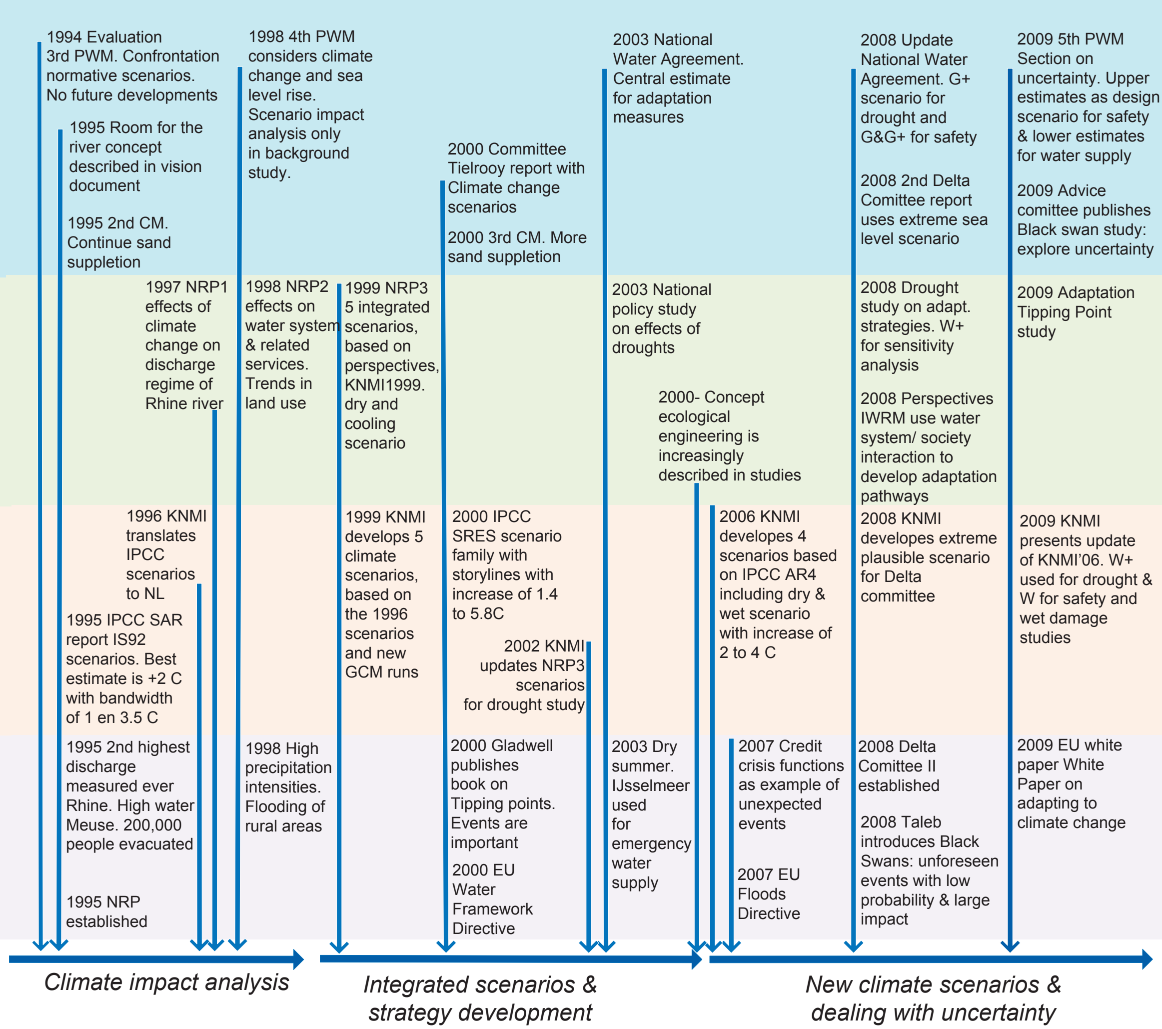


Figure 5: Historical perspective on developments in national water policy documents in the Netherlands, key research studies on climate and water, climate scenario studies and the context in which these studies were made. PWM = National Policy Memorandum on Water Management. CM = Coastal Memorandum.

water in the policy analysis. The PAWN-study mentions that *'at places where the uncertainty in the results has an impact on the conclusions, either a sensitivity analysis is executed or different scenarios are described.'* (Rijkswaterstaat, 1985, page 138). The study concluded that even in case of the 'maximum trend scenario' for irrigation, wherein many farmers would use sprinklers, no large interventions were needed. These conclusions were adopted in the 2nd PWM.



Climate Change Scenarios and Impact Analysis on the Water System (1988 - 1998)

By the end of the 1980s, experiments with Global Climate Models (GCMs) indicated that the signal of anthropogenic warming would soon emerge from natural variability (Hansen, 1988; Moss et al., 2010). The International Panel on Climate Change (IPCC) published its first assessment including four scenarios in 1990 (IPCC, 1990). The scenario 'business as usual' (BaU) assumed no or few policies to limit greenhouse gas emission and was presented with a lower, best and upper estimate. The other three 'accelerated policy' scenarios described future climates after emission reduction. In the second assessment report, the BaU scenario was elaborated in the IS92 scenarios (IPCC, 1995). Dutch researchers developed the global model IMAGE for impact assessment and policy development regarding greenhouse gases (Rotmans, 1990; Alcamo et al., 1999).

In this period, the first studies on climate and water appeared in the Netherlands. In a coastal defense study three sea level rise scenarios were considered, namely: the 'policy' scenario including sea level after global implementation of climate change mitigation policies; the 'anticipatory' scenario describing the best guess; and the 'unfavourable' scenario describing the best guess plus standard deviation (De Ronde and Vogel, 1988). Based on these scenarios, the subsequent ISOS (Impact of Sea level rise On Society) study quantified impacts, and identified policy options (Rijkswaterstaat and Delft Hydraulics, 1988). The study focused on safety against flooding, using scenarios on sea level rise, river discharges, wind and tidal conditions. The ISOS study was the first to include changes in river discharges in the scenarios. Socio-economic developments were excluded because of their uncertainty.

Now that safety and water supply were managed well, the government shifted its focus to water quality because: *'pollution, together with overexploitation of water and an unbalanced spatial planning have resulted in an unsustainable water system'* (Rijkswaterstaat, 1988, page 5). Accordingly, the 3rd PWM, entitled 'Water for now and the future', focused on ecological and chemical water quality provided that safety was guaranteed. The Brundtland report (Brundtland, 1987), which put sustainability high on the international political and public agenda, clearly inspired this quality focus. policy makers defined future targets based on past conditions, and identified policy options to reach these target conditions under different scenarios. The scenarios included extrapolations of ongoing water demand trends and the intended result of environmental policy defined by the Ministry of the Environment. Although this ministry published three estimates, only the central estimate was considered.

While research studies extended their scope by using integrated scenarios, policy makers were focusing on safety issues. Triggered by the 1993 and 1995 flood events and the increased attention to climate change and sea level rise, the Dutch government installed the committee Tielrooy to analyse whether current water management was sufficiently prepared for future climate change and sea level rise. This committee adopted three of the KNMI1999 scenarios, which were similar to the KNMI1997 scenarios, but ignored the 'dry' scenario, because this scenario contained complementary signals compared to the other scenarios (wetter and warmer, drier and warmer, drier and colder). Socio-economic developments were only considered in a qualitative sense. In the final report, guiding principles to prepare for climate change were explicitly put forward: *'anticipate instead of react, create more room for water, and do not only discharge, but also store water'* (CW21, 2000). As an alternative for confining water in narrow zones between dikes, creating more room for water was an upcoming paradigm in river management, aiming at decreasing water levels in times of peak discharges, and enhancing nature's quality at the same time (Dienst Landelijk Gebied, 1999; Silva et al., 2000). Regarding coastal zone management, the government decided in 2000 to double the amount of sand for beach nourishment in response to new insights on long-term morphological developments (Rijkswaterstaat and IMAU, 2000).

In 2003, several governmental organisations agreed in a so-called National Water Agreement (NWA) to define and implement strategies for coping with climate change and sea level rise by 2015, and to explore the necessary strategies for 2050 (Ministerie van Verkeer en Waterstaat, 2003). Water boards should adopt the guiding principles of the committee Tielrooy, and *'at least use their central estimate scenario for 2050 with an outlook to 2100 to develop measures'*.

Until this period, policy makers neglected 'drought' as a possible effect of climate change. In 2002, the government studied the balance between fresh water demand and supply (RIZA, 2005). The dry summer of 2003 was a welcome surprise for getting the subject on the political agenda. KNMI updated the 1999 scenarios and re-introduced a 'dry' scenario in a revised version based on RCM results (Beersma, 2001). For the analysis also land use changes were included as well.

New Climate Scenarios and Adaptation Policy in Legislation (2006 - present)

Based on extended and improved information of amongst others the IPCC's fourth assessment (IPCC, 2007a), KNMI developed new climate scenarios; KNMI'06 scenarios (Van den Hurk et al., 2007; Katsman et al., 2008). As uncertainty due to emission scenarios was smaller than the uncertainty due to climate models, temperature was used as discriminating factor. A second relevant factor was the circulation regime. This resulted two scenarios with a moderate temperature increase (+1°C) and two with strong temperature increase (+2°C), which were further distinguished by a strong or weak change of atmospheric circulation over Europe. For sea level rise a bandwidth was given to cover the large variety in the sea level rises predicted by different climate models for different global warming scenarios. The four KNMI'06 scenarios were a problem for the water managers as this precludes the selection of a central estimate, as was prescribed in the NWA of 2003, and the adequacy of designed policy options needed to be reconsidered. The NWA was updated in 2008, and prescribed for different water related problems the use of only one of the KNMI'06 scenarios (Ministerie van Verkeer en Waterstaat, 2008). In 2009, KNMI reflected on the KNMI'06 report based on new scientific understanding and recent observations (Klein Tank and Lenderink, 2009). Although KNMI did not see the need for defining new scenarios, the scenarios with the moderate temperature changes were now considered less plausible than those with the larger changes. Consequently, again the guidelines in the NWA (Ministerie van Verkeer en Waterstaat, 2008) was outdated. For example, for studies on drought the NWA prescribed to use the 'moderate dry' scenario, while according to the update of KNMI for this kind of situations the 'stronger dry' scenario would be more plausible.

In 2007, the government established the second Delta committee for identifying actions to prevent future disasters (Delta Committee, 2008; Kabat et al., 2009), as the expected future climate change and sea level rise *'can no longer be ignored'* (Delta Committee, 2008, page 5). Next to the KNMI'06 scenarios, the committee considered a high-end scenario existing of a plausible upper limit of sea level rises in 2100 and 2200 for a robustness test of policies and investments (Vellinga et al., 2008; Katsman et al., 2011). The high-end scenario learnt policy makers that the Netherlands can overcome sea level rise and climate change, but that the water system has to be adapted. The advice resulted in a Delta Act and is presently being elaborated on in the so-called Delta Programme.

Climate change and sea level rise were now on the political and public agenda. In the 5th PWM, (Rijkswaterstaat, 2009) climate change and sea level rise played an important role. The report had a separate chapter about dealing with uncertainties on climate change. The four KNMI'06 scenarios were described in detail, while socio-economic trends and future targets were described qualitatively. Again a scenario was prescribed for strategy development, meaning that the system should be prepared for coping with the situation described in a specific scenario. The report stated, that *'For the choice of a scenario the societal risk is important. For safety issues the risk is larger, than for drainage and water logging issues. In case of low flexibility and high societal risk, there is a preference for the upper limits of climate change.'* (Rijkswaterstaat, 2009, page 28). The report mentions the difficulties of including new scientific information: *'The availability of repeatedly new scenarios results in the risk that decision making will be postponed due to the uncertainties. ... On the one hand it is strived to use most recent insights while on the other hand stable assumptions are needed for decision making and implementation. New insights can not result in new assumptions and evaluations.'* (Rijkswaterstaat, 2009, page 27). The report identified policy options to reach the described targets, and presented a planning scheme with research and decision milestones.

At European level, the Flood Directive (2007/60/EC) came into force in 2007. This directive aims at mapping and reducing flood risk and, as one of the measures, mapping flood-prone areas categorised to low, medium (likely return period $\geqslant 100$ years), and high probability. The Flood Directive refers to these categories as scenarios. The 5th PWM states that it will incorporate this Directive in the Dutch legislation in the next planning period.

Dealing with Uncertainties about the Future: New Approaches (2006 - present)

After 2000, the awareness raised that uncertainty over the future will remain and cannot be eliminated (cf. Van Asselt 2000). More research does not automatically reduce uncertainty but may even increase it. Taleb (2007) emphasised future uncertainty with the introduction of the 'Black Swans' concept. These are unforeseen occurrences (unknown unkowns) with a low probability of occurrence but having a large impact. Although from a different field, the recent 'economic crisis' raised awareness that (unexpected) events influence our world view. New approaches for dealing with uncertainties emerged (e.g. Dessai and Hulme, 2004; Carter et al., 2007; Russill and Nyssa, 2009). Gladwell (2000) introduced the 'tipping points' concept to describe the catchiness of behaviour and ideas. Moser and Dilling (2007) used tipping points to conceptualise social change, and defined it as *'moments in time where a normally stable or only gradually changing phenomena suddenly takes a radical turn.'* (Moser and Dilling, 2007, page 492).

In the Netherlands, discussions on scenario updates led to a new approach, using the systems vulnerability to define Adaptation Tipping Points (ATP) indicating whether, and under what conditions, current water management strategies will continue to be effective under different climate changes (Kwadijk et al., 2010). In case of new scenarios, only the timing of an ATP needs to be updated. Events and surprises were recognised as triggers for adaptation, societal change and learning: not only the future endpoint, but also the pathway to this point is important. Therefore, a method to explore Adaptation Pathways was developed. By exploring pathways with transient scenarios, and including the dynamic interaction between the water system and society, policy makers can identify robust and flexible pathways or identify lock-ins (Chapters 3 and 4, Offermans et al. 2011).

Also, at a policy level new concepts emerged. Recently, both the Scientific Council for Government Policy and the Advisory Council for the Ministry of Transport and Water Management advised to consider uncertainty explicitly (Raad voor Verkeer en Waterstaat, 2009; Van Asselt et al., 2010a). The latter states that *'we should not only be prepared for expected but uncertain future climates, but also for unknown uncertainties, so-called Black Swans.'* Accordingly, policy development should incorporate proactive adaptation by using scenarios for characterisation of uncertainties, and indicators to monitor the necessity of policy revision. The council also states that *'policy based on an extreme scenario is liable to prove unduly expensive or unnecessary'* (page 53). This statement is in contrast with the second Delta Committee. The scientific council requested attention for normative foresights including a variety of values and perspectives (Van Asselt et al., 2010a).

The chair of the Delta Programme mentioned that: *'One of the biggest challenges is dealing with uncertainties in the future climate, but also in population, economy and society. This requires a new way of planning, which we call adaptive delta planning. It seeks to maximise flexibility; keeping options open and avoiding 'lock-in'* (Kuijken, 2011). These were starting points for a new approach for scenario design (Bruggeman et al., 2011). By analysing what makes policies for safety and water supply vulnerable, four climate and land use scenarios with small and large impact were established.

Originating from the 1990s, but becoming practice in the past years, is the paradigm shift occurring the the Netherlands from strategies of defence against water with hard engineering structures to a more 'soft' approach using natural dynamics of the system itself (cf. Inman 2010). The changing approach involves restoration of wetlands, beaches and natural floodplains, and is referred to as 'ecological engineering', 'building with nature' or 'green adaptation' (e.g. Van Koningsveld and Mulder, 2004; Waterman, 2008; Aarninkhof et al., 2010). These approaches are novel ways of dealing with uncertainty: instead of fighting unpredictable future events, adapting to what is happening (Inman, 2010).

2.4 KEY FINDINGS

2.4.1 *Did the Scenarios Enable Robust decision making?*

The central issue related to this question is whether the scenarios sufficiently represented relevant knowable uncertainties for enabling robust decision making on water policies. We observed that scenarios in policy analysis shifted from describing future water *demand* to water *availability* after the 3rd PWM. For the 1st PWM policy makers expected no relevant changes in water availability. Research studies focused mainly on water availability scenarios in terms of climate change, sea level rise and river discharges. Thus, few studies included all relevant knowable uncertainties for long-term water management.

Whether the relevant uncertainties were *sufficiently* represented can be assessed from the number, value range, temporal and dynamic nature and the amount of alternatives. Over the past decades, the number of scenarios has increased from one to multiple scenarios, thereby increasing the represented uncertainty range. All research studies included several scenarios; first only climate scenarios, later studies also included socio-economic developments. The first policy documents considered a single scenario only, while policy studies in the past 15 years used three to four scenarios. Still, the guidelines for climate adaptation following from these policy documents recommended using only one scenario for the design of water policies (Ministerie van Verkeer en Waterstaat, 2003, 2008). Hence, although policy makers recognised uncertainty about the future with several scenarios, they persisted focusing on a 'best estimate' of the future climate in terms of a best prediction, until KNMI (deliberately) presented four scenarios in 2006 (Van den Hurk et al., 2007). Thereafter, policy makers selected one of these four scenarios as 'best scenario' for strategy development for a specific problem such as safety or water supply. Thus, in practise the range of the uncertainties was not fully considered.

Although an increasing number of scenarios was introduced, most scenarios remained to be extrapolations of trends. This is reflected by the scenario names. The first four policy documents merely used 'business-as-usual' scenarios called 'trend', 'autonomous developments' and 'prognoses'. Few policy studies included a 'maximum trend', 'worse case' scenario. Only a few background studies tried to include alternatives, such as the 'discontinuity' scenario for the 4th PWM. In contrast, research studies explored more alternatives by considering several scenarios such as 'worse case', 'lower/central/upper' estimates, 'dry' and 'cooling' scenarios.

The dynamic and temporal nature of the scenarios were limited to defining a few projection horizons, in most cases the years 2050 and 2100. Scenarios described for these years were projections of climate and external context, resulting in a snapshot of the future situation beyond control of the water managers. Likewise, socio-economic drivers of water demand were considered as independent 'policy driven' or 'autonomous developments', which were gradual extrapolations of trends into the future. Adaptation options were then formulated and evaluated against external conditions at one future point. Scenario analysis for water management was, thus, a one-way pressure-impact analysis without response from society or water management, unlike global models, such as IMAGE (Rotmans, 1990). As a result, the water policy studies have ignored the dynamic path into the future with natural (year-to-year) variability, extreme events, the potentially large role of societal response to climate events and water management response to climate-associated events or changing socio-economic perspectives. It is only in recent scientific studies that this interaction is recognised, and that scenarios are becoming completed with these new relevant dimensions of time-series, dynamic interaction and surprises (Chapter 3).

The range of the values used in the scenarios is an additional indicator for the sufficient representation of uncertainty (see figure 6 and 7 for climate scenarios and supplementary information for socio-economic developments). The 1st and 2nd PWM used one value based on trends for water demand, but extended the range due to climate variability by analysing years with different net precipitation and discharge. Three studies translated socio-economic developments into land use maps. The projection year of these scenarios extended from 2015

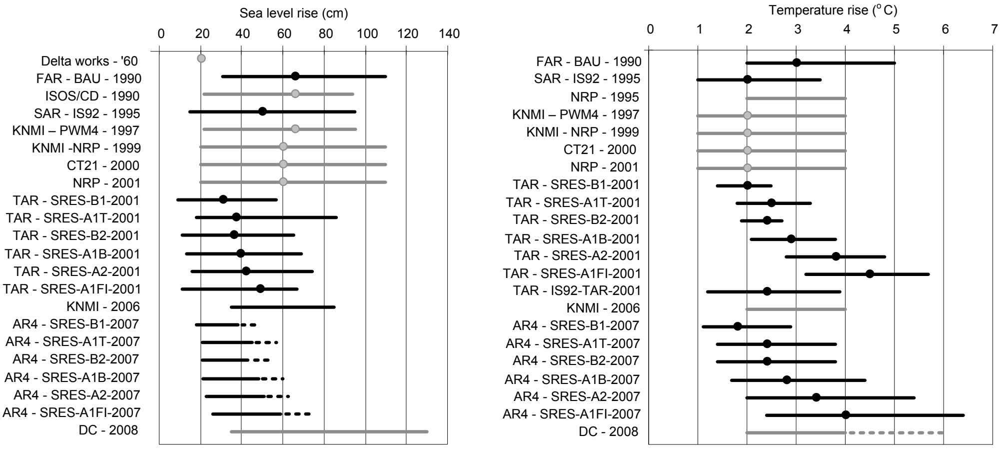


Figure 6: Values for global and local sea level rise for the Netherlands (left) and global temperature change (right) in 2100 for national and global climate scenarios (reference year 1990). FAR, SAR, TAR and AR4 refer respectively to the 1st, 2nd, 3rd and 4th IPCC report, NRP is National Research Programme, CT21 = Committee Tielrooy, DC = second Delta Committee. PWM = National Policy Memorandum on Water Management. Scenarios for the Netherlands are in grey. In the DC study, the global temperature range included for the sea level rise was larger (dashed line) than for the climate parameters such as precipitation (solid line). In the AR4 report sea level rise values were presented for the scenarios (solid line), and additional uncertain sea level rise was described in the report (dashed line).

to 2050 to 2100 resulting in an increase of the considered acreage change and the bandwidth for urban and nature, but not for agriculture. Regarding the climate scenarios, the bandwidth of the emission and global temperature changes in the IPCC scenarios has become larger. Previous climate scenarios for the Netherlands had similar ranges for the global temperature as the IPCC scenarios, but recent scenarios differ from the IPCC assessments. The bandwidth for global temperature rise used in the Netherlands (figure 6) is remarkably smaller than the IPCC scenarios at that time. This is caused by the fact that the KNMI scenarios represent approximately 80% of the total range of the output of the climate models, while IPCC scenarios presented the complete range. However, it is uncertain whether water managers and the general public in the Netherlands are aware of this difference, and only see the smaller uncertainty range. Over the years, KNMI's scenario values for summer precipitation have changed considerably, in contrast to the winter values. The introduction of the 'dry' scenarios reflects the awareness of larger uncertainty about future summer climate, as not only the magnitude, but also direction of the change differed in the scenarios.

The difference in projections of sea level rise between IPCC and the Dutch scenarios is striking (figure 6). While the IPCC scenarios show a trend to narrower ranges and smaller values for sea level rise, the KNMI kept the same range and the values were larger than the IPCC. These differences can mainly be explained from the different uncertainties included in the scenarios (e.g. the uncertainty in the contribution of ice sheets). In the AR4 study part of the uncertainties related to ice sheets was not included in the sea level scenario values, but only described in the report. These uncertainties were, however, included in the national KNMI scenarios, together with recent (scenario and field) studies which were not available at the time of the AR4 (Katsman et al., 2011). In addition, regional differences due to variation in ocean temperature, distribution of melt water over the oceans, and - in some studies - tectonic subsidence contribute to differences between the scenario studies. For example, in the 1990s studies values were derived from the IPCC estimates, supplemented with the natural trend and subsidence of the Netherlands (Van Asselt et al., 2001). The Delta Committee included a tectonic subsidence of 10 cm/year (Vellinga et al., 2008), while the studies in the 1990s included a subsidence of 5 cm/year. The high-end sea level rise explored by the 2nd Delta Committee was discussed thoroughly among researchers and policy makers. The values were larger than in the KNMI'06 scenarios, because the Delta Committee aimed at defining an 'upper plausible' limit of sea level rise by including a wider range of uncertainties and mechanisms underlying sea level rise for the Netherlands. Remarkably, this upper level is not that much higher than the upper ends of the uncertainty ranges put forward in 1990 in the national studies.

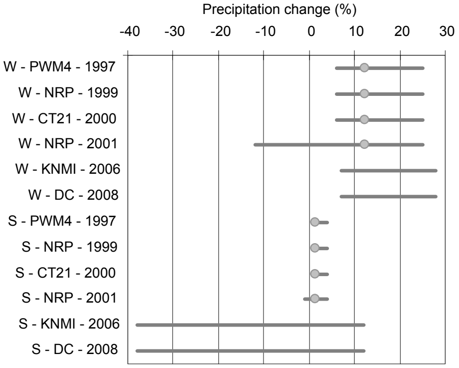


Figure 7: Values for precipitation change (w=winter; s = summer) in 2100 for different national climate scenarios. PWM = National Policy Memorandum on Water Management, NRP is National Research Programme, CT21 = Committee Tielrooy, DC = second Delta Committee.

2.4.2 *Did the Scenarios Enable Learning?*

Generally, scenario analysis in water policy studies enabled four different lessons: 1) Insight in impacts of climate change and socio-economic developments, as a result of several national, but also global studies (e.g. IPCC reports, ISOS and NRP studies); 2) The need and effectiveness of policies, such the 2nd PWM or the ATP study; and 3) The need for adaptation of targets and/or policies as a result of comparing scenarios with monitoring results (e.g. 2nd and 3rd PWM); and 4) Awareness about possible impacts of climate and socio-economic developments. For example, the second Delta Committee widely communicated its results through readable reports and YouTube videos accessible for the general public. This received a lot of media attention, and raised the awareness of the importance for developing water management strategies to prepare for the future. Furthermore, their 'worst case' scenario deliberately provoked lots of discussion among water managers in the Netherlands, which enhanced the exchange of ideas, and thus involved a large degree of learning according to the chair of the committee (Veerman, 2010). Flood and drought events corresponding with the scenarios, but also the public debate about issues (e.g. climate change, credit crisis) accelerated the influence of study results in policy implementation.

Both scenario analysis in water management and the science-policy interaction have clearly evolved in the past twenty years. In retrospective we can distinguish five evolutions that reflect the learning process of scientists and policy makers:

1. *From flood protection to integrated water management*: This shift was supported by lessons on the effectiveness of policies in scenario analysis. After the major flooding of 1953, water management focused on flood protection. However, in the course of time, and with the stepwise completion of the Delta works, attention was given to other water-related problems. In the PWMs the focus changed from water supply for economic purposes, via a cost-benefit analysis for maintaining water availability to water quality and nature, and eventually introducing the concept of 'integrated water management', which the 5th PWM extended with spatial planning issues. Also, the scientific studies show a learning process through an evolution in the studied subjects. The first research studies focused on safety against coastal flooding, which was later extended to large rivers and regional water systems and finally to impact assessments of water services.

2. *Towards integrated scenarios*: This shift was initiated by awareness that both water *availability* and water *demand* are relevant for water policy making, as well as the global and European shift to integrated studies. Also, scenario studies showed the relevance of integrated studies for decision making. Although coming from a different starting point, both scientific and policy studies moved towards integrated scenarios. Scientific studies first used climate scenarios. By the end of the 1990s, socio-economic developments were considered increasingly relevant. After only evaluating land use change trends and 'autonomous' socio-economic developments, integrated scenarios comprising both climate and socio-economic components were defined to explore different water management styles. The scenario content in the PWMs changed in correspondence with the purpose of the PWMs from water demand trends to climate scenarios, while at present integrated scenarios are considered. Still, the integrated scenarios are not yet fully employed for impact assessment or policy development. Furthermore, the influence of societal perspectives (e.g. on policy targets) remains to be fully incorporated in policy making.

3. *From predicting to exploring the future*: While policy makers experienced that the future turned out differently than envisioned, and some events occurred as complete surprise, evidence grew that we can not predict the future. Initially, prognoses only applied to possible changes in water demand. Estimates of future flood magnitudes - as required for the probabilistic flood protection approach - were based on autonomous developments or expert judgement. These 'predict and act' studies slowly shifted to an 'explore and anticipate' approach for which several scenarios were used. Still, the initial use of 'best guess' or 'central estimate' climate scenarios reflects the desire of predicting future conditions, although now associated with bands of uncertainty.

With the IPCC-SRES and KNMI'06 scenarios, the recognition that the future is uncertain and that there is no 'most likely' future, has increasingly settled in water management. Accordingly, research and policy studies not only aimed at improving the understanding of future developments such as climate change and reducing uncertainties, but also on developing methods for dealing with uncertainties about the future. This observed shift corresponds with observations of futurists (Van Asselt et al., 2010a; Slaughter, 2002; Van t Klooster, 2008). Both approaches, also referred to as forecasting and foresight, are still used next to each other (Van Asselt et al., 2010b). Also, in water management the predictive approach is still used when it comes to short term actions such as flood forecasting and determining the (long-term) design discharge. For short term drought management both forecasts and scenarios (foresights) are used. Some analysts propose to use probabilistic scenarios, but we have not observed these scenarios in the studies reviewed, but this could be initiated by the EU Flood Directive's approach, which prescribes to use scenarios with floods with low, medium and high probability.

4. *Interaction science, policy and events*: Most uncertainties about the future were first investigated by scientists, and later incorporated in policy, especially if events seemed to support the trends indicated by scenarios. For example, the 3rd and 4th PWM documents mentioned potentially relevant impacts of climate based IPCC results and scientific research in the preceding decades. In recent years, the turn-over rate from scientific studies to water management has speeded-up. Scientific studies involve stakeholders and while novel approaches in scenario analysis emerge briefly after being introduced in the scientific world in water management approaches as well.

5. *From fighting water to accommodating and adapting to water*: Since the 1960, awareness raise about potential effects of climate change as a result of scenario studies, and flood events. This awareness triggered a shift from focusing on 'hard' defensive infrastructures for flood protection to 'softer' measures for integrated water management, by using natural processes and accommodating water (e.g. 4th PWM). Thus, instead of static infrastructures with a long life time, easily adaptable policies to changing, unpredictable boundary conditions were chosen.

2.5 CONCLUSIONS AND RECOMMENDATIONS

This review describes the use of scenarios in water management studies in the Netherlands over the past 60 years. To identify what we have learnt from this experience, we analysed whether the scenarios enabled robust decision making and learning.

The opportunities for robust decision making resulting from scenarios increased, but are still not fully exploited, especially in policy making. Although the number of scenarios increased, for the strategy development often one scenario was appointed for design conditions. Rarely, all relevant uncertainties were included. Especially in the policy documents uncertainties in water *demand* or *availability* were considered, while none included social (perspective-based) uncertainty. The number of alternative futures increased, but scenarios mainly remained based on extrapolation of trends. Almost all scenarios used were snapshots at 2 or 3 time horizons, thereby ignoring pathways towards the endpoint, and disregarding the possibility that events may drastically change such pathways. All scenarios were surprise free. The 'Decision robustness' can thus be improved.

Differences in value range between different scenario studies can often be explained by reading details and communicating with the developers, which indicates that communication on assumptions is important for appropriate scenario use.

The scenarios enabled learning about possible impacts of developments, the need and effectiveness of policies, and the need for adaptation of policies. In addition, the scenarios raised awareness about potential future problems. The historical perspective shows a clear science-policy interaction. For example, first used in research studies, the policy documents took climate change and sea level rise up, as important developments to consider in strategy development; sometimes with a little help of a flood or drought event. We observed several paradigm shifts reflecting the learning process of scientists and policy makers: a) from flood control to integrated water management, b) from predicting to exploring the future with integrated scenarios and, c) from fighting water to accommodating and adapting to water.

Dealing with uncertainties appears to be a struggle, given the paradox between the desire to explore potential futures using several different scenarios, *and* the preference of water managers to design policies based on a single scenario that is not frequently updated. However, water managers need to face that the future is inherently uncertain, and scenarios are always likely to be updated by new scenarios as they result from a process of design and construction at a specific moment and location (Hulme and Dessai, 2008b). These uncertainties should not be used as a constraint to develop adaptation measures for water management (cf. Hulme and Dessai 2008b; Dessai et al. 2009).

We provide five recommendations for improving water policy development under uncertainty:

1. For sustainable decision making water managers should consider several scenarios to explore the relevant range of the uncertainties, and not selecting the most likely future or prescribing a 'design' scenario.

2. New approaches are available, which can together with scenario analysis support the development of sustainable measures. Several methods involve many computational experiments to analyse the effects of uncertain parameters (e.g. 'Exploratory Modeling' Bankes (1993)) to seek for robust decisions (Lempert et al., 2003, 2006) or seek to optimize robustness to failure – or opportunity for windfall – under severe uncertainty ('Info Gap' theory Ben-Haim (2001)). Walker et al. (2001) describe a planning process with different types of actions (e.g. 'mitigating actions', 'hedging actions') and signposts to monitor if adaptation is needed. Also, adaptation tipping points (Kwadijk et al., 2010) and exploring adaptation pathways with transient scenarios (Chapter 3) can be of assistance.

3. Scenario developers should clearly communicate the assumptions, purpose and limitations of scenarios, and the conditions under which the scenarios were made (process and time limits).

4. Tailored scenarios are needed to ensure relevant scenarios and appropriate use. To develop tailored scenarios water managers should assess the system's vulnerability and communicate this to scenario developers.

5. To improve scenarios and their use, evaluation of past scenarios remains useful. For this purpose, evaluation on 'Decision robustness' and 'Learning success' deserve further elaboration in terms of more explicit criteria concerning e.g. comparison with study's objectives, stakeholder involvement, pathway analysis, more precise addressing of the learning effect (who learned what and how?)

6. Instead of responding to flood and drought events, policy makers could identify triggers (Walker et al., 2001) and adaptation pathways (Chapter 3). The triggers give signals when it is time to make a decision and the adaptation pathways allow for identifying robust options and lock-ins.

Summarizing, exploring the future with several scenarios, analysing the vulnerability and good communication with scenario developers may help water managers to deal with uncertainties, and make sustainable decisions.

3

A METHOD FOR SUSTAINABLE WATER MANAGEMENT UNDER UNCERTAINTY

ABSTRACT

Development of sustainable water management strategies involves identification of vulnerability and adaptation possibilities, followed by an effect analysis of these adaptation strategies under different possible futures. Recent scenario studies on water management were mainly 'What-if' assessments in one or two future situations. The future is, however, more complex and dynamic. It involves general trends and unexpected events in both the water and social system. Moreover, both systems interact: society responds to events and the state of the water system changes in response to management. In this chapter we discuss a transdisciplinary approach. Key elements in the concept are 1) the model of Pressure, State, Impact, and Response 2) the Perspectives method to consider uncertainties of social and natural system and 3) the evaluation of the system using transient scenarios in which we consider time-series of trends, events and interaction between the water system and society. The effect analysis is executed with an Integrated Assessment metamodel based on simple cause-effect relations and response curves.

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3.1 INTRODUCTION

Water management generally aims at providing adequate amounts of water of proper quality for the various water-related services. Particularly in developed societies, water systems have been modified or trained to fulfil the demands of the water-services water in the longer term. Failure of the water system functioning, such as in the case of flood disasters, water shortage or severe pollution, has led in many cases to adaptation of the water system. Examples are dike enforcement, river regulation and reservoir building, or the establishment of wastewater treatment plants. In recent years, extreme floods, the need for ecological rehabilitation of rivers, and the prospect of future global change has raised the awareness that new water management strategies might be needed over the forthcoming years to ensure sustainable use of the water system over the 21st century. However, the future is surrounded by large uncertainties. Climate change and the hydrologic response are major causes of this uncertainty, as they may affect water availability. In addition, various unknown socio-economic and agro-economic developments will affect the hydrological cycle through land use changes or determine water demand through for example population growth or industrial expansion. Uncertainties are also introduced by social issues in terms of a change in our core beliefs, like a moral sense to care for the environment and the demand for sustainable developments. These factors together determine possible futures that are envisaged. Depending on the perspectives of the future, different water management strategies may be adopted. The question that arises is then: which is, given the uncertain future the most sustainable water management strategy[1]?

The objective of this chapter is to describe a new method for the development of sustainable water management strategies under uncertainty, taking into account different possible developments of the physical, socio-economic and social system. We start with considering the uncertainties involved in long-term water management, an overview of available methods for uncertainty analysis and how they can be applied in scenario analyses for long-term water management. The method will be illustrated by means of a hypothetical case.

3.2 UNCERTAINTIES IN LONG-TERM WATER MANAGEMENT

To establish our perception on the current and future state of the water system models are used (both conceptual and mathematical) describ-

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[1] We consider a water management strategy sustainable if it is 1) effective, indicating that objectives for people, profit and planet are achieved as much as possible; and 2) robust, which means that it is effective now and in the future and preferably independent of future conditions; or 3) flexible enough to adapt to future conditions. Sustainable strategies are future-proof strategies.

ing the natural environment and the socio-economic system. However, uncertainties limit our understanding of the system as well as our predictive capacity of the future state. The uncertainties that are involved in sustainable water management have two main types of sources (Van Asselt, 2000; Walker et al., 2003). The first is referred to as 'variability', which includes unpredictable randomness in natural processes, human behaviour, and social, economic and technological dynamics. The second source involves a lack of knowledge (epistemological uncertainty), originating from imprecise or incomplete observations of the system, conflicting evidence, indeterminacy of the system's state, or ignorance of the functioning of (parts of) the system (Van Asselt, 2000).

Uncertainties manifest themselves in different areas. Based on a review of several classifications (Van Asselt, 2000; Walker et al., 2003; Dessai and Hulme, 2004; Loucks and Van Beek, 2005; Beven, 2008) we categorise them into three different types:

1. *Natural uncertainties* involve the natural environment part of the system. These are due to variability (spatial and temporal) and epistemological uncertainties. An example is the uncertainty of extreme values, which plays a role in flood risk management. Extreme weather events and their impacts have been an important trigger for adaptive water management.

2. *Social uncertainties* arise from uncertainties in human response like future values and objectives, learning capabilities of society, human response and decision making process with stakeholders. The human response refers to (changes in) how 'we' (as a society) think about water management, and how we act. It refers not only to water management policy itself, but explicitly refers to water related behaviour and support for water management strategies broadly distributed within a society (Offermans, 2010). This response can be induced by reflection on historical results, by new information (like new technology or new measurements) or by events even outside the management area.

3. *Technological uncertainties* comprise model characteristics, and arise from uncertainties in model input data and model parameters, lack of understanding of processes, model incompleteness or oversimplification of processes. These uncertainties inevitably arise in modelling exercises of complex systems, such as climate change prediction and impact analysis.

3.3 CURRENT UNCERTAINTY ANALYSIS METHODS IN WATER MANAGEMENT

Different methods have been applied in water management to analyse uncertainty and its influence on decisions. In water management we distinguish two main groups of uncertainty methods. One group focuses on prediction of the future with statistical and quantitative methods. The other group explores the future in terms of 'what–if'–questions.

3.3.1 *Uncertainty Analysis to Predict the Future*

Sensitivity analysis studies the influence of variation in the model parameters and initial values on the model outcomes. Examples are Monte Carlo and Ensembles analysis, which result in probability distributions of model outcomes. Ensembles are used in climate forecasting to take into account the chaotic nature of the atmospheric dynamics.

Probabilistic approaches, like Bayesian statistics of fuzzy sets, are frequently used in flood risk studies or operational flood forecasting. These methods assume that uncertainty is caused by randomness and are applied when all uncertainties can be represented probabilistically (e.g. Bedford and Cooke, 2001). For decision making under uncertainty it is used in combination with utility curves.

Since not all uncertainties can be assessed in terms of probabilities, as is the case in long-term water management, new methods are being developed. The Info-Gap method explores different simulations with increasing uncertainty of parameters to examine the performance of strategies in relation to uncertain parameters (Ben-Haim, 2001; or cf. Hall and Harvey, 2009 for example on water management). Robust Decision Making (Lempert et al., 2003, 2006) uses modelled effects of strategies for different plausible uncertain input parameters and interprets this as an instance of traditional Bayesian decision analysis. By carrying out a large number of simulations the performance of a strategy under the applied uncertainties can be determined, to estimate its robustness.

3.3.2 *Uncertainty Analysis to Explore the Future*

Most long-term water management studies have adopted scenario analysis (sometimes in combination with one of the above methods), as adequate instruments to explore uncertain aspects of the future, the potential implications of future global change and possible strategies. This yields information on the sensitivity about aspects decision makers are worried about and aspect they should be worried about (Bentham, 2008).

An uncertainty method related to scenario analysis is the decision tree. A decision tree is a structured graph that shows the hierarchical dependencies of possible outcomes (Beven, 2008). Kwadijk et al. (2008) combined this method with a vulnerability assessment of the water system to future climate. This resulted in a decision tree showing tipping points until which a strategy is still effective and giving other options after this point.

Over the past decades, the IPCC has presented different sets of global scale emission and climate scenarios (IPCC, 1992, 2000). These scenarios initially comprised variants of 'Business-as-Usual' emissions (IS92) that were translated in global patterns of climate change. With the SRES scenarios (IPCC, 2000) a first attempt has been made to develop projections of future anthropogenic climate forcing based on plausible storylines of internally consistent global socio-economic developments. Instead of considering the uncertainty in the IS92 scenarios as a bandwidth around the 'most likely' central estimate (IS92a), the 4 SRES scenario families are considered equally likely to occur.

In recent years climate models have greatly improved along with increasing computing capacity, allowing finer spatial and temporal detail of the models and improving the representation of physical processes. Still, different climate models and ensemble transient runs of individual models result in large uncertainties in the climate response to increased greenhouse forcing. Remarkably, the band width of projected global warming resulting from the SRES scenarios and ensemble runs of climate models was larger than the one of the IS92 scenarios.

Scenario studies on water management were essentially 'What-if' assessments. Numerous studies were undertaken that assessed the potential impact of climate scenarios on water system and water related services (e.g. Arnell, 1998; Döll et al., 1998; Mortsch, 1998; Middelkoop et al., 2000; Droogers and Aerts, 2005). While the earliest studies focused on the climate induced changes in water availability, later scenario studies compared the changes in water availability with projections in water demand. These projections were derived from scenarios of autonomous socio-economic 'business-as-usual' development of the water users, such as flood protection, agriculture, industry, and navigation. However, uncertainty in these socio-economic aspects was not considered. The next step in scenario development was combining the climate and socio-economic developments in coherent, integrated scenarios. These scenarios describe different futures seen from different perspectives on the world, and the associated climate and socio-economic developments. Rotmans and De Vries, 1997, Hoekstra, 1998 and Middelkoop et al., 2004 used the Perspectives model, based on cultural theory, to explicitly consider uncertainties resulting from human perception of values and objectives. These studies allowed identifying mismatches between the 'world view' of society and water management and the applied management strategies. Indeed such shifts in societal perception of flood risk, ecological values or cultural awareness have in the past led to changes in river management. Examples are river rehabilitation projects undertaken along several European rivers (e.g. Buijse et al., 2003).

3.3.3 *Conclusion*

Although in recent years a lot of progress has been achieved in understanding the climate, uncertainties remain on e.g. climate projections, climate impacts and the benefits of adaptation measures (e.g. European Commission, 2007; IPCC, 2007b). Each time when the newest climate scenarios are established, this would require renewed impact studies and adapt water management strategies accordingly, which is a highly undesired situation. Another disadvantage is that the results of such climate-impact studies strongly depend on the chosen scenario(s) and the assumptions made on scientific and socio-economic uncertainties related to these issues.

Since water management involves both water availability and demand, it requires scenarios that consider both issues (Middelkoop et al., 2004). It is important that scenario studies not only compare different management strategies for different future states, but also consider the pathway towards the future state in order to include human response en natural variability.

Considering the relevant uncertainties, available methods and recent studies we conclude that not all uncertainties can be adequately addressed with existing methods (compare Van Asselt and Rotmans 2002). Current approaches lack natural and social uncertainty, especially in terms of events, surprises and, in particular, human response. There is thus a need for scenario studies that explore the pathways into uncertain futures, where water management may respond to events – both climate-related and socio-economic – and even may undergo a transition into a new management style.

3.4 TOWARDS A NEW METHOD FOR LONG-TERM WATER MANAGEMENT STRATEGIES UNDER UNCERTAINTY

We propose a transdisciplinary approach in which social and natural sciences are integrated. Key concepts of our approach are 1) the model of Pressure, State, Impact, and Response (PSIR) (OECD, 1993; Rotmans and De Vries, 1997), 2) the Perspectives method to consider both uncertainties in the physical and societal parts of the system, and 3) the establishment and evaluation of the system using transient scenarios with an Integrated Assessment metamodel. Transient scenarios comprise time-series (story lines) into the forthcoming century, that include both natural and socio economic events (e.g. floods, droughts; economic crisis), trends (e.g. climate change; changing public perception of safety or nature) and interactions between the water system and society (e.g. flood impacts; flood mitigation measures). The approach is elaborated in a conceptual framework and technological framework.

3.4.1 *Conceptual Framework*

The PSIR concept that describes the effect-chain is the underlying concept in our approach. Two important factors put pressures on the system. First, there are environmental pressures such as climate change and land use changes which influence the water availability. Secondly, socio-economic pressures determine the water demand and spatial claims. These factors influence the system state, including the water state (quantity and quality) and land use state (like land use, infrastructure). The state has an impact on social, economic and ecological services, such as drinking water supply, agriculture and habitats. The effects may lead to a response which involves a societal response of water and land use, a change in perception and valuation of the environment and water system, and an inherent policy-driven water management response. Offermans et al. (2011) and Valkering et al. (2008b) elaborate further on the response part of the PSIR chain.

A flow chart of our approach is presented in Figure 8. First, we start with an a-priori vulnerability analysis. The vulnerability of a system is the extent to which a natural or social system is susceptible to sustaining damage from climate change (IPCC, 1995). It depends on three key issues:

1. the sensitivity, the degree to which a system will respond to climate change (harmful or beneficial);
2. adaptive capacity, the degree to which a system can adapt to impact or diminish potential damages and
3. the degree of exposure.

For the vulnerability analysis we start at the end of the PSIR chain by describing optimal conditions and critical thresholds for each water-related function in terms of their physical boundary conditions. The physical boundary conditions where technical, economic, spatial or societal acceptable limits are exceeded are called tipping points. Analysing the vulnerability of a system quantifies to what extent the current situation is future-proof. Above all, it gives an indication of what water management strategies could be successful and the potential effects of climate change and sea level rise. By comparing the optimal conditions with the physical conditions under the current and future climate and sea level we can identify mismatches. This gives an indication of the current and future vulnerability in terms of vulnerable 'hotspots' for which adaptation strategies should be defined. Furthermore, desirable futures and objectives are described, which can be used to evaluate the performance of strategies.

The second step is to introduce Perspective-based uncertainty. The a-priori vulnerability analysis, as well as a preferred strategy and the

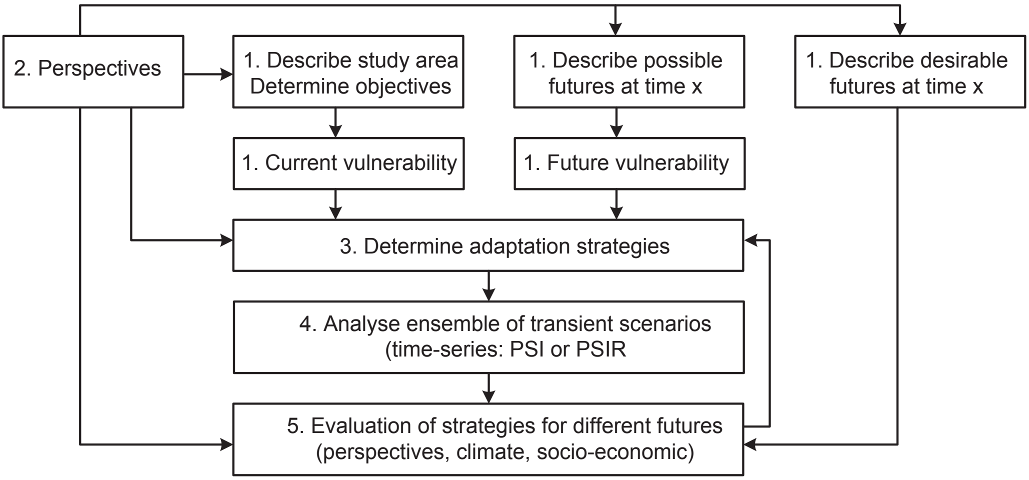

Figure 8: Flow chart of conceptual approach.

evaluation of results, are affected by our values and our perception on the functioning of the world. The Perspective concept is based on cultural theory (Douglas, 1970; Thompson et al., 1990) and further developed by Van Asselt (1995), Rotmans and De Vries (1997), Hoekstra (1998) and Middelkoop et al. (2000). A 'Perspective' is a consistent description of the perceptual screen through which people interpret the world, and which guides them in acting. In this study we consider three Perspectives: 1) the Individualist who believes in the power of market forces to regulate society, if climate change will occur, then free market and technology will provide solutions; 2) the Hierarchist who believes in the possibility of controlling nature and that behaviour of people, climate change is serious but controllable; 3) the Egalitarian who believes in natural forces, creativity, equity and chaos, climate change gets out of hand. We map the uncertainties, world views (on pressures and anticipated states and impacts), valuation of impacts (e.g. the objectives and desirable future), and potential management styles (responses) in a coherent way to these three Perspectives (Offermans et al., 2011).

The third step in our approach is to define a first set of strategies based on the Perspective-based vulnerability analysis. Depending on the dominant Perspective in society and water management, a different future pressure is anticipated, and the potential impacts on the water-services are interpreted and valuated in a different way. Accordingly, different sets of water management strategies may be initiated.

This step is followed by an analysis of the PSIR chain for transient scenarios to include social and natural uncertainty (step 4; Figures 8 and 9). As the future unfolds itself, trends such as sea level rise and economic developments will influence both water availability and demand. Natural events, either caused by climate variability or by climate change will occur, stochastically, and may result in (almost) impacts like flood and drought damage. In addition, social events will occur, such as the attention for opinion makers or 'icons' like Al Gore making the wide audience more aware of the risk of global change or the occurrence of the credit-crisis changing our expectations of the future. All together this may result in a change in water management style, or even into a different world view.

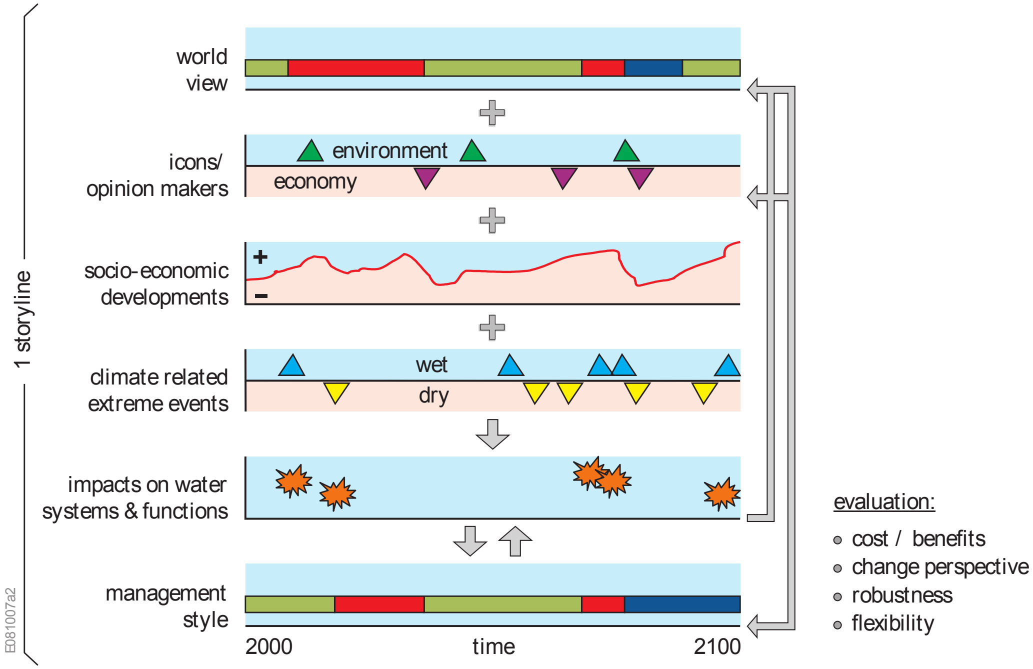

Figure 9: Flow diagram for the effect analysis of transient scenarios to evaluate the sustainability of strategies.

The PSIR chain is evaluated every 10 to 25 years, based on performance indicators for the three sustainability dimensions: people, profit, and planet. This will be done objectively in terms of water state and effects on water related services as well as through the eye of the Perspectives (step 5 in Figure 8). A Perspective-based evaluation involves answering questions like: Is society satisfied about the recent years? What will the future look like? Do we expect climate to change and if so with which rate and magnitude? Which water management strategies should we take (if necessary at all)? Is there enough support for our strategy or do we need to change our strategy? After answering these questions and adapting the management strategy the PSIR chain is analysed for the subsequent time interval. For each successive time interval, steps 3, 4 and 5 are repeated until the year 2100 is reached.

This process is then repeated for a set of pathways of different realisations of Pressures (both climate and socio-economic), States, Impacts on the water system and society, and water management Responses, resulting in ensembles of different model routes. This can be done by varying:

1. the initial Perspective of the water managers and corresponding management style and objectives;
2. realisations of the future with different stochastic events, resulting in flood or drought events, changes in socio-economic boundary conditions, and emergence of opinion makers;
3. underlying climate change scenarios;
4. underlying socio-economic scenarios, resulting in different trends in water demands.

The result is a set of storylines, together making up an ensemble of transient runs including dynamics due to natural and social variability and interaction between the physical and social system. The storylines can be established either in interaction with users, who determine the response (management and perspective) to realisations of Pressures and Impacts, or in an automated process in which the Impacts and Responses are formalised using pre-defined, Perspective-based response functions.

Each storyline will be evaluated on events, management style, impacts (damage, costs, and effects on nature) and changes in perspectives and summarised in adaptation pathways. Adaptation pathways will be presented in adaptation trees (e.g. like a decision tree), which present a sequence of measures and possible options after a measure becomes ineffective. The junctions are triggered by the transient scenarios and may occur in the near or far future or not at all depending on the realisation. Each strategy will be analysed on its performance using the following characteristics:

- Durability of a strategy: At what moment in time becomes is a strategy inadequate?
- Adaptation options: What adaptation options are left if a strategy must be adapted or replaced by a new one?
- Adaptation tipping points: What events are the causes of a tipping point of a strategy and how can we prepare for that?
- Sustainability of a strategy: considering the performance of a strategy under different possible futures and the possibility to adjust a strategy, which adaptation pathways are then sustainable? Can we find pathways which are both sustainable for physical and social events?

Subsequently, we will explore similarities and differences between these storylines and the performance of strategies. They will teach us about (un)sustainable strategies and the relative importance of the uncertainties involved. Threats and opportunities for different strategies will become clear, which can then be used to improve the strategies. We could for example identify no-regret or regret measures, analyse the risk of doing nothing or waiting and then analyse the range of possible futures.

3.4.2 *Technological Framework*

The technological framework was set up to analyse the performance for a large set of transient scenarios. Most of current available simulation tools require a very long calculation time in case of long time-series (25 – 100 year) or they are unable to run time-series or do not consider the society-water interaction. Therefore, we developed a PC-based computing framework with an Integrated Assessment metamodel (IAMM) that is able to run many long time-series and that is adequate to simulate the effects of transient scenarios and strategies on the water system as well as the interaction with the human system. The model is simplified in terms of processes and spatial information but is extended with dynamics associated with the stochastic time-series and society-water interaction. This allows for determining transition pathways towards new water management strategies.

The core of this IAMM comprises a rule-base of:

- metamodels describing cause-effect relations in the physical system, relating climate-related forcing to changes in the hydrological system,
- impact response functions describing the relation between state of the hydrological system for different sectors of user functions and a description of the recovery way (i.e. succession of vegetation) and time, and
- perspective and management response functions, describing the world view dynamics in relation to states, impacts or socio-economic events and (changes in) management style (see also Offermans et al. 2011).

The knowledge rules are based on outcomes of a detailed vulnerability analysis, results of complex hydrological and impact models, studies on social responses, and understanding of the dynamics in water management perspectives.

The concept for this rule-based method is derived from existing habitat analysis models (Guisan and Zimmermann, 2000; Haasnoot and

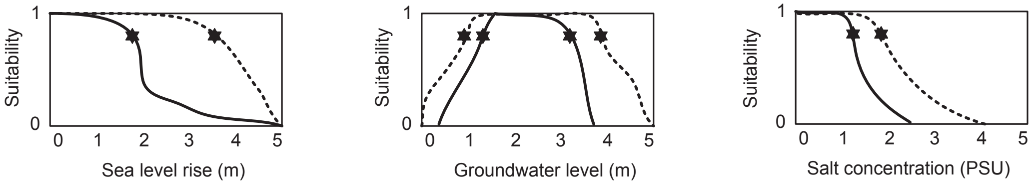

Figure 10: Three conceptual examples of the relation between natural boundary conditions and the suitability of a delta for a key sector. The straight line represent conditions for the present adaptation capacity, the dotted line represents conditions under new adaptation strategies. The adaptation tipping points (stars) are set arbitrarily at a level of 0.8 times the optimal conditions of the natural boundary for a given usage.

Van der Wolfshaar, 2009). In these habitat studies response curves defined by expert judgement or measurements are used to determine the habitat suitability for species or a group of species resulting in spatial information indicating a range of optimal conditions (value of 1) to conditions they cannot occur (value of 0). Likewise, we describe the optimal conditions for water related services and identify critical thresholds in terms of physical boundary conditions under which they can not function anymore (Figure 10). This information is stored in response functions, which are then used for the impact modelling. The adaptive capacity as a result of technical possibilities, knowledge and welfare can be taken into account by a change of the response curves. This information is also used for the a-priori vulnerability analysis.

The current version of the IAMM includes the following physical cause-effect relations:

- Discharge and water levels along the river;
- Water level and probability of dyke failure (based on Van Velzen, in prep);
- Water level and shipping suitability;
- Water level and flooding;
- Flooding and damage to houses and agriculture (De Bruijn, 2008);
- Flooding and vegetation types (based on Haasnoot and Van Der Molen 2005).

Performance indicators are the number of flooded dike rings, number of false and missed alarms, flood damage (euro), urban area flooded (km^2) and its frequency, percentage of time with hindered navigation time (%), nature area (km^2), and ecological diversity index. The judgement of the results for the indicators will depend on once perspective (Offermans et al., 2011).

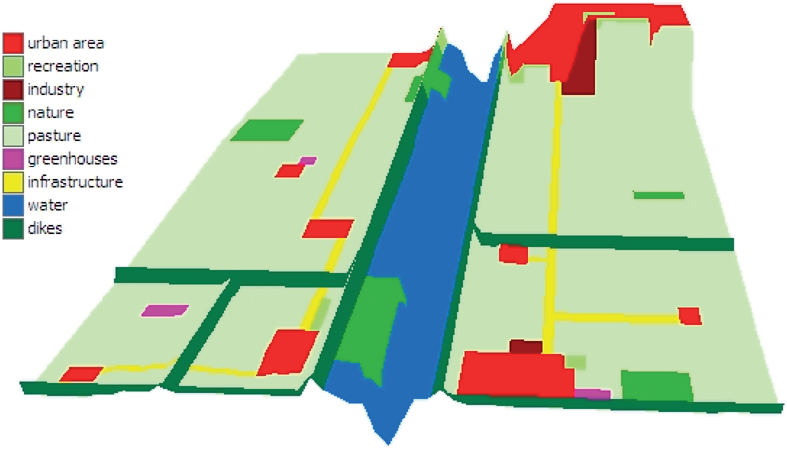

Figure 11: Three-dimensional image of the floodplain of the hypothetical case, The Waas (vertically exaggerated). Flow direction is from the back to the front.

The transient climate scenarios are based on simulations with the KNMI Rainfall Generator (Buishand and Brandsma, 1996) coupled to a hydrological model for the Rhine (Te Linde et al., 2010) in which the KNMI'06 climate scenarios (Van den Hurk et al., 2007) are incorporated as a linear change up to 2100. Climate variability is taken into account by analysing different possible time-series (realisations) belonging to a particular climate (change) scenario. On the scale of a delta global climate change is included external context as it is something which we can not influence at this scale. The same accounts for flood, drought and social events outside the study area. These physical events are like events experienced by society stochastic in nature. They are included by presenting headlines of newspapers to the model user or as response rules in the model.

3.5 HYPOTHETICAL CASE

The approach was elaborated for a hypothetical case, called the Waas that comprises a highly schematised river stretch. The floodplain of the Waas is bounded by embankments and has five dike rings. The upstream area on the left bank contains higher grounds, while in the remaining area surface elevation gradually decreases from the downstream direction. The area contains several urban settlements, as well as different types of agricultural land use, nature and recreation (Figure 11).

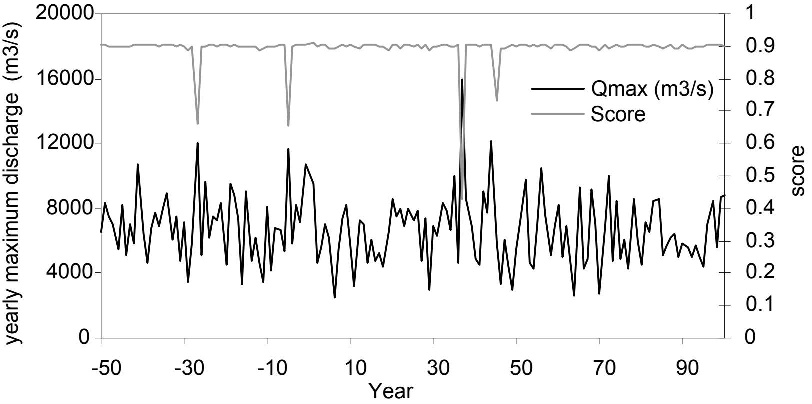

Figure 12: The yearly maximum discharges and the total score per year. The total score was calculated by comparing the results with the defined objectives.

Storyline of hypothetical case: the Waas In the past 50 years there were two flood events which flooded 4 dike rings in total. Around 25 years ago there was a flood (Figure 12). Unfortunately, a warning was not given. The total damage of the past 25 years was 1.36 Billion Euros of which 0.054 was due to agricultural damage. The available time suitable for shipping was 92%, which means that on average during 29 days per year the river water levels were too low for efficient navigation. The northern dikes overtop at a discharge around 15,000 m^3/s and the southern dikes at a discharge of approximately 10,000 m^3/s. Considering the historical discharges the exceedence probability of these discharges are respectively 1:255 year and 1:12 year. Figure 12 gives the yearly maximum discharges and the total score per year. The total score is calculated as an average of individual scores, which are an indication to what degree the beforehand determined objectives (e.g. flood damage, navigation availability) are achieved.

From a Hierarchist Perspective the past is a reason to act and heighten the dikes with 0.5 m in order to meet the standard, which is a flood with a recurrence time of 500 years based on the historical flood records (in this case 14000 m^3/s).

After the subsequent 25-years (year 0 to 25 in Figure 12), the total score is "good". There were no floods neither false nor missed alarms. Shipping suitability remained unaffected. In year 37 a record discharge of 16,000 m^3/s occurred. This changed the design discharge to 14,850 m^3/s. In reaction to this event embankments were raised again. In year 51 a flood event occurred. Although the embankment was higher than the top water level, and the failure probability was very low (2%), it failed due to instability.

Figure 13: Support for the chosen strategy ‘raising embankments’ decreases.

In this story line, society does no longer support this water management strategy, which is reflected in the media (Figure 13; see also Offermans et al. 2011). Consequently, a different water management strategy is adopted for the forthcoming time. This resulted in a “good” score for the remaining period and an increase of nature areas.

In storylines with different climate realisations but with the same strategy, rising of embankments was in some cases needed 4 times while in other realisations it was not needed at all. Still, flood events occurred due to instability of embankments. The strategy could be improved by decreasing the probability of failure due to instability by raising the dikes by 1 m or by making them wider.

3.6 CONCLUSIONS AND PROSPECTS

The approach we propose comprises three main improvements when compared to most previous scenarios studies on global change impacts for water management. Point of departure is to make the water system sustainable and future proof (in stead of only climate proof). Firstly, we integrate the physical world and socio-economic developments and their uncertainties using the Perspectives method. Secondly, we consider transient scenarios in the form of storylines, in which water management and the water system interact in a dynamic way to analyse many possible futures and adaptation pathways. Thirdly, by using simple an IAMM tool, we can carry out ensembles with realisations of the stochastic components of the natural and socio-economic system, for different underlying trends in climate and society.

Instead of attempting to build detailed models for different subsystems (e.g. ground water, ecology), we simplified our IAMM to the essence of the cause-effect relations, derived from existing more sophisticated models or simulation results. As a result, our IAMM can be applied in a large number of long (100-yr) scenario runs, without demanding huge computing effort and calculation time.

Different storylines were analysed with the IAMM, thereby considering different possible futures and adaptation pathways for water management. Like Van Asselt and Rotmans (2002) we create a space of possible futures, constrained by what is known. All these model runs will be used to evaluate water management strategies and transitions in water management for different scenarios and to assess 'utopian transition schemes', which describe adaptation paths, including a succession of the implementation of physical and policy measures and a description of activities to promote transitions. Adaptation pathways and trees can help to show possible options once a direction is chosen and whether a strategy leads to a dead end.

The a-priori vulnerability analysis makes the results less dependent on the chosen climate change scenario when compared to traditional approaches that investigate the cause-effect chain starting from the chosen scenario. This is useful in case new knowledge/scenarios become available.

Compared to previous studies which used the Perspectives method to include social uncertainty (Rotmans and De Vries, 1997; Middelkoop et al., 2000, 2004), experience with the hypothetical case indicates that our approach seems to focus more on dystopias than on utopias. This is probably the result of including the transient scenarios with events. The method can help to find vulnerabilities in a strategy in order to improve the strategy or help to find adaptation paths (if this happens we could change this strategy). If you have considered other strategies in case the future unfolds differently than you thought, you are better prepared and can adjust quicker or in time. It is like they say in crisis management, people who have thought about what to do in case something goes wrong have a higher chance to survive even if the future is different than they imaged. In the meantime, it is necessary to monitor and adjust your strategy when necessary.

In the current version of the IAMM we did not yet include uncertainties in the response curves of the PSI part. Rotmans and De Vries (1997) used a perspective based approach for this purpose. We acknowledge that in this PSI part uncertainty is present, but by analysing it in this way the result may be a sort of self-fulfilling prophecy if you analyse utopias. The approach remains though interesting to be used for analysing dystopias (e.g. what if the functioning of the world is conform the Individualist and not like the egalitarian perspective like we believe).

First results of this hypothetical case taught us that:

- Surprises of the social system and events in the physical system are important for decisions on water management strategies. It is not so much the precise event that gives information but considering possible events helps to analyse weaknesses or opportunities of strategies and improve sustainability.
- Strategies for the nearby future are mainly determined by climate variability, while for the longer term (50 year) climate change is important to take into account.
- The near future is important for our long-term situation. For example, an almost flood event may trigger adaptation activities and prepare the system for long-term climate change. Another example is rising dikes, which may result in floodplain areas behind the dikes where due to continued investment of infrastructure and built-up areas no longer space is available for water in the future. This makes it difficult to change to a strategy in which rivers may temporarily inundate these floodplains. An interesting question to analyse further with our method would be: if you raise the dikes, would it be better to make them at the right height or strength from the start so that it may be able to cope with all possible futures, taking the risk of overinvestment?
- A sustainable strategy could be a strategy which can cope with climate variability (to cope with the near future) and flexible enough to be prepared for any type of adaptation either caused by a change of climate, socio-economic development or perspectives.

Our starting point was to develop a method for sustainable water management strategies under an uncertain future. The first concepts of this method presented in this chapter will be further developed in the next years. This will involve elaboration of the interaction of the social and physical system including desk research and participatory stakeholder workshops and application of the method for a specific delta. The challenge is to have appropriate effect models and scenario analysis to make the right decision or at least reduce the risk of making the wrong decision.

4

AN EXPERIMENT ON EXPLORING ADAPTATION PATHWAYS: THE WAAS CASE

ABSTRACT

Exploring adaptation pathways into an uncertain future can support decision making in achieving sustainable water management in a changing environment. Our objective is to develop and test a method to identify such pathways by including dynamics from natural variability and the interaction between the water system and society. Present planning studies on long-term water management often use a few plausible futures for one or two projection years, ignoring the dynamic aspect of adaptation through the interaction between the water system and society. Our approach is to explore pathways using multiple realisations of transient scenarios with an Integrated Assessment MetaModel (IAMM). This chapter presents the first application of the method using a hypothetical case study. The case study shows how to explore and evaluate adaptation pathways. With the pathways it is possible to identify opportunities, threats, timing and sequence of policy options, which can be used by policy makers to develop water management roadmaps into the future. By including the dynamics between the water system and society, the influence of uncertainties in both systems becomes clearer. The results show, among others, that climate variability rather than climate change appears to be important for taking decisions in water management.

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4.1 INTRODUCTION

Water management is essential for living in river deltas. Population growth and potential climate change are increasing pressure on water management. The problem is that we do not know how the future will unfold. Despite this uncertainty decisions need to be taken, because impacts may be significant and the implementation of policies takes time. Also, some strategies may be feasible today but not in the future (in particular those that involve spatial planning). Traditionally, water managers tend to use 'best estimates' of the future based on central estimates of climate change and extrapolations of current socio-economic and water system trends. This wrongly implies that we can predict the future. Such an approach might be feasible for well-understood problems, but not for complex problems with deep uncertainty (Lempert and Schlesinger, 2000), such as long-term water management under changing conditions.

Several approaches for decision making under deep uncertainty have been developed. Scenario analysis aims to assess possible impacts and to design and test strategies under different hypothetical futures (e.g. Van der Heijden, 1996; Carter et al., 2007). Analysts use simulation models to quantitatively explore the future (e.g. Morgan and Dowlatabadi, 1996; Rotmans and De Vries, 1997; Van Asselt, 2000). Within this emerging school of computational scenario-based approaches it is common to use a limited set of scenarios for one or two projection years to define robust strategies; strategies that are insensitive to uncertainty (e.g. Middelkoop et al., 2004; Van Asselt and Rotmans, 2002). Besides robust strategies to either shape the future or to reduce vulnerability to uncertain developments, Dewar et al. (1993) used signposts to monitor the need for changes. This was a first step towards dynamic policy making. In contrast to static policies, the approach of adaptive policy making results in contingency plans and specified conditions, called *signposts* and *triggers*, under which the policy should be reconsidered (Walker et al., 2001). The concept of adaptive management also involves the ability to change policy practices based on new experience and insights (Pahl-Wostl, 2007). Instead of analysing impacts of pressures, Kwadijk et al. (2010) start at the other end of the cause-effect chain by assessing the system's vulnerability, which they then use to determine *adaptation tipping points* (ATP). These are points at which the magnitude of change is such that the current management strategy can no longer meet its objectives. When this point occurs depends on the scenario. Exploratory modelling uses computational experiments to explore uncertainties in both context and model (Bankes, 1993; Agusdinata, 2008; Kwakkel et al., 2010b). Lempert and Schlesinger (2000), for example, used exploratory modelling for creating a large ensemble of plausible future scenarios to find robust strategies for dealing with climate change. In the field of economics, Winkler et al. (2010) propose a conceptual framework (a hybrid of dynamic and static modelling) for climate change assessments of international market systems that involve long-term investments.

In an earlier chapter and a recent paper, we presented a method for exploring adaptation pathways for sustainable water management in river deltas under uncertainty (Chapter 3, Offermans et al. 2011). Adaptation pathways describe a sequence of water management policies enabling policy makers to explore options for adapting to changing environmental and societal conditions. Our approach comprises the use of an Integrated Assessment MetaModel (IAMM) to explore transient scenarios and can thus be considered as a member of the computational scenario-based approaches. While current scenario studies often consider (semi-)static situations in terms of a few plausible futures projected forward to one or two future years, we acknowledge pathways towards the endpoint by including dynamics from natural variability and the interaction between the water system and society. In the course of time, events may trigger policy responses and may change societal perspectives, including the interests and evaluation of strategies (see for historical examples Van der Brugge et al., 2005; Offermans, 2010). Adaptation over the course of time thus depends on the evolution of the pathway. The end point is therefore not only determined by what is known or anticipated at present, but also by what will be experienced and learned when the future unfolds (Yohe, 1990), and by the policy responses to events. Thus, policy making becomes part of the storyline, and thereby an essential component of the total uncertainty. With an adaptation map - a set of adaptation pathways - resulting from these analyses it is possible to identify opportunities, no-regret strategies, dead ends, and timing of a strategy, all of which can be used by policy makers to develop water management roadmaps into the future.

As most existing computational impact models (for example Vermulst et al., 1998; Delsman et al., 2008) demand too much computing time for simulating the dynamics of adaptation pathways, we have developed an IAMM based on these complex detailed models. Such metamodels are also referred to as 'low-resolution models' (Davis and Bigelow, 1998) or 'Fast Simple Models' (Van Grol et al., 2006). The concept of Integrated Assessment Models (IAMs) has been successfully applied on a global scale to analyse climate change and the effects of emission mitigation strategies (e.g. Rotmans and Van Asselt, 1996; Van der Sluijs, 2002; Schneider and Lane, 2005; Van Vuuren et al., 2009). In our study we apply the concept of IAMs for impact assessment and adaptation analysis in combination with transient scenarios and social response on a regional to local scale.

The objectives of the study presented here were to implement the method of exploring adaptation pathways in a case study and to evaluate the implementation and use of the results. The key questions addressed were: Can we establish simple though realistic cause-effect relations as building blocks of the IAMM? Does the IAMM yield plausible results? How can we establish storylines, and how do these evolve? How do we evaluate these storylines and what kind of decisions on water management can we make? To answer these questions we set up a modelling experiment for a hypothetical case inspired by a real-world river reach in the Netherlands. With the developed IAMM, we carried out numerous transient runs driven by different realisations of future climate, and analysed different water policy options as an adaptation pathway in each run, which we then summarised into an adaptation map. We evaluated the performance of the policy options and pathways according to three perspectives.

4.2 METHOD

Our method consists of a conceptual framework and a technological framework, which are elaborated in Chapter 3 and Offermans et al. (2011). This section briefly describes the method.

4.2.1 *Conceptual Framework*

Three concepts are the pillars of our approach: 1) the Pressure State Impact Response (PSIR) concept (OECD, 1993; Rotmans and De Vries, 1997; Hoekstra, 1998), describing interactions between the water and social system; 2) the Perspectives method, describing people's dynamic view on the value of water and how water should be managed; and 3) transient scenarios, describing possible futures in terms of time-series (Chapter 3).

The PSIR concept applied to water management can be illustrated by the following example: climate change and population growth (pressures) may decrease fresh water availability and increase the water demand (state), resulting in less drinking water and agricultural damage (impact), which may then cause a management response in terms of water storage in large basins (response) in order to supply water in the case of scarcity (state). Instead of the common linear use of the PSIR concept, we use it in an iterative process and proceed in cycles per time step (as suggested by Pahl-Wostl (2007)) and elaborate the response part by distinguishing between water policy and autonomous stakeholders' response (Offermans et al., 2011).

The Perspectives method is based on the Cultural Theory (Douglas, 1970; Thompson et al., 1990) and developed by the TARGETS research group (Van Asselt and Rotmans, 1997). A Perspective is a consistent description of the perceptual screen through which people interpret the world, and which guides them in acting and dealing with uncertainties. Applied to water, three active stereotypical perspectives, each with a different expectation about the future and a preferred strategy can be distinguished (Hoekstra, 1998; Middelkoop et al., 2004; Offermans et al., 2011): The *Hierarchist* believes in controlling water and nature, assigning major responsibilities to the government. Water is mainly seen as a threat to human safety, resulting in a preference for water policy options such as building and raising dikes and channelling, while leaving space for some economic and natural development. The *Egalitarian* focuses on the environment and equity, resulting in strategies such as room for the river, decreasing human demands, and relocation to higher areas. The *Individualist* adheres to a liberal market and a high trust in technology and innovation. Their preferred water management policies focus on cost effective and innovative projects, such as living on water and building offshore islands.

Transient scenarios describe possible futures from today to a point in the future, including changing conditions from a sequence of developments and events. We distinguish between 1) transient scenarios of external context that describe only the pressures (e.g. changing climate), and 2) complete transient scenarios, which are storylines including all the elements of the PSIR chain, including natural and socio-economic events (e.g. floods, droughts, economic crisis), trends (e.g. climate change, changing public perception of safety or nature), and interactions between the water system and society (e.g. flood impacts, flood mitigation strategies).

A simulation starts with a description of the past and current system state and possible and desired futures according to different Perspectives. Depending on the evaluation of the past and the expectations of the future, policies are adopted and strategies implemented. In each run of the IAMM, a year-by-year evolution of the whole PSIR chain occurs. For example, a climate realisation with corresponding precipitation results in a sequence of peak river discharges and associated impacts; strategies may then be implemented accordingly. In addition to events in the water system, societal events may occur. We interpret these events as external context, and include these as random components. Such societal events may well lead to changes in management, for example when budgets are reduced. Besides this responsive management, strategies may also be chosen in view of anticipated impacts (depending on the prevailing Perspective). Moreover, even a change in Perspectives may occur. For example, climate-related events may increase the awareness of potential climate change, or the absence of such events may decrease support for the implementation of strategies. Water management history in the Netherlands has shown, for example, that an accumulation of events caused the dominant Hierarchical perspective to become more Egalitarian (Offermans, 2010). The most important events contributing to this shift were the fire in the Sandoz factory (1986) causing all the fish in a radius of 100 kilometres to die, the Endosulfan poisoning of the Rhine (1969), and an increased visibility of water quality problems (i.e. foam, smelling water, dying fish). Besides these water quality related events, the Chernobyl disaster, a growing societal attention for environment and peace (Flower Power) and publications such as 'Silent Spring' and 'Limits to Growth' contributed to a move from Hierarchism towards Egalitarism. Management responses can be a priori entered into the IAMM through response rules, or can be derived from single or multiple users of the model, such as policy makers in a game setting. A single storyline is completed when the river has been managed for 100 years. Different pathways into the future arise from different climate scenarios, different realisations of the same climate scenario, external socio-economic events or trends, and due to different management responses during a scenario run. This set of different pathways represents the uncertainty for water management into the future.

We evaluate the policy options on their performance in each storyline using indicators for a sustainable strategy. The weights given to these indicators will generally differ for each Perspective. We first analyse the effects of individual strategies for all transient scenarios (all realisations of the scenarios) and for each scenario separately. These results are then used to determine the durability of a strategy, indicating under *what conditions* the strategy may fail to meet the objectives (reaching an adaptation tipping point (ATP)), and at *what point* in the future this may happen under each scenario and for each Perspective. We refer to this as the sell-by date of a policy option, which is the moment when an ATP is reached. By exploring all the relevant policy options after an ATP with a computational model, we established different pathways, which we then analysed on their performance according to targets (weights to the indicators) (Figure 14). The final adaptation map, manually drawn based on all the model results, presents the relevant pathways (e.g. it is not logical to establish houses on a mound and also make them able to float in case of a flood).

4.2.2 *Technological Framework*

The PSIR cycle is modelled using the IAMM in a number of transient scenarios with different responses to develop storylines. We designed the IAMM such that it fulfilled the following requirements: It must run fast enough to calculate 100-year transient scenarios when used interactively or participatorily in a game-like setting. Secondly, the IAMM should represent the dominant processes and natural variability but without unnecessary detail (as suggested by Booij, 2003). Finally, it should be able to implement individual policy options, reflecting a wide range of Perspectives in such a way that users can choose the pre-

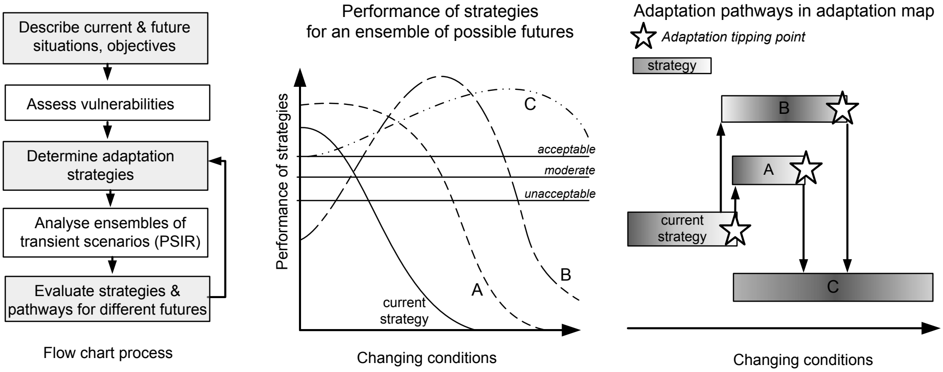

Figure 14: The construction of adaptation pathways is based on the performance of individual policy options (A, B, C) for an ensemble of possible futures. After an adaptation tipping point, the point at which a strategy fails to meet its objectives, all policy options are considered. Individual policy options are identified based on objectives and current and expected vulnerabilities.

ferred management response. The outcomes from the model should be such that users can understand them, and that the performance of strategies should be quantified by relevant indicators, which are measures of sustainability.

We used the technique of metamodelling to enable exploring many transient scenarios and management responses. Metamodels, or models of models, are simple aggregated models that approximate the behaviour of models that are more complex and detailed (Davis and Bigelow, 1998, 2003). They can be obtained purely statistically, also known as response surfaces (Kleijnen and Sargent, 2000), or theory-motivated, using physical and behavioural reasoning to determine the structure of the model and statistical analysis to determine the coefficients (Bigelow and Davis, 2003). This study's model is built up by a set of small metamodels describing parts of the cause-effect chain, which are then fully integrated. This idea of developing the IAMM in terms of cause-effect relations is derived from existing habitat analysis models (e.g. Guisan and Zimmermann, 2000) describing the relation between the potential occurrence of species and environmental conditions. Haasnoot and Van der Wolfshaar (2009) extended this with physical cause-effect relations describing the effects of policies on the environmental conditions.

The core of the IAMM comprises 1) metamodels describing cause-effect relations of the physical system, and 2) a response base describing the perspective dynamics and (changes in) management style in response to states, impacts, or societal events. The cause-effect rela-

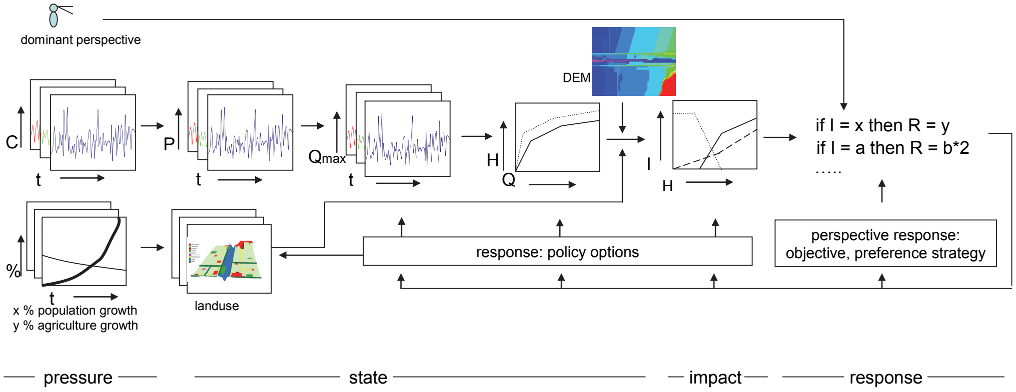

Figure 15: Schematisation of cause-effect relations and response functions in the IAMM. Climate realisations (C) are translated into precipitation (P), which are translated into discharges (Q) at the upstream boundary of the study area. Water level-discharge (H-Q) relations are used to derive water levels along the river. The resulting water levels are translated into an impact (I) using an elevation map and effect functions. Socio-economic realisations, such as population dynamics and agriculture area, are translated into land use. Management and perspective response functions relate impacts to strategies by means of input maps and effect functions.

tions relate the climate and socio-economic pressures to changes in the state of the hydrological system (e.g. precipitation and discharges, water levels) and social system (e.g. land use), and describe the impacts on the different water-related sectors (Figure 15). The metamodels are based on (the results of) complex hydrological and impact models applied in previous studies. The response rules for the hypothetical case are simple if-then relations, like: 'if x occurs in the water system then strategy y is implemented'.

4.3 IMPLEMENTING THE METHOD IN A HYPOTHETICAL CASE STUDY

4.3.1 *Study Area: the Waas Case Study*

The hypothetical case study, called the Waas, is inspired by a river reach in the Rhine delta of the Netherlands (the river Waal). The river and floodplain are highly schematised, but have realistic characteristics. The river is bound by embankments, and the floodplain is separated into five dike rings (Figure 16). A large city is situated on higher grounds in the south-east part. Smaller villages exist in the remaining area, including greenhouses, industry, conservation areas, and pastures.

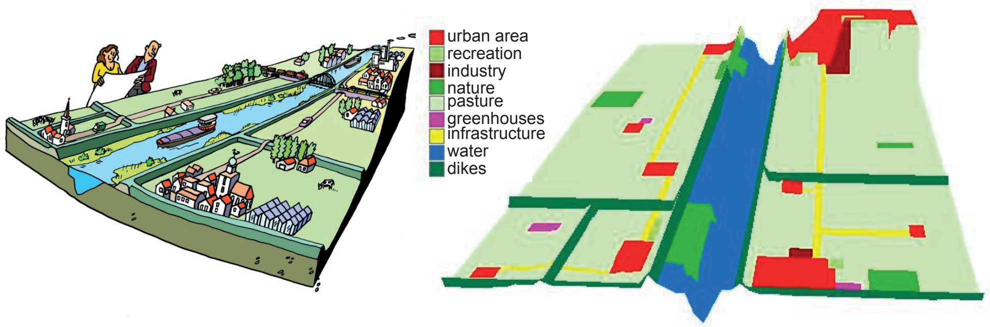

Figure 16: The Waas case study (left) is heavily schematised (right) into a three-dimensional image of the floodplain presenting the land use and elevations (exaggerated vertically). The flow direction is from back to front.

A scenario run starts on the basis of a 'report' of the assumed past 25-year history, in which the following occurred: There were two flood events, which flooded four dike rings in total. The total damage over the past 25 years was 2,810 billion Euros. On average, water levels were too low to allow navigation over 29 days per year (navigable time was 92%). The Waas population considered the first flood event as a matter of bad luck that could be prevented in the future by means of control- and engineering policies. After the second flood, people realised that climate change may have an influence, and that a control approach may not be sufficient to guarantee safety in the long run. Consequently, the citizens adopted a Hierarchical Perspective with some elements of the Egalitarian Perspective: the preferred strategies aim at controlling the system (Hierarchical). However, for the long-term they envision spatial solutions for dealing with increased peak discharges caused by climate change, which corresponds with an Egalitarian approach. The past flood and drought events demonstrate that the system has not been adequately managed. In the future, climate change and socio-economic developments may increase the pressure on the available space and potential future damages, so additional strategies are needed.

At the starting point policies can be taken to improve the state of the system such that future adverse impacts are reduced or prevented. Then the future starts to unfold in which events occur and additional policies can be implemented in each time step. To evaluate the performance of the individual policy options, indicators were used for the three pillars of sustainability: people, profit, and planet. The value ranges for the indicators (the targets) are based on the prevailing Perspective. The values given in Table 1 are those associated with the Hierarchist Perspective. The Egalitarian gives a more weight to the planet

Table 1: Indicators and their limits per 25 years for the Hierarchist Perspective. The limits are based on the average of occurrence per 25 years. The values in the column 'acceptable' can be considered as possible targets for policy makers in a Hierarchical world. Missed floods are floods without an alarm. The false alarms are events with an alarm without an actual subsequent flood occurrence. The 'diversity index for ecology' indicates the diversity of the potential vegetation types in the area and ranges from 0 to 1.

		Acceptable	Moderate	Unacceptable
People indicators	Number of missed floods/year	0	0-5	>5
	Urban area flooded km^2/yr	<0.2	0.2-0.5	>0.5
	Number of dike rings flooded/yr	0	1-2	>2
	Number of false alarms/yr	<1	1-2	>2
Profit indicators	Total flood damage (M euro/year)	<150	150-1,000	>1,000
	Agricultural flood damage (M euro/yr)	<20	20-50	>50
	Average non-navigable time (%)	<2	2-7	>7
Planet indicators	Nature area (km^2)	>14	12-14	<12
	Diversity index ecology	>0.5	0.4-0.5	<0.4

indicators than the Hierarchist and accepts a larger amount of floods and non-navigable time. The Individualist gives a more weight to navigation and flood damage than the Hierarchist. For the development of the pathways we used two indicators, which reflect the most important impacts for decision making. The indicator 'flood damage' was used for the flood management pathways and the 'percentage of non-navigable time' for the low flow pathways. To consider the potential effects of different Perspectives or changes in Perspective, the targets were set two times larger for the Egalitarian and two times smaller for the Individualist.

4.3.2 *Transient Climate Scenarios*

Three climate scenarios established by the Royal Dutch Meteorological Institute (KNMI) were considered: no climate change, G scenario, and Wp scenario (Van den Hurk et al., 2007). These scenarios cover a range of possible future climates in the Netherlands. The G scenario has a temperature rise of 1ÂřC in 2100, the winter-time precipitation increasing by 3.6% and the mean summer precipitation increasing by 2.8%. The Wp scenario has a temperature rise of 2ÂřC, winter-time precipitation increasing by 14.2%, but the mean summer-time precipitation decreasing by 19%.

The transient climate scenarios are based on simulations using the KNMI Rainfall Generator (Buishand and Brandsma, 1996). The Rainfall

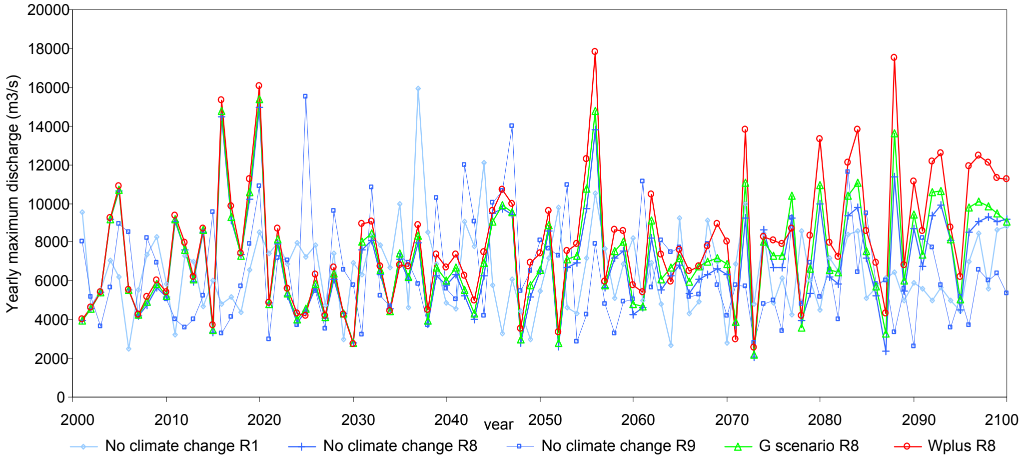

Figure 17: Transient scenarios for five realisations: three realisations of a scenario without climate change, one realisation for climate change scenario G, and one realisation for scenario Wp.

Generator gives an ensemble of 100 years of precipitation and evaporation data based on the probability of events. With the delta change approach (Lenderink et al., 2007; Te Linde, 2007), these series were translated into time-series for each climate change scenario (which are assumed to change linearly up to the year 2100). The precipitation and evaporation time-series for the scenarios were then used in a hydrological model for the Rhine (Te Linde et al., 2010) to produce discharge data for the Rhine at Lobith, which are the upstream boundary conditions for the IAMM. For each of the three climate scenarios, ten realisations of precipitation and evaporation events were considered for the next 100 years, resulting in 30 transient climate scenarios in total. The transient scenarios of climate-driven discharges include the maximum river discharge per year, the number of days per year at which ecologically-sound discharges are exceeded and the number of days per year that discharge is lower than several relevant discharges for shipping. Figure 17 gives an example of five of the transient scenarios used. The figure shows that the year to year variation is large, in comparison to the climate change trend.

4.3.3 *Implementation of Cause-effect Relations*

Figure 18 gives a schematic presentation of the cause-effect relations incorporated in the IAMM for the Waas case. These relations were all derived from validated models for an area similar to the hypothetical case. We implemented the IAMM and its cause-effect relations using PCRaster, a grid-based spatial analysis tool for dynamic modelling

(Van Deursen, 1995). The IAMM was checked for internal consistency and plausibility of the outcomes by expert judgement. Appendix B shows the most relevant cause-effect relations. Discharges arising from the transient climate scenarios were translated into water levels using stage-discharge relations for each grid cell along the river Waas. These relations were derived from modelling results using a 1D hydrodynamic model (SOBEK) for the river Waal in the Netherlands. The water levels were translated into a 2D surface, and were compared with the dike heights derived from the elevation map. Subsequently, the model calculated the probability of dike failure caused by piping or by wave overtopping by examining the difference between dike level and water level (Van Velzen, 2008). Whether the dike fails or not depends on a random number selected between 0 and 1. If that number is lower than the probability of dike failure, the dike is assumed to fail, even if the water does not overtop it. In the case of a dike failure, the water level was considered to be equal to the river water level in the whole dike ring. Damage due to the flooding of dike rings was calculated from the water depth, derived from the water level and a digital elevation map (DEM), and damage relations for the Netherlands given in (De Bruijn, 2008; Haasnoot et al., 2009). Using these relations, the model calculates, for each land use, the flood impacts per hectare, by multiplying the maximum potential flood damage in the cell under consideration by this water level-dependent damage factor (value between 0 and 1). The maximum potential damage and the shape of the damage curves were derived from the HISSM model (Kok, 2005). This yielded the total damage for sectors such as agriculture, industry, and housing.

Cause-effect relations for shipping, describing the water depth and the suitability for shipping were derived from the SHIPS@RISK model, which was developed in a previous study to determine the effects of low flows on transport cost by inland navigation over the Waal-Rhine rivers between Rotterdam harbour and the Ruhr hinterland (Middelkoop and Van Deursen, 1999). The suitability is expressed by a value between 0 and 1 (i.e. the fraction of total time that navigation is possible) and differs per type of vessel. For each relevant discharge (400, 600, 800, 1,000, and 12,000 m^3/s) the number of days with a lower discharge is multiplied by the suitability and then summed over all discharges, resulting in the total proportion of navigable time (%).

To model the impact on ecology, ecologically-relevant flood durations (2, 50, 150, and 365 days/year) were used to distinguish different ecozones with different riparian vegetation types (Haasnoot and Van Der Molen, 2005). From dry to wet areas, the following ecozones were distinguished: high water free zones (< 2 days/year), hardwood zones (2-50 days/year), softwood zones (50-150 days/year), drying zones (150-364 days/year), water with macrophytes (always under shallow water) and water without macrophytes (always under water, deeper

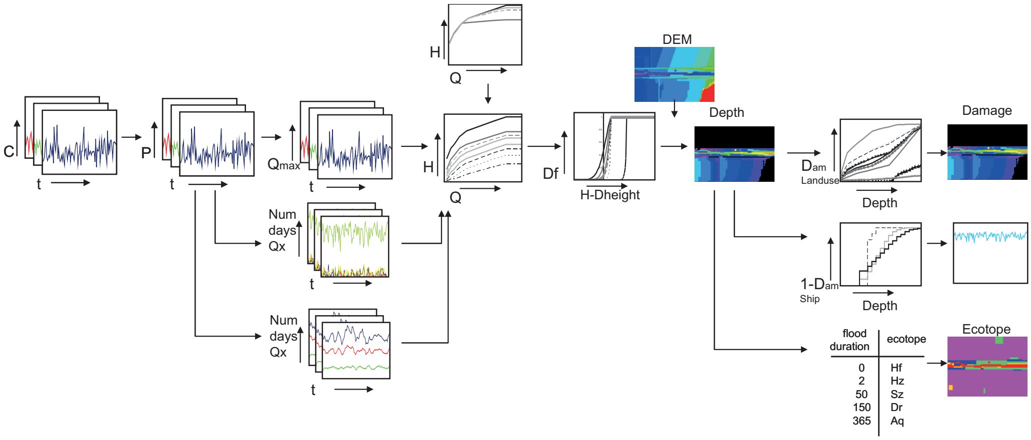

Figure 18: Schematisation of cause-effect relations incorporated in the IAMM for the Waas case. C = climate realisation, P = precipitation surplus, Qmax = maximum discharge, Num days Qx = number of days exceeding of lower discharges for discharges relevant for ecology or navigation, Df = chance of dike failure, Dheight = dike height, Dam = damage, Ecotope = ecozones, H = water level. The most relevant cause-effect relations are given in detail in Appendix B.

than 3 m). The effect on each ecozone was transformed into an diversity index for ecology by multiplying the relative area by a weighting factor. The sum of these weighted areas is then scaled to an index between 0 and 1. The weighting factor is 6 for the rarest zone and 1 for the most common zone.

4.3.4 *Identification of Policy Options*

Policy options were based on existing plans and potential strategies for flood management, nature development, and navigation (low flow management) in the Netherlands (Table 2). To ensure a diverse range of policy options, we related the strategies to the Perspectives and added strategies (if available) in the case a Perspective was under-represented. The options were implemented in the IAMM by changing input maps (e.g. dike height or position), adapting the cause-effect relations (e.g. stage-discharge relation, damage function), or changing the river inflow (resulting from successful cooperation with upstream regions).

4.3.5 *Simulations and Development of Adaptation Pathways*

Numerous simulation runs were executed for different (combinations of) policy options and realisations of transient climate scenarios. The result of each run is a time-series with the evolution of performance

Table 2: Description of the individual policy options and their total costs for the next 100 year and purposes. The costs are based on the situation in the Netherlands (see Appendix B for an explanation on how the costs were determined). *In the current situation large ships of 6,000 tonnes are used. **These costs depend largely on peak discharges and thus the scenario and realisation. In the table the average costs are given.

Abbreviation	Description	Cost (M€)	Purpose
DH500	Dike height rise to be able to cope with the 1:500 discharge, based on measurements	112**	Flood risk
DH1000	Dike height rise to be able to cope with the 1:1,000 discharge, based on measurements	142**	Flood risk
DH1.5	Dike rise: adapting to 1.5 times the second highest discharge ever measured ('rule of thumb measure')	228**	Flood risk
RfRl	'Room for the river' - Large scale: with extra side channels, the river has more space after a threshold discharge is exceeded	269	Flood risk & nature
RfRs	'Room for the river' - Small scale: with extra side channels, the river has more space after a threshold discharge is exceeded	138	Flood risk & nature
CopU	Upstream cooperation: discharges are reduced to 14,000 m^3/s	0.03	Flood risk
FloatH	Floating houses: resulting in damage functions with 10 times less damage	6	Flood risk
FaC	Fort cities: extra embankments around the cities	550-660	Flood risk
Mound	All cities will be raised by 4 m in the DEM, resulting in houses on a area of elevated ground	1006	Flood risk
SmallS	Use small ships* (300 ton) to ensure navigation at low discharges	40	Navigation (low flow)
MediumS	Use medium size ships* (3,000 tonnes) to ensure navigation at low discharges	40	Navigation (low flow)
SmallD	Small-scale dredging of the riverbed to ensure larger ships can keep navigating at lower discharges	0.015-0.02	Navigation (low flow)
LargeD	Large-scale dredging of the riverbed to ensure larger ships can keep navigating at lower discharges	0.18-0.22	Navigation (low flow)

indicators, and the sum for each performance indicator for each period of 25 years and for the total 100 years. Also, the total costs of the actions implemented during a scenario run were calculated. For the evaluation of the policy options, we analysed their robustness by comparing its performance with the ranges for the indicators given in Table 1, and by using the standard deviation of the performance. For each Perspective, different indicator ranges were taken (as described in section 3.1). We analysed the effects for all transient scenarios (10 realisations of three climate scenarios), for all realisations of each climate scenario separately, and for each 25-year period.

For the creation of pathways we used perspective-based targets for two indicators. For flood management we considered a limit for the total damage, and for the low flow strategies we used a limit for the non-navigable time. With these targets, we determined the sell-by date of each policy option. Pathways were then generated by using the sell-by date and based on the assumption that, if a policy option no longer meets the targets, it is necessary to add, or to shift to another policy option. Since only two policy options influence nature, nature was only taken into account in the evaluation of the pathways.

4.4 RESULTS

4.4.1 *Evaluation of the Robustness of the Policy Options*

4.4.1.1 *Flood Management Policy Options*

We first describe the average performance of the policy options for the indicators in a Hierarchist world (Table 1). Robust strategies result in acceptable indicator values under many futures. All flood policy options reduce the impact compared to the reference situation without implementation of policies (Figure 19). However, the only option for which all of the risk indicators of Table 1 are acceptable is raising the dikes to such an extent that they can cope with 1.5 times the second highest discharge in the past (DH1.5). Raising the dikes to a 1:1,000 discharge (DH1000) scores moderately well. Implementing the 'room for the river' on a large scale leads to a slightly larger number of dike rings being flooded, which, according to Table 1 makes this policy option unacceptable for this indicator. Implementing dikes around the cities (FaC) prevents the urban areas from flooding, resulting in the largest improvements compared to the reference case without policies taken.

Upstream cooperation alone is not an effective policy option. It lowers the peak discharge to 14,000 m^3/s, but floods and damage still occur. The dikes around the cities are most effective in reducing inundation of urban areas. The dike-raising options and 'room for the river' are subsequently less effective. Surprisingly, the policy option in which houses are built on artificial mounds does not score much better on this urban area indicator, than the reference situation. Apparently, the mounds are not high enough, although they were established at 4 m height. Out of the damage mitigation options, the dikes around the cities and floating houses are the most effective. However, the average absolute damage is higher than in the flood mitigation options. Whatever policy options were to be chosen, the costs of the policy options would still be well below the expected damage reduction (Table 2 and Figure 19).

As a second criterion for the robustness of strategies, the standard deviations of the evaluation criteria obtained for each policy option under all transient scenarios were compared. Robust strategies result in small standard deviations for the indicators, having acceptable indicator values at the same time. The relative performance for each option is similar to the absolute results. Dike-raising and large-scale 'room for the river' appear to be the most robust options, while the damage mitigation options are less robust. The standard deviation of the total damage is high for all policy options; thus, even the most robust strategy can result in large-scale damage.

The policy options were also evaluated for the 10 ensemble members of each climate scenario separately (presented in Appendix B). For all climate scenarios, the policy options raising the dikes to cope with 1.5 times the second highest discharge (DH1.5) and establishing dikes around the cities (FaC) result in the largest improvements compared to the reference situation. The differences in performance between the realisations without climate change and those for the G climate change scenario are small. This is in contrast to the Wp realisations, wherein none of the policy options leads to the fulfilment of the targets. In this extreme scenario, the dike-raising strategies for the 1:1,000 and 1:500 discharges perform better than giving more 'room for the river' on a large scale, which is different from results for all scenarios. This is because the dike-raising options depend on the changing conditions (they adapt over time), while the 'room for the river' options do not change.

Robust strategies are not only dependent on physical conditions, but also on societal conditions, such as a Perspective. In case the current Hierarchist Perspective changes into to an Egalitarian or Individualistic Perspective, the performance of the policy options would be evaluated differently (Figure 19). Only policy options DH1.5 leads to acceptable results for all Perspectives. The options 'room for the river' and DH1000 give acceptable results for the both the Egalitarian and Hierarchist Perspective. For the Egalitarian Perspective more policy options lead to acceptable results. The current policy options are not enough to achieve targets for the planet indicators; thus, better options need to be explored. For the Individualist Perspective only extreme dike raising will reduce the damage to an acceptable level. However, this policy option is very costly. As Individualists do not believe in extreme climate change, they may choose to take the risk and select the DH1000 option. Still, all policy options are much less costly than the potential damages are.

4.4.1.2 *Low Flow Policy Options*

For the low flow policy options, objectives are achieved using the small vessels and dredging options (Figure 19). Using small vessels significantly results in an annual navigable time that is 44 times larger than the reference situation with large vessels (current policy). Using medium-sized vessels hardly extends the navigable time. Robust policy options are the use of small vessels and dredging (either small or large scale), as indicated by acceptable indicator values and the small standard deviation. Comparing the results for each climate scenario separately shows that the realisations without climate change and the realisations belonging to the G climate scenario have more or less the same impact. Analysing the results per 25-year-time period shows that the average non-navigable time per year increases over time under the Wp scenario. Small-scale dredging meets the targets for the ensemble members of the G scenario and the scenario without climate change, but not for the Wp scenario in the final 25-year period.

In the case of a shift to an Egalitarian Perspective, there is no urgent need to change the policy, since the current policy scores moderately for the Egalitarian targets. From an Individualistic point of view, current large vessels and medium vessels are not effective. Consequently, the medium vessels are not only less robust due to the environmental conditions (low discharges), but also because of the potential future societal conditions (Perspective change).

4.4.2 *Development of Adaptation Pathways*

4.4.2.1 *Sell-by Date of the Policy Options*

To determine the sell-by date of the flood policy options, the damage per year for each option was considered separately for all 10 ensemble members for all 3 climate scenarios (Figure 20). For the current Hierarchist Perspective a policy was considered as being no longer durable when the cumulative damage is larger than 2500 M euro. This amount is comparable to the damage due to flooding of 4 dike rings or 2 floods in 2 dike rings. The first four years are not taken into account as the implementation of a policy options was assumed to take 4 years. A Perspectives change affects the indicators weights: the targets for the Individualist were set at half the values for the Hierarchist and the

	Dike rings flooded (#)	Urban area flooded (km^2)	Total damage (Meuro)	Agricultural damage (Meuro)	Non-navigable time (%)	Nature (ha)	Ip factor
			Flood policy options				
No policy	41 ± 14	26 ± 9	27362 ± 9750	1056 ± 383		13	N/A
DH500	8 ± 4	6 ± 2	5227 ± 2290	167 ± 83		13	5
DH1000	7 ± 3	5 ± 2	4285 ± 2128	139 ± 79		13	6
DH1.5	2 ± 2	2 ± 1	1256 ± 1274	41 ± 44		13	19
RfRl	8 ± 4	5 ± 2	4706 ± 2683	149 ± 88		20	5
RfRs	35 ± 13	20 ± 7	21767 ± 8375	748 ± 298		17	1
CopU	39 ± 13	24 ± 8	26077 ± 8919	1013 ± 356		13	1
FloatH	41 ± 14	26 ± 9	8479 ± 3146	1056 ± 383		13	2
FaC	41 ± 14	0 ± 1	6381 ± 2439	1056 ± 383		13	26
Mound	41 ± 14	20 ± 7	15837 ± 6252	1056 ± 1803		13	1
			Low flow policy options				
No policy					8.9 ± 3.15		N/A
SmallS					0.2 ± 0.00		44
MediumS					6.4 ± 3.58		1
SmallD					0.5 ± 0.03		19
LargeD					0.3 ± 0.10		19

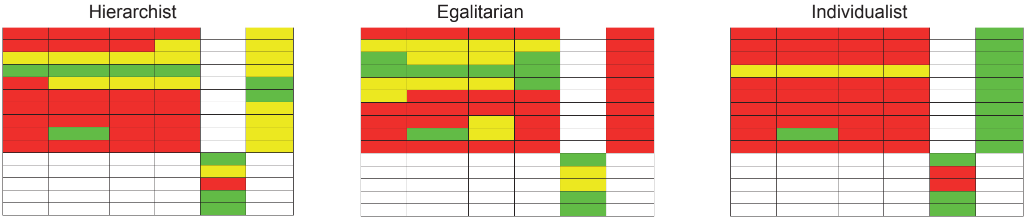

Figure 19: Scorecards with the average performance of all policy options for all ensemble members of all climate scenarios in 100 years. The 'Ip factor' refers to the improvement of the results compared to the reference situation without strategies. For the flood management strategies the average of the indicators is taken. Table 2 gives a description of the policy options. The three tables at the bottom indicate how each Perspective evaluates the performance for the indicators. The colours refer to the acceptability categories of Table 1 and indicate whether targets for each Perspective are achieved. Green: acceptable results; Yellow: moderate results; Red: unacceptable results.

targets for the Egalitarian were set at twice as large. As shown by the statistics, the sell-by dates of the policies differ a lot for the flood management strategies, not only among the policy options strategies, but also within the ensemble members of the climate scenarios, between the climate scenarios, and among the different Perspectives. The differences caused by the Perspectives are larger, than the differences due to the climate scenarios. Remarkably, the difference between the median values of the sell-by dates for the climate scenarios is quite large (more than 10 years) for only 5 policy options. For the low flow policy options, all these differences are negligible, except for 'small scale dredging' in the Wp scenario.

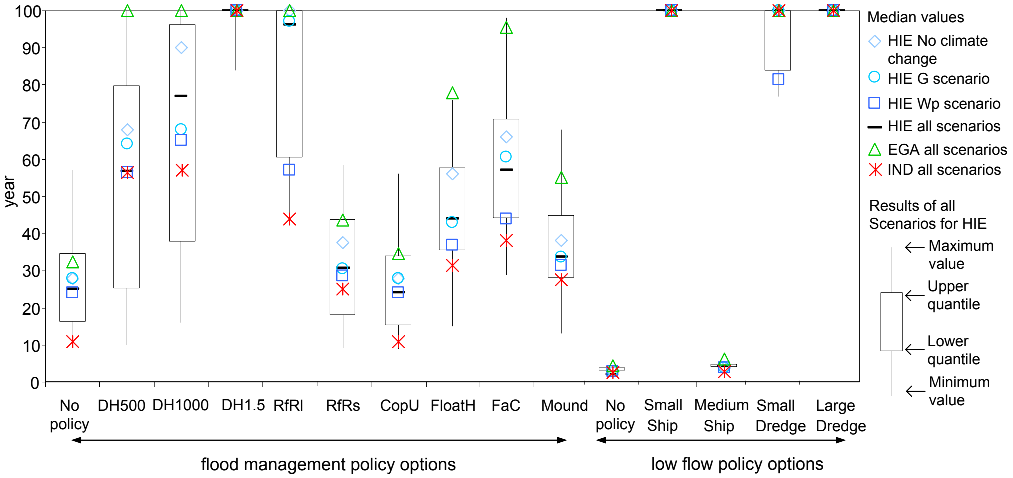

Figure 20: Box-whisker plots of the sell-by date of the strategies based on the results for all 10 realisations of all 3 climate scenarios in a Hierarchist future (HIE). The median values for each climate scenario separately and for the Egalitarian (EGA) and Individualist (IND) are presented. Left: Sell-by date of flood management policy options using the total damage of 2500 M euro as criterion. Right: Sell-by date of low flow policy options using a criterion of 2% of non-navigable time for 4 years in a row. For policy option abbreviations see Table 2.

From the current Hierarchist Perspective, raising the dikes to cope with 1.5 times the second highest discharge (DH1.5) and 'room for the river' (RfR) have the longest sell-by date, although in the case of RfR the spread within the realisations is large. For the low flow policy options, 2% of non-navigable time is taken as the criterion for the sell-by date, which means that for 7 days a year it is not possible to use the river for navigation. When this occurs for 4 years in a row the policy option is assumed to have failed, and is no longer durable. It appears that using large vessels (reference fleet) will soon limit the navigation too much due to problems with the water depth (Figure 20).

With medium-sized vessels the sell-by date is not much better. With small vessels, the sell-by date is 100 years for all climate realisations (i.e. no policy change is needed in any scenario). The same applies for the large-scale dredging. For the small-scale dredging, the average sell-by date is also good, but it is less compared to large-scale dredging (on average, 94 years for all climate scenarios, and 81 years under the most extreme climate scenario (Wp)).

4.4.2.2 *Low Flow Management Pathways*

The sell-by dates, based on the median values for the current Hierarchist Perspective, were used to develop the adaptation pathways. After an adaptation tipping point (ATP) is reached all other relevant options are considered. Depending on the climate scenario and the Perspective, the ATP is reached earlier or later (as shown in Figure 20). For the low flow policy options the difference in the sell-by date is rather small, except for policy option of small scale dredging. Figure 21 presents the possible adaptation pathways for low flow management. This adaptation pathways map presents different possible routes to get to a desired point (targets) into the future, similar to a Metro map of a city. The map shows the moment of an ATP (terminal station) and the other available policy options, where you can shift to in order to reach your targets (transfer stations). Some routes are not available in the (more severe) Wp climate change scenario (indicated with dashed line). One could argue that following this route to get to your destination is taking a risk, as if the Wp scenario becomes reality, targets are not achieved anymore, resulting in a need to shift to another policy to reach the destination by taking a transfer station. In such a situation the moment of an ATP occurs much earlier in the Wp scenario than it does in the scenario without climate change and in the G scenario.

Considering the sell-by date of the current ships (large vessels) it will soon be necessary to shift to one of the other four policy options in all climate realisations. When shifting to small vessels, it is possible to achieve the objectives for the next 100 years in all the climate realisations. The same applies if large-scale dredging is applied. Adaptation to medium-sized vessels will not help much. Within a few years it will be necessary to either shift to another policy option or combine it with the dredging policy options. The small-scale dredging is on average relatively durable, but choosing this option involves taking a risk as this is not effective for the whole 100-year period in all climate scenarios. In the realisations of the most extreme climate scenario the targets will not be achieved after approximately 77 to 86 years (depending on the realisation). It is, however, a flexible policy, since it allows the policy to be changed towards using small or medium-sized vessels or large-scale dredging without extra cost. For the low flow policy options, the

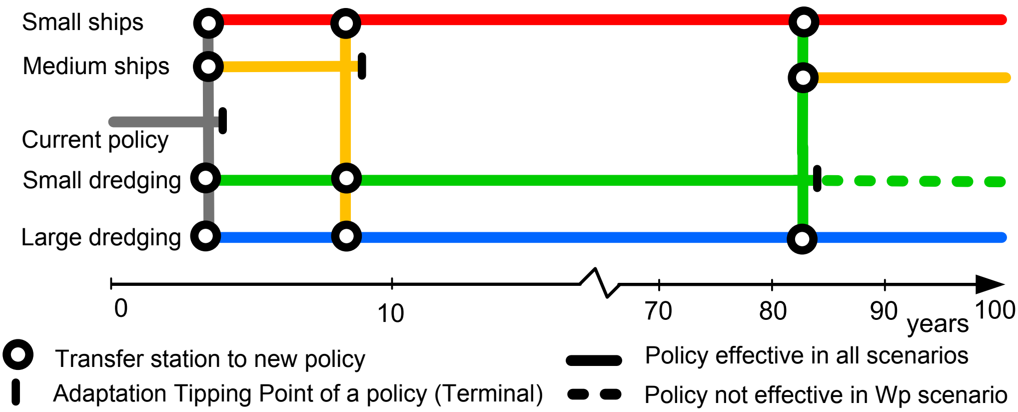

Figure 21: Adaptation pathway map for low flow management based on the median value for the sell-by date of policy options for all climate realisations in a Hierarchist world. The figure can be read like a map indicating several possible routes to get to a desired point (target) in the future. Similar to a Metro map the circles indicate a transfer station to another policy, only here it is not possible to go back since the lines present a route through time. The blocks indicate a terminal station at which an Adaptation Tipping Point (ATP) is reached. Starting from the current situation, targets are not achieved after 4 years. Following the grey lines of the current policy, one can see that there are four options which are left after this ATP. With the options small vessels and large scale dredging, targets are achieved for the next 100 years in all climate scenarios and for all perspectives. When medium vessels are chosen, an ATP is soon reached and a shift to one of the other 3 options is needed to achieve targets (follow the orange lines). With small scale dredging a shift is needed in case of the Wp scenario (follow the solid green lines). In the other scenarios, the targets are achieved for the next 100 years (the dashed line). For policy option abbreviations, see Table 2

effect of a Perspective change on the sell-by date, and thus the need to shift to another policy, is negligible.

4.4.2.3 *Flood Management Pathways*

The total damage accumulates to over 2500 M euro within 25 years in all climate scenarios in a Hierarchist future. River improvement policies are thus needed. Several options are open after the first 25 years. We only present the relevant options, meaning options which considerably extend the sell-by date of the policy, and have excluded options which are illogical (for example, it is not logical to first put houses on a mound, and later build floating houses). The pathways are generally based on the median values of the sell-by dates, but if an ATP occurs much sooner in the case of one of the climate scenarios, we indicated this. For the flood management a combination of policy options, which occurs after shifting to another policy, can extend the sell-by date in comparison to the ATP of an individual policy.

The policy options can be divided into flood mitigation and damage mitigation strategies (respectively upper and lower part of the flood pathways in Figure 22). Flood mitigation strategies prevent flooding (e.g. dike raising or 'room for the river'), while damage mitigation strategies accept a flood, but diminish or mitigate the flood damage (e.g. floating houses or houses on a mound). In the case that one of the damage mitigation strategies is chosen after 25 years, additional policies are needed after 34 to 57 years. Raising the dikes up to a design discharge of 1:500 or giving more 'room for the river' after these ATPs is sufficient to achieve the target for the next 95 to 100 years. From the flood mitigation strategies, raising the dikes extremely (DH1.5) would be very effective; in all the considered transient scenarios it will meet the target for the next 100 years. Raising the dikes to cope with the 1:500 and 1:100 discharge is effective for 57 and 77 years respectively (median values of all transient runs), but this may be earlier in the case that the Wp climate change scenario becomes reality. After these points, it is possible to add either more 'room for the river' or to implement one of the damage mitigation options. A combination with 'room for the river' or houses on a mound appears to extend the ATP a lot, but it is ineffective for the most extreme climate scenario (Wp). Thus, taking this route involves taking the risk that the target will not be achieved. With floating houses (FloatH) or additional dikes around the cities (FaC) the target is maintained until almost the end of the century.

4.4.3 *Evaluation of the Policy Options and Adaptation Pathways*

So far, we have analysed the robustness of strategies by determining their performance with targets for sustainability indicators for the

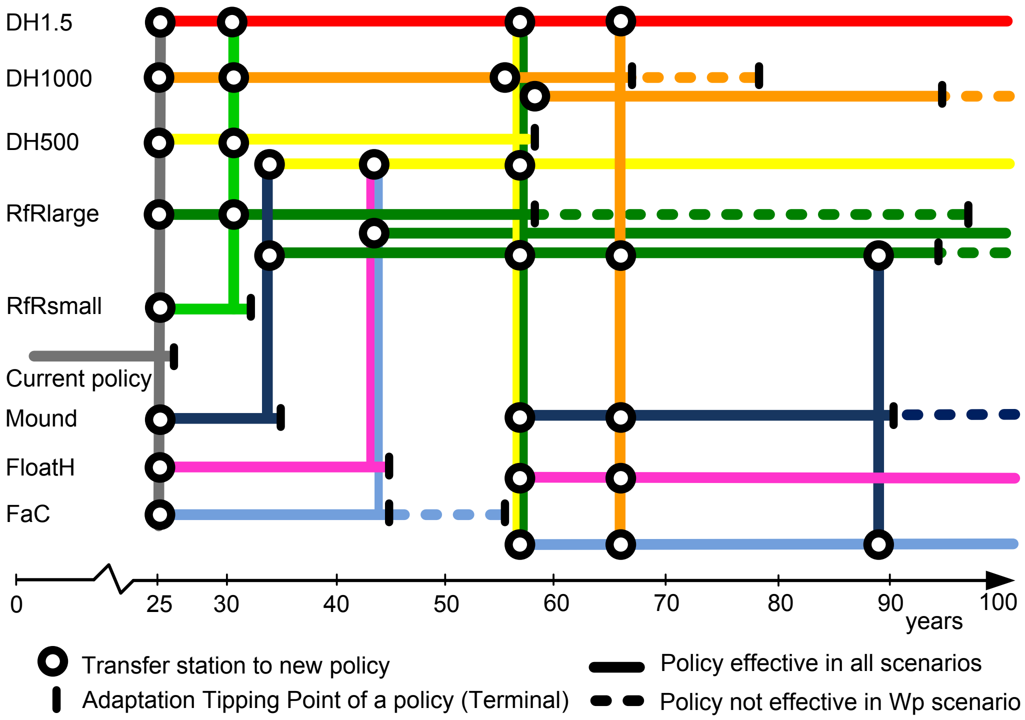

Figure 22: Adaptation pathway map for flood management based on the median value for the sell-by date of policy options for all climate realisations in a Hierarchist world. The figure can be read similarly to Figure 21. The map indicates several possible routes to get to a desired point (target) in the future. Similar to a Metro Map the circles indicate a transfer station to another policy. The blocks indicate a terminal station at which an Adaptation Tipping Point (ATP) is reached. Starting from the current policy, targets are not achieved after 25 years. After this ATP several options are left, which also have an ATP. When this occurs depends on the climate scenario and the Perspective as indicated with the sell-by date for these different conditions in Figure 20). In some situations an ATP is only reached in the Wp scenario. After this point targets are only achieved in the case of the no climate change or G scenario (dashed line). After switching to a new policy, the combined effect is different and often delays the moment of an ATP. In such cases more routes via the same policy are indicated with lines in the same colour. For policy option abbreviations, see Table 2.

three different Perspectives. We determined the sell-by date of the policy options by comparing the results per year with a target for the flood and low flow policy options for each Perspective, which we then used to develop adaptation pathways. The results show that flood mitigation actions are always needed to achieve the targets for the current Hierarchist Perspective, either 1) by raising the dikes extensively (in such a way that they are able to cope with 1.5 times the second highest discharge measured), 2) by combining the dike-raising options with the 'room for the river' measure, or 3) by combining one of the flood mitigation strategies with a damage mitigation measure. The dike-raising options score better in the most extreme climate scenarios than giving 'room for the river', as these strategies include adaptation through raising the dikes to the new design discharge after an event has occurred. This characteristic could be added to the other policy options to improve them. The low flow policy options of small ships and large-scale dredging will meet the targets in all transient scenarios. Choosing small-scale dredging includes taking a risk, as it does not meet the targets in the most extreme climate change realisations.

In addition to the climate scenarios, socio-economic developments may influence the effectiveness of the pathways. Although not explored with the transient scenarios, a potential influence on the pathways could be that some options may not be available in the future. Socio-economic developments may result in additional spatial claims, leaving no space left for strategies such as 'room for the river', which in the end may result in a lock-in situation with no policy options left. Thus, it may be worthwhile to first implement 'room for the river' and later on increase dikes if this would still be necessary, or at least reserve space.

For all policy options costs, are relatively low (Table 2), compared to the potential damages (Figure 19). Thus, although some policy options and pathways are much cheaper than others, from cost/benefit perspective all policy options perform well. Subsequently, implementing a sequence of policy options - which can be considered as an intensification of a strategy or which strengthen each other - would be even cheaper. Examples would be, first implementing small scale and later large scale 'room for the river' or the implementation of a sequence of dike raising options (although the latter should be considered with care, because the initial costs for dike-raising are very high).

Finding robust strategies under changing environmental conditions is already difficult. Increasing their robustness by making the strategies also robust for Perspective change is an extra challenge. In the previous section, this was explored by analysing the performance for Perspective-based targets. Another way of finding Perspective-robust strategies is through evaluating the strategies and pathways descriptively using the core beliefs of a Perspective (see Appendix B for a view of each Perspective on the policy options) and storylines describing potential futures with Perspective change. Strategies that are acceptable for all Perspectives - even if this is for a different reason - are more robust (Offermans et al., 2008). For example, 'room for the river' may be preferred by the Egalitarian, because it enhances nature and lowers water levels in the case of peak discharges, while the Hierarchist prefers this strategy, because it lowers the flood risk. Considering the past, it is possible to imagine that the current Hierarchist Perspective in the Waas may change (Offermans, 2010). Environmental calamities and increasing societal inequalities could enforce the non-dominant presence of an Egalitarian Perspective to become dominant. Individualists argue the Hierarchical bureaucracy and lack of innovation and technological inventions. A long period of severe drought, wherein typical Hierachist solutions (e.g. water storage and proper distribution), were not sufficient, could increase the popularity of typical Individualistic ways to manage water supply (e.g. market-based innovative solutions such as farmers who re-use water and develop drought resistant crops) (Offermans, 2010).

If the Perspective was to change to Egalitarian, 'room for the river' would be more appreciated, because of the impacts on the planet indicators. Both the Hierarchist and the Egalitarian evaluate this policy option well, raising the robustness of this policy. It is thus wise to either first select this option or to save space for it to be implemented later, in case the Perspective changes in the future. The Egalitarian is not in favour of dike-raising, since dikes are unnatural and disturb natural river functions. According to them, trying to control nature is inherently wrong. However, the Egalitarian targets for total damage are achieved with this policy option. Thus, although this policy option is not preferred, it may be implemented with support of this Perspective as part of finding consensus with Hierarchists. In an Egalitarian world, it is more likely that society prefers the small vessels above the large-scale dredging, because of possible ecological impacts and because the latter policy should be implemented each year, which may not seem sustainable. From the policy options considered in the experiment, only 'floating houses' and 'houses on a mound' are preferred strategies for the Individualist. These strategies are, however, inadequate to achieve the Individualist targets. So, either other Individualistic policy options should be explored, or they must shift to Egalitarian or Hierarchist policy options.

4.5 EVALUATION OF THE METHOD

By applying our approach for a hypothetical case we have learned about the strengths and weaknesses of the approach, which we elaborate in this section. A strength of the method is that the resulting pathways give information on the effectiveness and timing of policy options. In addition, the interactions between the social and water system makes the pathways more realistic. The use of transient scenarios supports the development of pathways by enabling the analysts to assess under which conditions and time span a strategy may fail. Other studies that also presented pathway information - in the sense that they mention either the durability (Kwadijk et al., 2010) or the planning of strategies through time (EA, 2009) - first assessed under what sea level rise a strategy may fail and then determined the moment when this occurs by linking the specific value of sea level rise to a scenario assuming a linear change between now and an end-point scenario. However, for strategies needed for coping with extreme events of for example precipitation and discharges, the transient scenarios are a useful tool. Working with the IAMM and transient scenarios increases the knowledge of the system and the potential impact of dynamics through natural variability and the interaction between the water system and society. This feedback was received after using a game setting with policy makers. Water managers and other stakeholders can experience the effects of (the interaction between) water and social events and how this influences the decision making.

Different types of uncertainty, as distinguished by Haasnoot et al. (2011), are now included in the analysis for decisions on water management. Natural uncertainty is included through the different realisations of the scenarios. Social uncertainty is now included through the Perspectives method by taking into account different possible futures, individual strategies, and weights to the indicators through different value ranges, enabling the development of robust strategies under changing physical, socio-economic, and societal conditions.

The IAMM allows rapid assessment of many transient scenarios. The different parts of the IAMM are completely integrated through the cause-effect relations, which interact in each time step. This enables real dynamic modelling and provides insight into the dynamic part of the system, in contrast with most other IAMs, which often consist of linked submodels (Rotmans and Van Asselt, 2001; Schneider and Lane, 2005).

The weaknesses of the method are related to the simplifications made. Simplifications are needed when complexity is increasing, such as done in this study by including the water-society interaction and by considering many time-series. The challenge is to capture enough detail and process information by the models to ensure that they perform adequately for analysis and decision making. The simplicity of the response curves may result in underestimation or disappearance of some effects. For a real case study it will be necessary to validate the IAMM, as was argued by Schneider (1997) and executed by Van Vuuren et al. (2009). Hodges and Dewar (1992) and Hodges (1991) discuss uses of unvalidatable models. Our use falls into one of their categories.

In the current case study, we analysed flood and low flow policy options in separate pathways. This was possible because neither pathway influence the other, since the flood reduction policy options had no effect on low flows and vice versa. In integrated water resources management in the real world, different strategies serving different objectives may interfere and affect multiple river services. Furthermore, integrated water resources management concerns a larger number of river-related services, leading to multiple targets, that all should be considered in developing water management strategies and associated decision making. This will lead to additional evaluation pathways for e.g. ecology, agriculture, industrial water use, and recreation. Obviously the different pathways will then mutually depend on each other. This will make determining robust strategies and pathways less straightforward. Furthermore, in the real world socio-economic developments will influence the effectiveness of strategies and pathways as well; some policy options may be feasible now but not after several decades. We plan to explore these issues in a subsequent real-world case study.

The influence of Perspective change on the pathways could be further explored, for example by simulating Perspectives with the model through more complex response rules and by including diversity in Perspectives (dominant and non-dominant Perspectives, non-stereotypical Perspectives, and different Perspectives at different levels).

A worthwhile addition to the pathways could be the use of signposts and triggers for deciding when additional or other strategies should be implemented such as done by (Dewar et al., 1993; Walker et al., 2001; Kwakkel et al., 2010b), although, it may be difficult to find good triggers for water management. For example, water managers would like to know if climate change is happening because of the potential increase of floods and droughts. However, measuring for example peak discharges as a sign that climate change is happening is very difficult, because of high natural variability and the short time period of measurements (Diermanse et al., 2010).

In spite of its limitations, it seems worthwhile to explore the method further for a real case study. Also validation is needed, in order to assure an appropriate model for decision making on long-term water policy options.

4.6 CONCLUSIONS

The objectives of the study presented here were 1) to implement the adaptation pathway approach for sustainable water management with an IAMM and transient scenarios, and 2) to experiment with this implementation to see whether to assess the relevance of such an approach for decision making under uncertainty.

The hypothetical case demonstrated that it is possible to apply the method and to achieve plausible results that could be useful for decision making under uncertainty. With the IAMM and transient scenarios, we explored and evaluated adaptation pathways. A map of adaptation pathways presents not only the feasible policy options, but also when and where they will fail. When a strategy becomes ineffective and thus reaches its Adaptation Tipping Point depends on how the future will unfold in terms climate, socio-economic, and Perspective conditions; the shape of the pathways thus remains the same, but the time span differs. The maps do show that for some strategies this timing does not differ much. Also, more types of uncertainty are taken into account. By using transient scenarios and the iteration in the PSIR chain, the natural variability and dynamics in the water and social system, as well as the interaction between these systems, become more explicit in effect analysis and policy development. This is important for an adaptive approach to cope with uncertainty (Pahl-Wostl, 2007). The results show, for example, that climate variability, and Perspectives (in terms of targets) may be at least as important for decision making as climate change, especially for the mid- to long-term. Using the IAMM in a workshop setting confirms this conclusion, as the response of users was *reactive* to the events (caused by climate variability) rather than anticipating future events (climate change). The Perspective-based evaluation has the possibility for ensuring pathways that not only lead to sustainable water management under different possible physical and socio-economic developments, but also under different possible societal futures (perspectives).

The adaptation pathways may support decision making under deep uncertainty. Because of the interaction between the water system and society, the method may even support decision making in the case of persistent problems, which are characterised by a complex interaction of broad societal trends and physical (natural) processes (such as climate change) and the involvement of many stakeholders with different but plausible perspectives (Rotmans, 2006).

5

IMPROVEMENT OF THE METHOD: DYNAMIC ADAPTIVE POLICY PATHWAYS

ABSTRACT

A new paradigm for planning under conditions of deep uncertainty has emerged in the literature. According to this paradigm, a planner should create a strategic vision of the future, commit to short-term actions, and establish a framework to guide future actions. A plan that embodies these ideas allows for its dynamic adaptation over time to meet changing circumstances. We propose a method for decision making under uncertain global and regional changes called 'Dynamic Adaptive Policy Pathways'. We base our approach on two complementary approaches for designing adaptive plans: 'Adaptive Policy Making' and 'Adaptation Pathways'. Adaptive Policy Making is a theoretical approach describing a planning process with different types of actions (e.g. 'mitigating actions' and 'hedging actions') and signposts to monitor if adaptation is needed. In contrast, Adaptation Pathways provides an analytical approach for exploring and sequencing a set of possible actions based on alternative external developments over time. We illustrate the Dynamic Adaptive Policy Pathways approach by producing an adaptive plan for long-term water management of the Rhine Delta in the Netherlands that takes into account the deep uncertainties about the future arising from social, political, technological, economic, and climate changes. The results suggest that it is worthwhile to further test and use the approach.

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5.1 INTRODUCTION

Nowadays, decision makers face deep uncertainties about a myriad of external factors, such as climate change, population growth, new technologies, economic developments, and their impacts. Moreover, not only environmental conditions, but also societal perspectives and preferences may change over time, including stakeholders' interests and their evaluation of plans (Offermans, 2010; Van der Brugge et al., 2005). Traditionally, decision makers in many policy domains, including water management, assume that the future can be predicted. They develop a static 'optimal' plan using a single 'most likely' future (often based on the extrapolation of trends) or a static 'robust' plan that will produce acceptable outcomes in most plausible future worlds (Dessai and Hulme, 2007; Dessai and Van der Sluijs, 2007; Hallegatte et al., 2012). However, if the future turns out to be different from the hypothesised future(s), the plan is likely to fail. McInerney et al. (2012) liken this to "dancing on the top of a needle". But, as the future unfolds policy makers learn and usually respond to the new situation by adapting their plans (ad-hoc) to the new reality. Adaptation over the course of time is not only determined by what is known or anticipated at present, but also by what is experienced and learned as the future unfolds (Yohe, 1990) and by the policy responses to events (Chapter 4). Thus, policy making becomes part of the storyline, and thereby an essential component of the total uncertainty — in fact, Hallegatte et al. (2012) include the adaptation of decisions over time in an updated definition of 'deep uncertainty'.

To address these deep uncertainties, a new planning paradigm has emerged. This paradigm holds that, in light of the deep uncertainties, one needs to design dynamic adaptive plans (Chapter 3 and De Neufville and Odoni 2003; Albrechts 2004; Schwartz and Trigeorgis 2004; Hallegatte 2009; Hallegatte et al. 2012; Ranger et al. 2010; Swanson et al. 2010). Such plans contain a strategic vision of the future, commit to short-term actions, and establish a framework to guide future actions (Albrechts, 2004; Ranger et al., 2010). The seeds for this planning paradigm were planted almost a century ago. Dewey (1927) argued that policies should be treated as experiments, with the aim of promoting continual learning and adaptation in response to experience over time. Early applications of adaptive plans can be found in the field of environmental management (Holling, 1978; Lee, 1993; McLain and Lee, 1996), and involve the ability to change plans based on new experience and insights (Pahl-Wostl et al., 2007). Collingridge (1980) argues that, given ignorance about the possible side effects of technologies under development, one should strive for correctability of decisions, extensive monitoring of effects, and flexibility. Rosenhead

(1972; 1990) presented flexibility, in terms of keeping options open, as an indicator to evaluate the robustness of strategies under uncertainty.

This planning paradigm, in one form or another, has been receiving increasing attention in various policy domains. Dynamic adaptive plans are being developed for water management of New York (Yohe and Leichenko, 2010; Rosenzweig et al., 2011), New Zealand (Lawrence and Manning, 2012), and the Rhine Delta (Delta Programme, 2010; Jeuken and Reeder, 2011; Roosjen et al., 2012; Delta Programme, 2012a), and have been developed for the Thames Estuary (McGahey and Sayers, 2008; Lowe et al., 2009; Sayers et al., 2012; Wilby and Keenan, 2012; Reeder and Ranger, online). Such applications are also arising in other fields (see Swanson and Bhadwal, 2009a; Walker et al., 2010, for examples).

A large number of approaches and computational techniques exist to support decision making under deep uncertainty (see e.g. Metz et al., 2001; Dessai and Van der Sluijs, 2007; IISD, 2006; Swanson et al., 2010; Hallegatte et al., 2012; Walker et al., 2013, for an overview of a strand of approaches). With respect to approaches, the Thames2100 project used decision trees to analyze sequential decisions for preparing the Thames Estuary for future sea level rise. In the Netherlands, Real Options Analysis has been used to assess optimal costs and benefits of pathways for fresh water supply of the Southwestern Delta (Van Rhee, 2012) and for studying how flexibility can be built into flood risk infrastructure (Gersonius et al., 2013). To show dependencies of choices for shipping, a decision tree has been used in the Dutch Delta Programme (Delta Programme, 2010). Roadmaps have been used to illustrate a sequence of actions in water management studies (e.g. for the lakes IJsselmeer (unpublished) and Volkerak Zoommeer Projectteam Verkenning oplossingsrichtingen Volkerak-Zoommeer, 2003). The Backcasting approach aims at describing a desirable future, and then looking backwards from that future to the present to develop a pathway of actions needed to realise this future (Lovins, 1976; Höjer and Mattsson, 2000; Quist and Vergragt, 2006). Assumption-Based Planning begins with an existing plan and analyzes the critical assumptions in this plan (Dewar et al., 1993). It uses signposts to monitor the need for changes. Robust Decision Making is an approach that uses many computational experiments to create an ensemble of scenarios against which candidate actions are evaluated in order to develop robust actions (Lempert et al., 2006; Groves and Lempert, 2007). Several planning approaches consider reassessment and the ability to change policies based on new insights in a planning circle (Willows and Connell, 2003; Loucks and Van Beek, 2005; Pahl-Wostl, 2007; Swanson and Bhadwal, 2009a; Ranger et al., 2010). The Panel on America's Climate Choices (2010) refers to this as 'iterative risk management' that 'is a system for assessing risks, identifying options that are robust across a range of possible futures, and assessing and revising those choices as new information emerges.' Among the computational techniques are Scenario Discovery (Bryant and Lempert, 2010; Lempert and Groves, 2010), Exploratory Modeling and Analysis (Bankes, 1993; Bankes et al., 2013), and Info-Gap decision theory (Hall and Harvey, 2009; Korteling et al., 2012).

These approaches and computational techniques, although developed for different purposes, have been found valuable for designing adaptive policies (Bankes, 2002; Lempert et al., 2000; Hall et al., 2012; Hallegatte et al., 2012; Hamarat et al., 2013; Lempert et al., 2002). They differ in terms of the concepts employed, and provide different kinds decision support information (Hall et al., 2012). Consequently, they have different strengths and limitations. This situation calls for research into comparing the various approaches and techniques, providing an understanding of their relative strengths and weaknesses, and identifying the contexts within which each of the approaches and techniques is most appropriately employed (Ranger et al., 2010; Hall et al., 2012; Hallegatte et al., 2012). In addition, we argue that it is worthwhile to assess the extent to which the different terminologies used signify real differences in the underlying concepts, for this can contribute to harmonizing the field.

In this chapter, we analyze two existing adaptive planning approaches and show how the employed concepts are partially overlapping and partially complementary, resulting in an integration of the two approaches. We look at Adaptive Policy Making (Walker et al., 2001; Kwakkel et al., 2010a) and Adaptation Pathways (Chapter 4). Adaptive Policy Making provides a stepwise approach for developing a basic plan, and contingency planning to adapt the basic plan to new information over time. Adaptation Pathways provide insight into the sequencing of actions over time, potential lock-ins, and path dependencies. An example of a family resemblance between concepts used by these two approaches is the concept of an adaptation tipping point (Kwadijk et al., 2010) used in Adaptation Pathways and the notion of a trigger from Adaptive Policy Making. An adaptation tipping point is the point at which a particular action is no longer adequate for meeting the plan's objectives. A new action is therefore necessary. A trigger specifies the conditions under which a pre-specified action to change the plan is to be taken.

A fundamental challenge in planning research is the assessment of the efficacy of new planning methods and concepts. The problem is pointedly summarised by Dewar et al. (1993, p. 58) "nothing done in the short term can 'prove' the efficacy of a planning methodology, nor can the monitoring, over time, of a single instance of a plan generated by that methodology, unless there is a competing parallel plan". With respect to how a planning concept is tested, the planning research literature tends to look towards controlled real world application (Dewar et al., 1993; Hansman et al., 2006; Straatemeier et al., 2010). However, analogous to other design sciences (Frey and Dym, 2006), the evaluation of a planning concept can also utilise other sources of evidence (Kwakkel and Van Der Pas, 2011; Kwakkel et al., 2012). Evidence can come from planning practice, from virtual worlds that represent the world of practice but are not the world of practice (Schön, 1983), and from theoretical considerations. In this chapter, to assess the efficacy of the outlined integration of Adaptive Policy Making and Adaptation Pathways, we use such a virtual world in the form of applying the presented planning concepts to a real-world decision problem currently faced by the Dutch National Government. This application serves to illustrate the concept, describes how it could be used to develop a dynamic adaptive plan, and offers a first source of evidence of its efficacy through a critical reflection on the application.

The chapter ultimately proposes a method for decision making under deep uncertainty called Dynamic Adaptive Policy Pathways, which is a combination of Adaptive Policy Making and Adaptation Pathways. We first provide short introductions to each of the underlying approaches, and then explore how the two approaches can be integrated into a single approach based on the strong elements of both to produce a dynamic adaptive plan. We demonstrate the approach by producing a dynamic adaptive plan for water management of the Rhine Delta region of the Netherlands that takes into account the deep uncertainties associated with global climate change.

5.2 THE TWO UNDERLYING APPROACHES

5.2.1 *Adaptation Pathways*

The Adaptation Pathways approach is summarised in Figures 23 and 24 (Chapters 3 and 4). Central to adaptation pathways are adaptation tipping points (Kwadijk et al., 2010), which are the conditions under which an action no longer meets the clearly specified objectives. The timing of the adaptation point for a given action, its sell-by date, is scenario dependent. After reaching a tipping point, additional actions are needed. As a result, a pathway emerges. The Adaptation Pathways approach presents a sequence of possible actions after a tipping point in the form of adaptation trees (e.g. like a decision tree or a roadmap). Any given route through the tree is an adaptation pathway. Typically, this approach uses computational scenario approaches to assess the distribution of the sell-by date of several actions across a large ensemble of transient scenarios. This distribution can be summarised in box-whisker plots, and the median or quartile values are used in generating an adaptation map. The exact date of a tipping point is not important;

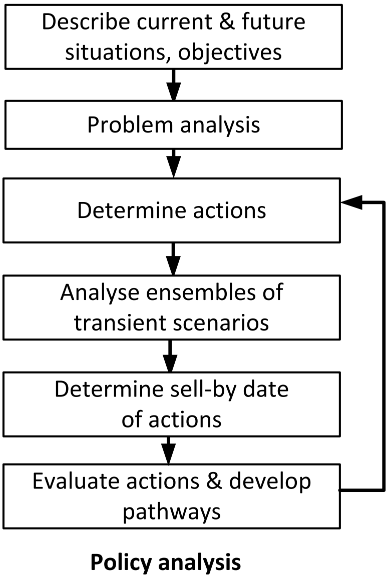
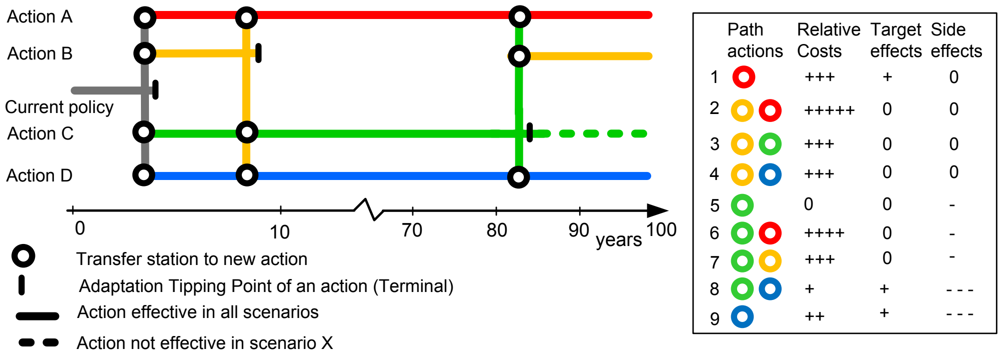


Figure 23: Stepwise policy analysis to construct Adaptation Pathways.

the moment should be roughly right — for example, "on average the tipping point will be reached within 50 years, at earliest within 40 years, and at latest within 60 years". The effects of sequences of actions can be assessed in the same way as individual actions. To cope with the presence of different stakeholders, values, and worldviews, cultural perspectives can be used to map these out (Van Asselt and Rotmans, 1997; Hoekstra, 1998; Middelkoop et al., 2004; Offermans, 2010).

The Adaptation Pathways map, manually drawn based on model results or expert judgment, presents an overview of relevant pathways (see Figure 24 for an example). Similar to a Metro map (see, for example, http://www.wmata.com/rail/maps/map.cfm), the Adaptation Pathways map presents alternative routes to get to the same desired point in the future. All routes presented satisfy a pre-specified minimum performance level, such as a safety norm (a threshold that determines whether results are acceptable or not). They can, thus, be considered as 'different ways leading to Rome' (as is true of different routes to a specified destination on the Metro). Also, the moment of an adaptation tipping point (terminal station), and the available actions after this point, are shown (via transfer stations). Due to unacceptable performance of some actions in a selection of scenarios, some routes are not always available (dashed lines). decision makers or stakeholders may have a preference for certain pathways, since costs and benefits may differ. An overview of such costs and benefits for each pathway can be presented in a scorecard (e.g. Walker, 2000). With the adapta-



	Path actions	Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟠 🔴	+++++	0	0
3	🟠 🟢	+++	0	0
4	🟠 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟠	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Adaptation Pathways Map **Scorecard pathways**

Figure 24: An example of an Adaptation Pathways map (left) and a scorecard presenting the costs and benefits of the 9 possible pathways presented in the map. In the map, starting from the current situation, targets begin to be missed after four years. Following the grey lines of the current policy, one can see that there are four options. Actions A and D should be able to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, a tipping point is reached within about five years; a shift to one of the other three actions will then be needed to achieve the targets (follow the orange lines). If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed in the case of Scenario X (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years (the dashed green line). The colors in the scorecard refer the actions A (red), B (orange), C (green), and D (blue).

tion map, decision makers can identify opportunities, no-regret actions, lock-ins, and the timing of an action, in order to support decision making in a changing environment. That is, the adaptation map can be used to prepare a plan for actions to be taken immediately, and for preparations that need to be made in order to be able to implement an action in the future in case conditions change. The example of Figure 24 shows that actions are needed in the short-term. Choosing action B may be ineffective as soon additional actions are needed. Choosing option C involves taking a risk, as additional actions may be needed in case scenario X becomes reality. In combination with a scorecard of the costs and benefits for the pathways, a decision maker could make an informed decision.

5.2.2 *Adaptive Policy Making*

Adaptive Policy Making is a generic structured approach for designing dynamic robust plans (Marchau et al., 2009; Kwakkel et al., 2010b;

Ranger et al., 2010). Conceptually, Adaptive Policy Making is rooted in Assumption-Based Planning (Dewar et al., 1993). Figure 25 shows the steps of the Adaptive Policy Making approach for designing a dynamic adaptive plan (Kwakkel et al., 2010b). In Step I, the existing conditions of a system are analysed and the objectives for future development are specified. In Step II, the way in which these objectives are to be achieved is specified by assembling a basic plan. This basic plan is made more robust through four types of actions (Step III): mitigating actions (actions to reduce the likely adverse effects of a plan); hedging actions (actions to spread or reduce the uncertain adverse effects of a plan); seizing actions (actions taken to seize likely available opportunities); and shaping actions (actions taken to reduce failure or enhance success). Even with the actions taken in Step III, there is still the need to monitor the plan's performance and to take action if necessary. This is called contingency planning (Step IV). Signposts specify information that should be tracked in order to determine whether the plan is meeting the conditions for its success. In addition, critical values of signpost variables (triggers) beyond which additional actions should be implemented are specified. There are four different types of actions that can be triggered by a signpost, which are specified in Step V: defensive actions (actions taken to clarify the basic plan, preserve its benefits, or meet outside challenges in response to specific triggers that leave the basic plan unchanged); corrective actions (adjustments to the basic plan); capitalizing actions (actions to take advantage of opportunities that can improve the performance of the basic plan); and a reassessment of the plan (initiated when the analysis and assumptions critical to the plan's success have clearly lost validity).

Once the complete plan has been designed, the actions to be taken immediately (from Step II and Step III) are implemented, and a monitoring system (from Step IV) is established. Then time starts running, signpost information related to the triggers is collected, and actions are started, altered, stopped, or expanded in response to this information. After implementation of the initial actions, the implementation of other actions (from Step V) is suspended until a trigger event occurs.

5.2.3 *Comparison of the Approaches*

Table 3 compares the features of Adaptive Policy Making and Adaptation Pathways. Both approaches aim at supporting decision makers in handling uncertainty in long-term decision making and emphasise the need for adaptivity in plans in order to cope with deep uncertainty. More specifically, they both offer support in choosing near-term actions, while keeping open the possibility to modify, extend, or otherwise alter the plans in response to how the future unfolds.

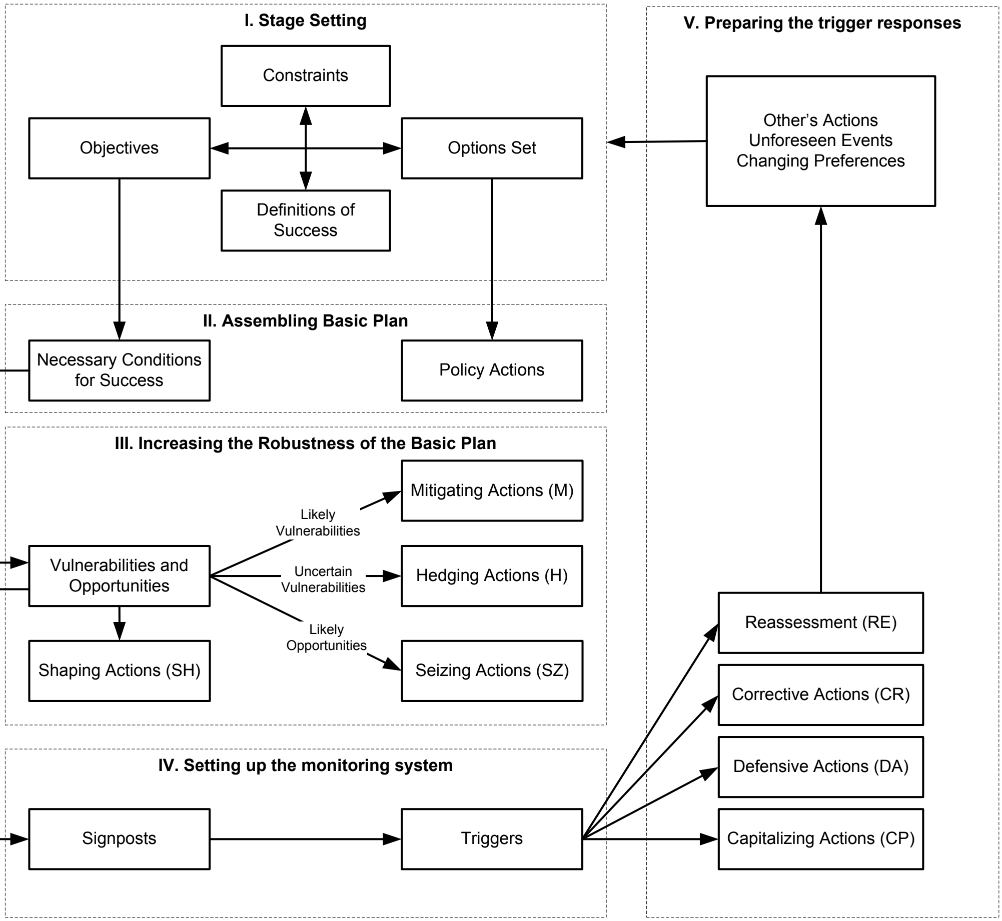


Figure 25: The Adaptive Policy Making approach to designing a dynamic adaptive plan (Kwakkel et al., 2010b).

Table 3: Comparison of the approaches

Aspect	Adaptive Policy Making	Adaptation Pathways
Focus	Starts from a vision of the decision maker and creates a plan for realizing this vision and protecting it from failure.	Explores actions for achieving objectives over time by including dynamic interaction between the system and society.
Consideration of the multiplicity of futures	Indirectly via vulnerabilities and opportunities.	Explicitly via transient scenarios.
Planning process	Comprehensive stepwise approach for designing a plan.	Short stepwise approach for designing Adaptation Pathways.
Clarity on how to design a plan	Limited; a high level framework that can be translated into a specific plan in many different ways.	Application oriented, with a clear link to the use of models to develop a specific plan.
Types of actions that can be taken	Distinguishes many different types of actions that can be taken (e.g. hedging, mitigating, shaping, etc.).	No specific categorisation of actions is used. Several actions and pathways are presented. A variety of actions are identified based on different societal perspectives.
Desirable plan	One basic plan is developed. No clear guideline on how develop the basic plan.	Several pathways are presented. Different perspectives result in different preferred pathways. No focus on how to identify promising pathways when confronted with a large number of possible actions.
Consideration of types of uncertainties	In principle, any uncertainty can be accounted for.	In principle, any uncertainty can be accounted for. Explicit attention is given to social uncertainty.
Flexibility of resulting plan	Flexibility is established through the monitoring system and associated actions.	The Adaptation Pathways map clearly specifies when a policy should be changed, and what the next action should be.
Dynamic robustness of resulting plan	Dynamic robustness results from the monitoring set up in Step IV and the actions taken in Step V.	Dynamic robustness is produced indirectly via the idea of a 'sell-by date' and the shift to another action.

The ways in which the two approaches offer decision support are quite different. Adaptation Pathways provides insight into the sequencing of actions over time, taking into account a large ensemble of transient scenarios. The transient scenarios allow for a wide variety of uncertainties about future developments to be taken into account in the planning process. Not only trends and system changes are included, but also uncertainty due to natural variability. The use of a fast and simple model allows for exploring a wide variety of pathways over the ensemble. These results can be used to sketch an Adaptation Pathways map. Dynamic robustness of the resulting plan is indirectly handled through the identification of an adaptation tipping point, the sell-by date, and the shift to other actions. The pathways map provides information to the decision maker, but gives no guidance on how the decision maker can translate this into an actual plan.

Adaptive Policy Making supports the decision maker in a different way. It specifies a stepwise approach to designing a plan. First a basic course of action is developed in light of well specified objectives. Then, the vulnerabilities and opportunities of this course of action are identified, and different types of actions to be taken now or in the future to either cope with the vulnerabilities or capitalise on the opportunities are specified. Through the identification of opportunities and vulnerabilities, a wide variety of uncertainties can be accounted for. The specification of a monitoring system and associated actions results in a dynamically robust plan. However, Adaptive Policy Making offers no clear guidance beyond these concepts. That is, questions, such as how can one identify vulnerabilities, how should the actions be sequenced, or how does one decide whether to hedge against a vulnerability or to specify a monitoring system with actions to handle the vulnerability in the future if and when it arises, are not addressed explicitly.

5.3 A NEW APPROACH: DYNAMIC ADAPTIVE POLICY PATHWAYS

The combination of Adaptive Policy Making and Adaptation Pathways, which we call Dynamic Adaptive Policy Pathways, results from using the strengths of both approaches. In short, this integrated approach includes: transient scenarios representing a variety of relevant uncertainties and their development over time; different types of actions to handle vulnerabilities and opportunities; Adaptation Pathways describing sequences of promising actions; and a monitoring system with related contingency actions to keep the plan on the track of a preferred pathway. The steps in the approach are presented in Figure 26.

The first step is to describe the study area, including the system's characteristics, the objectives, the constraints in the current situation, and potential constraints in future situations. The result is a definition of success, which is a specification of the desired outcomes in terms of

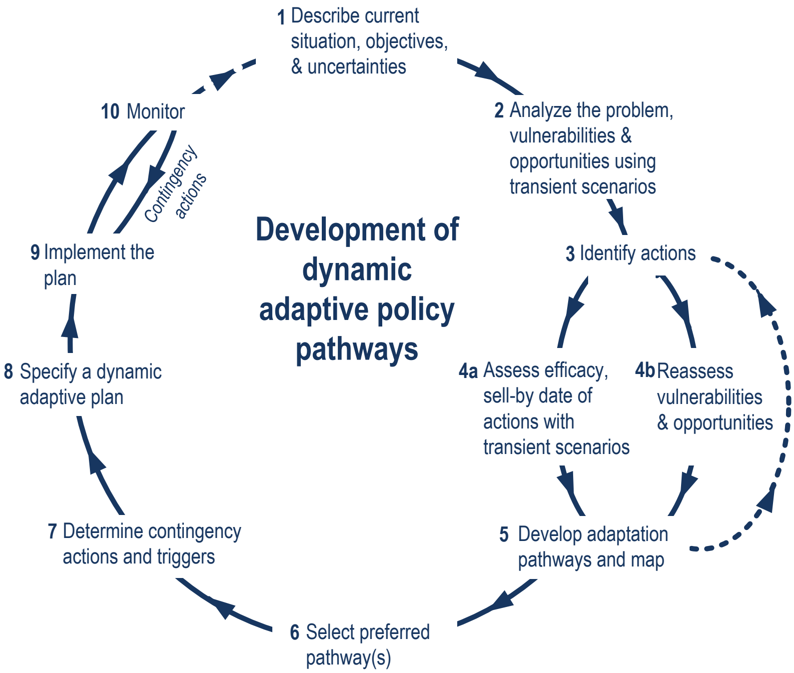


Figure 26: The Dynamic Adaptive Policy Pathways approach

indicators and targets that are used in subsequent steps to evaluate the performance of actions and pathways, and to assess the 'sell-by dates' of the actions. The description of the study area includes a specification of the major uncertainties that play a role in the decision making problem. These uncertainties are not restricted to uncertainties about the future, but can also cover uncertainties related to the data or models that are being used (Kwakkel et al., 2010a).

The second step is the problem analysis. In this step, the current situation and possible future situations are compared to the specified objectives to identify whether there are any gaps. The possible future situations are 'reference cases' assuming no new policies are implemented, and consist of (transient) scenarios that span the uncertainties identified in step one. A gap indicates that actions are needed. Both opportunities and vulnerabilities should be considered. Opportunities are developments that can help in achieving the objectives, while vulnerabilities are developments that can harm the extent to which the objectives can be achieved. The identification of opportunities and vulnerabilities can be based on the analysis of the reference cases, which can best be accomplished using a computational model.

In the third step, one identifies possible actions that can be taken to meet the definition for success. These actions can thus be specified in light of the opportunities and vulnerabilities previously identified and can be categorised according to the types of actions specified in the Adaptive Policy Making framework (i.e. shaping, mitigating, hedging, and capitalizing actions). The aim of this step is to assemble a rich set of possible actions. An identification of actions for different perspectives could enforce this (e.g. done by Offermans, 2010).

The fourth step is to evaluate the actions. The effects of the individual actions on the outcome indicators are assessed for each of the scenarios and can be presented using scorecards. The results are used to identify the sell-by date for each of the actions. Furthermore, the vulnerabilities and opportunities need to be reassessed. Was the action able to reduce or remove a specified vulnerability? Was the action able to utilise a specified opportunity? Does the action create new opportunities and/or vulnerabilities? Ineffective actions are screened out (Walker, 1988), and only the promising actions are used in the next steps as the basic building blocks for the assembly of Adaptation Pathways.

The fifth step is the assembly of pathways using the information generated in the previous steps. It is conceivable that the reassessment of the vulnerabilities and opportunities in the previous step triggers an iterative process (back to step 3) wherein new or additional actions are identified. Once the set of actions is deemed adequate, pathways can be designed. A pathway consists of a concatenation of actions, where a new action is activated once its predecessor is no longer able to meet the definition of success. Pathways can be assembled in different ways. For example, analysts could explore all possible routes with all available actions. Each of these routes can then be evaluated on its performance. However, some actions may exclude others, and some sequences of actions may be illogical. In addition, fundamental criteria, such as the urgency of actions, the severity of the impacts, the uncertainty involved, and the desire to keep options open, could be used to develop a set of promising pathways. The result is an adaptation map, which summarises all logical potential pathways in which 'success' (as defined in Step 1) is achieved. Note that actions need not be a single action, but can be a portfolio of actions, constructed after iteration of Steps 3 - 5.

The sixth step is to develop a manageable number of preferred pathways. Preferred pathways are pathways that fit well within a specified perspective. It can be useful to specify two to four pathways that reflect different perspectives. This will result not only in the identification of physically robust pathways, but also 'socially robust' pathways (Offermans, 2010). The preferred pathways will form the basic structure of a dynamic adaptive plan (like the basic plan in the Adaptive Policy Making framework).

The seventh step is to improve the robustness of the preferred pathways through contingency planning — in other words, to define actions to get and keep each of the pathways on track for success. In general, these are actions to anticipate and prepare for one or more preferred pathway (e.g. keep options open), and corrective actions to stay on track in case the future turns out differently than expected. We distinguish three types of contingency actions from Adaptive Policy Making: corrective, defensive, and capitalizing actions, which are associated with a monitoring system and trigger values. The monitoring system specifies what to monitor, and the triggers specify when a contingency action should be activated.

The eighth step is to translate the results from all of the previous steps into a dynamic adaptive plan. This plan should answer the following question: Given the set of pathways and the uncertainties about the future, what actions/decisions should we take now (and which actions/decisions can be postponed)? The plan summarises the results from the previous steps, such as targets, problems, and potential and preferred pathways. The challenge is to draft a plan that keeps the preferred pathways open for as long as possible. Thus, the plan specifies actions to be taken immediately, actions to be taken now to keep open future adaptations, and the monitoring system.

Finally, the actions to be taken immediately are implemented and the monitoring system is established. Then, time starts running, signpost information related to the triggers is collected, and actions are started, altered, stopped, or expanded in response to this information. After implementation of the initial actions, activation of other actions is suspended until a trigger event occurs.

5.4 CASE STUDY: RHINE DELTA IN THE NETHERLANDS

We illustrate and test the approach of Dynamic Adaptive Policy Pathways for the Rhine Delta in the Netherlands, and focus on the IJsselmeer area. In 2007, the Government established the Second Delta Commission for identifying actions to prevent future disasters (Delta Committee, 2008; Kabat et al., 2009), since the expected future climate change and sea level rise 'can no longer be ignored' (Delta Committee, 2008, p. 5). The Commission's advice resulted in the enactment of a Delta Act, and is presently being elaborated in a Delta Programme. The chair of the Delta Programme summarised their main challenge as follows: "One of the biggest challenges is dealing with uncertainties in the future climate, but also in population, economy and society. This requires a new way of planning, which we call adaptive delta planning. It seeks to maximise flexibility; keeping options open and avoiding 'lock-in'" (Kuijken, 2010). This corresponds well with our integrated approach, and thus provides an appropriate case to use as an illustration. However, we have made many simplifying assumptions. So, what follows can be used only for illustrative purposes and a first tentative test of our approach. The steps we mention refer to the steps in Figure 26 .

Step 1 and Step 2: Current Situation and Problem Analysis

The Netherlands is a densely populated country, two-thirds of which is vulnerable to being flooded by the sea or large rivers. A sophisticated and comprehensive water management system satisfies the water system requirements for living in a delta. But, for coping with future changes such as global climate change, adaptation may be needed. Having the right amount of water for users, at the right time, in the right place, and at socially acceptable costs is a key target for the Ministry of Transport, Public Works and Water Management (Rijkswaterstaat, 2011). The objective of the Delta Programme is "to protect the Netherlands from flooding and to ensure adequate supplies of freshwater for generations ahead." (Delta Programme, 2010). Accordingly, we define 'success' as follows: 'The plan will be successful if no floods occur, and if there is enough fresh water during the next 100 years. The frequency of water shortage will be at least similar to the present situation (once in 10 years a water shortage may occur).' Constraints would include the various EU Directives that the Dutch Government must follow. For example, the Water Framework Directive implies that ecological and water quality objectives have to be met. These Directives imply that we need to add another target to our definition of success: 'the plan will be successful if it does not result in negative impacts on nature'.

The Water System and its Functions in the Current Situation

There are several key water characteristics that need further explanation for our case (see Figure 27). After the Rhine enters the country, the water is distributed over three branches – the Waal, Nederrijn, and IJssel – by means of a weir at Driel. The IJssel supplies the IJsselmeer and Markermeer lakes with fresh water. The Afsluitdijk dam protects the adjacent areas from flooding and enables water storage in the lakes. The levels of the IJsselmeer and Markermeer are carefully maintained with sluices, to ensure safety in the winter and enough fresh water in the summer. Safety from flooding is expressed in standards of a probability per year that a critical water level will occur — e.g. 1:1250 years (Rijkswaterstaat, 2011). These standards (also called 'norm frequencies') are laid down by law for every dike ring area, and depend largely on the economic activities, the number of inhabitants, and flood characteristics associated with the dike ring. The Haringvliet sluice gates and the Maeslant storm surge barrier protect the Rhine estuary from (mainly coastal) flooding. The Haringvliet sluices also limit salt intrusion into the river.

The IJsselmeer and Markermeer are the main water reservoirs in the Rhine Delta in the Netherlands. During dry periods, water from these lakes is used to supply large parts of the Netherlands. Despite the extensive network of ditches and canals and the large amount of water storage, the water supply is insufficient to fulfill the fresh water demands during dry periods. During such periods, a priority list is used to distribute fresh water for different uses. The major uses of water are for agriculture (for irrigation), for flushing (to mitigate adverse impacts for agriculture and drinking water from the upward seepage of salt water and salt intrusion in the waterways near Rotterdam), and for water management itself (to maintain water levels in the lakes and canals). Drinking water and industry are also important uses, although the quantity used for these is negligible compared to the other uses.

The Water System and its Functions in the Future

Future socio-economic developments, climate change, and sea level rise, may require changes to the water management system. Recently, four water-related scenarios were developed for the Netherlands (Bruggeman et al., 2011; Te Linde et al., submitted). These 'Delta scenarios' cover two representations of future climate (based on Van den Hurk et al., 2007) and two sets of socio-economic developments in the Netherlands. The climate scenarios cover a range from moderate increases in temperature and precipitation (10°C, 3.6% precipitation in the winter, and 2.8% in the summer; used in the scenario 'Crowd') to a large temperature increase (20°C in 2100; used in the scenario 'Warm'), a large precipitation increase in winter (14.2%), and a large precipitation decrease in the summer (19%). The sea level can increase (35–85 cm in 2100). The socio-economic scenarios describe a population change from the current 16 million to 12 million or 24 million in 2100, together with major changes in agricultural land use. These scenarios would result in an increase in water demands from the regional areas to the national water system due to less rain and lower river discharges, more salt intrusion, and/or agricultural changes; and an increase in flood risk due to sea level rise, higher river discharges, and population and economic growth.

Step 3: Determine Actions

For illustrative purposes, we focus on the IJsselmeer area, and consider in our analysis only the main alternative actions, whereas in reality the entire Rhine Delta and all kinds of combinations of actions are possible.

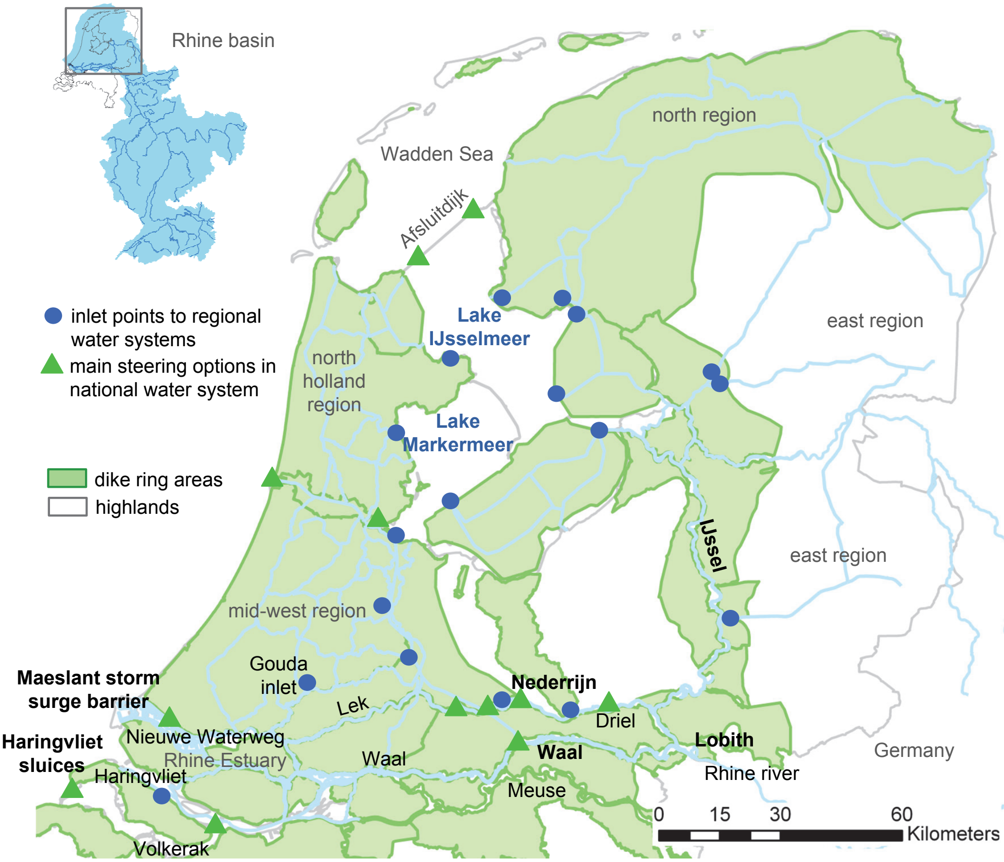


Figure 27: Case study location: Rhine Delta in the Netherlands, with focus on the IJsselmeer area.

As a result of our problem analysis, it is clear that the IJsselmeer area will become even more important as a storage basin for providing fresh water in times of drought. Either the water storage capacity needs to be increased, or the (growth in) water demand needs to be reduced. To increase the water storage, the water level of lake IJsselmeer can be either increased in the spring, and then used during dry periods, or decreased in dry periods. Water demands can be reduced by increasing the efficiency of water use in the regional system, by changing to salt and/or drought tolerant crops, and/or by decreasing agriculture or moving agriculture to areas with appropriate environmental conditions. Some of these actions can be taken without changing the current infrastructure; these can be considered as improvements of the current system. For other actions, the infrastructure would have to be changed considerably. To ensure safety from flooding in case of sea level rise and increased river discharges in the winter, flood management actions would need to be taken as well. Safety for the areas adjacent to the IJsselmeer can be achieved by either raising the water level in correspondence with the sea level, so the excess water can be drained under gravity into the Wadden Sea (of course, dikes need to be raised accordingly as well), or by building large pumps for discharging water into the Wadden Sea. If the first action is chosen, the extra amount of water can be used in times of drought. If the second action is chosen, water inlets and shipping sluices need to be adapted for enabling water use during drought. Table 4 provides an overview of this set of actions.

Step 4: Assess Efficacy, Sell-by Date of Actions, and Reassess Vulnerabilities and Opportunities

Table 4 presents an assessment of the efficacy of each individual action and its sell-by date based upon expert knowledge, previous studies on possible actions, and preliminary modeling results for 2050 and 2100 indicating how much water (in cm IJsselmeer lake level) is needed to supply the amount of water demanded for an average, dry, and extremely dry year for the different scenarios (Klijn et al., 2011). For determining the sell-by date, we assume a linear change of climate and socio-economic developments. For the actions focusing on reducing the water demand, no model results were available. Together with stakeholders (water boards) the impact of these actions was translated into the amount of IJsselmeer water needed. Table 4 shows that the current plan is likely to be sufficient for achieving objectives for approximately 30 years. After this point, changes are likely to be needed. Improvements that can be made to the current system should enable the sell-by date to be extended by approximately 10 years.

The flood management actions and the actions for fresh water supply influence each other. A higher water level for increasing storage

Table 4: Actions and assessment of their relative performance in terms of impacts on safety, fresh water capacity, side impacts on nature areas and shipping in the IJsselmeer and IJssel region, and sell-by date of actions based on preliminary expert knowledge and modeling results.

*Legend: - - large negative impact, - negative impact, o no or minor impact, + positive impact, + + moderate positive impact, + + + large positive impact.

** These impacts are considered as positive as this facilitates the preferred drainage of excess water from the IJsselmeer to the Wadden Sea under gravity.

Action	Impact				Sell–by–date (years)	Costs
	Safety	Fresh water	Nature	Shipping		
Flood management actions						
Increase target water level and the dikes correspondingly for enabling discharging under gravity to sea.	+++	++	- -	- -	> 2100	+++
Keep the same target water level by increasing pump capacity largely.	+++	0	0	0	2100	++
Fresh water supply actions						
Increase water level to +1.1 m in spring, and adapt regional water system infrastructure. More water to the IJssel River in spring.	+++ **	++	- -	- -	>2100	++
Increase water level to +0.6 m in spring, and adapt regional water system infrastructure. More water to the IJssel River in spring.	++ **	+	- -	-	2070-2090	+
Increase water level to +0.1 m, using current infrastructure	+ **	+	-/+	0	2050-2060	0
Decrease water level to -0.8 m in dry periods, and adapt infrastructure.	0	+++	+	-	2100	++
Decrease water level to -0.6 m in dry periods, and use current infrastructure. Accept navigation obstructions during extreme droughts	0	++	+	- -	2060-2070	+
Adapt water distribution Rhine branches: more water to IJssel River during droughts	0	+	0	+	2040	0
Improving current plan with flexible water levels	0	+	0	0	2030-2040	0
Reduce water demand to the national water network, by improving the management of the regional network	0	+	0	0	2050-2070	+
Reduce water demand and damage by changing to salt and/or drought tolerant crops	0	+++	0	0	> 2100	++
Reduce water demand by change land use to nature and/or urban areas	0	+++	++	0	> 2100	+

capacity will, at the same time, allow the system to discharge under gravity (depending on the sea level). If policy makers were to decide to ensure safety against flooding by increasing the pump capacity and keeping the same target water level, fresh water supply actions with an increase of the water level would be screened out. There is also a relation between the actions in the IJsselmeer area and other regions in the Rhine Delta. For example, as part of the actions to ensure safety along the Waal and Nederrijn, more Rhine water could be distributed to the IJssel. In this case, enough capacity should be available in the IJsselmeer, implying that the water level can be raised at earliest in the beginning of spring. In some years, there will not be enough water to do this. Starting earlier with raising the water level would be possible only if the dikes were raised sufficiently. If more water is transported to the IJssel, there will be less water for the river branches to the western part of the country (Waal and Nederrijn), and thus less water for holding back the salt intrusion from the sea, making the water inlet at Gouda less reliable. In that case, the Midwest area might be supplied by IJsselmeer water. If, however, policy makers were to decide to close the Rhine estuary, this would not be necessary.

With the impacts of the actions in mind, the vulnerabilities and opportunities need to be reassessed. For example, if the IJsselmeer level is raised, achieving the EU Directives (Water Framework Directive, Habitat Directive, Birds Directive) may be endangered, due to the disappearance of shallow waters that provide an important habitat for species.

Step 5: Develop Pathways

Figure 28 shows the Adaptation Pathway map for the 10 actions for fresh water supply from Table 4. For flood management, two actions are available. They are not presented in the Adaptation Pathways map, but they influence the preferences for certain pathways, as explained above.

To construct the pathways, the actions are grouped into actions influencing water demand and actions influencing water supply. Actions with long sell-by dates are shown on the top or bottom of the map, while actions with short sell-by dates are shown close to the current plan. The next step is to add the sell-by dates and all the possible transfers to other actions that would extend the sell-by date. Sometimes actions affect each other. If the sell-by date for an action will increase considerably, this is shown by an additional line in the same color. Next, illogical actions are eliminated (background color in contrast to bright colored logical actions). For example, implementing one of the large actions first is illogical, as this may not be necessary to achieve success, and it can be implemented later as well. It is also less logical, once policy makers have chosen to significantly adjust the water level,

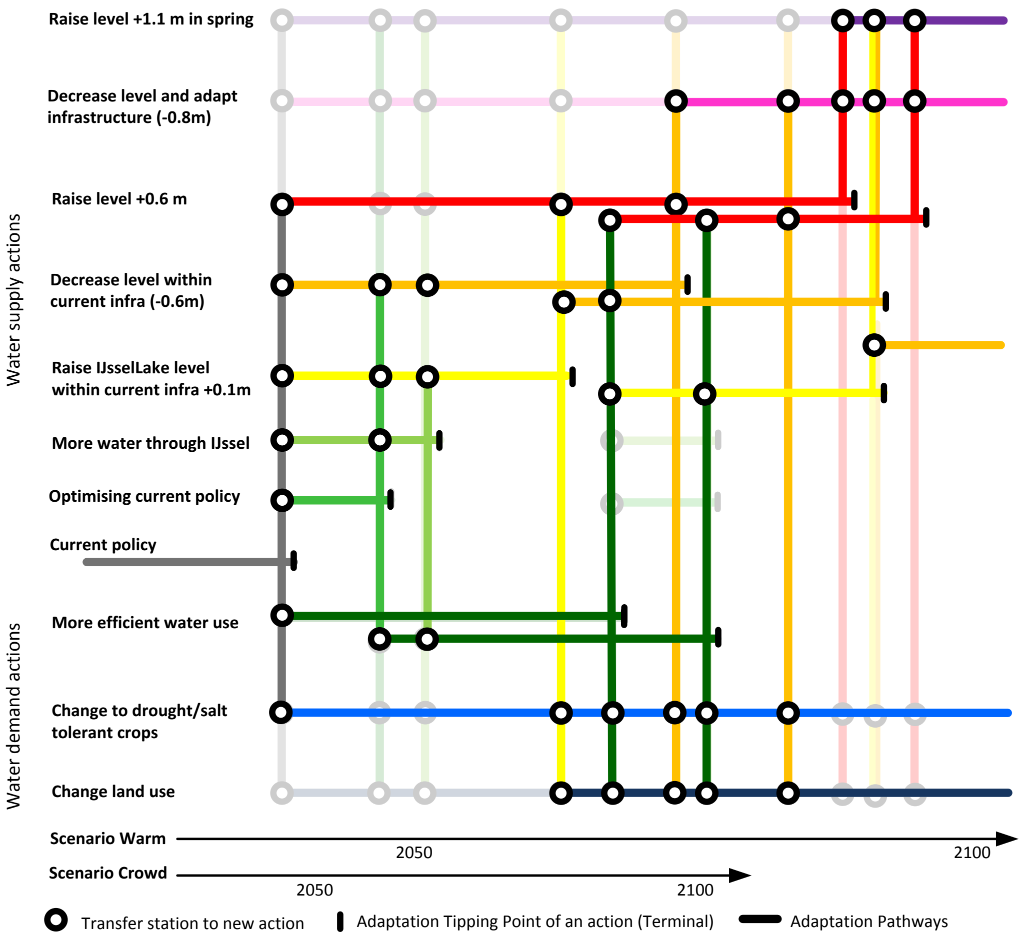


Figure 28: Adaptation pathways map for fresh water supply from the IJsselmeer area.

to switch to changing the crop type or land use. The sell-by date of an action depends on the scenario and the objectives. This is shown with the two x-axes, one for each scenario.

Step 6: Select Preferred Pathways

From the Adaptation Pathways map, preferred pathways can be selected. Different decision makers and stakeholders can have different preferred pathways, depending on their values and beliefs. Figure 29 presents an example of the preferred pathways for archetypes of three perspectives: Hierarchist, Egalitarian, and Individualist (see e.g. Hoekstra, 1998; Middelkoop et al., 2004 on these perspectives related to water). For example, Hierarchist believes in controlling water and nature, assigning major responsibilities to the government. This means a preference for actions related to managing water levels and water use. The Egalitarian focuses on the environment and equity, resulting in strategies for decreasing water demands by adapting functions to their environment (other crops or their relocation). The Individualist adheres to a liberal market and a high trust in technology and innovation. This means a preference for facilitating technological developments for more efficient with water use and drought tolerant crop types. Portions of the preferred pathways are similar. The point at which the paths start to diverge can be considered as a decision point. In our case, there are three decision points: (1) after 'current plan', (2) after 'raise the IJsselmeer level within current infrastructure', and (3) after 'more efficient water use'. The preferred pathways could be a start of a discussion on an adaptive plan. In addition, combinations of these pathways could be drawn as paths that have support from more than one perspective. For example, starting with 'more efficient water use in the regional areas' could be followed by a small raising of the IJsselmeer water level (+0.1 m), and, if needed, that water level can be raised more, or the water demand could be reduced by changing crop types. The short-term action is one that all perspectives could agree upon, and can thus be considered a socially robust action (Offermans, 2010).

Step 7: Determine Contingency Actions, Signposts, and Triggers

To get or stay on the track of a pathway, contingency actions can be specified. For example, the Government could stimulate the growth of salt and/or drought tolerant crops with subsidies, or by limiting water availability and holding farmers responsible for finding 'enough' water. Keeping the option open for an increase of the IJsselmeer level will require spatial planning rules (e.g. allow adaptive building only outside the dike rings). If structures need to be replaced, they can be built

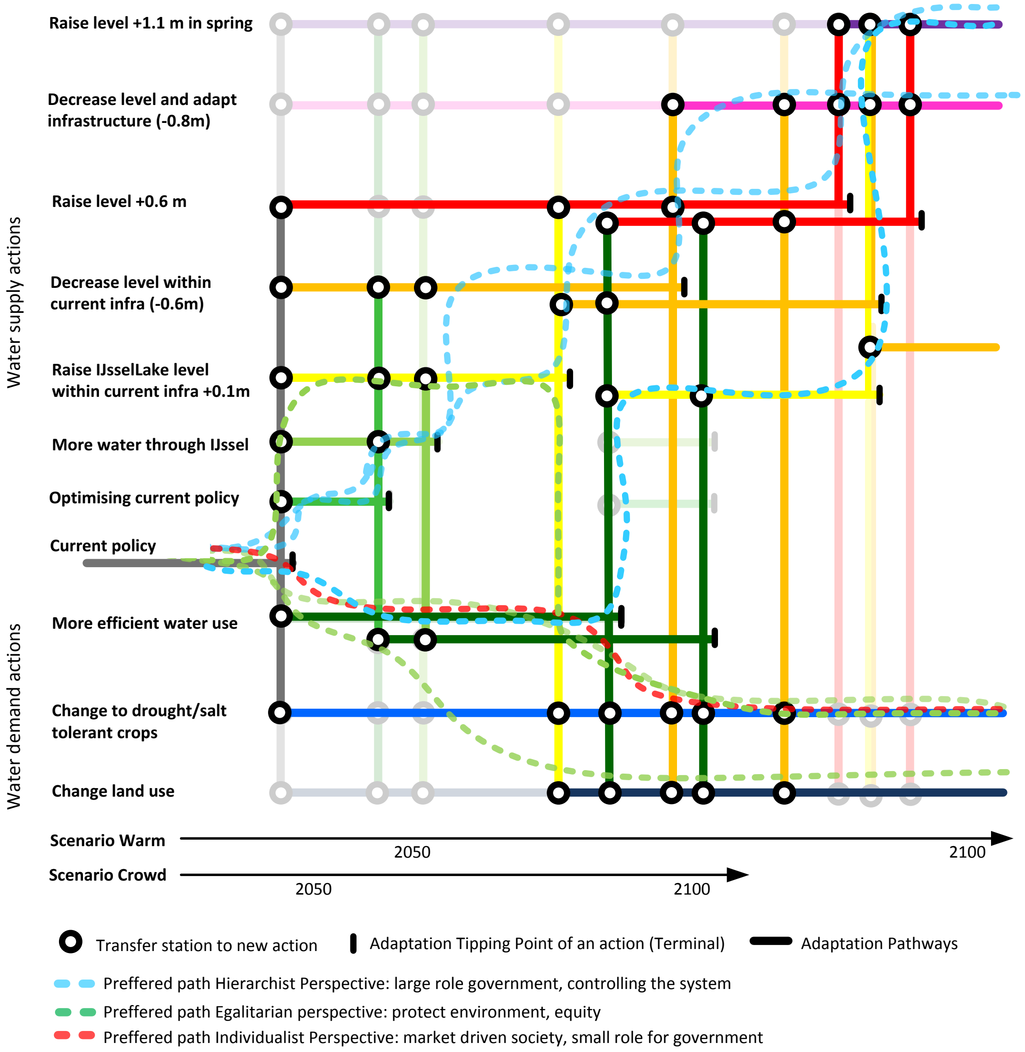


Figure 29: Adaptation pathways map with preferred pathways for three different perspectives.

such that they are already able to cope with future actions. Corrective actions need to be taken to achieve objectives for nature. Constructing shallow zones and islands can mitigate the negative impacts of raising the water level. This can bring opportunities for dredging companies.

We distinguish three different groups of signposts and triggers: (1) trends and events in the natural environment (the water system); (2) human-driven impacts on the water system, such as the autonomous adaptation of farmers or a change in upstream water use; and (3) societal perspectives about the future, such as expectations about climate change and population growth, knowledge about (or belief in) the effectiveness of certain policies, and societal values, such as the wish to protect nature and the amount of accepted flood/drought risk. The amount of agricultural area and the crops used could be an appropriate trigger for changes in water demand, since they can be well monitored and change slowly over time.

Step 8: Specify a Dynamic Adaptive Plan

Based on the problem, objectives, and pathways from the previous steps, a dynamic adaptive plan can be specified. Considering the scenarios, the amount of water storage needed in the future requires up to a 1.5m water level in the IJsselmeer. Raising the water level is the preferred action from a safety point of view, because in that case water can be discharged to the Wadden Sea under gravity. However, in the short- and mid-term (2080) this action is not needed. To keep this option open, spatial planning rules could be implemented. Initial actions can focus on improving the performance of the current plan by introducing a flexible water level (e.g. outside the growing season, the water level may drop) and making more efficient use of water in the regional areas (e.g. have a separate area for brackish and salty groundwater, in order to decrease the amount of water needed for flushing). To keep other options open, the Government could invest in research and development of drought and/or salt tolerant crops. The plan for future actions needs to be ready, in case a window of opportunity arises for adapting the water system to potential future conditions. An example of such an opportunity is when infrastructure (sluices, dams, etc.) requires maintenance. At the same time as maintenance is being carried out, new structures could be added that would be able to cope with an increase or decrease of the water level in the IJsselmeer. Huq and Reid (2004) assign the label 'mainstreaming' to actions that incorporate "potential climate change impacts into ongoing strategies and plans". Another window for opportunity arises in the case of a dry year. In such a year, societal support for implementing such actions is likely to be higher.

Steps 9 and 10: Implementation of Dynamic Adaptive Plan and Monitoring

The first actions of the plan are implemented, and the Government continues monitoring sea level rise and climate changes. Furthermore, the Government monitors changes in water demands through land use changes and determines additional signposts together with water boards (water managers of the regional system) and representatives of the agricultural sector.

5.5 EVALUATION OF THE METHOD

In this chapter, we have presented an approach for supporting decision making under uncertain global and regional changes, called Dynamic Adaptive Policy Pathways. This approach assists in designing dynamic adaptive plans, and is built upon the best features of two existing adaptation methods. From the concept of Adaptive Policy Making we used the ideas of (1) thinking beforehand of ways a plan might fail and designing actions to guard against such failures, (2) preparing for actions that might be triggered later, in order to keep a plan on track to meeting its objectives, and (3) implementing a monitoring system to identify when such actions should be triggered. From Adaptation Pathways, we used the idea of an Adaptation Pathways map, which visualises sequences of possible actions through time, and includes uncertainties concerning societal values through perspectives. The map is enriched with triggers from Adaptive Policy Making, which indicate when each new action should come into force.

We illustrated the integrated approach by applying it to a case inspired by a real strategy development project to prepare the Dutch water system for future climate change taking into account socio-economic developments. By applying our approach to a real world case, we have learned about the strengths and weaknesses of the approach, which we elaborate in this section.

A strength of the method is that it stimulates planners to include adaptation over time in their plans – to explicitly think about actions that may need to be taken now to keep options open, and decisions that can be postponed. Thus, the inevitable changes become part of a larger, recognised process and are not forced to be made repeatedly on an ad hoc basis. Planners, through monitoring and corrective actions, would try to keep the system headed toward the original goals.

The concept of Dynamic Adaptive Policy Pathways may be difficult to understand. But, the ten clearly defined steps described in Sec. 5.3 provide a set of clear tasks that, if followed, result in a dynamic adaptive plan. We have discussed the method with water and spatial planning policy advisors and policy makers in the Netherlands at both the national and regional/local level. On the one hand, the approach is comprehensive and more complex than a traditional scenario-strategy impact analysis for one or two points in the future. On the other hand, planners have experienced that plans change over time, and an adaptive strategy is an attractive idea for planners facing deep uncertainty. Moreover, if political conditions are unsuitable, the approach helps to determine for how long a decision can be postponed. Thus, despite the complexity, both policy advisors and policy makers have shown an interest in the method (see e.g. EEA, 2013). The adaptation pathways presented in the 'metro map' and the triggers and signposts are considered particularly valuable, as these components of the method are the main new characteristics compared to classical policy planning approaches. For a discussion with high level decision makers a simplified pathways map, based on preferred pathways, could be used in combination with a more comprehensive map as background information. The case presented here has served as an inspiration for the Dutch Delta Programme, and is included in their implementation guide for 'adaptive delta management' (Van Rhee, 2012). Currently, adaptation pathways are being developed for fresh water supply and flood risk management. New model results show that with the pathways presented here, an acceptable water shortage may occur once in 100 years, and that for a target of once in 10 years the sell-by dates are further away (e.g. current plan may be sufficient for achieving objectives for approximately 50 years if the target is sufficient water for once in 10 years).

The moment of an adaptation tipping point (the sell-by date) helps in identifying possible paths. However, most actions cannot be implemented immediately at their sell-by date. For those, we need to include a lead time. The thinking behind triggers helps in identifying required lead times. However, climate change may be difficult to detect, especially changes in extremes, due to large natural variability compared to the magnitude of change (Diermanse et al., 2010; Hallegatte, 2009; Pielke, 2012, see, e.g.). For example, water managers would like to know if climate change is happening because of the potential increase of floods and droughts. However, measuring (for example) peak discharges as a sign that climate change is happening is very difficult, because of high natural variability and the short time period of measurements (Diermanse et al., 2010). Still, land use, population changes, and sea level rise are gradual developments that are easier to detect.

With respect to decision making, Adaptation Pathways provide insights into options, lock-ins, and path dependencies. Thus, an Adaptation Pathways map provides a valuable starting point for decision making on short-term actions, while keeping options open and avoiding lock-ins. All pathways satisfy a minimum performance level regarding the main targets. Still, some pathways are more attractive than others due to costs or negative/positive side effects. This can be used to select a set of preferred pathways. Potential future decisive moments can be identified based on the lead time of actions and the points where preferred pathways start to differ.

To determine the success of actions and pathways, quantitative targets are needed. However, in reality, policy makers sometimes choose to keep these targets vague, making it difficult to determine the efficacy of an action and pathway. Exploring different quantifications of the targets can show the effects of the different targets, which may support a discussion about appropriate targets. A worthwhile elaboration on the approach presented here would be the evaluation of pathways with e.g. a cost-benefit analysis or a multi-criteria analysis.

The visualisation of the pathways is seen as attractive by policy makers. This way of visualizing works best if the objectives can be summarised in a single main objective, such as 'fresh water supply for different sectors' or 'safety against flooding'. In our case, we considered two main objectives that influenced each other. Because the flood management actions did not vary a lot, the relation between the two sets of actions could be easily described. In the Dutch Delta Programme the situation is more complex due to planning for different areas that have different pathways that influence each other.

The use of perspectives is an element that has previously received little attention in the planning literature. We used different perspectives (or visions) of the different stakeholders to identify alternative preferred pathways and socially robust actions (Offermans et al., 2008; Offermans, 2010). Different stakeholders may support different plans, but they can also have different reasons to support the same plan. For example, allocating 'room for a river' may be preferred by some because it enhances nature and lowers water levels in the case of peak discharges, while others may prefer this action solely because it lowers the flood risk. Development of pathways using stakeholder participation (decision makers and stakeholders) has been explored in a game setting (Valkering et al., 2012). In this way, uncertainties arising from decision making, and preferences among plans arising from different perspectives, can be further explored.

The analytical basis of the approach (e.g. for determining sell-by dates and developing pathways) can be supported with computational scenario-based approaches. Making the necessary runs in a reasonable amount of time requires a policy model that is fast and simple, but accurate enough to simulate the relevant transient scenarios and assess the relative effects from a wide variety of actions for the full set of performance indicators over time. Currently, there is no such model of the Rhine Delta in the Netherlands. Therefore, we assessed the effectiveness and sell-by dates of the possible actions using expert judgment and model results from previous studies. We were able to assess the relative impacts qualitatively. McDaniels et al., 2012 used expert judgment to explore robust alternatives. But, for a better determination of the sell-by dates, a computational exploration is crucial. There is a need for fast simple models that are suitable for exploring actions over time in order to develop adaptation pathways. More complex models can then be used to obtain more detailed information about the performance of the most promising actions resulting from the initial exploration.

Further work is also needed on computational techniques that can help in identifying opportunities and vulnerabilities and developing promising pathways. In a real case, the combination of actions and consequently the number pathways can be huge. To support the identification of the most promising sequences of actions, we are working on an improved computer-assisted approach for designing an adaptive policy to evaluate candidate pathways over an ensemble of possible futures and assess their robustness (Kwakkel and Haasnoot, 2012). Lempert and Groves, 2010; Lempert et al., 2006 present a computer assisted approach to develop robust strategies across a variety of deep uncertainties, grounded in Exploratory Modeling and Analysis (Agusdinata, 2008; Bankes, 1993; Bankes et al., 2013). We are developing a 'workbench' to support such computational scenario-based techniques. Early experiences with the workbench indicate that using a fast and simple model, exploring uncertainties in addition to climate change, and accounting for the joint impact of all the uncertainties, in support of the development of adaptation pathways is useful and feasible (Kwakkel and Haasnoot, 2012).

5.6 CONCLUSIONS

In light of the deep uncertainties decision makers are facing nowadays, a new planning approach is needed that results in plans that perform satisfactorily under a wide variety of futures and can be adapted over time to (unforeseen) future conditions. Various techniques are available (e.g. Robust Decision Making, Real Options Analysis, decision trees, roadmaps, and several policy planning approaches) that have been or are being applied for supporting planning under deep uncertainty (e.g. in the Thames Estuary in the UK, the Rhine-Meuse delta in the Netherlands, and New York City and the Port of Los Angeles in the USA). We have used two complementary approaches for planning under deep uncertainty — Adaptive Policy Making and Adaptation Pathways — to develop an integrated approach based on the strong features of each of them. This approach, called Dynamic Adaptive Policy Pathways, results in an adaptive plan that is able to deal with changing (unforeseen) conditions.

Key principles of the Dynamic Adaptive Policy Pathways approach are: the use of transient scenarios representing a variety of relevant uncertainties and their development over time; anticipating and corrective actions to handle vulnerabilities and opportunities; several Adaptation Pathways describing sequences of promising actions; and a monitoring system with related actions to keep the plan on the track of a preferred pathway. The approach supports the exploration of a wide variety of relevant uncertainties in a dynamic way, connects short-term targets and long-term goals, and identifies short-term actions while keeping options open for the future. There is evidence that such policies are efficacious (Kwakkel et al., 2012) and cost-beneficial (Yzer et al., under review). In the end, all this has to fit into a political process, which has always been a real source of 'deep uncertainty'. Political circumstances can give a window of opportunity (or not) to implement the designed adaptive plan. Also, the adaptive plan could be used to create the right political circumstances, for example by showing potential lock-ins, potential adverse impacts, and for how long a decision can be postponed. The Perspectives method could be used to frame the plan for different societal perspectives (as illustrated by Offermans et al., 2008).

In this chapter, we have illustrated and tested the approach using a virtual world inspired by a real world decision problem currently faced by the Dutch National Government in the Delta Programme. We were able to apply the method, and this result was received with great interest by policy makers of the Dutch Delta Programme. The results suggest that it is worthwhile to further use and test the approach for a real quantitative case study, other policy domains, and other countries.

6

FIT FOR PURPOSE: A FAST, INTEGRATED MODEL FOR EXPLORING PATHWAYS

ABSTRACT

There is a need for a new generation of water policy models that are appropriate for supporting decision making under uncertain changing conditions. An emerging novel decision support approach is the exploration of adaptation pathways which provide insight into policy options and path dependencies. To build adaptation pathways, the dynamic interaction between water system, society and policy response needs to be analysed over time for a set of plausible futures. Such an analysis can become quite complex and requires substantial computing time. A fast, integrated model can facilitate this analysis. Here, we describe the requirements, development, and evaluation of such a model for exploring adaptation pathways in the Rhine delta in the Netherlands in the context of a real-world decision problem currently faced by the Dutch National Government. We used a set of integrated metamodels to describe the whole cause-effect chain and refer to this as an Integrated Assessment MetaModel (IAMM). The results of our case show that a fast, integrated model was found to be fit for the purpose of screening and ranking of policy options over time in order to build adaptation pathways and support strategic decision making under uncertainty. A complex model can subsequently be used to obtain more detailed information about the performance of the most promising options and most troublesome scenarios or periods of interests arising from the exploration with the fast, integrated model.

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6.1 INTRODUCTION

Decision makers sometimes face deep (severe) uncertainties (Lempert et al., 2003; Hallegatte et al., 2012). Deep uncertainties arise not only from external factors, such as climate change, population growth, and economic developments, but also from the interactions between society and the environment. Over the course of time society learns and adapts to changes and events, making policy responses an essential component the total uncertainty about the future. Despite these deep uncertainties, decisions need to be taken, as implementation of actions takes time and being too late may result in adverse impacts or the inability to implement desired policy options.

To address deep uncertainties literature often suggested to use adaptive policies that can be changed over time (Chapter 3, and e.g. Walker et al. 2001; Albrechts 2004; Schwartz and Trigeorgis 2004; Hallegatte 2009; Ranger et al. 2010). In practice, such plans are being developed for the water management of New York City (Yohe and Leichenko, 2010; Rosenzweig et al., 2011), and the Rhine Delta (Delta Programme, 2010; Jeuken and Reeder, 2011; Roosjen et al., 2012; Delta Programme, 2012a), and have been developed for the Thames Estuary (Lowe et al., 2009; Wilby and Keenan, 2012; Reeder and Ranger, online). For examples in other policy domains see Swanson and Bhadwal (2009b) and Walker et al. (2010).

Exploring adaptation pathways (Chapters 3 and 4) constitutes a novel approach to develop a dynamic adaptive policy. When exploring adaptation pathways, a multitude of plausible futures and policy actions needs to be explored over time in order to assess what actions can be taken to achieve targets, despite how the future unfolds. Often, a computational model is used to support such an exploratory scenario analysis (Morgan and Dowlatabadi, 1996; Rotmans and De Vries, 1997; Lempert and Schlesinger, 2000). Two main requirements of such a model can be identified.

Firstly, to assess impacts of environmental changes and policy actions on relevant outcome indicators for the decision making in complex systems such as river deltas, an integrative assessment is needed (Jakeman and Letcher, 2003; Laniak et al., 2013; EEA, 2013). An integrated model enables impact assessment of the whole system including relevant feedbacks. Welsh et al. (2012) call this a 'new generation model'. They argue that 'with the increasing complexity of water management sectoral applications, such as separate groundwater and surface water models, are becoming outdated and that water managers are increasingly looking for new generation tools that allow integration across domains to assist their decision making processes for short-term operations and long-term planning; not only to meet current needs, but those of the future as well'. Integrated Assessment Models (IAMs) have been successfully applied on a global scale to analyse climate change and the effects of emission mitigation strategies (e.g. Rotmans and Van Asselt, 1996; Van der Sluijs, 2002; Jakeman and Letcher, 2003; Schneider and Lane, 2005; Van Vuuren et al., 2009; Laniak et al., 2013). We apply the concept of IAMs for adaptation analysis on a regional to local scale.

Secondly, simulating a wide envelope of plausible futures, policy actions and their combinations over time can be time-consuming and computationally expensive. A fast model is, therefore, a prerequisite to limit the computation time and still be able to execute many simulations. Such a model is also useful for assessing the sensitivity of model outcomes to alternative equations describing components of the model. To build a fast model the technique of meta-modelling can be used. Metamodels are models of models intended to mimic the behaviour of complex models, called the base model (see e.g. Davis and Bigelow 2003; Walker and Van Daalen 2013). Such models are also known as 'low resolution models', 'repro models' or 'fast and simple models'. Metamodels have been built i.e. for simulating rainfall-runoff (Jakeman and Hornberger, 1993), analysing airport policies (Van Grol et al., 2006; Kwakkel et al., 2010b), assessing flood risks (Ward et al., 2011; Kramer et al., 2012) and screening of flood management actions (Van der Most et al., 2002; Schijndel, 2005).

This chapter focuses on how an appropriate model for exploring adaptation pathways in water management can be built and evaluated. An appropriate model represents the dominant processes and natural variability, and the relevant policy actions and outcome indicators for decision making, but without unnecessary detail (Booij, 2003). The questions then arising are: how far one can go in simplifying the model? How complex does a model need to be? What would an appropriate model for exploring adaptation pathways look like?

The process of building a model for exploring adaptation pathways is similar to building any other model (e.g. Jakeman et al., 2006; Gupta et al., 2012; Walker and Van Daalen, 2013; Bennett et al., 2013):

1. Define the model purpose and context,
2. Conceptualise the system,
3. Implement the model,
4. Evaluate the model.

We illustrate the development of the model by means of a case for the Rhine delta in the Netherlands. At the time of writing, the Dutch National Government is working on a large study, called the Delta Programme, which aims to prepare the Netherlands for climate change and sea level rise with a dynamic adaptive plan that guarantees efficient flood protections and fresh water supply now and in the future.

This chapter follows the four main steps of model building:

1. Based on the objectives of the Delta Programme, we defined the purpose of the model in terms of the scenarios, policy actions, outcome indicators, and relevant processes that should be simulated with the model and describe its role developing adaptation pathways (Section 6.2).
2. The main characteristics of water management in the Rhine delta are described in a conceptual structure of the model (Section 6.3).
3. The model structure and parameters are described. To make the model fast and integrated, the model consists of metamodels describing the whole cause-effect chain, and is referred to as an Integrated Assessment MetaModel (IAMM) (Section 6.4).
4. To evaluate whether the performance of the IAMM is acceptable, we used the idea of using closed questions as presented by Guillaume and Jakeman (2012). The main question is: *Given the simplifications associated with the model, does the model produce credible outcomes with sufficient accuracy for the screening and ranking of promising actions and pathways in order to support the strategic adaptive planning decisions in the Rhine delta?* As large integrated policy models used to assess impacts of (future) actions can not be evaluated against historical data only (Jakeman et al., 2006; Walker and Van Daalen, 2013), we defined – in cooperation with potential end-users – appropriate performance metrics for a set of subquestions the model should be able to answer (Section 6.5).

We end this chapter with a discussion on the approach and the results (Section 6.6).

6.2 MODEL PURPOSE AND CONTEXT

The purpose of the model is to support the strategic decision making of the Delta Programme by acting as a laboratory environment, to evaluate whether the main alternative policy options or sequence of these policy options (adaptation pathways) could achieve objectives.

6.2.1 *The Delta Programme*

The main task of the Delta Programme is 'to protect the Netherlands from flooding and to ensure adequate supplies of freshwater for generations ahead.' (Delta Programme, 2010). Therefore, impacts of climate change, sea level rise, socio-economic developments and policy actions are assessed. Climate change and socio-economic developments may result in a) an increase in flood risk due to sea level rise, higher river discharges, and population and economic growth; b) lower water availability in the summer due to less rain, intensified evapotranspiration and lower river discharges, and more salt intrusion in the rivers; and c) an increase in water demands from the regional areas to the national water system due to less rain, more salt intrusion, and/or changes in the agricultural sector.

In the Delta Programme, five main strategic topics for decisions have been identified:

1. *Flood protection standards*: given the increase of economic value of flood protected areas, what are proper safety levels, and how should these be expressed and implemented in a policy.
2. *Flood risk management in the Rhine–Meuse Estuary*: what measures need to be taken to guarantee compliance with protection standards? How is the Rhine discharge distributed over the river branches and should estuaries be protected from coastal flooding by flood barriers or not?
3. *Fresh water availability*: How can future water demands be met in a sustainable and economically effective manner?
4. *Water level in the IJsselmeer area*: Should water levels be raised to make use of energy efficient gravitational drainage, or should current water levels be maintained and pumping capacity increased accordingly?
5. *Adaptation through spatial planning*: what spatial planning measures can contribute to reduction of flood risk, and how can non-structural measures reduce flood risk in existing flood prone areas?

The focus of this study is on flood and drought risk management in the main rivers, IJsselmeer lakes and rural areas (topics 1, 3, 4 and 5). The model should allow to evaluate the impacts of relevant pressures (climate scenarios and socio-economic developments) and policy options that are being considered in the Delta Programme. In addition, to explore adaptation pathways, the model should be fast enough to dynamically simulate long time-series (e.g. 100-year scenarios) and a large number of policy options in a limited period of time. The outcomes from the model should include the relevant indicators for the decision making in the Delta Programme.

6.2.2 *Adaptation Pathways*

The concept of Adaptation Pathways is summarised in Figure 30 (Chapters 3 and 4). Central to this concept are adaptation tipping points (Kwadijk et al., 2010), which are the conditions under which an action no longer meets the clearly specified objectives. The timing of the adaptation tipping point for a given action, its sell-by date, is scenario dependent. After reaching a tipping point, additional actions are needed to reach the defined objectives. As a result, a pathway emerges. Multiple pathways are developed using expert judgement and a computational model. In a scenario run, for each time-step the impacts of drivers on the water system are estimated, and policy actions are implemented if necessary. For example, a climate realisation results in a sequence of river discharges and associated impacts; policies may then be implemented accordingly. Different pathways into the future arise from different climate scenarios, different realisations of the same climate scenario, different external socio-economic events or trends, and different policy responses.

An Adaptation Pathways map, manually drawn based on model results or expert judgment, presents an overview of relevant pathways. The map presents a sequence of possible actions after a tipping point in the form of adaptation trees (e.g. like a decision tree or a roadmap; see Figure 30 for an example). Given the adaptation map and signposts, decision makers can make an informed decision on a dynamic adaptive policy plan in a changing environment that is able to achieve their intended objectives despite the myriad of uncertainties.

6.3 CONCEPTUALISATION OF THE SYSTEM

The water system of the Rhine delta in the Netherlands is presented in Figure 27. It has several key characteristics that should be incorporated in the model as shown in the model diagram (Figure 31).

The water distribution over the Rhine delta is as follows: After the Rhine enters the Netherlands, the water is distributed over the branches Waal, Nederrijn, and IJssel by means of a weir at Driel. In general, 2/3 of the inflow goes to the Waal, and 1/3 to the Nederrijn and IJssel. The IJssel supplies the IJsselmeer and Markermeer lake with fresh water. From the rivers, canals and lakes, water is distributed to other parts of the country through an extensive network of ditches and canals.

To protect the country against flooding, flood prone areas are surrounded by a set of dikes (a dike ring area). The Haringvliet sluice gates and the Maeslant storm surge barrier protect the Rhine estuary from coastal flooding. During periods of peak flow in the Rhine, the Haringvliet sluices will open completely. The flow in the Nieuwe Waterweg is maintained to its specified maximum flow (1500 m^3/s) for minimal disturbance of shipping. The Afsluitdijk dam protects the adjacent areas of the IJsselmeer and Markermeer from coastal flooding. In the winter half year, the lake levels are carefully maintained with sluices at the dam at -0.4 m MSL to store high river discharges, if necessary.

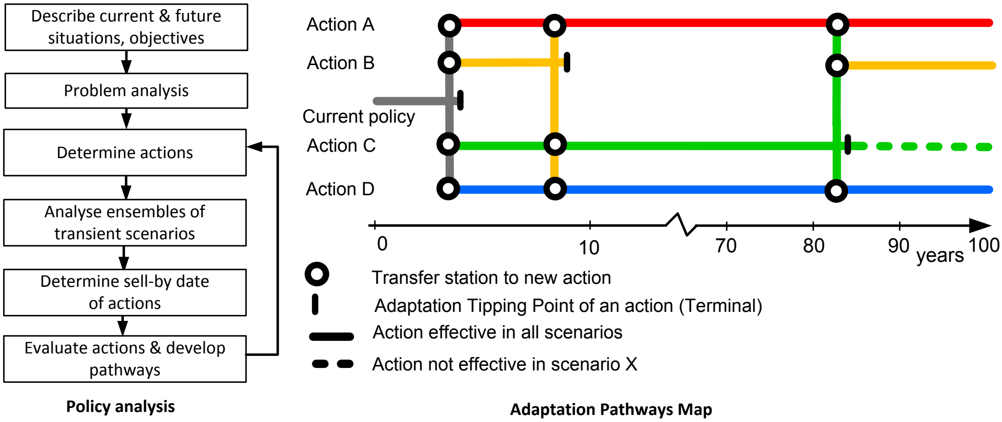


Figure 30: Stepwise policy analysis to construct Adaptation Pathways (left) and an example of an Adaptation Pathways map (right). In the map, starting from the current situation, targets begin to be missed after four years: an adaptation tipping point is reached. Following the grey lines of the current policy, one can see that there are four options. Actions A and D should be able to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, a tipping point is reached within about five years; a shift to one of the other three actions will then be needed to achieve the targets (follow the orange lines to a transfer station). If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed in the case of Scenario X (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years (the dashed green line).

Salt intrusion is also an important pressure in the delta. At low Rhine discharges the flow in the Nieuwe Waterweg is set as high as possible to limit salt intrusion by setting the flow through the Haringvliet barrier gates at its minimum (10 m^3/s), required to flush Haringvliet. In addition, water is used for flushing brackish water out of the rural areas.

There are multiple water demands in the delta. The major demands are for agriculture (for irrigation), for flushing (to mitigate adverse impacts for agriculture and drinking water due to salty upward seepage water and salt intrusion in the river), and for maintaining water levels in the rivers, lakes and canals (for navigation and mitigating infrastructural impacts). Drinking water and industry are also important water consumers, although the quantity used for these uses is negligible compared to the other uses.

To enable navigation through the rivers during low Rhine discharges, a minimum amount of water (25 m^3/s) is supplied to the Nederrijn, and the flow in the Nieuwe Waterweg is set as high as possible.

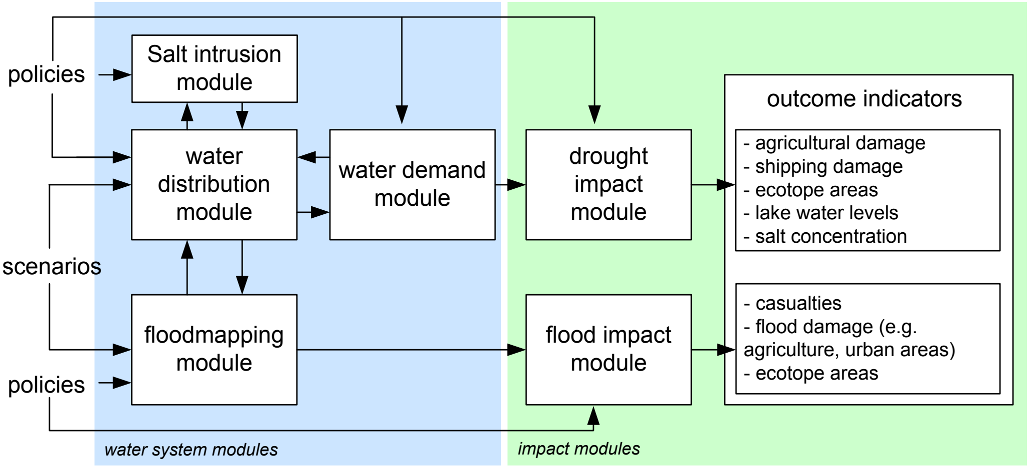


Figure 31: Model diagram

The IJsselmeer and Markermeer are the main fresh water reservoirs to mitigate impacts of droughts in the rural areas. In the summer half year, water levels are maintained higher than in winter (-0.2 m MSL) to be able to provide enough fresh water. During dry periods, water from these lakes is used to supply large parts of the delta. Still, during dry periods water supply can be insufficient. For the mid-western region the inlet of river water near Gouda is an important source. Occasionally, the Gouda inlet can not be used due to a high salt concentration (current norm is 200 mg Cl/l) as a result of the water intrusion in the Nieuwe Waterweg.

The scenarios describe the relevant changes in pressures on the delta, and include climate change, sea level rise, land use and economic changes. The policies refer to flood and drought risk actions. Flood risk policy actions, include: dike raising, strengthening dikes, room for the river, increasing drainage capacity at the Afsluitdijk, adapting target levels IJsselmeer, adaptive building in floodplains, and land use changes. Drought risk actions include: raising target levels IJsselmeer, allowing IJsselmeer water level to drop below threshold levels, land use changes, changing water distribution among the main Rhine branches, reducing water demand from rural areas, increasing flow capacities, increasing sprinkling for agriculture, and changing norm thresholds for salt concentration at the Gouda intake.

Impacts on nature, in terms of ecotope areas have not been included, because this study focuses in this study on flood and drought risk management. For the same reason, water quality is not considered, except for salt intrusion in the Rhine Estuary.

6.4 MODEL DESCRIPTION

The spatial scheme of the models includes the main river branches, canals, and the large lakes represented by links and nodes, and a spatially distributed representation of the rural areas. The temporal resolution is 8 to 11 days period (2 periods of 10 days and the remainder of the month). Within a 10-day period, we can assume that water is distributed over the Netherlands, thus for this timescale we can use a 'bucket model'-approach. Also, periods of droughts manifest themselves at 10-days to monthly timescale. Although flooding events occur at a smaller time scale, flood impacts are considered in a simplified manner by considering the maximum discharge per 10-day period and discarding the form and duration of the high water wave that occur at a timescale of hours/days. This is sufficient for strategic decision making related to the Delta Programme. The input of the model consists of transient scenarios on river discharges flowing into the system, precipitation and evaporation, and water levels at the Wadden Sea side of the Afsluitdijk. The output indicators reflect the information needed for the decision making and was derived from the existing complex model currently used in the Delta Programme, and consultation of potential end-users.

The model consists of an integrated set of modules as presented in the model diagram (Figure 31), which we further explain below. For building the modules for drought risk assessment we used a set of complex models (the base models) originating from the PAWN project (e.g. Wegner, 1981; Goeller et al., 1983, 1985), and further elaborated by the research institute of the Ministry (e.g. Vermulst et al., 1998) and – later – a consortium of Dutch research institutes (NHI project team, 2013; Delsman et al., 2008). For flood management the model comprises the results of a complex hydrological model (De Bruijn and Van der Doef, 2011). The model is implemented using the programming language PYTHON (Van Rossum and Drake Jr, 1995) and the spatial environment module PcRaster (Van Deursen, 1995).

The description of the details of the model is split into two main parts: 1) modules describing the *water system* in terms of water availability and demand, and 2) modules describing the *impacts* of flooding and water scarcity. The model considers the main alternative policy options of the Delta Programme as described in Section 6.3. Appendix C presents the model equations.

6.4.1 *Water System Modules*

The water system modules describe the water state by simulating the transport of water from the Rhine at Lobith through the main river channels and canals to the large lakes in the IJsselmeer area and to the rural areas. Inflow into the rivers comes from the transient scenarios in terms of the average and maximum discharge per 10-day period. The water level at the Wadden Sea at the Afsluitdijk gives boundary conditions for drainage of excess water. In the rural areas a water demand is simulated based on local climate conditions.

The *water distribution module* simulates the water flow in the sections of rivers and canals and the water levels of the lakes. Desired, maximal and minimal discharges (e.g. for flushing or shipping) are specified for river sections, and target levels are specified for the IJssel lakes. The system is schematised in a network of nodes and links (Figure 32). The links (solid lines) represent the waterways that bring water into and across the country. The nodes (circles) represent the conjunctions of these waterways and the IJssel lakes. The nodes representing the lakes have a target level and can store water.

The regional areas are simulated in the *water demand module*. The water demand is summed for sets of small watersheds - districts (squares) - that are linked to the network via the nodes (dashed line). Characteristics of the links and nodes are taken from the PAWN project (Wegner, 1981) and updated with recent information from the Ministry. In addition, to inflow of the Rhine river, discharge of the Meuse and Vecht rivers, are dummy values derived from an empirical relation between the flows of the Rhine and these rivers

The distribution over the three main Rhine branches is represented by a discharge dependent curve. For most links the flow is calculated from the water balance at a certain node. For others and also for some districts, distribution keys of the PAWN project are used. In the Rhine estuary the water distribution is determined by general operation rules of the Haringvliet sluices.

For the IJssel lakes, first a water balance for all three lakes together is calculated, resulting in an average level for each lake. The water level determines the discharge capacity from the IJsselmeer lake to the Wadden Sea, and the inlets from the Markermeer and IJsselmeer to the regional canals that distribute the water to the North and North-Holland region. The discharge capacity at the Afsluitdijk depends also on the water level at the Wadden Sea and is calculated for the average 10-day period water level in the Wadden Sea assuming that this average water level will last 8 hours/day (Deltares 2012, Appendix C).

The *Flood mapping module* describes which areas are flood prone as well as the probability of flooding. Rhine discharges arising from the transient climate scenarios are translated into water levels using rating curves based on observations (Rijkswaterstaat, online) for a selection of potential breach locations used in the Delta Programme. Subsequently, the model calculates the probability of dike failure caused by piping or by wave overtopping by examining the difference between dike level, water level and the strength of the dike (Van Velzen, 2008). Whether the

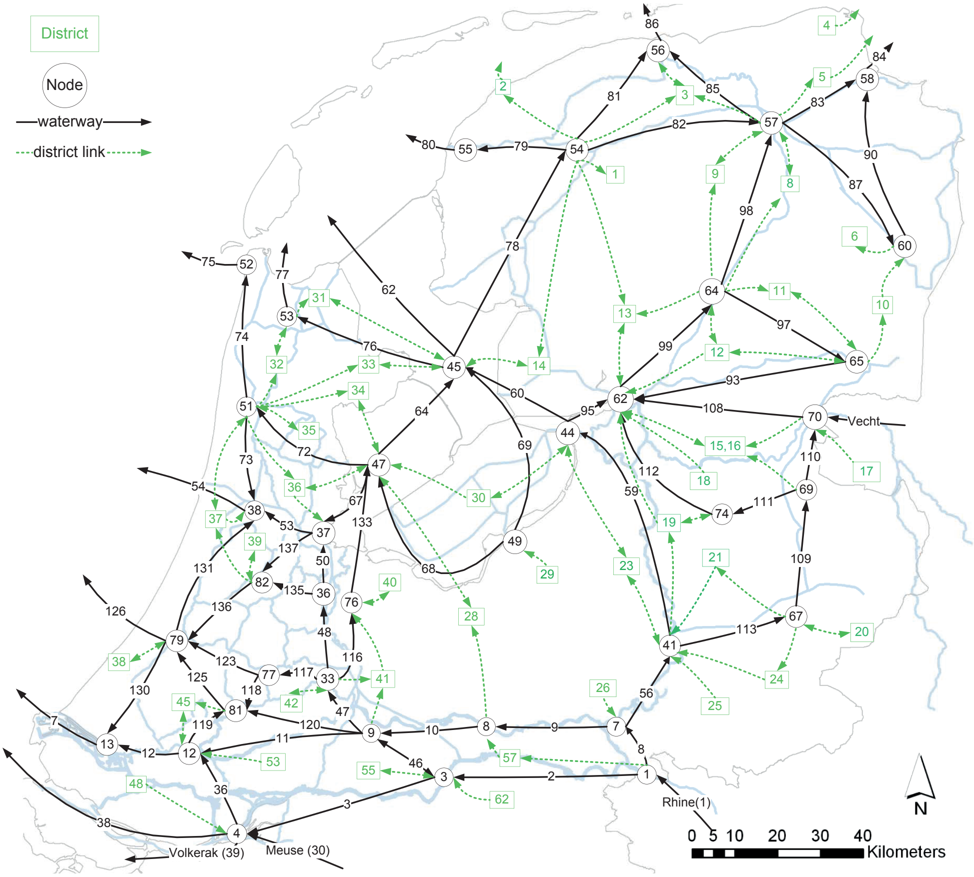
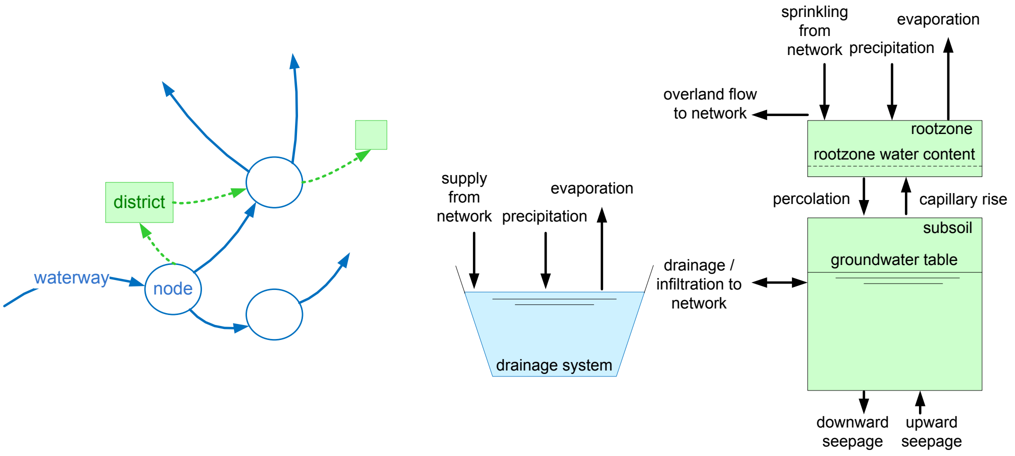


Figure 32: Schematisation of the water distribution network

dike fails or not depends on a random number selected between 0 and 1 (the seed is fixed). If the drawn number is lower than the probability of dike failure, the dike is assumed to fail, even if the water does not overtop it.

The *Salt intrusion module* simulates the salt concentration at the Gouda inlet in relation to river discharge and sea level rise. This module is based on an empirical correlation between the Rhine discharge at Lobith based on measurements for 2003-2011 and results of simulations with a 1D hydraulic model (SOBEK) for dry years (Van den Boogaard and Van Velzen, 2012).

The *Water demand module* results in water demands for irrigation and water level control in rural areas and is a simple two layer groundwater model with a resolution of 1,000 m grid cells, taking into account a limited number of land use and soil types (Figure 33). The cells are aggregated over a watershed area (called district) linking the rural areas to the water distribution network. The water distribution module calculates whether this water is available or not and supplies a requesting district with the available amount of water. In each time step the interaction between regional water system and the national distribution network is considered in terms of water demand and supply. Soil moisture characteristics (e.g. crop factor, water retention curves), initial groundwater conditions and the spatial distribution of 23 soil types, 19 land use classes, elevation and target water levels are derived from the input maps of the complex model (NHI project team, 2013).



water distribution over the network *water demand from districts to the network*

Figure 33: Schematisation of the working of the distribution network, the local drainage system and the subsoil

For each layer in each grid cell a water balance is calculated. First the potential evaporation is calculated by multiplying the reference evaporation with a crop factor that is specified for each crop and ten-day period. The crop factors are derived from the complex model (PAWN) and increased by a factor (1.2) based on higher crop factors for transpiration used in the more recent version of the complex model (NHI) to improve the calculated water demand. The actual evaporation is a function of the potential evaporation, the available moisture in the root zone, and the soil moisture suction (pF value). Below a certain point the actual evaporation equals the potential evaporation, at wilting point (suction = 16,000cm) there is no evaporation, and in between the actual evaporation deceases linearly. Lateral flow from groundwater to local surface water and vice versa is a function of groundwater depth relative to surface water level. Water flowing from the root zone to the subsoil (percolation) depends on the root depth, porosity and precipitation. Capillary rise (flow from subsoil to root zone) is calculated as a function of the groundwater depth below the surface level and the root zone suction and is derived from the Saltmod model (Oosterbaan, 2001). The main equations used in this module are given in Appendix C. When the groundwater level is below a critical depth there is no capillary rise. When the water level is shallower than halfway the root zone, the capillary rise is at maximum, and between that it decreases linearly describing the so-called S-curves (Kabat et al., 1994). The lower boundary condition of each plot is an annual seepage flux taken from results of the complex model for an average year. In case the root zone and subsoil are saturated, excess water is moved through surface runoff. In urban areas surface runoff is a function of the net precipitation and a discharge coefficient of 0.8.

The water demand is determined from the difference between the actual and potential evaporation. The amount of water requested for maintaining the target water level in the local surface waters areas is derived from the net precipitation and the surface area of these waters.

6.4.2 *Impact Modules*

The impacts modules describe impacts in terms of flood damage and casualties, shipping damage and agricultural drought damage.

The *Flood impact module* gives an estimate of the damage, casualties and affected people in an inundated area, depending on whether the dikes are breached or overtopped, and whether people have been evacuated in advance of inundation. In case the dike fails, the flood depth and consequently the damages and casualties will be much larger compared to flood depth caused by overtopping of the dike due to high water levels without breaching. The latter may occur, in case of the implementation of 'unbreachable' (strong and wide) dikes. Whether people are evacuated or not, depends on the dike fragility (the chance of breaching or overtopping of a dike). The impact estimates are based on damages per dike breach location based on a-priori determined inundation patterns and damages calculated with a complex combined 1D-2D hydrodynamic inundation model (SOBEK) for each potential dike breach location (Deltares, 2012). To assess potential floods in the IJsselmeer, the lake water levels are compared with threshold values.

The *Drought impact module* calculates the impacts of low flows on navigation and the agricultural damage due to lack of fresh water. The impact on navigation is calculated in terms of the extra costs to transport the load on the trajectory between the Netherlands and Duisburg (Germany) and is developed by Van Velzen (2012). Increased navigation cost for other waterways within the Netherlands is very small compared to this amount. The additional costs are calculated using the discharge, the discharge-water depth relation at a critical location (near Nijmegen), and a water depth–cost relation.

To assess the impact of salt intrusion for fresh water supply the salt concentrations of the salt module are compared with the norm values of the water inlet at Gouda. If the salt concentration exceeds the norm, the water intake is halted.

The impact of drought on crop production is based on the Agricom model (Abrahamse et al., 1982; Prinsen and Verschuur, 1995) and is calculated as a piecewise linear function of the ratio of actual and potential evaporation. If it is equal to 1 the crop receives enough water, and the damage is zero. With decreasing ratio, drought damage increases to maximum at a so-called death point. This so-called drought damage fraction is the part of the potential crop yield that will be lost due to drought. The potential crop yield is the maximum crop yield given the weather circumstances, and when enough water would be available. With the damage fraction the survival fraction is calculated: the fraction of the crop that can still potentially grow and result in a specific yield. This is combined with the remaining yield of a time step to calculate the final damage fraction for each year.

Table 5 gives an indication of the simplifications made in the IAMM in comparison to the complex base models to make the model fast and integrated. These simplifications involve: lower time resolution and spatial resolution, and averaged rather than distributed inputs.

6.5 MODEL EVALUATION

While scientific and engineering models are often validated through estimating whether the model is similar (within specified limits) as the real-world values, this study's model is a policy model that simulates situations which can not be observed (futures and not yet implemented policy options). The traditional modeller's criterion - model accuracy in terms of the extent to which historical data are reproduced - is there-

Table 5: Overview of the main characteristics of the IAMM and the base models

Flood risk assessment modules		
Aspect	IAMM	*Base models*
Temporal resolution	10 days	Hours
Spatial resolution	Damage per dike ring area, 2–3 breach locations per dike ring	Damage per 100 m grid cells, 3–6 breach locations per dike ring
Input	Maximum Rhine discharge at Lobith,	Rhine discharge at Lobith, land use maps, maps with number of inhabitants
Structure	Q-h relations, dike-failure curves, damage tables	Statistical approach for different design conditions, 1D and 2D hydraulic model
Output	Flooding damage and casualties per dike ring over time	Probability of flood risk, casualties, flooding damages

Drought risk assessment modules		
Aspect	IAMM	*Base models*
Temporal resolution	10 days	1 day, water distribution 10 days
Spatial resolution	1,000 m grid cells, 69 links, 45 watersheds (districts), 38 nodes, 2 layer groundwater module	250 grid cells, 140 watersheds (districts), subdivided into 8,750 smaller watersheds, >250 nodes >300 links, > 7 layer groundwater module
Input	Average Rhine discharge at Lobith Precipitation and evaporation for 6 meteorological regions Average sea level Wadden Sea	Average Rhine discharge at Lobith Precipitation and evaporation for grid cells of 250 m
Structure	Water distribution, water demand, drought impact module	Set of coupled models for saturated zone, unsaturated zone, regional surface water, national surface water, agricultural damage. 2D hydraulic model for salt concentration
Output	Annual drought damage for agriculture and shipping, water shortage over time	Drought damage for agriculture, water shortage for a year specified characteristics

fore not the only metric used in the evaluation of the model (Jakeman et al., 2006).

We evaluated the IAMM against the results of the base models derived from previous studies and against observations for pre-specified periods of interest within 1975–2004. We then assessed whether differences would have implications for the decision making using closed questions for key outcome indicators for the strategic decisions.

First, a visual performance analysis was done through comparing graphs of outcome indicators. Next, we compared the model behaviour with the behaviour of the base models and historical data (e.g. dry and wet periods should be reproduced at least relatively). In addition, we evaluated the model structure through testing of equations and extreme conditions tests (Barlas, 1996). Subsequently, the performance was evaluated more thoroughly for a set of metrics. If needed, the purpose, design and implementation of the model were reassessed.

This section presents the reference data selected, the metrics for evaluations expressed as closed questions and discusses the model performance based on the metrics.

6.5.1 *Reference Data*

For the evaluation of the model, data is needed for periods of interests. These include wet, dry and average hydrological years. In the Rhine delta, typical wet periods with high river flows have occurred in the winter of 1976, 1993, 1995, the year 1985 was especially wet in the rural areas. Typical dry periods with low precipitation and low summer river flows have occurred in 1976, 1989, 1991 and 2003 (Beersma and Buishand, 2007; Beersma et al., 2004). The years 1976, 2003, 1991 are in the top 10 list with the lowest observed discharges between 1901-2003 (De Wit, 2004). 1995 and 1996 were both years with a greater than average precipitation shortage and 1996 had also relatively low flows. Results from the flood risk base model existed of flooding damages for key dike breach locations. From the drought risk base models results were available for the year 1975, 1976, 1988, 1989 and 2003 and included flows in river sections, water level IJsselmeer, water demand from districts, the total damage for agriculture for the Netherlands and a map of the agricultural damage for the mid-western region. Observations were available for the river discharges for 1989–2003, water levels in the IJsselmeer for 1975, 1976, 1988, 1989 and 2003; salt concentration at Gouda in 1976, 1988, 1989; and precipitation deficit for the mid-western region for 1975-2003. As in the past no floodings have occurred and as the flood damages are derived from the results of the base model, we can only test whether the IAMM simulates floodings in case of hypothetical extreme discharges or near floodings in case of the peak discharges of 1993 and 1995.

6.5.2 *Evaluation Metrics*

To determine appropriate metrics, we built upon the idea of Guillaume and Jakeman (2012) to use closed questions to make clear what the model can(not) do. In our study, the main question is: *Given the simplifications associated with the model, does the model produce credible outcomes with sufficient accuracy for the screening and ranking of promising actions and pathways in order to support the strategic adaptive planning decisions in the Rhine delta?* This question can not be answered as it is not clear what is meant with sufficient. The closed questions should be such that there is no wiggle room; the answer is either yes, no, or sometimes. Therefore, we defined a number of closed questions related to the five main strategic decision topics in the Delta Programme (Table 6). The questions are grouped and answered per overarching (more ambiguous) questions.

Our starting point for the evaluation is that the uncertainties/errors in the model results should be lower than the impacts of the pressures and should not result in a different strategy (e.g. would a different decision be made if the water levels are assessed with an uncertainty bandwidth of ± 5cm?). The questions were formulated iteratively in consultation with potential end-users: once we answered the question, we reconsidered whether we build the right model, used the right question and used the right test. The model should produce the right signal for a decision for the right reason (the model can not be a black box as it will be used for impact assessment of future situations). Therefore, not only the outcome indicators were considered, but also the main variables used to determine this outcome.

6.5.3 *Model Performance*

In this section, we discuss the appropriateness of the model by answering the evaluation questions as presented in Table 6.

Can the model predict the occurrence of river flooding events and related damages?

The model did not simulate dike breaches for the period of 1975-2004, which corresponds with observations. In 1993 and 1995 the probability of dike failure was higher than in other years, but still very low (<1%) followed by the years 1983, 1988, 1989. The dike failure increases with discharge, and rises from 0.01 at 13,000 m^3/s to 1 at 18,000 m^3/s at Lobith. The discharges on the main Rhine branches are the main driver for flooding events in the current situation. For the high discharges of 1993 and 1995 (±10,000 and 12,000 m^3/s) the differences for the Nederrijn were less than 2% of the observed discharge, for the IJssel river

Table 6: Closed questions used for evaluating the model's performance.

1. Can the model predict the occurrence of river flooding events and related damages? (Decision 1)
    - Does the model simulate a similar distribution of water (<200 m^3/s) over the main Rhine branches in comparison with the reference data for high flows (10,000 m^3/s–16,000 m^3/s)?
    - Does the model simulate a similar distribution of water (<200 m^3/s) over the main Rhine branches in comparison with the reference data for extreme peak flows (>16,000 m^3/s)?
    - Does the model simulate higher dike failure probabilities in high water situations as observed in 1993 and 1995 compared to average flows?
    - Does the model simulate flooding events in case of high discharges (>16,000m^3/s)?
    - Does the model simulate more flood events with increasing discharges?
2. Can the model predict the impact of low river flows on navigation? (Decision 3)
    - Can the model simulate the relative damage in average and (extremely) dry years?
    - Can the model simulate the annual ship damage with an error width that is lower than the differences between average and (extremely) dry years (± 1 million euro)?
3. Can the model predict how often the salt concentration of the fresh water supply in the mid-west exceeds the inlet norm? (Decision 3)
    - Can the model simulate the number of 10-day periods (± 3) that the salt concentration exceeds 200, 300 or 400 mg Cl/l?
    - Can the model simulate the discharges at Nederrijn ± 20 m^3/s during low discharges?
4. Can the model predict the IJsselmeer water levels in winter half year? (Decision 1 and 4)
    - Can the model simulate whether the IJsselmeer water level exceeds a threshold value of +0.1m MSL in the winter half year?
5. Can the model predict the IJsselmeer water levels in summer half year? (Decision 3 and 4)
    - Can the model simulate whether the IJsselmeer water level drops below target level, below threshold value of -0.3m MSL or -0.4 m MSL in summer half year?
    - Can the model simulate discharges at IJssel during low flows in such a way that the influence on the calculated water levels in the IJsselmeer is small (< 2 cm)?
6. Can the model predict the fresh water demands from rural areas? (Decision 3 and 4)
    - Can the model predict the variation in time of the fresh water demand for irrigation and water level control from the rural areas to the main waterways?
    - Can the model simulate the total water demand for these uses in summer half year within ± 5 m^3/s?
7. Can the model predict drought damage for agriculture? (Decision 3 and 4)
    - Can the model distinguish the relative damage in average and (extremely) dry years?
    - Can the model simulate credible actual and potential evaporation, the precipitation shortage and moisture shortage?
8. Can the model assess impacts of scenarios and policy actions? (All decisions)
    - Are relevant variables and parameters included?
    - Does the model provide credible and informative results for impact assessment of scenarios and policy actions on relevant outcome indicators for the decision making?

the discharges were up to 20% (± 400 m^3/s) smaller than the observations, and for the Waal the 6 to 9% lower (±600 m^3/s). The differences of the IJssel and Waal could be relevant for decision making regarding high flows, as they are in the same order of magnitude as the effects of some of the actions currently being considered, but the Delta Programme focuses on extreme peak discharges. Would the same water distribution rules been used as the ones used in the complex model, than the differences would have been much smaller. This could be easily improved without impacts on the model structure and calculation time. For peak discharges, these distribution rules are already the same as in the complex model.

The flood damages are only indicative and do not take into account water depth, flow velocity and duration of high water. These damages are based on current socio-economic conditions. By including socio-economic scenarios, future damages could be estimated. To improve this part of the model, more breach locations could be taken into account. Also, water level-water depth and water depth-damage relations could be included to improve the damage estimate. However, for the strategic decision making the *exact* damage is less important, than the information whether flooding events occur or not. We evaluated the model appropriateness for assessing changes in the probability of flooding events by analysing the response to changes in river discharges, water levels, dike height and dike strength in the future. An indication of impacts from socio-economic developments can be estimated using a multiplier.

Can the model predict the impact of low river flows on navigation?

To evaluate the model results for shipping damage, we used the discharge deficit. This is the difference between a threshold value (1,800 m^3/s at Lobith) and the average discharge in a 10-day period summed for the summer half year if the discharge is below that threshold (Beersma et al., 2004). Thus, years with a high discharge deficit have a relative large number of 10-day periods with an average discharge lower than 1,800 m^3/s and/or a very low discharge. The model results correctly reflect the years with a large discharge deficit over the past decades (figure 34). However, using the discharge deficit as reference has limitations, as for several years lower discharges occur outside the summer half year. This explains why for some years the model simulates relatively high damages while the discharges deficit is relatively low. Van Velzen (2012) concluded that their discharge-water depth-damage relation, that is also used in this model, estimates the damages reasonably well (in the same order of magnitude but overestimated) based on a comparison of an event in 2011 wherein ships could not use the river due to a capsized ship (1.27 million euros/day) with model results for a very small water depth (1.5 million euros/day).

From this we conclude that the model can discriminate the drought damages for navigation for (extremely) dry and wet years, and that it can be used to assess impacts of changes in discharges, water depth at the critical location, fleet composition and transport load. The model can not estimate the impacts of changes in river bed morphology.

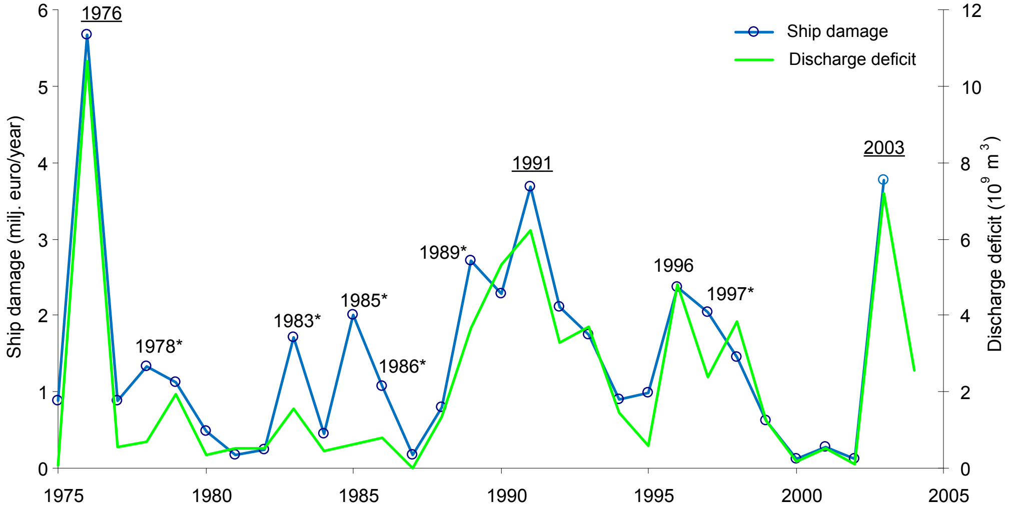


Figure 34: Simulated total damage for navigation (million euros/year) and the observed discharge deficit (m^3/year)for the summer half year. The years 1976, 1991 and 2003 are in the top 10 low flows. Years with an asterisk (*) have low flows outside of the summer half year, resulting in differences between the damage and discharge deficit.

Can the model predict how often the salt concentration of the fresh water supply in the mid-west exceeds the inlet norm?

The IAMM and the complex model show more or less the similar fluctuations in salt concentration at the Gouda intake point (Figure 35). However, salt concentrations during peaks are much lower in the IAMM than in the complex model (200–500 mg Cl/l). Comparing both model results with observations indicates that the IAMM underestimates the peaks and the complex model overestimates them. For 1976 and 1989 the number of 10-day periods that the simulated concentration is above the critical level is 17 and 8 for the complex model and 15 and 5 for the IAMM (Table 7). The IAMM could be used to estimate the change in the number of 10-day periods that Gouda is vulnerable for closing, but the user should be aware that the model underestimates the concentrations with 50 to 100 mg Cl/l. Potential end-users of the Delta Programme use 250 mg Cl/l as threshold value. With this threshold value the model provides appropriate results to assess whether the Gouda intake would more (or less) vulnerable for closing under changing environmental conditions or after implementation of policy actions in comparison to the reference situation. The model can not be used to estimate the salt concentration per 10-day period.

Improvements of this part of the model can be obtained by a better simulation of the low flows in the Rhine Estuary. The complex model simulates lower discharges into the Nieuwe Waterweg in case of flows between 1,250 m^3/s and 1,500 m^3/s (more is going into Haringvliet). In case of flows lower than 1,250 m^3/s into the Nieuwe Waterweg, both models simulate the similar discharges for the Nieuwe Waterweg and Haringvliet.

Table 7: Number of 10-day periods for 5 salt concentration categories at the Gouda intake for 2 dry years. For 1976, the total number of decades with observations is 28 instead of 36.

	1976			1989		
Salinity [mg Cl/l]	Observations	Complex model	IAMM	Observations	Complex model	IAMM
<100	0	7	4	2	18	11
100-200	6	12	17	19	10	20
200-300	19	7	10	13	3	4
300-400	0	1	3	2	4	1
> 400	3	9	2	0	1	0

Can the model predict the IJsselmeer water levels in winter half year, and in the summer half year?

As the inflow from the IJssel river into the IJsselmeer lake is an important variable for the water level, we first assessed whether the model simulates these flows appropriately. For the year 1989 (with flows < 4,000 m^3/s) differences vary between -25 to +45 m^3/s with average of 10 m^3/s, which would result in a ±0.006 m water level difference in the IJsselmeer (0.03 m at maximum), and can thus be considered as appropriate for the strategic decision making in the Delta Programme.

Model results for the water level in the lake IJsselmeer are presented in Figure 36 for two periods of interest. The observations (grey lines) show that the water level varies both in time and space. In the summer of the dry years (1976 and 2003), the water level drops below target level (-0.2 m MSL) in both models, although the complex model shows a larger decrease (in 1976 this is -0.4 m versus -0.3 m MSL in the metamodel). For the summer of 1976, the IAMM results match better with the observations, while the complex model results follow the observations better in 2003. Nevertheless, 2003 observations from other sites

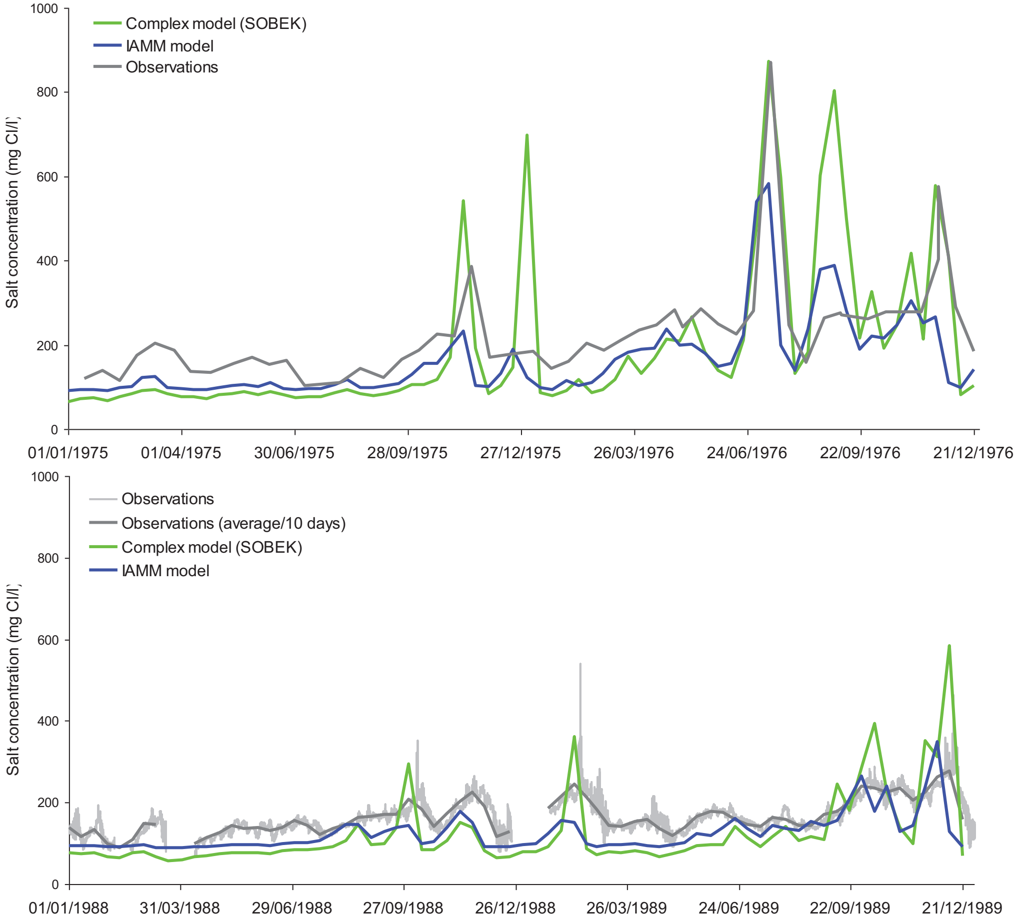


Figure 35: Salt concentration at the Gouda intake (mg/l) for the complex model, the IAMM and observations.

along the lake, fit better with the IAMM (they are not presented as they were not available digitally). In 1988 and 1989 the water level follows the target level in both models. In winter, a temporary, wind-induced increase of the sea level can limit the drainage capacity at the Afsluitdijk. This complex model does not account for these limitations (others do, but these results were not available). Therefore, this model does not show a level increase in the winter. The IAMM follows the observations better, although it is not able to simulate all peaks during the winter and for some peaks the increases are lower (0.1–0.2 m). This is probably caused by the fact that the IAMM uses the average level in the Wadden Sea to calculate the drainage capacity, while in reality storms may temporarily increase the levels reducing the capacity. To improve this part of the model, the temporal resolution would need to be changed to days, but this would increase the run time enormously, making the model inappropriate for exploring pathways.

To conclude, the model can be used for strategic decision making on target levels in the IJsselmeer. For the summer half period it is relevant to know whether water levels drop below approximately -0.3 m MSL as in that case water intakes may need to be cut short and below -0.4 m infrastructural damages start to occur. However, results for the winter period should be used with care and only used indicatively, as levels can be underestimated. This is a consequence of the time resolution of the model. Consequently, the model can not assess short-lasting (daily) changes that may occur as a result of high wind speeds during storms. The model can assess the limited drainage capacity as a result of sea level rise.

Can the model predict the fresh water demands from rural areas?

The water demands for sprinkling and water level management show similar values and variations in time in both models (Figure 37 shows results for district 1; Friesland in the north region). The difference in the total water demand in the growing season (summer half year) varies per year and per district. In 1976 the total water demand is on average -1.6 m^3/s (-4.5 %) lower in the IAMM than for the complex model, for 1989 -0.3 m^3/s (-10%) while for 2003 the difference is 5 m^3/s (+36%). For the total water demand for water level management the differences are larger: -2.5 m^3/s, 12.5 m^3/s, and 26 m^3/s in 1976, 1989 and 2003. Differences are not only caused by the model structure but also by the differences in the input. The IAMM model uses 6 meteorological regions, while the complex model uses a 250 m grid. Still, the IAMM model simulates the demands in most districts and years roughly well. In some cases, the water demand for maintaining the regional water levels is largely overestimated. As a result, there situations may occur wherein the IAMM model may indicate that actions are needed, while the complex model does not. Still, for the ranking and screening policy options,

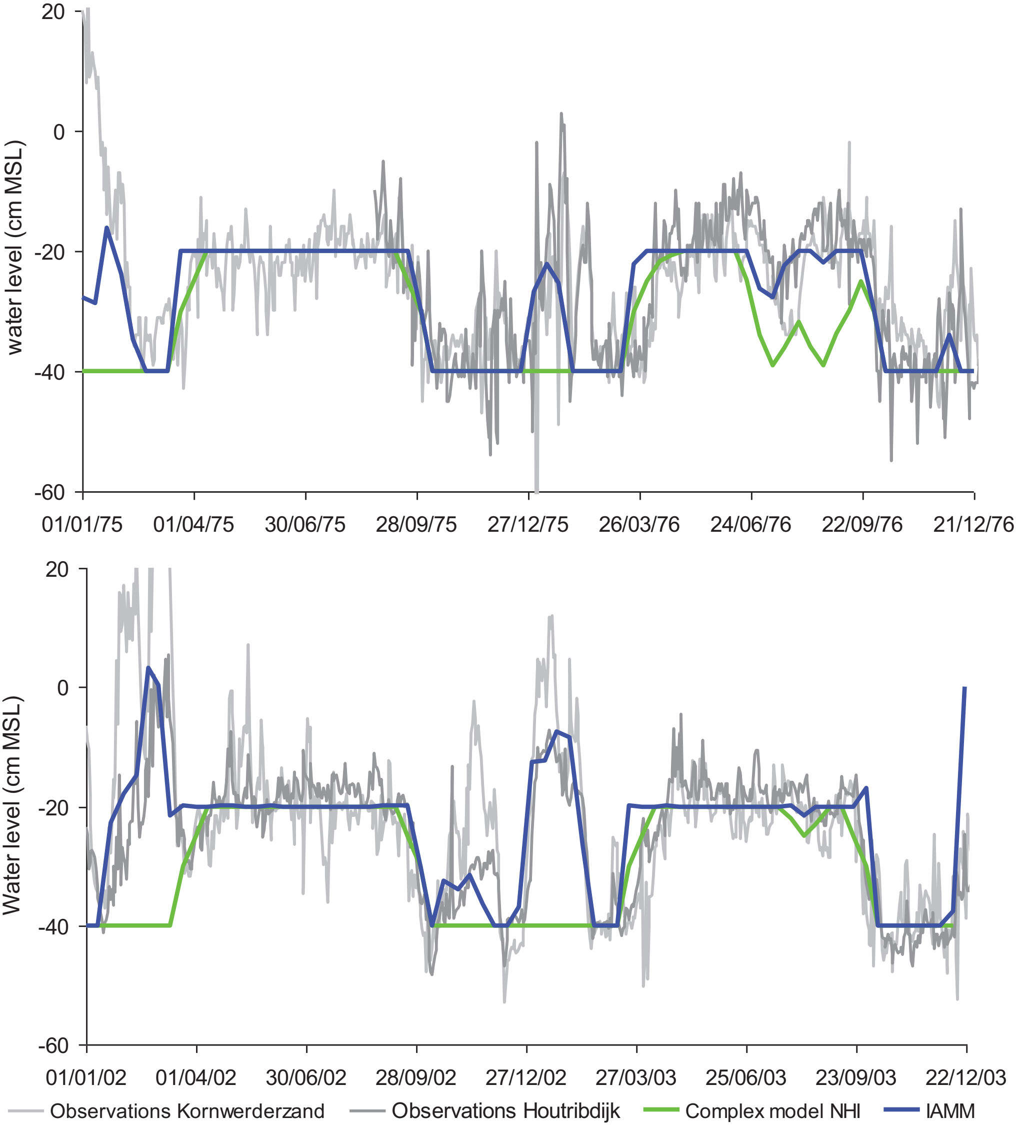


Figure 36: Simulated and observed water levels in lake IJsselmeer for two dry periods (1975-1976 and 2002-2003). The monitoring location Kornwerderzand is located near the Afsluitdijk, while Houtribdijkzuid is located at the border with lake Markermeer.

the IAMM model performs acceptably, although, improvements can be made. Further analysis of what causes the differences requires that the inputs of both the complex and metamodel are the same.

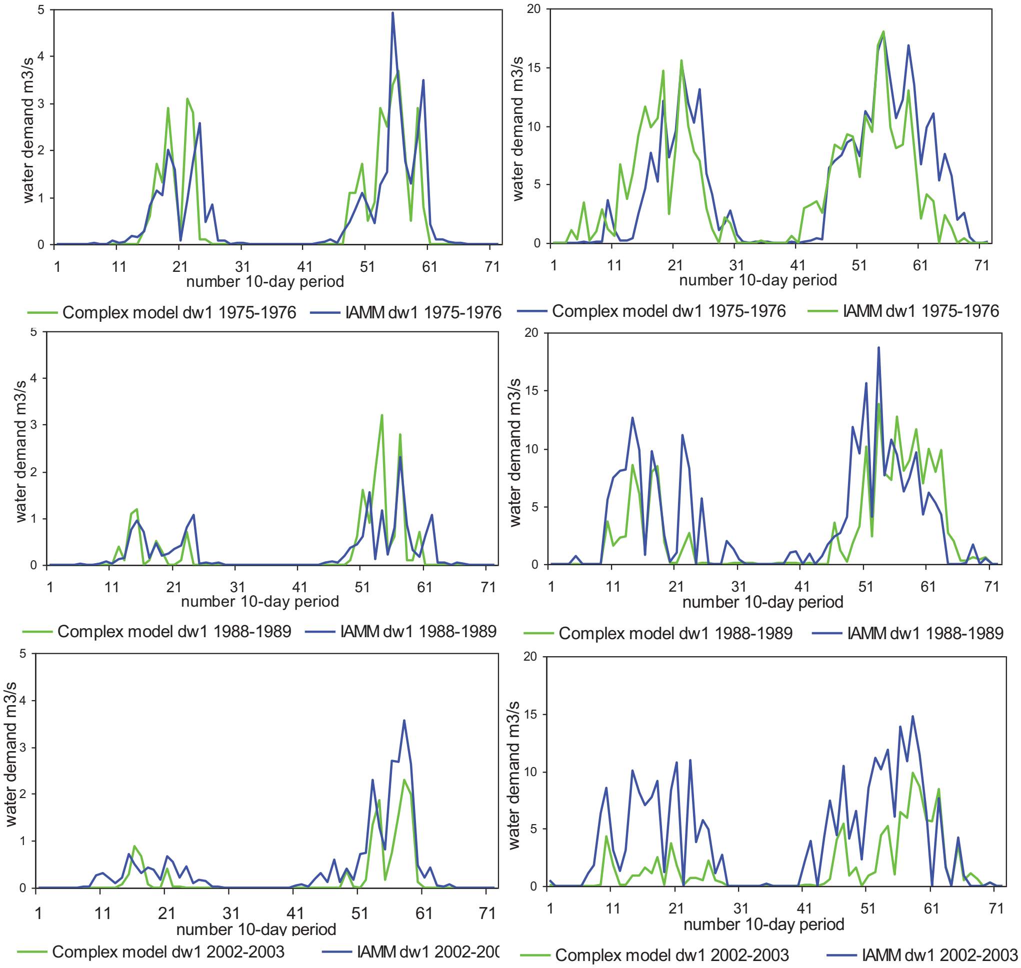


Figure 37: Water demand for sprinkling (left figures) and for water level control (right figures) for district 1 Friesland for three dry periods (1975–1976, 1988–1989 and 2002–2003)

Can the model predict drought damage for agriculture?

The model simulates high damages for known dry years (1976, 1989, 2003) with the highest for the extreme dry year of 1976, low damages for wet years (1985), and moderately damages for 1995 and 1996. Figure 38 shows the total damage for the Rhine delta in relation to the precipitation deficit based on observations in the mid-western area. Differences can be caused by the different scales of the observations and the model results. The relative total damage per year is also similar to the complex model in the sense that the extreme dry year of 1976 has the highest damage, followed by the two dry years of 2003 and 1989. Comparing the damage maps with a damage map for the mid-western area indicated that the IAMM overestimates the damages.

To find the cause of spatial differences, we compared the actual and potential evaporation and their ratio as these are the basis for the calculation of the drought damage. The pattern of these evaporations is quite similar to the pattern of the complex model, although the IAMM seems to respond more strongly to drops in net precipitation. The difference for the total potential evaporation in the growing season is 3% to 5% for most districts, and quite large for districts Friesland and Amstelland (20-70%). Differences are mainly due to different input in precipitation and evaporation (the IAMM uses 6 meteorological regions, while in the complex model a spatial distribution of 250 m is used), and secondarily differences in the crop factors used. The actual evaporation differs 18% to 43%. This difference is caused by the simplification in the processes, spatial and time resolution. Consequently, the ratio between the actual and potential evaporation is lower, resulting in a higher damages than the complex model.

The model can be used to simulate changes in the total agricultural damage per year and possibly also for different regions. The model can not be used to simulate absolute damages or damages at a more detailed scale. For ranking of policy options for the Delta Programme this is sufficient as these actions are also on national or regional scale.

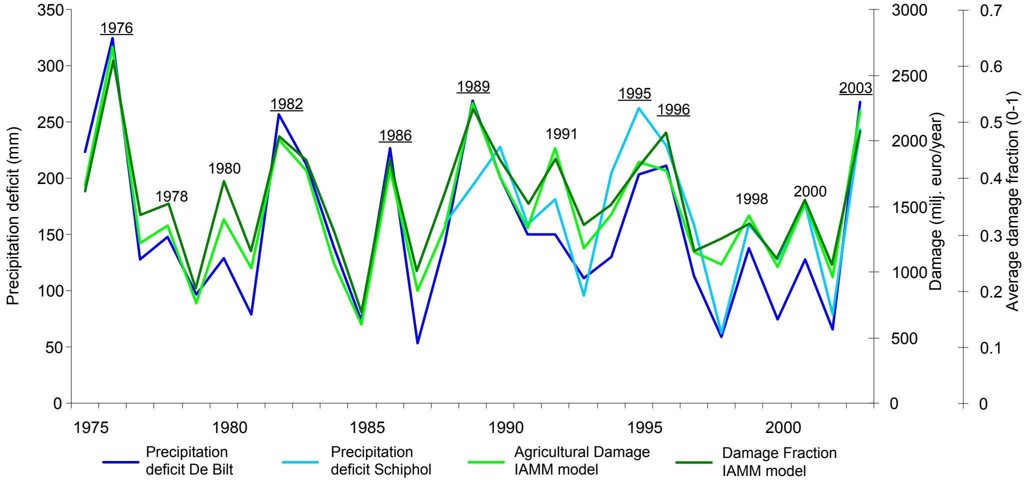


Figure 38: The simulated total agricultural damage per year, the average damage fraction, and the Standardised Precipitation Index based on observations for two locations (in the mid-western area).

Can the model assess impacts of scenarios and policy actions?

To assess impacts of climatic and hydrologic pressures the model uses time-series of sea level rise, precipitation, evaporation, and river discharges at Lobith. Impacts of socio-economic pressures can assessed by changing land use, crop-damage curves, sprinkling installations, and using a correction factor specified per dike ring area to consider impacts on flooding casualties and damages. The policy actions described in Section 6.2 can be implemented in the model. To assess whether the models responses correctly to scenarios and policy actions, we simulated a climate change scenario and all policy actions, evaluated the plausibility of the impacts on the relevant outcome indicators based on expert judgement together with potential end-users and results from the complex models, and adapted the model if necessary.

The following model results were achieved: With increasing river discharges in the winter (effect of climate change) flooding events start to occur, and occur more frequently and in more dike ring areas at higher discharges. If flood risk policy actions are implemented in the model, the occurrence of flooding events decreases. Increasing the dikes to cope with a design discharge of 18,000 m^3/s does indeed only result in floodings at higher discharges. With decreasing river discharges in summer (effect of climate change), the water levels in the IJsselmeer are frequently below summer target level of -0.2 m MSL (up to -0.6 m MSL). With increasing sea level, the water level in the IJsselmeer is more frequently above the threshold value of 0.1m MSL in the winter. With increased drainage capacity at the Afsluitdijk winter water levels can be better maintained. A decrease of 30% in water demand for both agriculture and water level control lowers the IJsselmeer levels only for several cm, which is very small compared to the accuracy of the model, but end-users found it plausible. Impacts of climate change on agriculture were not visible as a result of the assumption that farmers will use other water sources to avoid damages (similar to the complex model). Therefore, we extended the model with an outcome indicator describing the water shortages per district based on the difference between the water demand from the rural areas to the national network and supply from the national network. Raising the summer target water levels in the IJsselmeer did sometimes increase water shortage, as the model limited the inlets in case the water level dropped below target levels. Based on this result, we adapted the model, such that users can choose the priority: either the districts get priority and their demand resulting in a drop of water levels or the target water level gets priority and rural areas are cut down in water supply and get less than they demand. With an increasing number of areas with sprinkling installations the water demand for agriculture increased and the damages decreased. Diverting more water to the IJssel and thus reducing the flow on the Nederrijn, ensures that water levels in the IJsselmeer are achieved more frequently, but it increases the salt concentrations at the Gouda intake. Increasing the inlet capacity at Gouda diminishes water shortages.

6.6 DISCUSSION AND CONCLUSIONS

In this chapter, we described the need for a new generation policy model for exploring adaptation pathways to support decision making under uncertainty, and illustrated the building and evaluation process of such a model for the Rhine delta. Potential end-users working on the Delta Programme confirmed the need for a fast model to explore policy actions over time. Not only the speed and an understandable model structure were seen as an advantage, but also the possibility to use such a tool in discussion with stakeholders. Effects of combinations of actions can be shown interactively and new actions could be added quite easily.

A model for exploring pathways should be able to simulate policy actions over time for a multiplicity of possible future, and provide credible outcomes of interest with sufficient detail and accuracy for decision making at the delta scale. This requires that the model is fast enough to do many simulations in a limited period of time, and integrated in the sense that it describes that system and its feedbacks as a whole. Therefore, this model fits within what some call a fast and simple model, repro model or metamodel, and within group of integrated assessment models. We refer to our model as an Integrated Assessment MetaModel (IAMM).

The process of building the required policy model is similar to building any other model. The main difference with other models is in the evaluation of the model. In addition to the traditional comparison of hydrological model output to observed data, we used metrics such as the model's ability to simulate a variety of scenarios, policy actions, and the calculation speed of the model. The use of closed questions (Guillaume and Jakeman, 2012), that were iteratively formulated in consultation with end-users, proved to be valuable in specifying what to model can(not) do. However, the iterative adaptation of the questions felt occasionally artificial. By focussing the metrics on specific variation within the historical data, the evaluation was not dominated by the predominant historical behavior. Starting point for the evaluation was that the uncertainties/errors in the model results should be smaller than the changes caused by the pressures or resulting from interventions of the pressures and should not result in a different strategy.

We have illustrated the approach by building and evaluating an IAMM for the Rhine delta in the context of a real-world decision problem currently faced by the Dutch National Government in the Delta Programme. The results of our example show that it is possible to build a model that is fit for the purpose of exploring pathways in the Rhine delta. The model is fast enough to assess impacts of transient scenarios and policy actions over time (100 year simulation takes approximately 1 hour) and performs acceptably to screen and rank policy options to support the strategic decision making the Dutch Delta Programme is facing. However, the model results should be used with care and at the appropriate scale, because of the simplifications in time, space and processes. A complex model can be used to obtain more detailed information about the performance of the most promising options and most troublesome scenarios or periods of interest arising from the exploration with the fast, integrated model. A number of improvements have been identified. For example, different time-steps could be used for different aspects of the model. For the IJsselmeer water level in the winter a shorter time-step is needed to improve the results. Also, the water distribution rules for high flows (10,000–14,000 m^3/s) should be adapted. The impact of uncertainties/errors in these rules is large and relevant for the decision making on flood protection, especially in case of peak flows. Although the IAMM and the complex model perform the same at this point, such discharges have never been observed, thus uncertainties in these rules should be included in the decision making. Currently, we are improving the assessment of flooding damages using spatial mapping of flood depths and damages in relation to land use changes, and expanding the impact assessment to the Rhine Estuary. The model lacks impact assessment on nature which is an import outcome indicator for an assessment of the sustainability of a water management plan. We will further test and apply the model by developing adaptation pathways for the Rhine Delta.

7

EXPLORING ADAPTATION PATHWAYS FOR THE RHINE DELTA IN THE NETHERLANDS

ABSTRACT

Decisions on whether or not to adapt to possible future change are complicated by the high uncertainty in projections of the future, that originate not only from external factors such as climatic change, population growth and economic developments, but also from the interaction between society and its environment. Dynamic Adaptive Policy Pathways provides a stepwise approach for developing an adaptive plan that can cope with changing, uncertain future conditions. Pathways describe the policy options after a policy performs unacceptably and thereby reaches an adaptation tipping point. The thus designed policies seek to maximise robustness by designing actions that perform well in multiple plausible futures, and flexibility by avoiding 'lock-ins' and keeping options open where and when possible. The approach was used to simulate policy planning in the Dutch Rhine delta with a fast, integrated model. Pathways were explored in multiple scenarios using an ensemble of possible climate realisations. Promising pathways were checked for consistency across multiple policy objectives. The case study showed that the approach can be applied to a real-world decision making problem. The results were received with great interest by potential end-users.

This chapter will be submitted as Haasnoot, M. et al. Exploring adaptation pathways for decision making under uncertainty: a Dutch water management example.

7.1 INTRODUCTION

Worldwide, decision makers from governments, NGOs and businesses face the question of how, how much and when to make long-term investments in adapting to climatic change. These decisions are complicated by the high uncertainty in projections of the future (referred to as deep uncertainty; Lempert et al. (e.g. 2003); Hallegatte et al. (e.g. 2012)), that originate not only from external factors such as climatic change, population growth and economic developments, but also from the interaction between society and its environment. Notably, policy response to environmental effects may affect societal developments (such as urbanisation) and available future policy options, thus putting the system on a particular track or pathway. For example, the 1953 flood event in the Netherlands has led to the adoption of a new, probabilistic approach for flood defense as well as to the implementation of the 'Delta Works', and the 1993 and 1995 flood waves of Rhine and Meuse rivers stimulated the implementation of the 'Room for Rivers' project. Before initiating such an adaptation path, it is useful to consider whether it indeed may lead to a desired future, given the uncertainties about the future.

Despite the presence of these deep uncertainties, some policy decisions have to be taken with some urgency as the adaptive actions may take a long time to be implemented. This means that in some cases, adaptation has to be initiated before effects of, for example, climatic change actually become noticeable in the observational record. Additional research and continued and improved monitoring, while in itself useful, may take too long and/or may not sufficiently reduce uncertainties. Uncertainties thus remain high at the time of decision making.

Adaptive policies can be used to manage deep uncertainties. They explicitly allow to respond to the unfolding of the future: events, improved system understanding, changes in the environment and changes in societal preference. Thus, adaptive policy making explicitly anticipates change. It seeks to maximise robustness by designing actions that perform well under multiple possible futures, and to maximise flexibility by keeping options option to avoid 'lock-ins'.

In the Netherlands, the Dutch Delta Programme presented Adaptive Delta Management (ADM), an adaptive policy approach that is directed towards the safety and socio-economic targets, and at the same time flexible in how and when to implement management interventions (Delta Programme, 2010, 2012a; Van Rhee, 2012). ADM aims to support decision making on spatial and water system planning in the delta under uncertainty by anticipating long term challenges resulting from climatological and socio-economical changes. To do so, planners consider adaptation and development pathways instead of end-point solutions and time frames wherein actions are needed. In addition, they seek connection with other investment agendas.

Given that the principles of adaptive policy making have been adopted in the Netherlands, a key challenge is how to operationalise Adaptive Delta Management. Scientists have proposed a variety of approaches for developing adaptive plans in various policy domains, including water (Chapter 3 and Ranger et al. 2010), transport (De Neufville and Odoni, 2003; Kwakkel et al., 2010b), spatial planning (Albrechts, 2004), and investment decisions (Schwartz and Trigeorgis, 2004; Hallegatte et al., 2012). Also, in other deltas and coastal cities, scientists and planners are working on similar approaches to support water management strategies under uncertain change, for example: New York City (Rosenzweig et al., 2011; Yohe and Leichenko, 2010), New Zealand (Lawrence and Manning, 2012), and the Thames Estuary (Lowe et al., 2009; Reeder and Ranger, online; Sayers et al., 2012; Wilby and Keenan, 2012).

The development of adaptation pathways (Chapters 4 and 5) constitutes a novel alternative to the traditional 'end-point' scenarios. It supports the development of an adaptive policy plan that is able to achieve its objectives despite uncertain changing conditions. Pathways are sequences of actions to be taken over time that can be followed to cope with a multiplicity of futures. They help to consider what options are left after a policy performs unacceptably. The pathways approach has been integrated into a stepwise policy analysis framework Dynamic Adaptive Policy Pathways (Chapter 5).

In this chapter, the approach of Dynamic Adaptive Policy Pathways (DAPP) is applied to develop an adaptive plan for a real-world situation: the water management decision in the Rhine delta in the Netherlands as considered in the Delta Programme. Pathways are explored using expert judgment and an Integrated Assessment MetaModel as described in Chapter 6. By application to a case study, it is explored whether this method can indeed be applied to a real-world case, how it contributes to robust and flexible policy making, what its strengths and weaknesses are and how it can support the operationalisation of Adaptive Delta Management. The chapter first introduces the DAPP approach, and then describes the application to the Rhine delta. Next, the resulting pathways are presented and translated into a preliminary adaptive plan.

7.2 APPROACH: DYNAMIC ADAPTIVE POLICY PATHWAYS

7.2.1 *Overall Approach*

Dynamic Adaptive Policy Pathways (DAPP) is a stepwise policy analysis approach that builds on the principles of adaptive policy making (Walker et al., 2001; Kwakkel et al., 2010b), adaptation tipping points

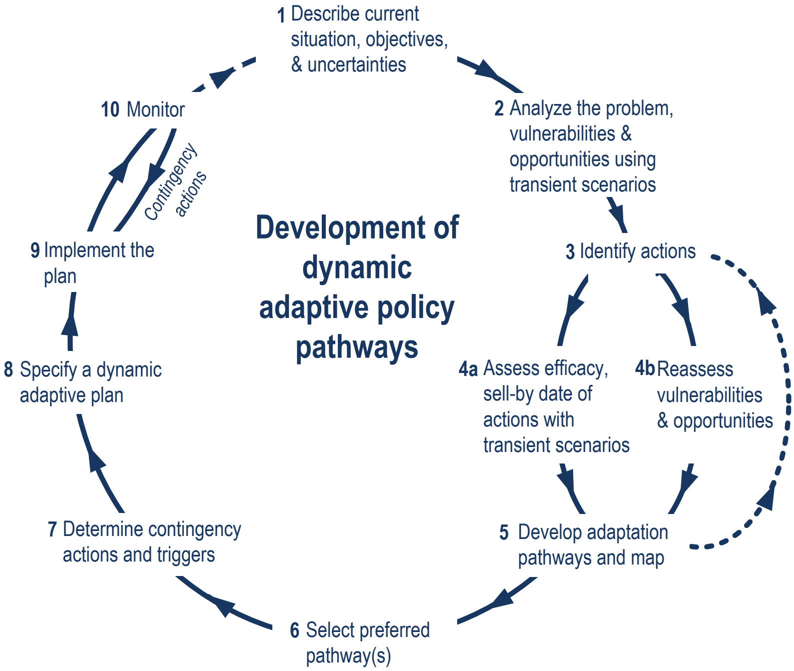


Figure 39: The Dynamic Adaptive Policy Pathways approach

(Kwadijk et al., 2010) and adaptation pathways (Chapters 3 and 4). Figure 39 shows the overall approach. We first describe the different steps in the approach and then elaborate on the construction of adaptation pathways. For a more detailed description, see Chapter 5.

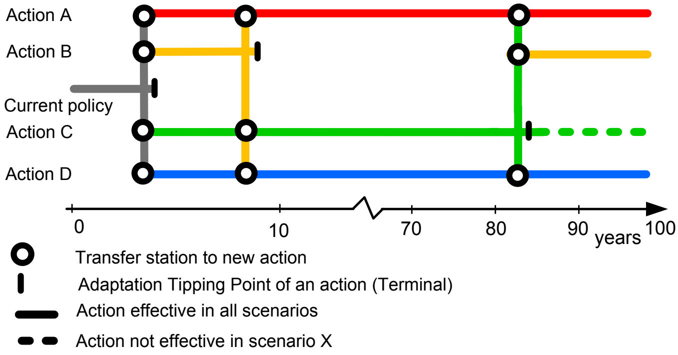
DAPP starts with a description of the setting including of objectives in terms of indicators and target values, constraints, and uncertainties relevant for the decision making (step 1). The uncertainties are used to generate an ensemble of plausible futures in the form of transient scenarios. The ensemble is analysed to reveal if and when policy actions are needed for achieving the specified objectives (step 2). Next, policy actions are identified to address vulnerabilities and opportunities (step 3), and their efficacy in reaching the objectives is assessed (step 4). An adaptation tipping point occurs when an action no longer meets the objectives and thus performs unacceptably (Kwadijk et al., 2010). The timing of a tipping point – the sell-by date of an action – is scenario dependent. In subsequent steps, the actions are used as the basic building blocks for the design of adaptation pathways (step 4 and 5). An adaptation pathway consists of a sequence of policy actions, where a new policy action is activated once its predecessor is no longer able to meet the objectives. An 'adaptation pathways map' provides an overview of relevant pathways and their connectedness, and of possible actions that can be taken after a tipping point has occurred (see Figure 40 for an example). Based on costs and benefits, possibly presented in a scorecard (see Figure 40), preferred pathways are identified (step 6) that are used to construct an adaptive plan (step 8). The plan describes which actions should be taken now to be robust and flexible, keep options open against low costs. Signposts and triggers (step 7) are specified to monitor whether actions should be implemented earlier or later or whether reassessment of the plan is needed (step 10).

7.2.2 *Construction of Pathways*

In this study, pathways were constructed by means of expert judgement and computer simulations for flood and drought risk management for differing regions in the Rhine delta. Together with experts involved in the Delta Programme, policy actions and their adaptation tipping point and sell-by date were assessed using end-point scenarios for 2050 and 2100. With computer simulations the action's performance were assessed over time for an ensemble of 100-year transient scenarios. For each transient scenario and each policy action, the moment of a tipping point was assessed by considering when an action performs below two threshold values: one for a 'moderate impact' events and one for a 'severe impact' events. One severe event and a few moderate events can both result in a tipping point. The threshold values were determined together with fellow researchers and experts contributing to the Delta Programme. From an ensemble of runs, statistics of sell-by date values were determined (e.g. shortest, longest, median) and presented in box-whisker plots.

To construct the pathway maps, the policy actions were grouped. Actions with long sell-by dates are shown on the top or bottom of the map, while actions with short sell-by dates are shown close to the current plan. The next step was to add the sell-by dates and all the possible transfers to other actions that would extend the sell-by date. Each action has its own color. Sometimes actions affect each other. If the sell-by date for an action increased considerably, this is shown by an additional line in the same color (see e.g. Figure 42). Next, nonsensical actions were eliminated (background color in contrast to bright colored logical actions). For example, it may be nonsensical to implement large scale actions in the near future, if other (flexible) actions are sufficient.

Pathways were also generated in joint consultation with water managers involved in the Delta Programme by means of storylines. Storylines are narratives of plausible futures including climate change, socio-economic developments and policy actions. The storylines were combined and plotted on an adaptation map.



	Path actions	Relative Costs	Target effects	Side effects
1	🔴	+++	+	0
2	🟡 🔴	+++++	0	0
3	🟡 🟢	+++	0	0
4	🟡 🔵	+++	0	0
5	🟢	0	0	-
6	🟢 🔴	++++	0	-
7	🟢 🟡	+++	0	-
8	🟢 🔵	+	+	- - -
9	🔵	++	+	- - -

Adaptation Pathways Map **Scorecard pathways**

Figure 40: An example of an Adaptation Pathway map. Starting from the current situation, targets are first missed after four years. Following the grey lines of the current policy, one can see that there are four options that can be implemented after this point. Actions A and D should be able to achieve the targets for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, a tipping point is reached within about five years; a shift to one of the other three actions will then be needed to achieve the targets (follow the orange lines). If Action C is chosen after the first four years, a shift to Action A, B, or D will be needed in the case of Scenario X (follow the solid green lines). In all other scenarios, the targets will be achieved for the next 100 years (the dashed green line). The scorecard at the right provides information on costs and benefits of the pathways, thereby supporting the decision making on (a) preferred pathway(s).

7.3 APPLICATION OF THE APPROACH TO THE RHINE DELTA IN THE NETHERLANDS

7.3.1 *The Delta Programme and the Rhine Delta in the Netherlands*

We applied the DAPP approach to the Rhine Delta in the Netherlands. Although the Dutch Delta is well protected at present, future climate and socio-economic changes may require adaptation. In 2008, the Committee on Sustainable Coastal Development (best known by its more colloquial name 'Second Delta Committee') recommended to develop and implement a so-called Delta Programme which' objectives would have to be to keep the Netherlands a safe and attractive place to live and work (Kabat et al., 2009; Delta Programme, 2012a). These recommendations were adopted by the Dutch government. The main task of the Delta Programme is to develop a long-term policy that guarantees flood protection and sustainable freshwater supplies that are economically efficient, both now and in the future. The Delta Programme is directed by the Delta Programme Commissioner. It is organised along three national sub programmes devoted to flood risk, fresh water supply and spatial planning, and six regional sub programmes. All sub programmes are interconnected, because the effects of interventions in one region can extend to other regions.

In this study, we focus on the part of the Delta Programme that involves the Rhine delta. The main physical characteristics of the Rhine Delta and its control structures are presented in Figure 27. After the Rhine enters the country, the water is distributed over the branches Waal, Nederrijn and IJssel. The river IJssel supplies the IJsselmeer and Markermeer lakes with fresh water. This supply is controlled by a weir in the Nederrijn at Driel. The Afsluitdijk barrier protects adjacent areas from flooding, and enables water storage in the lakes. Lake levels are carefully controlled by means of outlets in the barrier in order to maintain target water levels of -0.2 m MSL during summer half year and -0.4 m MSL during the winter half year. Flood safety standards are expressed in terms of an average return period, e.g. 1,250 years for the river region. The standards are laid down in law for every dike ring area, and depend on the economic activities, the number of inhabitants and flood characteristics. Thus, they are risk-based. The Haringvliet sluice gates and the Maeslant storm surge barrier protect the Rhine Estuary from (mainly coastal) flooding. The Haringvliet sluice also limits salt intrusion into the river. The Nieuwe Waterweg is still open and the large depth of this main shipping route requires a lot of river water to push back the salty water for fresh water supply in the Midwest region.

The IJsselmeer and Markermeer are the main water reservoirs. In dry periods, water from these lakes is used to supply large parts of the delta with fresh water. If the water level in the lakes or rivers drops too much, ships have difficulty navigating through the sluices and damage to ships and infrastructure may occur. For the Midwest region the inlet of river water near Gouda is an important source of fresh water. Despite the extensive network of ditches and canals and the large amount of water storage, the water supply is insufficient to meet the fresh water demands in dry periods. During periods of low Rhine flows, the Gouda intake can not be used due to high salt concentrations in the lower river (current norm is 200 mg Cl/l). The major uses of water are for agriculture (for irrigation), for flushing (to mitigate adverse impacts for agriculture and drinking water due to salty upward seepage water and salt intrusion in the river), and for maintaining water levels in the lakes and canals. Drinking water and industry are also important water consumers, although the quantity used for these is negligible compared to the other uses.

In the future, climatic change and socio-economic developments may result in increased in water demand, reduced water supply and increased flood risk. The drivers for the increased water demand are intensified evapotranspiration, more salt intrusion, and changes in the agricultural sector. Lower water availability in summer results from reduced precipitation, lower river flows and more salt intrusion in the rivers. Increased flood risk is due to sea level rise, higher river discharges, and population and economic growth. In addition, recent insights on the stability of river embankments forced the government to reconsider whether flood prone areas are sufficiently safe.

The Delta Programme describes strategic decisions on the following five topics:

1. *Flood protection standards*: given the increase of economic value of flood protected areas, what are proper safety levels, and how should these be expressed and implemented in policy.

2. *Flood risk management in the Rhine–Meuse Estuary*: what measures need to be taken to guarantee compliance with protection standards? How is the Rhine discharge distributed over the river branches and should estuaries be protected from coastal flooding by flood barriers or not?

3. *Fresh water availability*: How can future water demands be met in a sustainable and economically effective manner?

4. *Water level in the IJsselmeer area*: Should water levels be raised to make use of energy efficient gravitational drainage, or should current water levels be maintained and pumping capacity increased accordingly?

5. *Adaptation through spatial planning*: what spatial planning measures can contribute to reduction of flood risk, and how can non-

structural measures reduce flood risk in existing at flood prone areas?

The present case study focuses on flood risk management along the main Rhine branches and in the IJsselmeer region, and on drought risk management for areas that are supplied with river water (the Midwest region) and areas that are supplied with fresh water from the IJsselmeer.

7.3.2 *Policy Actions*

To address both current and possible future problems and support the strategic decisions, we consider the main alternative policies identified by the Delta Programme 2012a. Flood risk policy actions (Table 8) aim to prevent flooding and/or mitigate flood damage. Actions include: raising and strengthening river dikes, lowering river water levels, adaptation of the distribution over its branches, and land use change. A barrier in the Rhine Estuary can reduce flood risk and limit salt intrusion in case of low Rhine flow. Water levels in the IJsselmeer can be allowed to rise along with sea level rise to enable drainage of excess water under gravity. However, this requires raising of the adjacent dikes as well. Alternatively, water levels can be maintained by either enlarging the gravitational discharge capacity or building large pumps for discharging water into the Wadden Sea. Raising the water level requires raising dikes and adapting infrastructures. Keeping current target water levels may require adaptation of water inlets and shipping sluices to enable water use during drought.

Droughts may result in damage for crops and infrastructures (e.g. embankments and buildings). Moreover, associated low flows and water levels hamper navigability of rivers and lakes. Drought risk policy actions (Table 9) aim to reduce these adverse effects by provision of fresh water and by reducing water demand. Water storage in the IJsselmeer lake can be temporarily increased by raising its water levels. When using the lake's water to meet water demands, its water level will drop. This may limit navigability and may require large infrastructure adaptations along the IJsselmeer area. If the level drops below -0.4m MSL, water transport to the regional water systems is almost zero and only possible if additional (temporary) pumps are installed. As a result, districts supplied by the IJsselmeer lakes receive less water than asked for resulting in water deficits. Water deficits may also occur due to capacity limits of regional canals. The degree to which levels drop depends on whether priority is given to supplying to the rural areas or to maintaining the water levels of the IJsselmeer lakes. In some of the simulations, higher priority was given to the rural areas, while in others higher priority was given to the levels of the lakes. In this case study, changes in water levels for lake Markermeer are not explored, as this would require too much adaptation for current cities and therefore this is not a viable policy action.

Crops are irrigated by means of sprinkler installations if this is economically viable. If drought events occur more frequently or if they are more severe, farmers can adapt by using additional sprinkler installations. Note that, strictly speaking, this would not constitute a policy action on the part of the government, but rather an autonomous response. This is indeed a scenario that is included in the Delta Programme's Fresh Water sub programme. In the scenario, highly valuable crops are fully irrigated by means of sprinkler installations. Meadows, corn and sugar beet fields are irrigated with double intensity compared to current situation. For other crops, intensity increases by 50% with the exception of potato fields, that require no additional irrigation through sprinkling compared to the current conditions. Obviously, with this intensified sprinkling demands more fresh water is needed to supply these regions.

Water demands can be reduced by increasing the efficiency of water use in the regional system, by changing to salt and/or drought tolerant crops, and/or by decreasing agriculture or moving agriculture to areas with more appropriate environmental conditions. Actions to increase or safeguard the fresh water supply via Gouda in case of lower river discharges in summer include increasing the intake capacity, implementing a bubble screen to limit salt intrusion in the Rhine Estuary and closing of the estuary with a sea barrier. To enable navigability of the rivers enough water needs enter the Nederrijn river branch.

A preliminary assessment of the costs for some of the actions has been done within the framework of the Delta Programme. Costs for raising the river dikes to meet the present design norm while taking into account the recent insights in the failure mechanisms are estimated at M€ 4,300 for the whole of the Netherlands (including Meuse river) (Kind, 2013). To accommodate a design discharge of 17,000 m^3/s estimated costs for raising dikes and room for the rivers are similar: M€ 4,000 (Kind, 2013). Implementing 'unbreachable' dikes is more costly, and is estimated at M€ 13,000. Costs for increasing the IJsselmeer intake capacity to improve storage water use in case water levels drop below -0.3 m MSL are estimated at M€ 8 million (Delta Programme, 2012b). In case water levels drop below -0.4 m MSL, costs rise considerably as not only the intake capacity should be raised, but also embankments need to be strengthened to avoid slides due to instability. Estimated costs are M€ 31 for allowing the water levels to drop until -0.5 m MSL and M€ 60 until -0.8 m MSL. Raising the water levels is relatively more expensive as it requires the dikes to be raised to ensure safety against flooding. Costs for raising the water level to -0.1 m MSL, +0.1 m MSL and +0.5 m MSL are estimated at respectively M€ 14, M€ 62 and M€ 187 (Delta Programme, 2012b).

Table 8: Overview of flood risk management options and their potential impacts.

Option	Description	Potential impacts and purpose of actions
Ref	Reference situation without policy actions	
D17	Raising the dikes to cope with discharge of 17,000 m^3/s at Lobith	River flood events
D18	Raising the dikes to cope with discharge of 18,000 m^3/s at Lobith	River flood events
Cdike	Unbreachable climate dikes: wide strong embankments that may overtop without breaching in case of high discharges	River flood events
Rfr	Room for the river: with extra side channels, the river has more space after a threshold discharge is exceeded.	River flood events
Q1600	Adapted water distribution at discharges > 16,000 m^3/s. 80% (instead of 66%) of the surplus is diverted to the Waal and the rest to the IJssel. E.g. at 18,000m^3/s 1600 m^3/s to Waal and 400 m^3/s to IJssel	River flood events
Q2000	Adapted water distribution after discharges > 16,000 m^3/s. All extra water above 16,000 is diverted to Waal. (2,000 at 18,000m^3/s)	River flood events
LUadap	Adapting land use to mitigate flood damage (e.g. floating houses)	River flood damage
DC2	Enlarge gravitational drainage capacity at Afsluitdijk with factor 2	IJsselmeer floods
PC500	Add pump capacity at the Afsluitdijk of 500 m^3/s	IJsselmeer floods
PC1000	Add pump capacity at the Afsluitdijk of 1,000 m^3/s	IJsselmeer floods
L06	Change IJsselmeer target levels to MSL+0.6m and MSL+0.2m for summer and winter respectively	IJsselmeer floods

Table 9: Overview of drought risk management options and their potential impacts.

Option	Description	Potential impacts and purpose of actions
Ref	Reference situation without policy actions	
IJ285p	Structure at Pannerden to enable desired discharge of 285 to the IJssel river during low flows. At low flows (<2,000 m^3/s) 0.66 to Waal instead of 0.8	Supply agriculture and water level control, IJsselmeer Infrastructure & navigability, River navigability
IJ400p	Structure at Pannerden to enable desired discharge of 400 to the IJssel during low flows, increased capacity water inlet Midwest region with factor 2	
L01	Change IJsselmeer summer target levels to +0.1m MSL	Supply agriculture and water level control, IJsselmeer Infrastructure & navigability
L06	Change IJsselmeer target levels to +0.6m MSL and +0.2m MSL for summer and winter respectively	
L-06	Water levels IJsselmeer are allowed to decrease until -0.6m MSL. Water supply to districts has higher priority than target levels IJsselmeer	
DA0.8	More efficient water use in regional water system: decrease water demand for agriculture with factor 0.8	IJsselmeer Infrastructure navigability
DW0.8	More efficient water use in regional water system: decrease water demand for maintaining water levels in regional areas with factor 0.8	
DAW0.7	More efficient water use in regional water system: decrease water demand for maintaining water levels and for sprinkling in regional areas with factor 0.7	
DApl	Increase sprinkling plausible maximum.	Supply agriculture, IJsselmeer infrastructure & navigability
BS100	Bubble screen that mitigates salt intrusion in Rhine Estuary such that it results in similar concentrations to a 100 m^3/s higher discharge	Supply agriculture and water level control to Midwest area
BS200	Bubble screen that mitigates salt intrusion in Rhine Estuary such that it results in similar concentrations to a 200 m^3/s higher discharge	

7.3.3 *A Model for Assessing the Performance of Policy Actions*

To assess the performance of the scenarios and the policy actions over time we used a fast, integrated model that was especially developed for this purpose and is described in detail in Chapter 6. The model comprises 1) a model of the water system in terms of water availability and demand, and 2) a model of the impacts of flooding and water scarcity. In addition, the model allows simulation of effects of interventions on water availability and impacts. Water quality is not considered, except for salt intrusion in the Rhine Estuary.

Transient scenarios were used as input to simulate impacts over time. The climate scenarios in this study are based on the KNMI'06 G (+2°C in 2100) and Wp scenarios (+4°C in 2100) (Van den Hurk et al., 2007, 2006). Thus, changes in precipitation and temperature are linear in time, i.e. the changes in 2100 are twice as large as the changes in 2050 (Beersma, 2012; Haasnoot et al., in prep). The ensemble of ten realisations for each of the No Change, G and Wp scenarios was developed with the KNMI precipitation generator for the Rhine basin (Beersma, 2001). Time-series for Rhine discharges into the Netherlands were obtained by using the transient time-series of temperature and precipitation (for different locations in the Rhine basin) as input for a hydrological model of the Rhine (i.e. the HBV-Rhine model; Te Linde 2011). This yielded 3 times 100 years of Rhine discharges per day, comprising natural variation in the occurrence of peak and low flows (Figure 41). Water levels in the Wadden Sea were constructed by making use of the bootstrap technique (Efron and Tibshirani, 1994). Thus, a 1,000-year time-series was generated by sampling with replacement of individual years from the 1961–1995 period, i.e. the same base period that was used for the precipitation generator for the Rhine basin and for the ten 100-year time-series of precipitation and evaporation in the Netherlands. For the G and Wp scenarios, a range of sea level rise was included. This resulted in an ensemble of 50 realisations: 10 No Climatic Change realisations, 10 G scenario realisations combined with the lower estimate for sea level rise, 10 G scenario realisations combined with the upper estimate for sea level rise and 20 Wp scenario realisations, again using 10 upper and 10 lower estimates for sea level rise.

Water availability is based on a simulation of water distribution from the Rhine at Lobith through the main river channels, canals and the large lakes in the IJsselmeer area. The model estimates flow in the sections of rivers and canals, and the water levels of the lakes, taking into account desirable, maximum and minimum discharges (e.g. for flushing or shipping) that are specified for certain sections, and target levels for the IJsselmeer lakes. The water level in IJsselmeer is a major control of the discharge capacity at the Afsluitdijk from IJsselmeer in to the

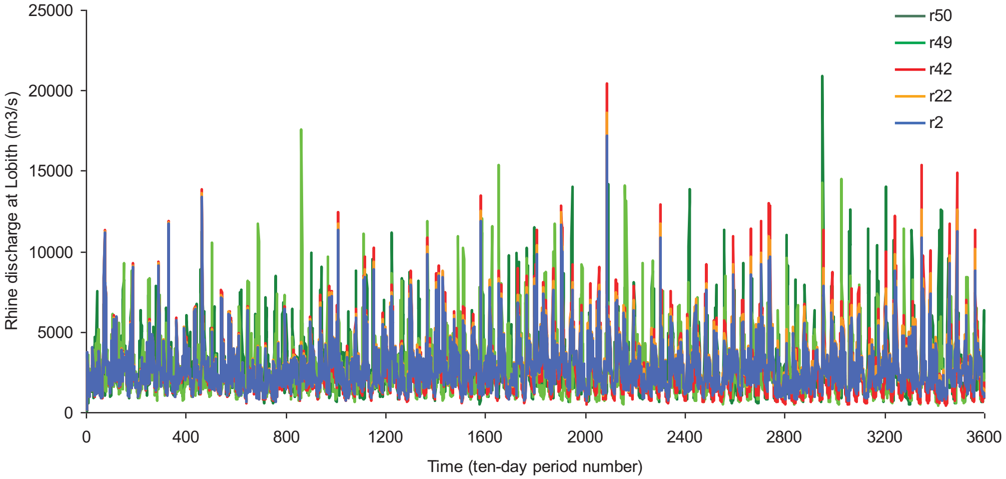


Figure 41: Example of the transient scenarios for the Rhine discharge at Lobith for a scenario without climate change (r2), climate change scenario G (r22) and climate change scenario Wp (r42, r49, r50). Realisations r2, r22 and r42 have similar natural variability. Realisations r42, r49 and r50 result from the same climate scenarios, but different in year-to-year variability.

Wadden Sea, and for the inlets from the Markermeer and IJsselmeer to the regional canals that distribute the water to the provinces bordering the lakes. The discharge capacity at the Afsluitdijk depends also on the water level in the Wadden Sea.

Water demand for sprinkling and water level management results from a simple gridded, two layer groundwater model on a 1km by 1km resolution. The model takes into account a limited number of land use and soil types. For each layer in each grid cell, a water balance is calculated based on the precipitation, evaporation, drainage, infiltration, percolation, capillary rise and seepage. The simulation results for the cells are aggregated over a watershed area linking the regional areas to the water distribution network. The water demand for sprinkling is estimated from the difference between actual and potential evaporation. The amount of water required for maintaining the target water level in the local surface waters areas is derived from the net precipitation and the surface area of these waters.

Salinity levels at the Gouda inlet are estimated using an empirical relation between river discharge and sea levels. As a result of low flows, salinity may reach a threshold at which the inlet supplying the Midwest region with fresh water is stopped.

Impacts on flood risk in the river region include river floodings and related casualties and damages. River floodings are determined from the Rhine discharges by translating them into water levels using rating curves for a selection of potential breach locations (De Bruijn and Van der Doef, 2011). Subsequently, the model calculates the probability of dike failure caused by piping or by wave overtopping by examining the difference between dike level and water level (Van Velzen, 2008). The damage, casualties and affected people in an inundated area depend on whether the dikes are breached or overtopped, and whether people have been evacuated in advance of inundation. These impact estimates are based on inundation-damage look-up tables in combination with a-priori determined inundation patterns calculated with a complex combined 1D-2D hydrodynamic inundation model (SOBEK) for each potential dike breach location (De Bruijn and Van der Doef, 2011). For the IJsselmeer, flood risk is estimated by analysing the extent and duration of a threshold lake level.

The impact of low flows on navigation is calculated in terms of the extra costs to transport goods between the Netherlands and Ruhr area in Germany. These cost estimates were developed by Van Velzen (2008). They are calculated using the Rhine discharge, the discharge-water depth relation at a critical location (near Nijmegen), and a loading depth–cost relation for different ship types.

Decreases in crop production due to drought are based on the Agricom model (Abrahamse et al., 1982) and calculated as a piecewise linear function of the ratio of the actual and the potential evaporation. It was assumed that in case of water shortage, farmers with sprinkling installations will use different water sources to prevent crop damage. Consequently, this damage is only affected by changing hydrological conditions from the climate realisations, land use changes and autonomous adaptation such as increase of sprinkling installations. Impacts of drought risk actions are reflected in IJsselmeer water levels and the supply deficit: the percentage of the total water demand from the regional areas that cannot be supplied by the main system. The IJsselmeer water levels are also used to estimate drought impacts on infrastructure and navigability in the IJsselmeer, caused by a temporarily shallow fairway.

7.4 ADAPTATION PATHWAYS FOR THE RHINE DELTA

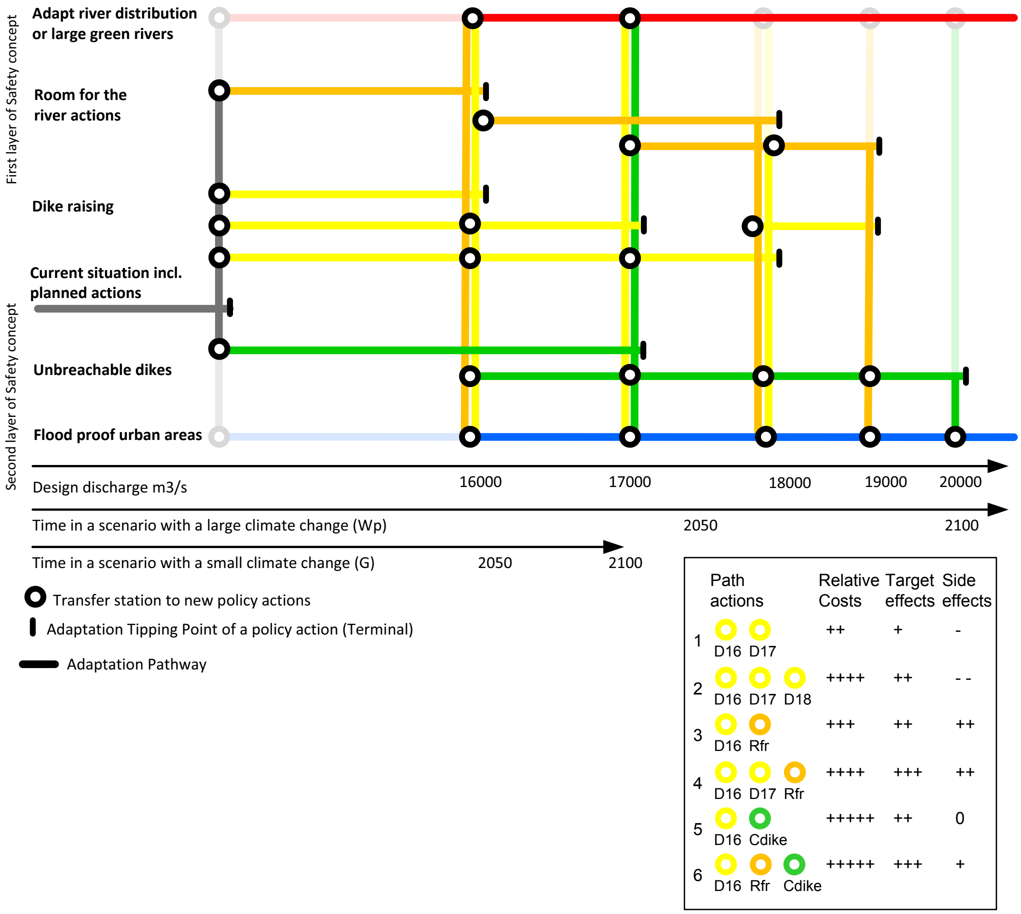
Pathways were developed for flood risk management of the upper river and the IJsselmeer region, and for drought risk management in terms of fresh water supply from the IJsselmeer and fresh water supply towards the Midwest region. Most pathways were first constructed in consultation with experts and water managers contributing to the Delta Programme, and then further elaborated using the modelling results of the transient scenarios. In addition, the mutual influence among decisions on flood and drought risk management among the different regions are discussed.

7.4.1 *Flood Risk Management – Upper River Region*

In the expert judgment based adaptation maps for flood risk in the upper river region, we put the policy actions against the design discharges, as this is an important driver that is surrounded with uncertainties. Depending on the scenarios, the design discharge may increase faster or slower (two additional horizontal axes). A separate adaptation map was developed for each of the Rhine branches as the promising policy actions differ among the different branches. For example, summer river bed widening is possible along the Waal and IJssel branches, but only to a very limited extent along the Nederrijn-Lek.

Figure 42 shows the pathways for the Waal branch. In this region, the actions that are planned to be carried out in the near future consist of strengthening of the river dikes that do not meet the present protection standards according to the updated test and design rules (see section 7.3.1), and actions aiming at lowering of the water level by giving more space to the river (grey line). These actions are insufficient to control the flood risk over a longer time span. Therefore, five alternative policy options were defined. The first option consists of actions that result in lowering of the water level during flood by giving more space to the river (e.g. lowering of flood plains; orange lines). Experts involved in the Delta Programme expect that these actions can only partly solve the problem. If we start with the implementation of these actions, we will eventually have to continue with another action. Other actions include dike strengthening (yellow lines) (either with a large increase in one action or in successive smaller steps), development of 'unbreachable climate dikes' (green lines) (e.g. De Bruijn et al., 2013), adaptive construction of houses and other buildings (blue line), or application of very large measures, such as the development of a 'Green River' i.e. a new river branch or spillway that will only be flooded during extreme events and remains dry otherwise (red line). As it is not very likely that this type of actions will be selected now, we made the first part of this route translucent. The resulting map (Figure 42) show all possible adaptation pathways that – given the policy options considered – result in a safe river region in the future.

Storylines were developed by water managers involved in the Delta Programme for the river region. Although some actions in the storylines were very location specific, they could be plotted on the map presented in Figure 42. An example of such a storyline is: *The new insights in the failure mechanism of river embankments requires large scale dike strengthening. This will be done in the short term. Expected risk reduction per invested euro is being used as a criteria to prioritise the dike sections*



	Path actions	Relative Costs	Target effects	Side effects
1	D16 D17	++	+	-
2	D16 D17 D18	++++	++	- -
3	D16 Rfr	+++	++	++
4	D16 D17 Rfr	++++	+++	++
5	D16 Cdike	+++++	++	0
6	D16 Rfr Cdike	+++++	+++	+

Figure 42: Adaptation pathways for the Waal river in the Netherlands and a scorecard for the most promising pathways

(i.e. the section that has the largest contribution to the total flood risk will be strengthened first). Compensation of the impact of climate change is done by giving more room to the river (e.g. by lowering of floodplains, excavation of side channels or relocation of river dikes). This is more expensive than dike strengthening, but has additional benefits by enhancing the environmental quality as well. The excavated clay can be used to strengthen the dikes.

Most storylines included dike raising actions or provision of additional room for the river (or combinations of these actions). All (except one of 7) pathways started with maintenance of the dikes, to ensure that they are able to cope with the present design discharge of 16,000 m^3/s. Only one pathways started with providing more room for the river. The reason to start with this action, was that it will be more difficult to implement this action in the future due to limitations in available space (due to socio-economic developments) and, probably, in societal support. Raising dikes and improving their strength to meet the design conditions can also be done later as they require less space, or can be done with alternative constructions instead of ground. Alternative options, such as flood proof urban areas, were not considered. In most pathways, current spatial reservations, which are made to implement (more) room for the river at a later stage, if necessary, were stopped. Consequently, if the future design discharge would exceed 18,000 m^3/s, additional dike raising will be the only logical next step, as other options will then be very costly and have a large societal impact. This could be considered as a potential lock-in situation. For each storyline, opportunities were identified together with the regional water managers. For example, if the plan is to raise the dikes, such an action can be implemented if maintenance is needed; the clay that comes available when implementing room for the river actions can be used to raise the dikes. Potential inflexibilities (which occur in case of high costs to switch or add an action) are e.g. switching from delta dikes to room for the river, or from dikes to room for the river at a later stage if no spatial reservations were made.

With the computational model, the efficacy of the identified policy actions over time was assessed for the ensemble of transient scenarios. Appendix D gives an example of the results for flood damage. The occurrence of an adaptation tipping point is based on performance on the following outcome indicators: flood damage and casualties. Results were deemed unacceptable after the occurrence of two small and/or one large flood event. To assess whether these events occurred, threshold values were used: 50 and 1000 casualties and 2 and 20,000 million€ flood damage for small and large events respectively.

The sell-by dates (here referred to as sell-by years) for the ensemble of transient scenarios are presented in Figure 43. The range of the sell-by year is very large for the reference situation and raising the dike to a level associated with a design discharge of 17,000 m^3/s, and

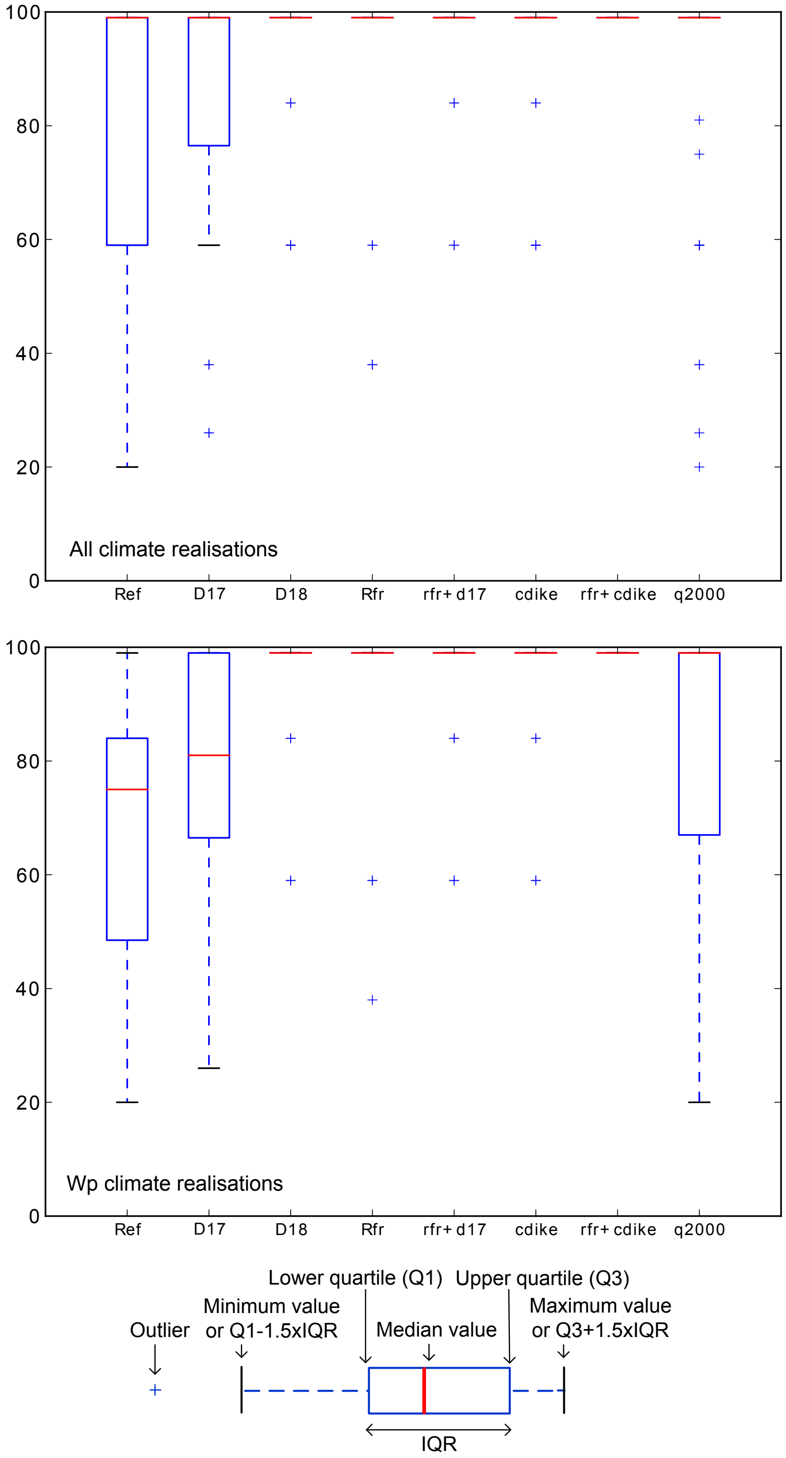


Figure 43: Box-whisker plot of the sell-by years based on the threshold values for casualties for the ensemble of transient scenarios (upper) and for the Wp climate realisations (lower) and different policy actions. For explanation of the abbreviations see Table 8.

Table 10: Overview of flood risk management options and their approximate sell-by discharge. For explanation of the abbreviations see Table 8

Policy action	ATP discharge [m^3/s]	Policy action	ATP discharge [m^3/s]
Ref	15,500	Q2000 + D18	18,000
Q1600	16,000	Cdike + D17	18,500
Q2000	16,000	Rfr	18,500
D17	17,000	Cdike + D18	19,500
Q2000 + D17	17,000	Rfr + D17	19,500
Cdike	17,500	Rfr + D18	20,000
D18	18,000		

has many outliers for the other policy actions. With most actions the sell-by year is prolonged to the end of the century or more, but flood events may still occur earlier as showed by the outliers. The question is whether this is acceptable or not. The difference between the No Climate Change and Scenario G realisations is small. In the Wp scenario the median value for sell-by year shifts from 100 to 75 in the reference case (no policy actions). Doubling the threshold values changes the results: in the no-change scenario all realisations and policy actions perform acceptably, in the G scenario only two outliers for the reference situation, and in the Wp scenario the median value for the sell-by year in the reference case extends to 80. Still, looking at the differences for the ensemble of scenarios, this does not radically change the conclusions. Although the sell-by year is sensitive for threshold values and climate scenarios, the main differences are caused by natural variability of the river discharges, as reflected in the realisations for each scenario. Extreme discharges causing floodings rarely occur, both in reality as well as in the simulations. If they occur in a climate scenario they are larger due to increased precipitation, especially in the Wp scenario, and at the end of the century due to the transient nature of the scenarios.

In order to investigate whether the sell-by dates based on expert judgement are roughly correct, we also assessed the critical discharge under which a policy action results in floodings and thus reaches an adaptation tipping point (Table 10). Comparing these results with the initial expert judgement resulted in small differences in the pathways from those initially produced on expert judgement. For example, combinations of room for the river and dike raising actions have acceptable results at large discharges than presented in the map, with differences ranging from 500 to 1,000 m^3/s. Also, the room for the river action simulated with the model was at a larger scale than the one presented in the adaptation map, and can thus cope with higher discharges. Remarkably, the action that modifies the water distribution along the Rhine branches still result in several flood events in the ensemble results.

7.4.2 *Flood Risk Management – IJsselmeer Region*

For flood risk management in the IJsselmeer region two alternatives are available: maintaining the current target water levels through extra discharge or pump capacity, or increase water levels to enable gravity draining. ATPs for the flood risk policy in the IJsselmeer are defined as the occurrence, during the winter half year, of one of the following events: the water level exceeds +0.1m MSL but not+0.3m MSL for three ten-days periods (small event) or, the exceedence of +0.3m MSL for one ten-day period at least.

With current target levels, an ATP is reached after ±5, 30 or 70 years (min, median, max values; see Figure 44). In the No Change realisations, the ATP is reached after ±55 years (median), in Scenario G after ±30 years and in Scenario Wp after ±25 years. Doubling the gravitational discharge capacity reduces the number of 10-day periods above threshold considerably and delays an ATP in most of the realisations, but not for many of the Scenario Wp realisations (median ±80 years) or for several outliers in the No Change realisations (earliest after 60 years). Additional pumping capacity of 500 m^3/s is not sufficient to prevent outliers which may result in an ATP after ±55 years at earliest. A risk averse policy maker could implement a pump with a much higher capacity of for example 1,000 m^3/s; in that case water levels seldomly exceed +0.1m MSL, even in the Wp scenario with the large sea level rise.

Evaluating the policy action of increasing the water level to +0.2m MSL requires adaptation of the ATP threshold values, as this action inevitably requires increase of the heights of the embankments along IJsselmeer. If, for example, levee heights are increased by 0.5m, an ATP is reached after ±45 years (median value for all realisations) in case use the same relative threshold values. A 1m increase of levee height would result in acceptable results in all realisations until 2100. If the ATP criteria would change such that higher water levels would be acceptable, reaching an ATP would be extended to ±80 years with threshold values of +0.4m MSL and +0.6m MSL for the conditioned mentioned above. With these threshold values the doubling of the gravitational discharge capacity and the pump of 500 m^3/s would be sufficient to reach the target until 2100.

Based on the ATP's an adaptation map was generated for flood risk management in the IJsselmeer (Figure 45).

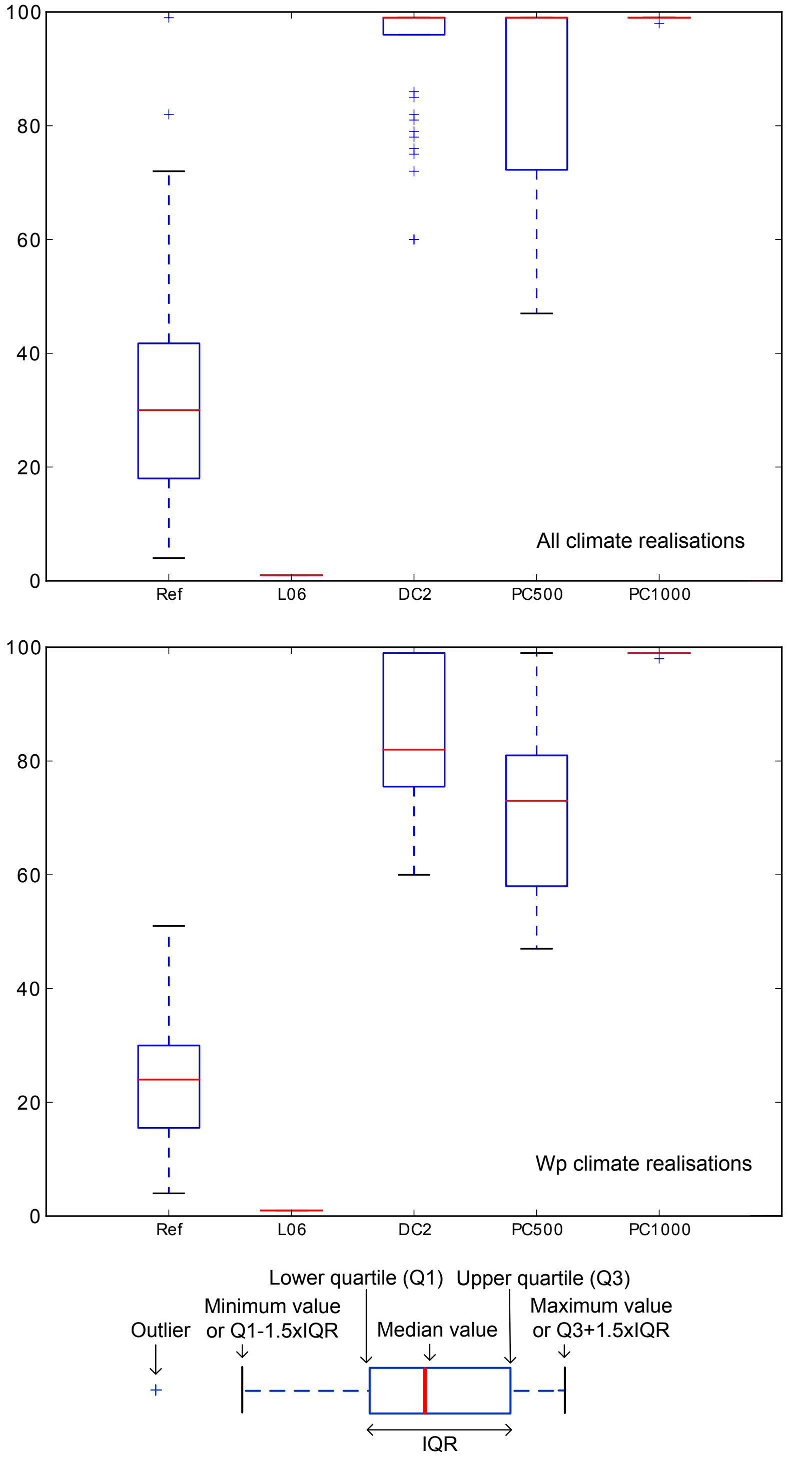
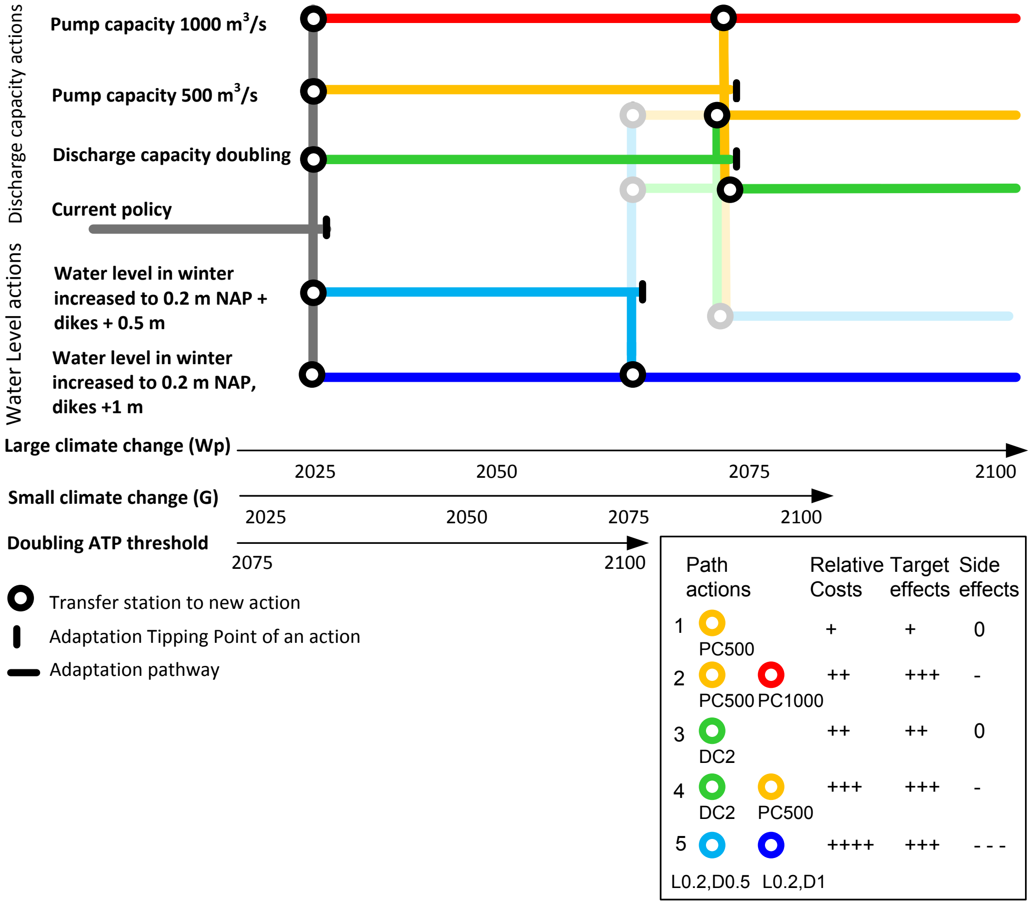


Figure 44: Box wisker of the sell-by years of for flood risk management actions in the IJsselmeer for all realisations (upper) and for the Scenario Wp realisations (lower). For abbreviations of policy actions see Table 8.



	Path actions		Relative Costs	Target effects	Side effects
1	○ PC500		+	+	0
2	○ PC500	○ PC1000	++	+++	-
3	○ DC2		++	++	0
4	○ DC2	○ PC500	+++	+++	-
5	○ L0.2,D0.5	○ L0.2,D1	++++	+++	- - -

Figure 45: Adaptation pathways map for flood risk management actions in the IJsselmeer and a scorecard for the most promising pathways

7.4.3 *Drought Risk Management – Fresh Water Supply from IJsselmeer*

Figure 28 (Chapter 5) shows the preliminary adaptation pathways map that was based on expert judgment and preliminary model results for endpoint scenarios. It shows the ten main alternative policy options regarding fresh water supply from IJsselmeer including actions aiming at increasing the storage capacity (upper part) or decreasing water demand (lower part). A plausible pathway could be for example, a small raise of lake levels to +0.1 m MSL and then either increase the level even more, or accept that, in drought conditions, the level drops to -0.6 m MSL. The latter results in difficulties for navigation, but this action can be implemented without serious adaptation of infrastructure. To limit flood risk along this pathway, discharge capacity needs to be increased to keep water levels low enough during the winter (see Section 7.4.2).

The efficacy of promising policy actions was assessed over time with the computational model. The following indicators and threshold values were used to determine whether an adaptation tipping point occurs for fresh water supply from IJsselmeer: 1) water level in IJsselmeer: if during the summer half year one of the following events occurs at least twice: the level drops between -0.3 m MSL and -0.4 m MSL during two ten-day periods or below -0.4 m MSL for one ten-day period; 2) agricultural damage: if the damage, measured over a two-year period, exceeds M€ 1250 in two years or if damage from a single event exceeds M€ 2500 (the damage associated with the model simulation of the most severe drought event on record in the Netherlands, 1976, was estimated at M€ 2060). In addition, water shortage was used as indicator for evaluating the results.

Agricultural damage shows both a high inter-annual variability and, in the climate change scenarios an increasing trend. The differences between Scenario G and No Change realisations are relatively small (Figure 46). As it was assumed that farmers will continue to sprinkle crops even if their water supply is limited, most policy actions have little effect on agricultural damage. The one exception is the autonomous adaptation wherein farmers increase the number and capacity of sprinkling installations. Impacts of climate change and policy actions are, therefore, visible in the extent to which target levels are reached in the IJsselmeer area and the amount of water shortage (percentage of water not supplied from the main water system to the regional areas).

Water demand for sprinkle irrigation and water level control is especially high in dry years. The climate scenarios No change and G have similar results for water demand and water levels in the IJsselmeer. As the frequency and intensity of droughts increases with more severe climate change of the Wp scenario, this is also reflected in the increasing water demand. After 2060-2070, water levels in IJsselmeer drop

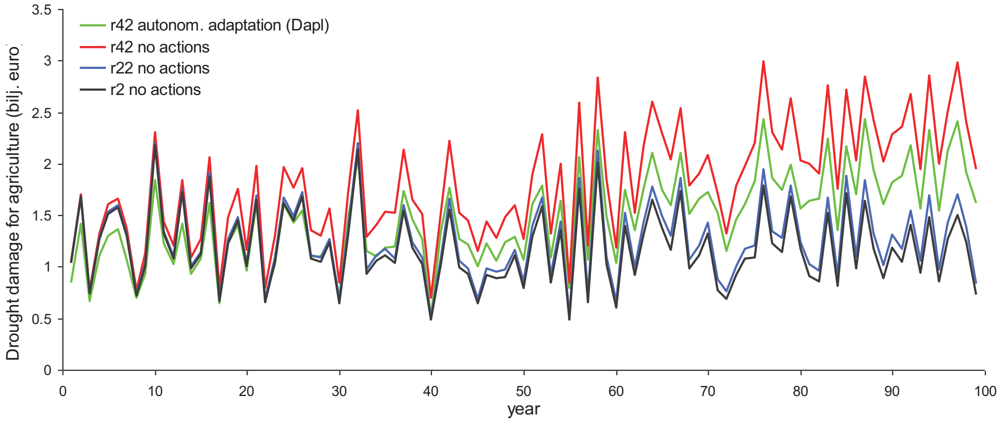


Figure 46: Drought damage for agriculture for a realisation without climate change (r2), two climate realisations (r22 = G scenario and r42= Wp scenario) and autonomous adaptation of farmers (DApl).

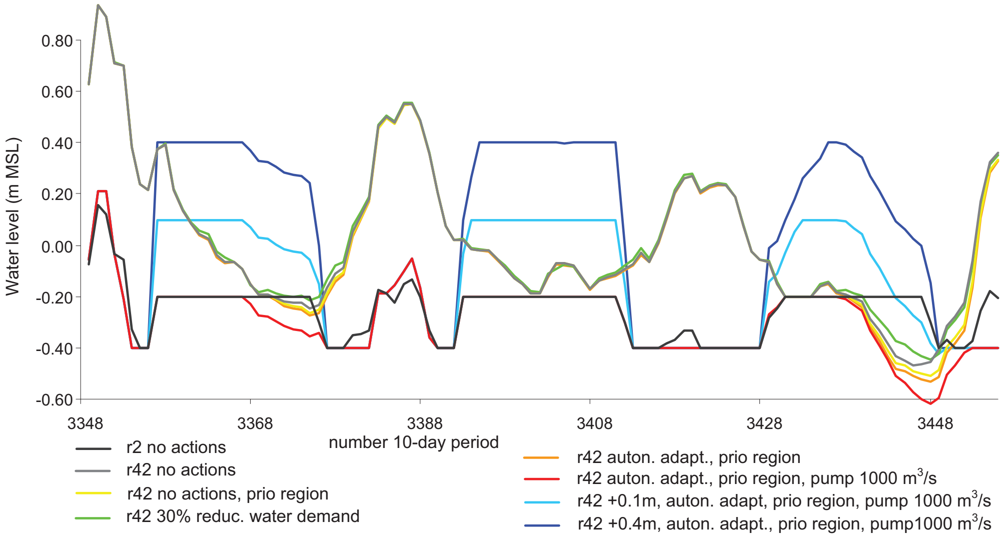


Figure 47: Water level in IJsselmeer for 2093-2096 (10-day periods number 3348-3456) for different climate realisations and policy actions. R2 = without climate change. R42 = similar realisation but with Wp scenario. Auton. adapt. = autonomous adaptation of farmers. 'prio region' indicates that water is supplied to the rural areas first and water levels in the IJsselmeer are allowed to drop. Pump 1000 m^3/s = increase of pump capacity with 1000 m^3/s to drain excess water to the Wadden Sea.

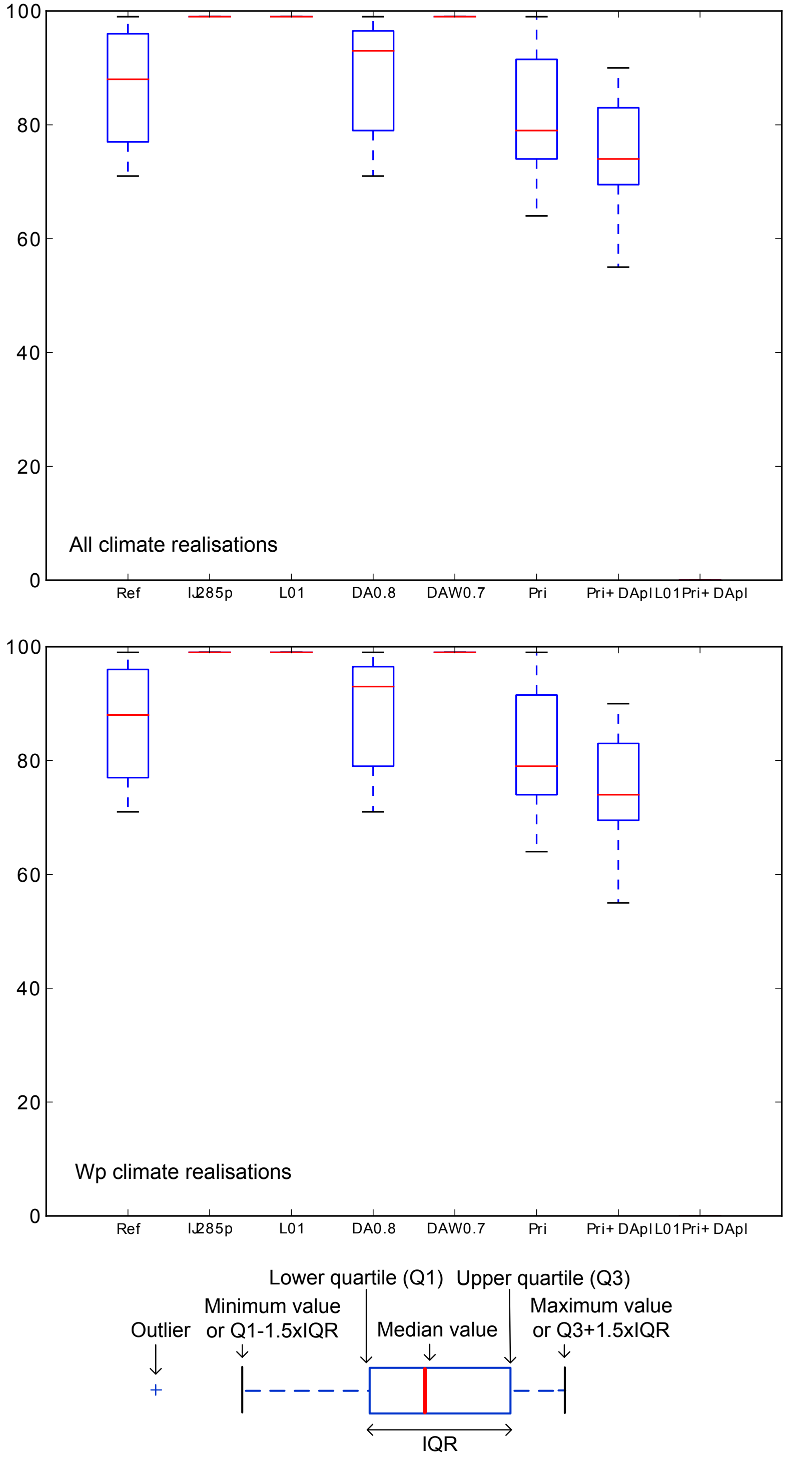
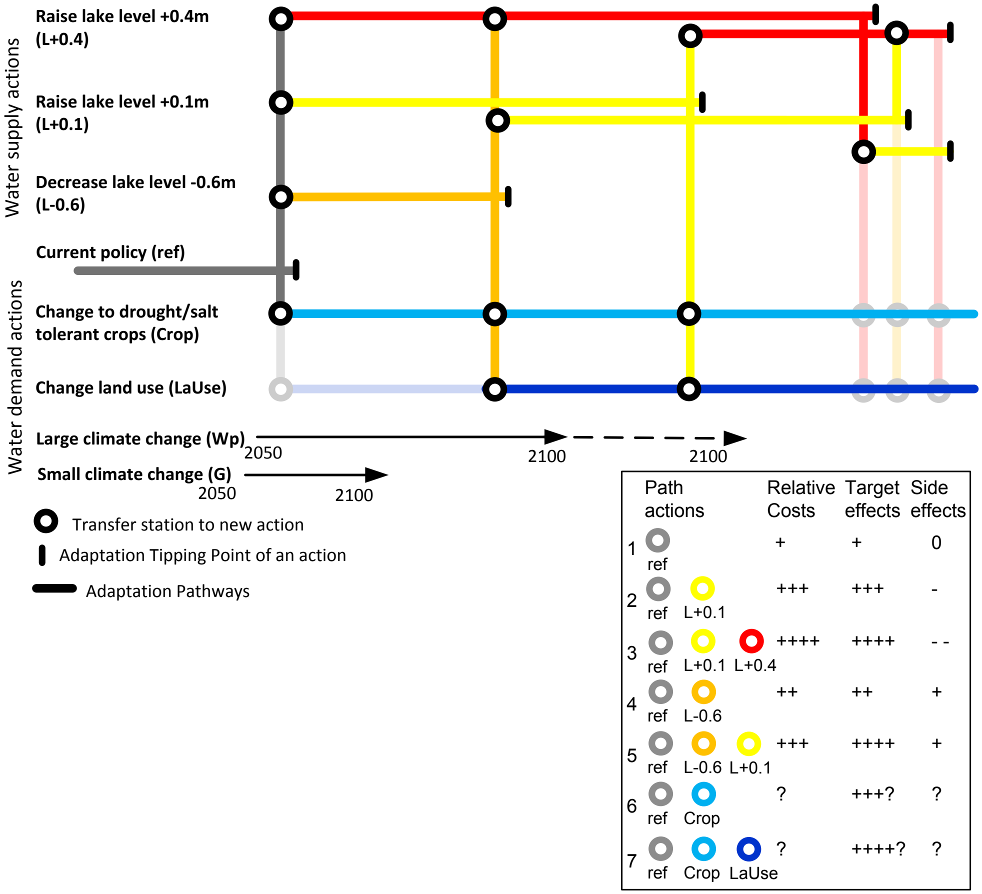


Figure 48: Box wisker of the sell-by years for drought risk management actions in the IJsselmeer for all realisations (upper) and for the Wp realisations (lower) based on threshold values for the IJsselmeer level. See Table 9 for the abbreviations.



	Path actions	Relative Costs	Target effects	Side effects
1	ref	+	+	0
2	ref L+0.1	+++	+++	-
3	ref L+0.1 L+0.4	++++	++++	- -
4	ref L-0.6	++	++	+
5	ref L-0.6 L+0.1	+++	++++	+
6	ref Crop	?	+++?	?
7	ref Crop LaUse	?	++++?	?

Figure 49: Adapted adaptation pathways map for fresh water supply from the IJsselmeer based on modeling results and a scorecard for the most promising pathways. The dashed line in the x-as of the Wp scenario indicates the uncertainties in the results. Raising the level to +0.1m MSL is almost always sufficient, but may not be sufficient if farmers increase sprinkling amounts and if the water supply capacity is increased.

increasingly below target level, sometimes even below -0.4m MSL (Appendix D). Although at these low levels, water transport to the regional systems by gravity is severely limited, lake levels drop further due to low inflow and increased evaporation. In addition, the transport capacity of regional canals limits the water supply. Hence, despite the use of IJsselmeer water for water supply, shortages remain, especially in the northern region.

Policy actions that aim to increase the storage capacity in the IJsselmeer area affect water levels and, hence, water deficits. A snapshot of the impact on water levels is presented in Figure 47. Diverting more water to the IJssel river is effective, but it requires adaptation at both bifurcations at Pannerden and at IJssel-Nederrijn. Especially the former could be very expensive as it requires an additional water control structure to be built, but it does help to reach target water levels in IJsselmeer. Increasing the water level during the summer half year to +0.1m MSL is possible even if inflow reduces considerably like in the Wp scenario. With this policy action, water level rarely drops below -0.2m MSL. Water deficits still remain, even if the IJsselmeer water level is raised significantly, due to limitations of the inlet capacity from the IJsselmeer to regional areas, and the capacity of the canals and channels within in the rural areas. With unlimited drainage capacity from the IJsselmeer to the regional areas, shortages remain only in the eastern part of the northern region as a result of water supply limits of regional canals.

More efficient water use in the regional areas (to decrease water demands) does not contribute much to reduce drops in water levels of the IJsselmeer. Even if waterboards and farmers would be able to succeed in reducing water demand by 30%, the impact on IJsselmeer levels is modest (0.05m or less). If farmers would adapt autonomously to climate change induced intensified periods of droughts by installing more or larger sprinkling installations, the water demand would increase. In that case, raising the summer water level target to +0.1m MSL is not sufficient in all years in the Wp scenario. Levels will then either be raised more, or water levels lower than -0.4m MSL should be accepted.

ATPs for drought risk management are reached much later than for flood risk. An ATP for the summer water levels in the IJsselmeer occurs after ±70 years at the very earliest (Figure 48). In more than half of the realisations, ATPs do not occur in the present century for the simulations without policy actions. In Scenario Wp realisations, the median occurrence of ATPs is after ±85 years. In all realisations, many policy actions delay the timing of the first ATPs until beyond the 100 years considered. If autonomous adaptation by farmers is included in the analysis, results change considerably: ATPs then occur after ±55 years at the earliest (median value Wp scenarios: ±75). Raising the IJsselmeer water levels to +0.1m MSL with unlimited drainage capacity is sufficient in almost all years in transient scenarios, except in 4 years in the 50x100 year transient scenarios. Would the supply capacity in the regional areas be adapted, this may occur more often. Based on the model results, the original expert judgement adaptation map was adapted (see figure 49).

7.4.4 *Drought Risk Management – Fresh Water Supplies to the Midwest Region*

The intake near Gouda is an important fresh water inlet for the rural areas in the Midwest region. In the current situation, the threshold value for the salt concentration is 200 mg Cl/l. We assessed that an ATP occurs if one of the following events occurs: the salt concentration exceeds 250 mg/l but not 500 mg/l for 5 ten-day periods, or exceeds 500 mg Cl/l for 2 ten-day periods.

The ensemble results show that an ATP may occur already soon (±15 years, median value; Figure 50). Doubling the threshold values extends the moment of an ATP to ± 35 years for the Scenario Wp realisations and beyond 100 years for the Scenario G and No Change realisations (not in figure). Implementing a bubble screen that lowers the concentration to levels similar to an increased inflow of 200 $^{m^3}/_{s}$ (BS200) does extent the moment of an ATP to beyond 100 years for No Change and G scenarios, and to ±35 years for Scenario Wp scenario (median value).

Increasing the capacity of the Gouda inlet is another policy action aiming to reduce drought risk for areas depending on the inlet in the Rhine Estuary. If this capacity is doubled, water shortages are much smaller for the Midwest area. During summer, shortages can be reduced from 100% to approx. 20% – 30%.

As this analysis reveals a limited set of policy options, there was no adaptation map constructed: a bubble screen (BS200) could be implemented, but in case of the Wp scenario either increased salt concentrations have to be accepted or water needs to be derived from elsewhere.

7.4.5 *Mutual Influence among Decisions on Flood and Drought Risk Management and among Different Regions*

IJsselmeer flood and drought risk management actions affect each other. A higher water level for increased storage capacity will, at the same time, allow the system to discharge under gravity (sea level permitting). If policy makers were to decide to ensure safety against flooding by implementing pump capacity and keeping the same target water level, most of the fresh water supply actions with an increase of the water level would be inappropriate.

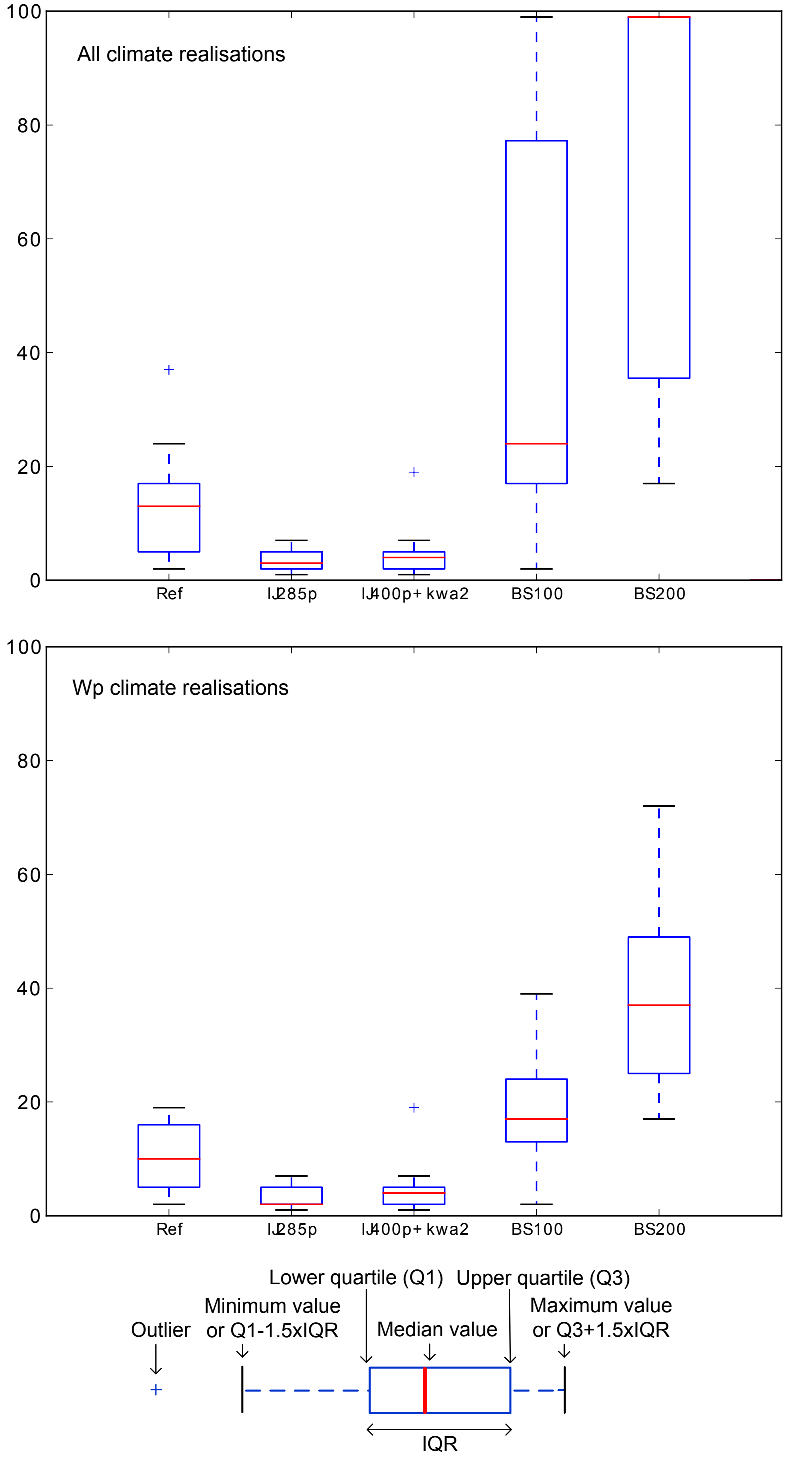


Figure 50: Box whisker plots for the sell-by year for fresh water supply of the Midwest region based on salt concentration at the Gouda inlet for all realisations (left) and for the Wp scenario realisations (lower). For abbreviations of policy actions see Table 9.

If, in dry periods, more water is transported to river IJssel to increase water storage, there will be less water for the river branches that flow towards the western part of the country (Waal and Nederrijn), and therefore less water for preventing the salt intrusion from the sea, making the water inlet at Gouda less reliable. In that case, an ATP for the Gouda inlet in the Rhine Estuary occurs even sooner in the reference situation, and doubling the threshold value does not have much impact the sell-by years. The Midwest area might then be supplied by IJsselmeer water (the so-called 'Tolhuissluisroute') , which will then need additional storage capacity. If, however, the Rhine Estuary were closed by means of a new barrier, this would not be necessary.

Flood risk management decisions in the Rhine Estuary affect the drought risk in that area and flood risk actions in the river area. Would a sea barrier be built to protect Rotterdam from coastal flooding, salt intrusion into the river mouth will also limited. The current inlet point at Gouda will be able to supply fresh water to the Midwest region. If the closure is permanent by building a dam instead of sluice, the upstream river region will need considerable adaptation for assuring safety against flooding in that area as this requires large scale additional actions. A permanent barrier will limit the river's discharge capacity into sea. Rather, water has to be transported via the Hollandsch Diep to Grevelingen. A movable barrier requires less adaptation measures, but these would still be considerable in comparison to the 'no barrier' option. In case of closure during events, there are two options for diverting the water: either by transferring water to river Waal or to a new river branch ('New Lek'). If river Waal is chosen, the required discharge capacity would be larger. If the Rhine Estuary will remain open, 'unbreachable' climate dikes and evacuation plans need to be implemented to limit flood risk. The river area can be kept safe by creating more room for the river or by raising the dikes. If this is not sufficient, extreme peak discharges water can be managed by diverging water to river IJssel. However, bifurcation points of rivers are unstable places; such an action may influence morphology and result in unstable embankments and should thus be further researched before implemented.

7.5 FROM PATHWAYS TO AN ADAPTIVE PLAN

Starting point for an adaptive plan are the costs and benefits of promising policy options and pathways. Promising policy options include 'No-Regret' actions that have additional benefits or have an acceptable performance in multiple scenarios (robust), and 'Avoid Regret' options that enable flexibility against low costs. Moreover, actions with high social support are often also socially robust. Decisive moments can be identified based on the timing of the adaptation tipping points, the required implementation time of actions and the points in time where preferred pathways start to diverge.

Flood Risk Management – Upper River Region

For flood risk management in the river's riparian areas, the results described in the previous section suggest that several pathways provide acceptable performance. Considering the storylines developed by the Delta Programme practitioners, paths that include dike raising actions or combinations of room for the river and dike raising may have more societal preference than the other. When to implement these actions is not obvious from the sell-by years. In all scenarios an unacceptable flood event may occur sooner or later. The probability of this event is higher in Scenario Wp, especially towards the end of the century. Risk averse planners may, therefore, prefer to take sufficient actions now to be able to manage discharges of 18,000 m^3/s (17,200 m^3/s is the highest discharge occurring in the No Change realisations). 'Monitor and Adapt' is not an effective strategy in this region. A peak discharge has to occur with such responsive or reactive attitude before actions will be taken, and this will result in high damages and many casualties. A 'near miss', on the other hand, may provide a window of opportunity to implement a plan. But even in that case, from the discharge record that has occurred so far, it is not obvious which climate scenario is being realised (See for example the realisations in appendix D and (Diermanse et al., 2010)). The large year–to–year variations in annual peak flows as contained in our climate realisations does to allow to detect whether a realisation is drive by a changing climate. In case of an increased frequency of low flows, it is more likely that Scenario Wp is occurring. Monitoring of global temperature and low flow trends may provide information about which scenario is becoming reality (or if the scenarios should be adapted).

Providing additional 'room for the river' may become increasingly difficult due to potential future urbanisation of the floodplains. To keep this option open, spatial planning actions could be taken (e.g. allow only adaptive building through e.g. houses on mounds). While not impossible, in practice, such spatial planning rules — that only allow costly actions — are often difficult to maintain in a densely populated delta where citizens like to live close to rivers and coasts. Starting with 'room for the river' would avoid these difficulties. For these actions, embankments need to be moved further away from the main river channel, followed by floodplain excavation. The latter action allows for raising embankments using the excavated floodplain clay that has just come available.

Within the storyline design session with Delta Programme, participants identified a modification of the peak discharge distribution over the Rhine branches and design conditions as key decisions. At discharges exceeding 16,000 m^3/s, at least 80% of the excess water is diverted to the river Waal. Although the question has been raised if it would be more cost efficient to modify this discharge distribution and divert all excess water (in excess of 16,000 m^3/s) to the Waal, most storylines suggest that a decision on the discharge distribution will not be taken before 2050. Alternative actions, such as providing more room for the river, are likely to be implemented earlier. However, some of the latter could become unnecessary if the peak discharge distribution is changed. Therefore, a decision about adaptation of the distribution should preferably be done on the short term.

Actions are based on two critical, so-called load bearing (Dewar et al., 1993) assumptions. The first assumption is that it is physically impossible for discharges exceeding 18,000 m^3/s to occur at Lobith, unless the river conveyance capacity in Germany is increased. The latter is unlikely to happen. This was a conclusion reached by a group of international researchers (Kwadijk et al., 2012). If, however, the upstream neighbour does indeed increase the river's conveyance capacity, management of discharges exceeding 18,000 m^3/s should be included in policy. To minimise failure of this assumption, cooperation with Germany and monitoring upstream development should be part of the strategy. In our realisations discharges over 18,000 m^3/s occur three times, twice in Wp, one in G. The second assumptions is that the distribution of water over the Rhine branches can be controlled. There is, however, no experience with the discharge distribution at very high discharges.

Flood and Drought Risk Management – IJsselmeer Region

For reasons of flood risk and drought risk management, IJsselmeer water levels can either be raised or maintained at current levels. Given the costs for adapting embankments and other infrastructure to higher water levels, the presently preferred action in the Delta Programme is to maintain water levels at their current values (Delta Programme, 2013). Doubling the capacity of gravity drainage is costly and therefore should have a long lifetime (over 80 years). Should, however, climate change develop along the lines of Scenario Wp then this action would only be effective until 2060–2080 (minimum, median). In that case, this action could be a 'Regret-Action'. Pumps have a much shorter lifetime (±20 years). In contrast to the river region, where extreme events are drivers for the tipping point, the gradually changing sea level rise is an important driver for the IJsselmeer flood risk tipping point. Consequently, this driver can be more readily anticipated upon. Installing a pump with a capacity of 500 m^3/s could be a first action. This may be sufficient in case of both the No Change and G scenarios (see Figure 48 and appendix D). Should Scenario Wp become reality, additional capacity can be installed (e.g. 1,000 m^3/s) by the time the life time of the pumps is reached. There are some reservations that can be made with this strategy. Currently, Europe's largest pumping station has a capacity of 260 m^3/s (the IJmuiden pumping station, also in the Netherlands). The required capacity at IJsselmeer should at least be double that, and quadruple that even in case of Scenario Wp coming true. Moreover, pumping stations use a considerable amount of energy and can fail due to mechanical problems or failing energy supply. The pumping strategy thus implies high confidence in technology and may be considered a less sustainable option because of its energy consumption and it is counteracts to future environmental conditions ('pumping the Rhine river out of the delta'). Some people would prefer to raise the water level and drain by use of gravity, as this is less likely to fail and is more sustainable. To keep this option open, spatial planning rules should be implemented (e.g. only allow adaptive building).

To provide sufficient additional storage capacity in IJsselmeer for coping with future climate change, water levels need to be raised by up to 1.5 metres, several studies suggested (Delta Committee, 2008; Van Beek et al., 2008). This requirement largely originates from the anticipated increase in water demand for sprinkle irrigation due to more frequent and more intense droughts and assumes that flow capacities of the inlet from IJsselmeer to rural areas and the regional canals will be adapted (especially in the northern region). This study does not confirm the need for this amount of storage water; a maximum of 0.7 m in the IJsselmeer lake is enough. Moreover, autonomous developments of farmers and adaptation of flow capacities can be monitored to decide if and when additional adaptation is required. For drought risk management, initial actions can, therefore, focus on allowing the water levels to drop to -0.6m MSL in dry periods. This requires limited infrastructural changes, and would not jeopardize flood safety and allows for sufficient water supply in many realisations. If more water is needed, summer water level could be increased to +0.1m MSL. In that case, compensation actions need to be implemented for mitigating adverse impacts on habitats for flora and fauna in the lake. For how long this action is sufficient or not depends on autonomous adaptation of farmers, adaptation of intake capacities and the acceptability of a seldomly occurring drop of water levels below threshold values. If and when water demand increases due to autonomous adaptation of farmers, additional water storage is needed, to ensure supply of water demands. However, the costs are high, and this amount of storage water is rarely needed, also in Wp scenario. In addition, to enable the water reaching the rural areas, capacities of the regional canals need to be increased as well. Opportunities for such adaptation arise when maintenance is being carried out. The same is true for water management infrastructure along the IJsselmeer: in case maintenance is required, new structures could be added that would be able to cope with an increase or decrease of the water level in IJsselmeer. To keep options open that reduce water demand, the Government could invest in research and development of drought and/or salt tolerant crops.

Drought Risk Management – Midwest Region

Salinity levels at the inlet near Gouda frequently exceed threshold values, making droughts / low flows a problem even in the present day. Reducing salinity levels can be done by installing a bubble screen that mitigates mixing of fresh and brackish water. Such an action would extend the sell-by year to the end of the century, but not in case of Scenario Wp. For this area, alternative options need to be considered to manage Scenario Wp. These include moving the inlet upstream, using IJsselmeer water and allowing the inlet of brackish water e.g. in combination with salt tolerant crops. Doubling the inlet capacity reduces water shortages in the Midwest region. However, if policy makers were to decide to close off the Rhine Estuary, these actions would not be necessary. To avoid 'Regret-Options' it would be worthwhile to make this decision soon.

7.6 DISCUSSION

The present chapter describes an application of the 'Dynamic Adaptive Policy Pathways' approach (Chapter 5) to the development of a dynamic, adaptive plan for long-term water management in the Rhine Delta in the Netherlands. With a fast, integrated model the effectiveness of policy actions was assessed quantitatively under an ensemble of transient scenarios. The real-world case study revealed lessons about the approach, e.g. on how it can contribute to robust and flexible policy making, and how it can support operationalisation of the concept of adaptive delta management. Although, the data and policy actions are similar to the real-world decision problem currently addressed in the Delta Programme, the chapter focuses on the method and the results should, therefore, be considered in that context.

Adaptation Tipping Points (ATP) help to identify for how long a policy action will perform acceptably. To assess in which conditions an ATP of a policy action occurs, quantitative targets are needed. However, it is not trivial to define these targets and related threshold values. Policy makers sometimes opt to keep these targets vague, making it difficult to determine an ATP or the efficacy of a pathway. Exploring multiple targets can show the sensitivity of an ATP for these targets; this may support a discussion on targets. On the other hand, the Delta Programme has already identified some tipping points even though no clear quantitative targets were set.

The sell-by date of a policy action, as determined by the timing of an ATP, also depends on the climate and socio-economic scenarios. For some actions, the time span of the sell-by date is large, making it difficult to decide when to start the implementation. Consequently, for actions that are affected by developments associated with considerable change compared to natural variability, the timing of an ATP is easier to estimate than ATPs resulting from extreme events. For example, the timing of an ATP of a coastal barrier that is caused by sea level rise is relatively easy to determine. In contrast, the ATP of river dikes depends on the occurrence of extreme river discharges which are characterised by high natural variability and not easily detectable trends. This makes ATPs less useful for a system that fails to meet the targets in case of extreme events, but performs reasonably otherwise. It is possible to define the conditions under which a policy action performs unacceptably, but *when* this occurs is often difficult to assess. In those cases, it may be better to adapt immediately or to take at least also flood damage mitigation actions.

Adaptation pathway maps give insight in available options after an adaptation tipping point and if lock-ins may occur. In this case, pathways were developed for flood and drought risk management in various, differing regions. A national adaptation map does not seem useful, because too many actions with different purposes need to be integrated. By identifying conflicts and synergies between these pathways, some actions and pathways seem more feasible than others. For evaluation of the pathways, actions and evaluation targets should be sufficiently specific. The development of pathways turned out to be an iterative process. While quantitative information about the performance of actions became available from the model results, some actions were screened out and other added. Together with information on costs, benefits and societal preference of actions, preferred pathways can be identified. A scorecard, such as presented in Figure 40 would therefore be a valuable next step in the development of an adaptive plan. The following quote from the most recent Delta Programme publication shows that pathways can indeed be used to operationalise adaptive delta management (ADM) (Delta Programme, 2012a): *'Development pathways or adaptation pathways offer a strong approach to show which options are needed, when they should be implemented and how long-term objectives influence short-term decisions'*. Moreover, the links with other investment agendas, one of the key principles in ADM, fits well with the identification of opportunities, such as maintenance of structures and No Regret options.

In the storyline design session for the Delta Programme, participants mentioned that the approach helped to identify key decisions and potential lock-ins. Developing storylines made participants aware that they had implicit preferences for river bed widening and levee height raising strategies, and that actions related to spatial planning must be considered as well. Other feedback indicated that for some, the Pathways approach was slightly difficult to understand. These individuals found the storylines helpful in understanding the pathways.

Transient scenarios helped in identifying ATPs and raised awareness about the importance of natural variability for adaptation. Extreme discharges, that can easily result in an ATP, can occur in all scenarios and realisations, with or without climate change. This implies that for flood risk management policies in the upstream river areas, Monitor and Adapt is not an appropriate strategy. For IJsselmeer flood risk management however, this can be appropriate because the gradually changing sea level rise is an important driver.

In this case study, an Integrated Rapid Assessment Metamodel was used. The model is computationally efficient, allowing for calculating the effects over multiple scenarios and many realisations. This constitutes a major benefit over more detailed models that operate at a higher resolution and at a higher time step. To wit, the analyses discussed in this chapter required approx. two thousand hours of computer time. If the analysis had been performed with the present Delta Programme model, the required computational time would have exceeded three million hours. Realistically speaking, analyses such as that described here would not have been possible. The drawbacks, however, of using a metamodel should not be forgotten either: some processes may be modelled less accurately and as a result, uncertainties may be larger. Still, for screening of promising policy options and pathways the model is appropriate (Chapter 6).

7.7 CONCLUDING REMARKS

As the need to act to climate change is recognised, the attention of policy makers shifts to the question of *how*, *how much* and *when* investments should be made, given the very large uncertainties that are generally associated with projections of future?

The Dynamic Adaptive Policy Pathways approach in combination with a fast, integrated model could indeed be applied to the real-world case to the design of a long-term water management plan for the Rhine delta in the Netherlands. Currently, the Dutch government is working on such a plan in the framework of the Delta Programme. Combining a fast, integrated model and an ensemble of transient scenarios supports the quantitative exploration of possible adaptation pathways. The impact of autonomous adaptation was found to be considerable, and should thus be considered to ensure a good performance of the plan. The concept of adaptation tipping points appeared less useful for situations where only extreme events matter. The approach was especially useful in providing insights on the timing of adaptation measures, on identifying options and path-dependencies, in what actions should be taken immediately to realise targets in the near future and what actions should be taken to keep options open. In conclusion, the method established in this study can provide a valuable contribution to operationalisation of the concept of Adaptive Delta Management, which is one of the key elements in the Delta Programme.

8

CONCLUSIONS AND REFLECTION

8.1 OVERVIEW OF THE PRESENTED RESEARCH

This thesis has presented a new approach for developing a sustainable water management strategy, taking into account the uncertainties about the future. To develop long-term water management strategies policy makers have been using scenarios. A review of scenario use in water management studies over the past 60 years in the Netherlands revealed that the possibilities for robust decision making increased through a paradigm shift from *predicting* to *exploring* futures, but the scenario method has remained not fully exploited for supporting decision making under uncertainty. I described our first ideas on a new method in terms of a conceptual and technological framework. I tested and further developed the method by following the steps of the conceptual framework and developing an Integrated Assessment MetaModel (IAMM) according to the technological framework for a hypothetical case. This case, called the Waas, was inspired by a real-world river stretch (Waal) in the Rhine delta in the Netherlands. The Waas case was implemented in the Sustainable Delta game (Valkering et al., 2012; Deltares, online) and was used in participatory game sessions to develop storylines and understand water system-society interactions.

Based on the experiment of the Waas case, I improved the conceptual framework and combined it with the approach of Adaptive Policy Making (Kwakkel et al., 2010a; Walker et al., 2001). In this way, we enriched the framework with a comprehensive stepwise policy analysis and with triggers for identifying when to add or switch to other policy actions. The proof of the pudding is in the eating; the method was tested in a real-world case inspired by a decision problem the Dutch National Government is currently working on. This so-called Delta Programme aims to develop the 'Delta Plan' for the 21st century in order to keep the Netherlands safe and attractive, now and in the future, with an effectively organised flood risk management and fresh water supplies (Delta Programme, 2012a). As there was no appropriate computational model available, I developed an IAMM for the Rhine delta and used it to apply the improved framework to the Delta Programme in the Rhine delta in the Netherlands.

This chapter presents the key findings of this thesis by answering the research questions, reflecting on the research and providing a research agenda for exploring adaptation pathways.

8.2 ANSWERING THE RESEARCH QUESTIONS

The central research question in this thesis — *'How can we explore adaptation pathways to support a sustainable water management plan for river deltas taking into account uncertainties about the future?'* — will be addressed by answering the five subquestions in the next sections.

8.2.1 *What Is Meant by 'a Sustainable Water Management Plan'?*

To assess whether the new method contributes to the development of a sustainable water management plan, we need to define what we mean by a *sustainable* plan. In addition, we need criteria to evaluate the sustainability of a plan. While the original definition of sustainability focused on meeting the needs for both the present and future generations (Brundtland, 1987), it was later operationalised as meeting economic, social and environmental targets, and recently it has frequently been related solely to environmental issues. A well-known quote of Charles Darwin suggests that sustainable plans should be adaptive plans to survive changes (Walker et al., 2013): *"It is not the strongest of the species that survive, nor the most intelligent, but the ones most responsive to change."* Uncertainties about the future make adaptivity even more necessary.

To anticipate uncertain change, a sustainable plan should not only achieve economic, environmental, and social targets, but it should also be robust and able to be adapted over time to (unforeseen) future conditions. Therefore,

> *we define a sustainable water management plan as a plan that is able to achieve environmental, social and economic targets now and in the future by being robust, meaning performing satisfactorily under a wide variety of futures (conform Lempert et al. (2003)), and/or flexible (adaptive), meaning that it can be adapted to changing (unforeseen) future conditions.*

The *robustness* of a plan or action can be assessed using two criteria:

1. *Acceptable performance for economic, environmental and social indicators.* Robust actions result in acceptable indicator values under a wide variety of futures, and their performance is little sensitive to different futures.

2. *Acceptable performance for various Perspectives.* Robust actions are not only dependent on physical conditions, but also on societal conditions (Offermans, 2012). Actions can be evaluated differently by various actors, as they may give different weights to indicators, which is expressed by different threshold values for acceptability. Robust actions may provide a basis for consensus among stakeholders with different views about the future, because they would provide reasonable out-

comes no matter whose view proved correct (Lempert and Schlesinger, 2000). Robust actions perform acceptably for various Perspectives.

The *flexibility* (or adaptivity) of a plan is expressed by the ability to switch or add another action, or adapt the current action. Flexible actions can be adapted (e.g. intensification of the action), abandoned (switch to a different action), or extended (add an action) at low cost or with small societal impact. Flexible actions do not result in lock-ins and have little influence on potential future options (i.e. have less path-dependencies).

Examples of robust actions include 'hard' solutions or no-regret actions. Hard solutions, such as surge barriers and sea-dikes, can be robust in the sense that they are effective under a wide variety of futures, but it is a rigid approach with cost implications if the rise in sea level turns out to be different than anticipated. A no-regret action could be, for example, providing more room for the river by reconnecting old river branches to lower water levels in case of peak discharges. Although, this may not be necessary in case climate does not change, this may be acceptable, as it also enables achieving environmental targets in all futures.

Flexible actions are often 'soft' solutions and/or solutions with a short lifetime. Dredging the river to enable navigation in case of low flows is an example of a soft solution. If river discharges remain higher than expected, it is easy to stop this dredging. Flexible actions go hand in hand with the monitoring of uncertainty. Monitoring change works well for pressures that change gradually, such as sea level rise, but not for pressures that are mainly subject to large natural variability, such as peak river discharges.

8.2.2 *How Can We Develop Pathways?*

Traditionally, planners – including water policy makers – tend to use 'best estimates' of the future based on central estimates of climate change and extrapolations of current socio-economic and water system trends. This wrongly suggests that we can predict the future and assumes a static system. Such an approach might be feasible for well-understood problems in static systems, but not for complex problems with deep uncertainty (Lempert and Schlesinger, 2000) that occur in dynamic systems, such as long-term water management under uncertain changing conditions (Milly et al., 2008; NRC, 2011).

Our approach acknowledges the inherent uncertainties about the future, the existence of *adaptation tipping points* resulting from changing conditions, and plausible *adaptation pathways* towards the endpoint in the future. The need for such an approach starts from the observation that policies work well under a range of conditions, but have thresholds after which their performance is unacceptable. Moreover, uncertainties in climate change and socio-economic developments, and future policy responses are key uncertainties that need to be taken into account in the development of a sustainable plan: adaptation in the course of time is not only determined by what is known or anticipated at present, but also by what is experienced and learned as the future unfolds (Yohe, 1990) and by the policy responses to events (Chapter 4). In fact, Hallegatte et al. (2012) include the adaptation of decisions over time in an updated definition of 'deep uncertainty'.

Chapter 5 presented the improved conceptual framework, called 'Dynamic Adaptive Policy Pathways', that incorporates the development of adaptation pathways into a policy analysis. This stepwise policy analysis approach proved to be a good tool for exploring a wide variety of relevant uncertainties in a dynamic way, connecting short-term targets and long-term goals, and identifying short-term actions while keeping options open for the future. Key principles of the approach are: the use of transient scenarios representing a variety of relevant uncertainties and their development over time; anticipatory and corrective actions to handle vulnerabilities and opportunities; considering several adaptation pathways describing sequences of promising actions; and a monitoring system with related actions to keep the plan on the track of a preferred pathway.

The steps in the approach are presented in Figure 26. First, the system and targets are described. This is followed by a problem analysis in the current and future situation. The problem analysis should not only identify adverse impacts but also opportunities. To address the vulnerabilities and opportunities, policy actions are defined. A rich set of actions is assembled by considering different types of actions as defined by Kwakkel et al. (2010b), such as actions to reduce adverse effects or actions that seize opportunities, or by addressing the problem using different perspectives such as is done by Middelkoop et al. (2004) and Valkering et al. (2008a). In an iterative approach, promising actions are selected and their sell-by date is assessed under a wide variety of plausible futures. Promising actions are building blocks for the construction of pathways. Pathways are evaluated and improved. Based on the resulting improved pathways, an adaptive plan is constructed. The plan describes which robust and flexible actions should be taken now to anticipate change, while keeping options open to adapt against low costs, if necessary. Signposts and triggers are used to monitor whether actions should be implemented earlier or later, or whether reassessment of the plan is needed.

In this thesis, we mainly constructed pathways manually, using the individual actions, and the condition and moment that their tipping point occurs, as building blocks. A new action is activated once the previous action no longer meets threshold values of acceptable performance and thus reaches its tipping point. We explored all possible routes with all available actions. However, some actions may exclude others, and some sequences of actions may be nonsensical. Under *what conditions* an adaptation tipping point occurs was based on an assessment of the performance of (combinations of) these actions over changing conditions. *When* a tipping point occurs was derived from its performance over time. The performance over time and changing conditions was based on simulations with a computational model and/or by means of expert judgement. The moment an adaptation tipping point occurs (its sell-by date) differs per climate scenario, climate realisation, policy action and threshold value of acceptable performance. An ensemble of model runs with transient scenarios is an effective tool for determining the statistics of sell-by date values (shortest, longest, median, mean sell-by date, etcetera).

Another approach for generating pathways is the use of storylines that describe a narrative of plausible futures including climate change, socio-economic developments and policy actions. In joint consultation with water managers involved in the Delta Programme, pathways were generated in this way (Chapter 7). This helped the managers to get a better picture of how pathways could emerge. The results also pointed out the participants' preferences for specific actions, and raised awareness about potential 'tunnel-visioning'. The Sustainable Delta game allowed for including decision makers and negotiation between decision makers in the development of pathways. In a game-session, participants triggered policy responses to changes in the water system that were simulated with the Waas model (Chapter 4).

8.2.3 *How Can We Build and Evaluate a Computational Model to Explore Adaptation Pathways?*

Current models for water management are often mono-disciplinary, one-way coupled models, and build upon the perception that a good model is able to reproduce the real-world that is described by monitoring results from the past. Since these detailed and complex models are inappropriate for exploring pathways into the far future (100 year) within limited computation time, we had to build an appropriate model for this purpose.

A model for exploring pathways should satisfy two main requirements. Firstly, an integrative assessment of the whole system including relevant feedbacks is needed to assess the impacts of environmental changes and policy actions on relevant outcome indicators for decision making in complex systems such as river deltas (Jakeman and Letcher, 2003; Laniak et al., 2013; EEA, 2013). Secondly, a fast and simple model, that simulates dominant processes and natural variability adequately (despite its simplifications), is a prerequisite to limit the computation time to be able to simulate a wide envelope of plausible transient scenarios (e.g. 100 years time series) and a variety of policy actions and their combinations over time.

For building the model, we defined the boundaries of the model, the drivers it needs to be able to assess, the outcome indicators, and the policy actions that are needed to be able to support the decision making. A useful approach for this is an iterative process, wherein (potential) end-users reflect upon the model and its results, which is used to improve the model e.g. with additional outcome indicators and policy actions.

To build the models, the technique of metamodelling was used. Both the Waas and Rhine models consist of an integrated set of (theory-motivated) metamodels describing cause-effect relations of the whole cause-effect chain. Therefore, these models are categorised as Integrated Assessment MetaModels (IAMM). The cause-effect relations relate the climate and socio-economic pressures to changes in the state of the water system (precipitation, river discharges, water levels) and social system (land use) and describe the impacts on the different water related sectors. The metamodels were based on (the results of) complex hydrological and impact models applied in previous studies.

For the evaluation of the model performance, metrics were defined to assess whether the model was appropriate for its intended purpose. For the Waas case, the model was checked for internal consistency and plausibility of the outcomes by expert judgement. This was possible, because it was a hypothetical case. For a real-world case such as the Rhine delta, a more sophisticated approach was needed. Since it is a policy model intended for comparative analysis, such as ranking of policy options and drawing adaptation pathways, approximate results are sufficient. Therefore, not only the traditional modeller's criterion - model accuracy in terms of the extent to which historical data are reproduced - was used in the evaluation of the model, but also the model's ability to simulate a variety of scenarios, policy actions, and the calculation speed of the model was considered in the evaluation.

Using closed questions (Guillaume and Jakeman, 2012) for evaluating the model's performance forced us to be specific in describing for what purpose the model can (not) be used. In the Rhine study, the main question was: *Does the model produce credible outcomes with sufficient accuracy for screening and ranking of promising actions and pathways in order to support the strategic adaptive planning decisions in the Rhine delta in the Netherlands?* As this question still leaves room for various interpretations, we defined a set of closed questions related to the relevant outcome indicators for decision making in consultation with potential end-users. The starting point for the evaluation was that the uncertainties/errors in the model results should be smaller than the impacts of the pressures and should not result in a different strategy. To assess whether the model performs acceptably for the right reasons, not only the outcome indicators were considered, but also the main hydrological variables used to determine this outcome.

The Waas case showed that it was possible to build a fast, integrated model, and that such a model could be valuable for assessing the moment of an adaptation tipping point and exploring pathways. The Rhine case showed that a fast and integrated model has additional benefits: raising awareness of the impacts of climate variability and climate change, screening promising pathways, and supporting strategic decision making under uncertainty.

8.2.4 *How Can the Generated Pathways Support the Development of a Sustainable Plan?*

The aim of exploring adaptation pathways was to support the development of a sustainable plan.

The adaptation pathways map developed in this study provides a useful overview of relevant pathways (see for example Figure 24. All routes presented satisfy a pre-specified minimum performance level, such as a safety norm (a threshold that determines whether results are acceptable or not). They can, thus, be considered as 'different ways leading to Rome' or as different routes to a specified destination on the Metro. Also, the moment of an adaptation tipping point (terminal station), and the available actions after this point, are shown (via transfer stations). Due to the unacceptable performance of some actions in a selection of scenarios, some routes are not always available (sometimes indicated with dashed lines). Decision makers or stakeholders may have a preference for certain pathways, since costs and benefits may differ. A scorecard presents an overview of such costs and benefits for each pathway either for the whole ensemble of transient scenarios, for different time slices, and/or for a selection of (a) scenario(s).

The Adaptation Pathways map and the scorecard are the key instruments for preparing a plan for actions to be taken immediately, and for preparations that need to be made in order to be able to implement an action in the future in case conditions change. Moreover, it helps decision makers in identifying opportunities, no-regret actions, lock-ins, and the timing of an action, in order to support decision making in a changing environment.

The Perspectives method (Offermans, 2012) allowed us to define a rich set of actions and to identify preferred pathways for archetypes of perspectives (Chapter 5). Decisive moments can be identified based on the moment of the adaptation tipping points, the required implementation time of actions, and the points in time where preferred pathways start to diverge. Based on their preferences and the decisive moments, decision makers are able to specify short-term actions for mitigating adverse impacts and keeping options open to adapt, and identify triggers for monitoring, whether adaptation or reassessment of the plan is needed.

Working with transient scenarios improved awareness about the importance of natural variability for adaptation and thus for a sustainable plan. The scenarios helped to assess when a policy would perform unacceptably. Practising the scenarios on the Rhine delta showed that this is easier for actions sensitive to gradual changing conditions than for actions sensitive to extreme events. In consultation with stakeholders and participants of the game sessions, the transient scenarios proved valuable for a discussion about the efficacy of a 'monitor and adapt' strategy. With the transient scenarios, we were able to show that climate change may be difficult to detect, especially changes in extremes, due to the large natural variability compared to the magnitude of change. The transient scenarios also helped to develop storylines and raise the awareness among researchers and planners about the importance of interactions between the water system and society.

The approach presented in this thesis stimulates planners to include adaptation over time in their plans – to explicitly think about actions that may need to be taken now to keep options open, and decisions that can be postponed. Thereby, the inevitable changes become part of a larger, recognized process and are not forced to be made repeatedly on an ad hoc basis. Planners, through monitoring and corrective actions, should try to keep the system headed towards the original goals. The Adaptation Pathways map provides different routes to achieve acceptable results under a variety of futures and thus shows which actions are robust and which are flexible. This reduces the dependence of a decision on a single scenario and avoids early maladaptation (Reeder and Ranger, online). By considering different preferred pathways for various perspectives or stakeholders, the societal support of a plan can be assessed. This all contributes to the development of a sustainable plan.

8.2.5 *What Is the Value of the Approach, and for which Situations Is the Approach Appropriate?*

If a new approach is proposed, it needs to pass a test. In this thesis, the efficacy of the conceptual and technological framework was assessed by applying it to a virtual world based on a real-world river stretch (Waas case) and a real-world decision problem currently faced by the Dutch National Government (Rhine case).

Our experiments with the Waas and Rhine cases show that we were able to apply the stepwise approach, build a fast and integrated model, and achieve plausible results to assist in developing a sustainable plan. The approach appeared especially useful to support decision makers that are questioning *how*, *how much* and *when* investments should be made, given the very large uncertainties that are generally associated with projections of the future. What actions are needed on the short term and what actions can be postponed? Because the method acknowledges the interaction between the water system and society and the existence of difference perspectives, the method should be able to support decision making in the case of persistent problems, that are characterized by a complex interaction of broad societal trends, physical (natural) processes (such as climate change), and the involvement of many stakeholders with different but plausible perspectives (Rotmans, 2006).

Adaptation tipping points help to identify for how long a policy action will perform acceptably, and thus *when* investments should be made. To assess under which conditions a tipping point of a policy action occurs, quantitative targets are needed. Defining these targets and related threshold values is, however, not trivial, as policy makers sometimes opt to keep these targets vague, making it difficult to assess the occurrence of a tipping point and the efficacy of a pathway. In such a situation, the approach can support a discussion on targets by showing the sensitivity of the sell-by year of an adaptation tipping point for multiple targets and threshold values. Still, the Delta Programme has already identified some tipping points, even though no clear quantitative targets were set.

The moment at which a tipping point of a policy action may occur in the future – its sell-by date – depends not only on the targets, but also on the climate and socio-economic scenarios. This helps to specify when actions are needed at earliest or at latest (time span) given an ensemble of possible futures. For some actions, the time span of the sell-by date is, however, very large, making it difficult to decide when to start the implementation. Consequently, for actions that are affected by developments associated with considerable change compared to natural variability, the timing of a tipping point is easier to estimate than for tipping points resulting from extreme events. This makes adaptation tipping points less useful for assessing *when* to invest, in case the system under consideration is managed under a policy that fails to meet the targets in case of extreme events, but performs reasonably well otherwise. For these systems, it is possible to define the conditions under which a policy action performs unacceptably, but *when* this occurs is difficult to assess, as shown in our results for flood risk management of the Rhine case (Chapter 7). In those situations, it may be better to adapt immediately or at least to take flood damage mitigation actions.

An adaptation pathways map is an appropriate tool for presenting policy options and their timing under different plausible futures, thereby providing information on *how*, *how much* and *when* investments should be made. Ideally, to derive a clear adaptation pathways map, the number of actions is limited (e.g. < 20) and all actions contribute to the achievement of a clear main target, such as flood or drought risk management for a specified region. If the situation is otherwise, actions could be screened first to present only the most promising actions in an adaptation map, or actions could be clustered and once preferred (clustered) pathways are identified, they can be further described in detail in a different adaptation map that zooms in on the preferred pathways. From our experience with the cases, we learned that different main targets for different regions should be presented in different maps to keep the maps clear. Relations among the adaptation maps (if existing) are then identified by describing conflicts and synergies between pathways.

The fast, integrated models appeared valuable for assessing sell-by dates of the possible actions and the efficacy of pathways for the ensemble of transient scenarios. With the results, inefficient options were screened out and other promising options were added. This helps to overcome the problem of complex adaptation maps with many actions. The computational support for generating the pathways would not have been possible with the current computational model used in the Delta Programme, because of its long computation time and complexity. During the making of the Rhine IAMM model and the use of the Waas IAMM model in game sessions, these kind of models proved to be beneficial for quick understanding of the system (e.g. the sensitivity of outcome indicators for policy actions and drivers). The good performance of the Rhine model is related to the fact that the Rhine delta system is very much controlled, resulting in internal feedbacks that prevent chaotic behaviour (in contrast to, for example, climate systems). Still, the IAMM s might have essential drawbacks since the simplifications involved might result in impacts to be under- or overestimated or even overlooked, especially processes that occur at a small time-scale. A complex model should be applied to obtain more detailed information about the performance of the most promising options and most troublesome scenarios or periods of interest arising from the exploration with the fast and simple model. Concluding, the computational support of pathways and a sustainable plan works best for situations wherein both a fast, integrated model and a complex detailed model are available.

8.3 REFLECTION

In this section, I reflect upon the research presented in this thesis. First, potential contributions of this research to future water policy studies are described. The section closes with a research agenda for sustainable policy making under uncertainty.

8.3.1 *Contributions to Future Water Policy Studies*

This thesis has presented a step-wise approach and a computational model for exploring adaptation pathways to support the development of a sustainable water management plan under deep uncertainty.

The presented approach provides an alternative method to the traditional end-point scenarios often used in long-term water management studies. By assessing *when* an adaptation tipping point may occur (at earliest and at latest) and *what* options are left under a wide variety of futures, we ensure that the time component is made explicit, which is essential under uncertain changes. The following quote of the Delta Programme (2012a) illustrates this: *"Development pathways or adaptation pathways offer a strong approach to show which options are needed and when they should be implemented and how long-term objectives influence short-term decisions."*. Recently, the European Environment Agency mentioned adaptation pathways as a key emerging issue that will shape the future of adaptation in Europe (EEA, 2013).

While the assessment of timing of actions can be very valuable, it also runs the risk that actions will be postponed. In practise, we have seen that such notifications have been made in the context of the adaptive delta management in the Delta Programme, where this approach has been seen as an opportunity to postpone drastic measures and use the time gained to learn more about the change and develop innovative solutions (e.g. Government of the Netherlands, online). However, adaptive delta management should not be seen as an excuse to postpone actions (Delta Programme, 2012a). For tipping points related to gradually changing conditions this may work, but for others that are related to extreme events, such an approach runs the risk of being too late.

Transient scenarios can help raising awareness about the importance of natural variability and policy responses to social and physical events. In game sessions and in discussions with practitioners, we used the transient scenarios for what-if thinking experiments. Similar to classical scenario approaches, we asked people *What would you do if X happens?*; but, in our case we considered a sequence of what-if situations over time. This way they could experience the impacts of the (re)-occurrence of events and policy responses.

Events have always been important for water management. Traditionally, the probability of events is used to develop flood and drought strategies after an assessment of the potential impacts of a specified event. To imagine what impacts would look like, past events are often used to illustrate impacts. With transient scenarios, it is possible to follow developments over time. Moreover, in combination with an adaptation pathways map, the approach raises awareness about path-dependencies and the implications of ad-hoc policy responses. Frequently, this initiated a discussion about *'anticipatory'* versus *'monitor and act'* strategies.

The benefits of a fast, integrated model could be exploited more in water management practice. Most current decision support tools are developed from the perspective that good models simulate real-world situations accurately, and are not geared towards the needs of sustainable decision making under uncertainty. A lot of money is spent on improving model details, which is not necessary for decision making. A combination of complex and 'fast and integrated' models is much more valuable for decision support (Davis and Bigelow, 1998).

Several lessons for water management strategies can be drawn from this study. Climate variability and Perspectives (in terms of targets) may be at least as important for decision making as is climate change, especially for the mid- to long-term. Using the transient scenarios and metamodel in a game setting confirms this conclusion, as the response of users was *reactive* to the events (caused by climate variability) rather than *anticipating* future events (climate change). The results and game sessions confirm what Middelkoop et al. (2004) and Van Asselt et al. (2001) already concluded: *win-win* actions may in the end result in *loss-loss*. Sometimes, negotiation about actions (typical 'poldering' in Dutch) and the intention to act prudently and wait to see what happens, may result in inefficient and inflexible actions. So, here we have a paradox: on the one hand planners aim to achieve socially-robust actions, while on the other hand - in some situations - a clear direction needs to be chosen which often results in actions that are not acceptable for everyone. Searching for a spatial differentiation of actions may help to overcome this problem.

8.3.2 *Research Agenda*

This thesis has been about how exploring adaptation pathways could support the development of a sustainable plan under deep uncertainty. The approach has been illustrated and tested using both a hypothetical and a real-world decision problem currently faced by the Dutch National Government in the Delta Programme in the Rhine delta. The results were received with great interest by policy makers and scientists, and suggest that it is worthwhile to further use and test the approach. There are several key research challenges that still need to be addressed:

1. *Applicability to other countries and other scales.* In this thesis, we applied the approach to typical Dutch water systems at the scale of a river stretch and a delta. In other developed countries, similar approaches are emerging. For example, the Thames Estuary 2100 project used decision trees to analyse sequential decisions for preparing the Thames Estuary for future sea level rise (e.g. Lowe et al., 2009; McGa-

hey and Sayers, 2008; Reeder and Ranger, online; Sayers et al., 2012; Wilby and Keenan, 2012), flexible pathways are being developed for water management of New York (Rosenzweig et al., 2011; Yohe and Leichenko, 2010), New Zealand considers the adaptation tipping points approach valuable for making adaptation approaches more decision maker friendly (Lawrence and Manning, 2012), and Brown (online) and Weaver et al. (2013) present 'decision scaling' as a bottom-up approach that (similar to adaptation tipping points) uses climate models to estimate whether identified problematic climate changes are likely to occur in the future.

For developing countries where poverty and short-term vulnerabilities dominate over long-term concerns, the approach may need to be tailored to be effective (Ranger and Garbett-Shiels, 2011). Developing countries are rapidly changing and particularly vulnerable to coastal impacts due to rapid urbanization, including growing mega cities in subsiding deltas. In these countries, long-term planning is much less practised, as other (more urgent) problems exist. The challenge is to design actions that are also able to cope with potential future conditions (robust actions) or actions that leave room for adaptation if needed. Therefore, it is even more important to link (potential) future actions to current problems by e.g. searching for win-win options (Dessai and Wilby, online).

Applying an approach at another scale will affect the problems, impacts and policy actions that need to be addressed (Karstens, 2009). Pathways at the global and continental scale are interesting for scientists and policy makers (see e.g. EEA, 2013). They are, however, at a different scale than where most policy decisions are taken. Global pathways exist for CO2 emissions (Van Vuuren et al., 2011), but not for climate adaptation. At this scale, it may be difficult to select a single objective or a clear set of policy options. Moreover, present global and basin models have limited possibility for implementing policy actions. Still, it would be worthwhile to explore doing this, since current global studies on water focus on the impact assessment of global changes (often global climate change), and the next logical step is usually the development of policies. Such studies can support decision making on investments, e.g. where to invest in reservoirs, dikes, and/or social and spatial developments.

For both the adaptation pathways and the computational model, developed here, it would be valuable to know whether generic models and generic pathways could be developed. Although the appropriateness of adaptation varies in time and space and with geography, the more effective adaptation actions and pathways might be able to be further developed and applied in more generic terms. For example, for systems with similar problems, generic pathways may provide a first starting point before making a case-specific map. Hunt and Watkiss

(2011) presented generic pathways, showing adaptation options to be taken now (win-win, no-regret, monitoring, training), on the short term (decision with a long life or planning time) and on the long term.

2. *Further assessment of the efficacy of the approach in comparison to traditional policy making and in comparison to other new approaches for dealing with uncertainties*. The adaptation pathways approach could be compared with Robust Decision Making (Lempert et al., 2003), Real Options Analysis, Info-Gap decision theory (Hall and Harvey, 2009; Korteling et al., 2012), and decision trees (building upon Hall et al. (2012) who compared Robust Decision Making methods with Info-Gap methods). Such a comparison could focus on different characteristics and thus different situations for which different approaches could be valuable, but also on comparing the costs and benefits of adaptation pathways with the costs and benefits of traditional policies. This could improve the applicability and provide information on which circumstances the adaptation pathways approach could be most useful.

3. *Enrichment of pathways and scorecard with institutional and economic aspects*. Current pathways are now mainly focused on technical aspects. Most tools and applications have focused on policy actions in the physical system, and rarely on institutional and economic aspects of adaptation pathways. However, organisational and financing aspects are also needed for implementation of an adaptive plan. In this thesis, the Rhine case showed that autonomous adaptation could be very relevant for the sustainability of a plan. A more strategic and integrated approach of autonomous and planned adaptation could ensure that timely and effective integral adaptation measures are taken in a direction that is coherent across different sectors and levels of governance.

4. *The opportunities of multi-resolution modelling (Davis and Bigelow, 1998) could be further explored*. This thesis showed that a fast and integrated model can be valuable for exploring pathways and thereby decision making under uncertainty. Such a model can also be beneficial for screening of policy options and for exploring the effects of all kinds of uncertainties, such as is done in an 'Exploratory Modelling' analysis (Bankes, 1993). Other advantages of a fast, integrated model over a complex, detailed model are that it is easy to interpret, needs less input data, helps to get an understanding of the system (e.g. through a sensitivity analysis), and could be used for the screening of interesting actions and (periods of) scenarios. A complex detailed model could then be used for further impact assessment and strategy design.

In this thesis, we built an Integrated Assessment MetaModel based upon a comprehensive set of coupled models (Chapter 6). This bottom-up approach requires local data and knowledge that are not always accessible or available. Top-down approaches based on global datasets and satellite data carry the promise of geographical flexibility and global application, but run the risk of superficiality, lack of detail, and regional insensitivity. Also, the water system characteristics may be different and may require other kinds of models. Moreover, current global and basin models have limited possibility to explore policy options. A multi-resolution modelling approach, wherein top=down and bottom-up approaches are used, might be of useful in areas with limited availability of data and tools or for a rapid (preliminary) assessment in new areas.

5. *The computational development of pathways is still in its infancy*. In this thesis, we manually draw the pathways that emerge from the model results. Computational development of pathways is currently being investigated by Wijermans et al. (in prep), who use policy response rules to generate pathways, and Kwakkel and Haasnoot (2012), who improve the performance of randomly generaed pathways with genetic algorithms. With complex problems, such approaches become more useful, for example, for considering pathways for multi-objectives, or for including autonomous adaptation of stakeholders.

A

APPENDIX TO CHAPTER 2

Scenario characteristics

Characteristics of scenarios used in the national policy documents (National Policy Memorandum on Water Management, PWM) and research studies on climate and water. Next section gives a short explanation of the scenario typology used to describe the characteristics.

Name study	Year & reference	Purpose study	Context of study	Number	Type scenario	Quantitative / qualitative	Alternative futures	Time horizon	Name scenarios	Variables in the scenarios	How is uncertainty mentioned	Results of study	Policy / research
Delta works	1950-1960	Safety against coastal flooding	1953 storm surge resulted in numerous casualties and large scale flooding of south-western part of the NL.	1	Predictive - forecast	Quantitative	Small	+100 & +200	No information available	Sea level rise	No information available	Policy options implemented	Policy
1^{st} PWM	1968	Improve water supply	The Delta works were partly finished. Safety was ok. Increasing population and intensive use space industrialisation and more navigation result in higher demands on water (quantity and quality).	1	Predictive - forecast	Quantitative	Small	2000	Referred to as trends or prognoses	Water demand for agriculture, drinking and industry water. Climate variability is considered by analysing 2 different 'dry' years	Uncertainty about future water demand was acknowledged but no bandwidth given. Impact of uncertainties in upstream developments were considered small. Climate change, sea level rise and upstream developments influencing river Rhine discharge were mentioned not included..	Policy options defined and implemented. No additional policy options due to future developments	Policy
2^{nd} PWM	1984	Improvement water management, cost/benefit analysis	"Prognoses" on water demand needed to be revised. Also industry, shipping and nature were acknowledged as water users.	1	Predictive - forecast	Quantitative	Small	1976-1990	Reference/no policy, prognoses, maximum trend sprinkling scenario	Water demands for agriculture and drinking and industry water. Maximum trend (high growth industry and high sprinkling scenario). Climate variability is considered by analysing 5 different 'dry' years	Uncertainty about future and working of system were included by sensitivity analysis or scenarios. 1990 was chosen as future year because small uncertainties about developments	No extra policy options needed	Policy
PAWN study. Background study 2^{nd} PWM	1985	Provide insight in national water system in the Netherlands, assess potential problem and solutions	"Prognoses" on water demand needed to be revised. Also industry, shipping and nature were acknowledged as water users.	1	Predictive - forecast	Quantitative	Small	1976-1985/1990	Reference/no policy, prognoses, low and high sprinkling scenarios	Water demands for agriculture and drinking and industry water. Climate variability is considered by analysing 5 different 'dry' years	Uncertainty about future and working of system were included by sensitivity analysis or scenarios. 1990 was chosen as future year because small uncertainties about developments	No extra policy options needed	Policy/ Research
Discussion report Coastal defense	1988	Safety against flooding: impact and policy options	Jelgersma published curve on sea level rise. Establishment IPCC.	3	Explorative - external	Quantitative	Large	2050, 2100	Policy (autonomous developments), anticipatory (best guess), unfavourable	Sea level rise, wind power, tidal range	Sensitivity and scenario analysis. The chance that the future would be more unfavourable than worse case was estimated at 5 to 15 %.	Impact assessment	Research
ISOS	1988	Safety against flooding: impact and policy options	Jelgersma published curve on sea level rise. Establishment IPCC.	3	Explorative - external	Quantitative	Large	2050, 2100	Autonomous developments, best guess, unfavourable	Sea level rise, river discharges, wind power, tidal range	Sensitivity and scenario analysis was executed. Socio-economic developments were considered to be too uncertain to anticipate on. The chance that the future situation would be worse than the unfavourable scenario was estimated at 5 a 15%. River discharges were estimated (-5 and -10% in summer and +5 and +10% in winter.	Policy options implemented	Research

Name study	Year & reference	Purpose study	Context of study	Number	Type scenario	Quantitative / qualitative	Alternative futures	Time horizon	Name scenarios	Variables in the scenarios	How is uncertainty mentioned	Results of study	Policy / research
3rd PWM	1994	Implementation integrated water management. To achieve long-term objectives	Brundtland report on sustainability was published. Upcoming concern of the chemical and ecological quality of the rivers	1	Predictive-forecast, Normative	Quantitative and qualitative	Small (BAU)	not mentioned	Trends, target conditions, central estimate Environmental policy	Ecological normative scenarios. Alternative policy strategies. Trends agricultural water use, drinking water use, emissions and electricity production.	Some developments may make it difficult to achieve objectives. In that case objective may need to be adjusted. Impacts of climate change and sea level rise should be further investigated. Demand of society may change.	Policy options identified	Policy
Aquatic Outlook Background study 4th PWM.	1996	Define policy options to make the water system more resilient. Assess target conditions considering soci-economic developments	Brundtland report and the need for systematic quantitative analysis on how to achieve targets of 3rd PWM. Upcoming concern of the chemical and ecological quality of the rivers.	2 & 4 policies	Predictive - what-if	Quantitative and qualitative	Small for external scenarios and large for policies	2015, 2045	Land use: European Renaissance and Balanced Growth Policy: Business as Usual (Current Policy) 2015, Use Policy 2015, System Policy 2015, Radical change (Discontinuity) Policy 2045	Land use changes from socio-economic scenarios and policy options. Current climate conditions in terms of an average year and average river discharge were used	In case relevant, a sensitivity analysis was done for climate change and economic scenarios, including sea level rise and its impact on the lake IJsselmeer and an increase of the design discharge of the river Rhine. The document clearly stated that the strategy scenarios should be used as different policy options and elements for the final water management strategy in the 4th PWM.	Policy options	Policy
NRP1	1997	Impact assessment on discharge river Rhine	National Research Program on climate change.	2	Predictive - what-if	Quantitative	Small	2050, 2100	UKHI, XCCC (after GCM)	Temperature, evaporation wind, radiation	The bandwidth of the results is wide and is primarily caused by uncertainty in climate scenarios. Also, downscaling GCM and model variety play a role. Evaporation (influence of CO2 and biomass increase) is major uncertainty for low flows.	Impact assessment	Research
4th PWM	1998	Safety and sustainable water systems with good water quality	High waters at river Rhine & Meuse in '93 & '95 pointed out the vulnerability of living in a lowing lying river delta. Without policies future flood risk will increase due to climate change .	1	Predictive-forecast, Normative	Quantitative and qualitative	Small (BAU)	not mentioned	Prognoses, target conditions	Normative scenarios per water system and theme and prognoses for water demand for shipping, drinking & industry water (no agriculture)	There is uncertainty about effects of climate and sea level rise, more research is needed. Need to incorporate room for uncertain and unforeseen developments was expressed.	Guiding principles for policy options	Policy
NRP2	1999	Impact assessment water management in Netherlands	National Research Program on climate change.	3	Predictive - what-if	Quantitative	Moderate	2050, 2100	Reference (2050,2100), Lower, central, upper estimation	Temperature, precipitation, evaporation, sea level rise, land use (Netherlands & Rhine Upstream)	It was explicitly mentioned that scenarios are not predictions, but they were considered as a plausible basis for a what-if sensitivity analysis	Impact assessment and policy options identified	Research
Comittee Tielrooy	2000	Prepare for climate change and sea level rise	High waters at river Rhine & Meuse, evacuation of people from floodplain areas in '93 & '95, flooding regional areas '98.	3	Predictive - forecast	Quantitative and qualitative	Small	2030 for socio-economic 2050, 2100 for climate	Minimum, central, maximum scenario	Temperature, precipitation (year, summer, winter, rain), evaporation, sea level rise, river discharge (design, summer, winter).	The lower estimate will probably occur in the current trend, thus without greenhouse effect. Effects such as river discharge and sea level rise are presented as effects that will occur, with a maximum degree given by the maximum scenario	Guiding principles for policy options	Policy

Name study	Year & reference	Purpose study	Context of study	Number	Type scenario	Quantitative / qualitative	Alternative futures	Time horizon	Name scenarios	Variables in the scenarios	How is uncertainty mentioned	Results of study	Policy / research
NRP3	2001	Development of water management strategies. Method for integrated scenario analysis	High waters at river Rhine & Meuse, evacuation of people from floodplain areas in '93 & '95, flooding regional areas '98. IPCC report concluding global warming trend has been occurring over past century.	5	Explorative - external	Quantitative and qualitative	Large	2050, 2100	Lower, central, upper wet, upper dry, nao change	Temperature, precipitation, evaporation, sea level rise, land use, perspective	Include uncertainty about climate, socio-economic developments and perspectives	Impact assessment and policy options	Research
National Water Agreement	2003	Give guidance and norms for adaptation for regional governments	Results of committee Tielrooy needed to be translated in legislation (norms).	1	Predictive-forecast	Quantitative	Small	2050	Central estimation	Refer to Committee Tielrooy	Anticipate to climate change for at least the central estimate of the Tielrooy committee in 2050	Legislation	Policy
Drought study	2003	Impact assessment drought and identification of strategies	Awareness that water management focused a lot on wet conditions. Dry summer 2003. Dike breach of peat dike due to drought resulted in flooding.	3	Predictive-forecast	Quantitative	Large	2050	Lower (individualist), central (hierarchist), upper wet (egalitarian), upper (dry), change in transpiration, sensitivity analysis for land use change.	a.o. temperature, precipitation (year, summer, winter), evaporation, sea level rise, river discharge. Climate variability is considered by analysing 5 different 'dry' years.	Effects are presented in possibilities and a bandwidth is given. The bandwidth is a result of different scenarios. The relation is with these scenarios not always given. Sensitivity analysis was for effects of transpiration due to CO2 increase	Identification of strategies	Research
Drought management study	2008	Impact assessment drought and identification of strategies, update of previous drought study	New KNMI scenarios in 2006.	1	Possible - external	Quantitative	Small	2050	KNMI'06: moderate+, warm+	a.o. temperature, precipitation (year, summer, winter), evaporation, sea level rise, river discharge. Climate variability is considered by analysing 5 different 'dry' years.	Most extreme KNMI'06 scenario was taken to explore policy options using the following assumption: if it is not profitable to take measure under this scenarios, there is no reason to implement policies. Climate variability analysed by looking at characteristic years	Identification of strategies	Research
Perspectives IWRM	2008	Develop method to deal with uncertainty about the future	Pathway and interaction between society and water system is considered as important.	many	Explorative - external	Quantitative and qualitative	Large	chain, until 2100	Transient (time-series) scenarios based on KNMI'06, socio-economic scenarios	a.o. temperature, precipitation, river discharges, sea level rise, land use, perspectives.	Include uncertainty about climate, socio-economic developments and perspectives. Also interaction between society and water system	Method for decision making, ongoing project	Research
Update National Water Agreement	2008	Give guidance for adaptation for regional governments	New KNMI scenarios in 2006.	2	Predictive - forecast	Quantitative	Small	2050	KNMI'06: moderate+, warm+	Refer to KNMI'06	For tasks already considered the central estimate corresponding with the KNMI'06-moderate scenario should be used. If financial possible, policy options should be implemented given the uncertainties and extreme of KNMI'06 scenarios	Legislation with prescription of design conditions	Policy

Name study	Year & reference	Purpose study	Context of study	Number	Type scenario	Quantitative / qualitative	Alternative futures	Time horizon	Name scenarios	Variables in the scenarios	How is uncertainty mentioned	Results of study	Policy / research
Committee Veerman	2008	Chart a course of action to prevent future disasters and to raise awareness of the importance to develop strategies	Raising awareness on potential impacts of climate change and sea level rise.	4	Explorative - external	Quantitative and qualitative	Large	2050, 2100, 2200	Plausible upper limit (sea level), KNMI'06: moderate+, warm+	Refer to KNMI'06. Socio-economic trends qualitatively	There is still a lot of uncertainty about the extent and velocity of climate change and its effects. Use plausible upper limits of climate change to avoid that future generations will be confronted with unforeseen worse effects	Awareness, legislation, research program	Policy
5th PWM	2009	A safe and liveable delta now and in the future	Delta Committee	5	Normative - transforming, Predictive - forecast	Quantitative and qualitative	Large	several 2050, 2100	KNMI'06: moderate+, warm+; trends (socio-economic); plausible upper limit (sea level)	a.o. sea level, temperature, precipitation, number of wet days, wind velocity for winter and summer. Socio-economic and demographic trends are mentioned qualitatively	Uncertainty is explicitly mentioned in separate chapter. Develop robust and flexible strategies to deal with uncertainties about the future.	Guiding principles and roadmaps for decision making	Policy
Adaptation Tipping Point	2009	Explore vulnerability water management for climate change. Develop method to deal with uncertainty	Discussion at water boards on how to deal with 4 climate scenarios as central estimate can be chosen as norm.	4	Explorative - external	Quantitative	Large	chain, until 2100	KNMI'06: moderate+, warm+	Focus on sea level rise and river discharges	Assess vulnerability and use possible scenarios to determining timing of tipping point.	Method and indication of vulnerability	Research
Delta-scenarios for Delta Programme	2010, ongoing	Define policy options to prepare for climate change and sea level rise	Advice of Delta Committee	4	Explorative - external	Quantitative	Large	2050, 2100	Pressure, Steam, Warm, Quiet	a.o. temperature, precipitation, sea level, river discharge, population, economic growth, land use (urban, agriculture, nature). , Based on KNMI'06 and WLO socio-economic scenarios	Refer to two reports (Raad voor Verkeer en Waterstaat 2009 and Van Asselt 2010) which advice to include uncertainty explicity in policy analysis	Ongoing	Policy

Scenario typologies

In this chapter we characterise the use of scenarios based on two scenario typologies. First of all, we follow Van Notten et al. (2003) to describe 'why', 'how', 'what': what was the goal, the process design and the content of the scenarios? Regarding the goal of the scenario analysis they distinguish between normative and descriptive scenarios, which describe respectively preferable futures (including norms) and possible futures. Regarding the vantage point scenarios can be either forecasting, taking the present as a starting point, or backcasting, reasoning from future situation to explore paths to reach this situation. Qualitative versus quantitative scenarios is used as one of the characteristics for the process design. Qualitative scenarios are narratives, possibly developed together with stakeholders. Quantitative scenarios, frequently used in environmental studies, are often developed using computer simulations. Regarding the content of scenarios, Van Notten et al. (2003) use the temporal nature, nature of dynamics and the level of deviation as characteristics. Snapshot scenarios describe a moment in the future, while chain scenarios describe the evolvement to a certain point in the future. Scenarios can be either surprise free, often describing trends, or discontinuous, including events which change the developments abruptly. The level of deviation of scenarios refers to the extent to which alternative futures are described or whether only trends are considered.

The second typology we use distinguishes three categories for the classification of the scenario type, namely: 'predictive' (what will happen), 'possible' (what can happen?) and 'normative' (how can a target be reached?) scenarios after the typology of Börjeson et al. (2006). Within these three categories they further divide to achieve 6 types:

- forecasts scenarios: describe what will happen if the most likely development unfolds;
- what-if scenarios: are used to investigate what will happen on the condition of some specified near future events;
- external scenarios: focus on factors beyond the control of the relevant actors;
- strategic scenarios: incorporate policy measures of the intended scenario user;
- preserving scenarios: are used to find out how a certain target can be met; and
- transforming scenarios: are similar to the preserving scenarios but this target seems to be unreachable if the ongoing developments continue.

Values for socio-economic developments in the scenarios

The values are listed in Tables 11 and 12 on pages 204 and 205 respectively.

Table 11: Values for socio-economic developments in the scenarios

	1st PWM		2nd PWM		Aquatic Outlook background PWM4 (1996)				
Scenario name	Progn.	Progn.	Progn.	Progn.	Current	Current Policy	Use Policy	System Policy	Radical change Policy
Projection year	2000	2000 dry year Apr/Sep	1990 dry year	1990 extreme dry year		2015	2015	2015	2045
Urban area % of total area									
Agriculture % of total area					72	64	64	64	58
Nature % of total area									
Population (million)	17.9								
Economic growth (%/year)									
Drinking water demand houses (million m3/year)	1100	600	1500 (incl. industry)	1500 (incl. industry)					
Maintaining water levels and irrigation agriculture million m3 in 95% dry year	3300	3300							
Irrigation						-0.4	-0.4	-0.75	-1
Flushing / irrigation agriculture	12200	6100	991/1509	1470/2769					
Industry	5500	2700	+300 drinking & +150 groundwater	+300 drinking & +150 groundwater					

Table 12: Values for socio-economic developments in the scenarios

	backgr. PWM4, NRP2 (1999)				Drought study (2002)				Delta Programme (2011)			
Scenario name	Current	ER	BG	GS	Current	EGA	HIE	IND	Steam/Pressure		Warm/Quiet	
Projection year		2015	2015	2015		2050	2050	2050	2050	2100	2050	2100
Urban area % of total area	10	13	13	12	17	14	13	14	20	25	17	10
Agriculture % of total area	74	65	60	68	67	53	62	55	59	70	62	67
Nature % of total area	16	21	25	19	16	33	25	31	21	5	21	23
Combination Agriculture/Nature % of total area		1	3	1								
Population (million)						14.6	16.4	18.9	20	24	15	12
Economic growth (%/year)						1.5	2.75	3.25	2.6	2.0-2.6	0.7	0-0.5
Drinking water demand houses (million m3/year)						1500	1900	1900	-	-	-	-

B

APPENDIX TO CHAPTER 4

Most relevant cause-effect relations used in the IAMM

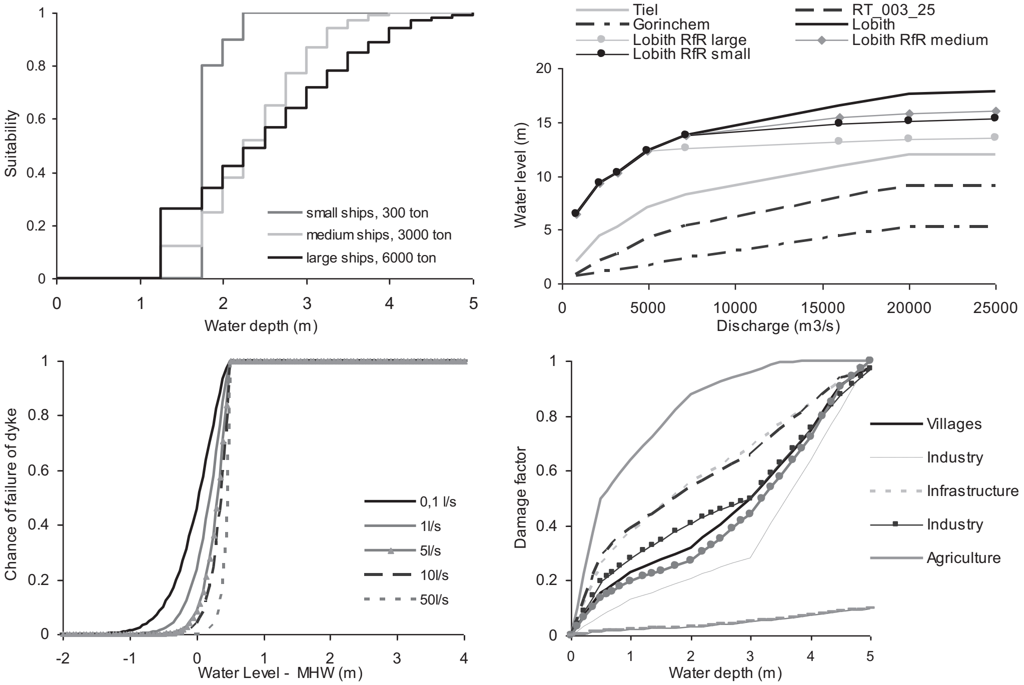


Figure 51: From left to right and top to bottom: suitability for three ship types in relation to water depth; stage discharge relations for different locations along the Waas; chance of dike failure in relation to the difference between the dike level and water level.

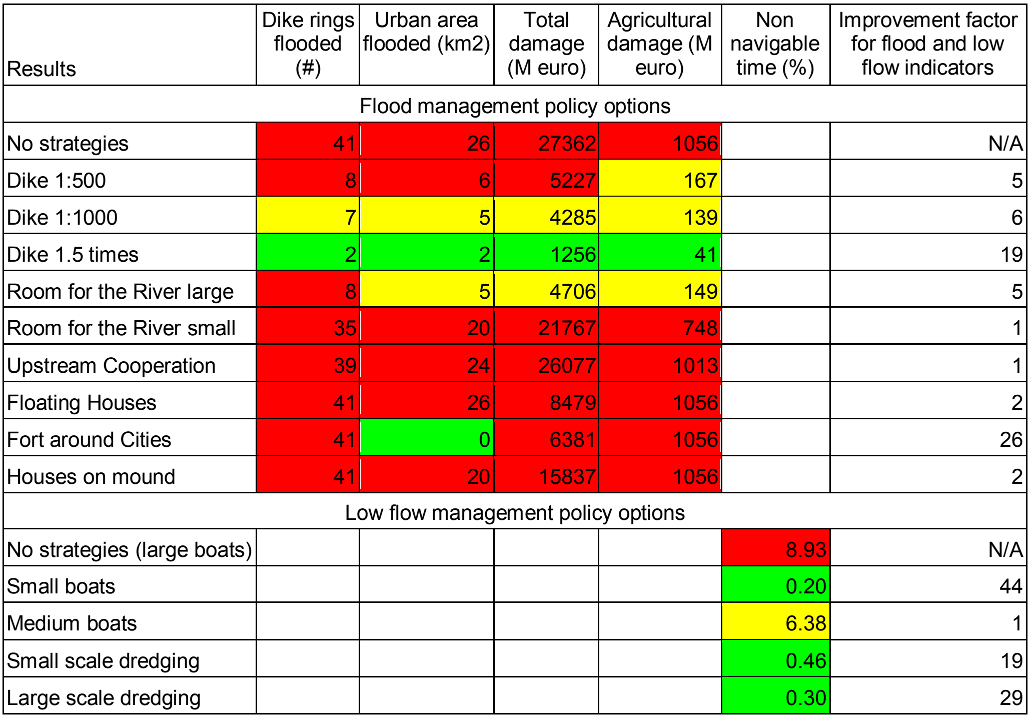
Absolute results for individual policy options

Tables 14 through 17 present the absolute results for individual policy options. For each policy option, the average performance is given for all ensemble members of all climate scenarios for the period of 100 years; and for each climate scenario separately. The colours refer to the acceptability categories for the Hierarchist (Table 1) and indicate whether targets are achieved (Green: acceptable; Yellow: moderate results; Red: unacceptable). Table 2 in the manuscript gives a description

Strategy	Total costs (Meuro/year)	Total costs (Meuro)	Explanation
DH500	1.1	Mean All 112 No cl. 82 G 100 Wp 152	Costs for dike raising include fixed costs and variable costs depending on the embankment length and amount of dike increase. For all ensembles for all transient scenarios, the costs for dike raising are calculated for each year (if they are raised). Each year the average dike height increase is calculated for the part of the dike that needs to be raised. Also the km of dike needed to be raised is calculated. This is used to calculate the costs based on the following formula for the costs of dike raising of 40 km of the river Waal*: (fixed_costs_97_Meuro + dike_raising)*exp(1)^0.00095*dike_raising_cm
DH1000	1.4	Mean All 142 No cl. 108 G 125 Wp 195	see DH500
DH1.5	2.3	Mean All 228 No cl. 219 G 231 Wp 236	see DH500
RfR-large	2.7	269	To give large scale room for the river dikes, are set back on two sides of the river (12 km length, 4m high). Building a new embankment (further away from the main channel) has two times higher fixed costs than dike raising. The variable costs depend on the embankment height and length. A small amount of urban area (4 ha) needs to be removed. Assuming 200 m2 per house, this corresponds to approximately 200 houses. We assume these houses will be bought for 0.03 Meuro each.
RfR-small	1.4	138	See large scale room for the river. For small scale room for the river dikes are set back on one side of the river only (6 km length, 4 m high).
CopU	0.003	0.03	Three fte government workers communicating with the upstream government to reduce peak flow.
FloatH	0.6	6.15	This involves 200 ha of urban area, where houses will be bought and rebuilt. These houses are about 5% more expensive than existing houses of 0.03 Meuro.
FaC	5.5 - 6.5	550-650	New embankments are built around the cities. Approximately 25 to 30 km of embankments of about 4 m are implemented.
Mound	10.1	1006	Mounds with an elevation of 4 m are built for 200 ha of urban area. Current houses need to be bought and rebuild. These houses are about 5% more expensive. Assuming 50 houses at 1 ha for 0.03 Meuro, results in 6.15 Meuro for buying and rebuilding the houses. Costs for building a mound is estimated at 5 Meuro/ha, resulting in 1000 Meuro for the mounds. This estimation is based on a pilot project in a Dutch polder along the river Waal. This project builds 9 mounds of 4 m height for 17 farms, removing and rebuilding the farms and building 6 km of new embankments and costs 90-100 Meuro**.
SmallS	0.4	40	Based on the assumption that the same load should be shipped and the potential load of the ships (300 ton for small ships), the number of ships needed to ship the load is calculated. The cost for a small ship is assumed to be 0.05 Meuro. NB Large ships (6000 ton) cost 1 Meuro. The total load for shipment is assumed to be 60,000 ton. Ships need to be replaced after 20 years.
MediumS	0.4	40	See small ships. Potential load for medium ships is 3000 ton. They cost 0.5 Meuro
SmallD	0.015 - 0.02	0.015 - 0.02	The amount of dredging per m3 is multiplied by the costs based on the yearly costs for the Port of Rotterdam (5 milj. m3 cost 11 to 14 Meuro/year)***. 70,000 m3 is dredged/year
LargeD	0.18 - 0.22	0.18 - 0.22	800000 m3/year

Table 13: Costs of the strategies based on the strategies along the river Waal in the Netherlands. *De Grave and Baarse (2011); **Waterschap Brabantse Delta (2013); ***AKWA (2001)

of the policy options. The improvement factor is the proportion of results for indicators with and without strategies. For the flood management strategies, the average of the indicators is taken.

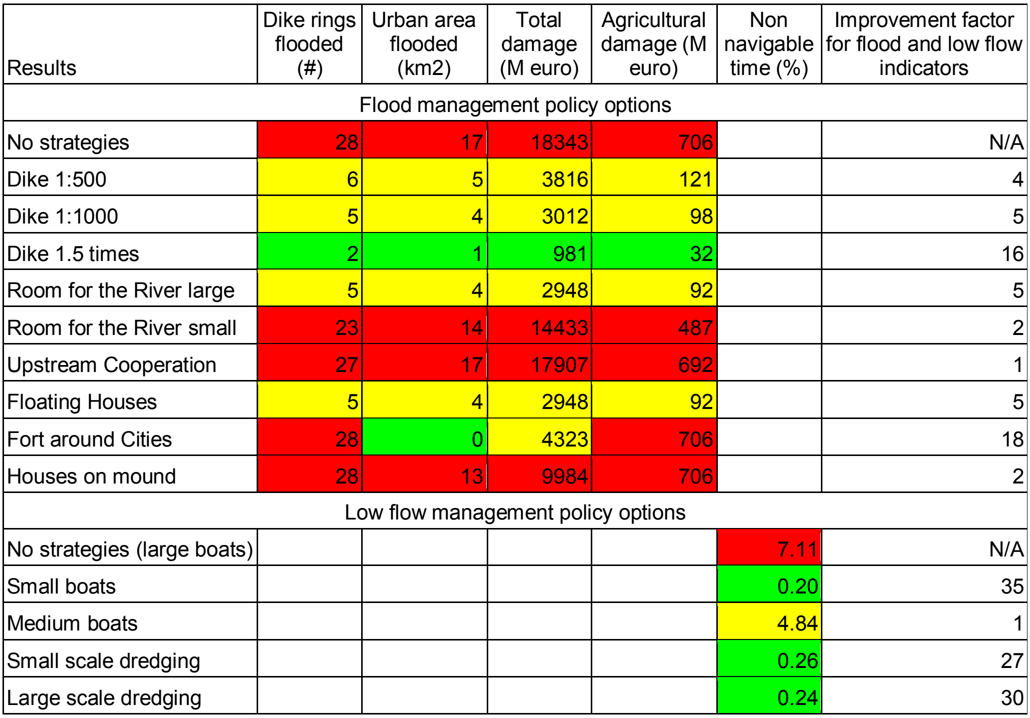


Results	Dike rings flooded (#)	Urban area flooded (km2)	Total damage (M euro)	Agricultural damage (M euro)	Non navigable time (%)	Improvement factor for flood and low flow indicators
Flood management policy options						
No strategies	41	26	27362	1056		N/A
Dike 1:500	8	6	5227	167		5
Dike 1:1000	7	5	4285	139		6
Dike 1.5 times	2	2	1256	41		19
Room for the River large	8	5	4706	149		5
Room for the River small	35	20	21767	748		1
Upstream Cooperation	39	24	26077	1013		1
Floating Houses	41	26	8479	1056		2
Fort around Cities	41	0	6381	1056		26
Houses on mound	41	20	15837	1056		2
Low flow management policy options						
No strategies (large boats)					8.93	N/A
Small boats					0.20	44
Medium boats					6.38	1
Small scale dredging					0.46	19
Large scale dredging					0.30	29

Table 14: Performance of the individual policy options for all ensemble members of all climate scenarios for 100 years

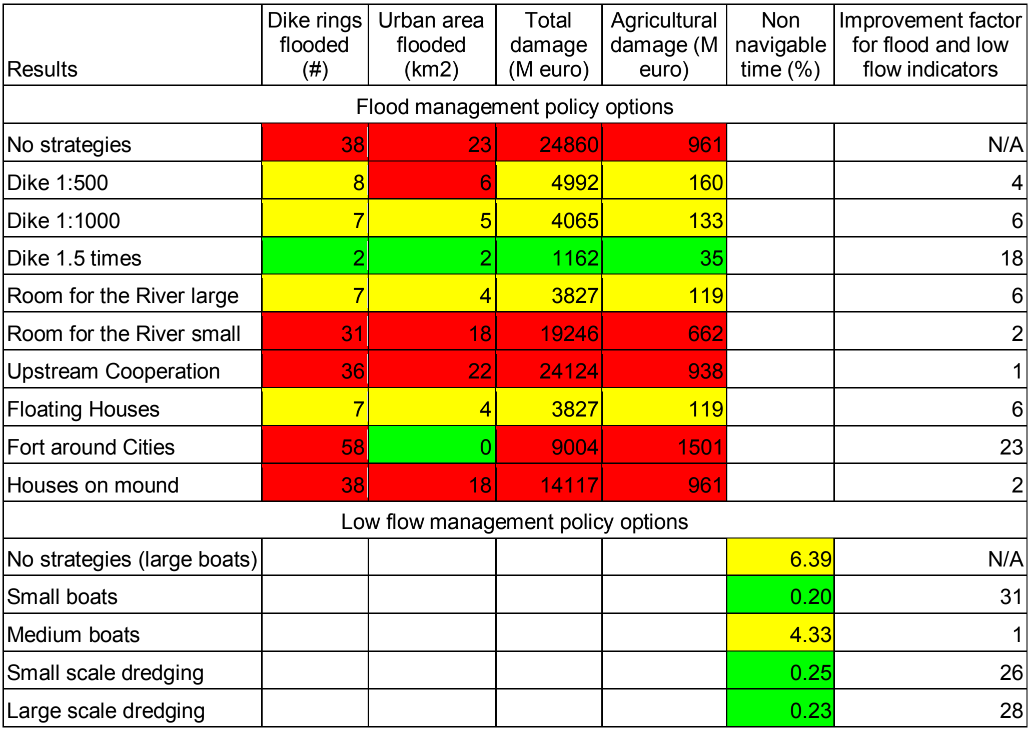
Relation Perspectives with the policy options.

The table below presents the view of each Perspective on the policy options. Green indicates preferable option, yellow an acceptable option, and red is unacceptable for this Perspective.



Results	Dike rings flooded (#)	Urban area flooded (km2)	Total damage (M euro)	Agricultural damage (M euro)	Non navigable time (%)	Improvement factor for flood and low flow indicators
Flood management policy options						
No strategies	28	17	18343	706		N/A
Dike 1:500	6	5	3816	121		4
Dike 1:1000	5	4	3012	98		5
Dike 1.5 times	2	1	981	32		16
Room for the River large	5	4	2948	92		5
Room for the River small	23	14	14433	487		2
Upstream Cooperation	27	17	17907	692		1
Floating Houses	5	4	2948	92		5
Fort around Cities	28	0	4323	706		18
Houses on mound	28	13	9984	706		2
Low flow management policy options						
No strategies (large boats)					7.11	N/A
Small boats					0.20	35
Medium boats					4.84	1
Small scale dredging					0.26	27
Large scale dredging					0.24	30

Table 15: Performance of the individual policy options for all ensemble members of without climate change



Results	Dike rings flooded (#)	Urban area flooded (km2)	Total damage (M euro)	Agricultural damage (M euro)	Non navigable time (%)	Improvement factor for flood and low flow indicators
Flood management policy options						
No strategies	38	23	24860	961		N/A
Dike 1:500	8	6	4992	160		4
Dike 1:1000	7	5	4065	133		6
Dike 1.5 times	2	2	1162	35		18
Room for the River large	7	4	3827	119		6
Room for the River small	31	18	19246	662		2
Upstream Cooperation	36	22	24124	938		1
Floating Houses	7	4	3827	119		6
Fort around Cities	58	0	9004	1501		23
Houses on mound	38	18	14117	961		2
Low flow management policy options						
No strategies (large boats)					6.39	N/A
Small boats					0.20	31
Medium boats					4.33	1
Small scale dredging					0.25	26
Large scale dredging					0.23	28

Table 16: Performance of the individual policy options for all ensemble members of the G climate scenario

Results	Dike rings flooded (#)	Urban area flooded (km2)	Total damage (M euro)	Agricultural damage (M euro)	Non navigable time (%)	Improvement factor for flood and low flow indicators
Flood management policy options						
No strategies	58	37	38884	1501		N/A
Dike 1:500	11	8	6872	221		5
Dike 1:1000	9	7	5780	185		6
Dike 1.5 times	3	2	1626	55		21
Room for the River large	13	8	7342	235		5
Room for the River large	50	29	31621	1095		1
Upstream Cooperation	54	33	36201	1408		1
Floating Houses	13	8	7342	235		5
Fort around Cities	41	0.4	6381	1056		37
Houses on mound	58	29	23410	1501		1
Low flow management policy options						
No strategies (large boats)					13.30	N/A
Small boats					0.20	65
Medium boats					9.97	2
Small scale dredging					0.87	15
Large scale dredging					0.45	30

Table 17: Performance of the individual policy options for all ensemble members of the Wp climate scenario

Results	Hierarchist	Egalitarian	Individualist
Flood management policy options			
Dike 1:500	🟩 Dikes offer safety and have proven to be a reliable strategy to control discharges and prevent floods. The higher the safety norm, the more preferred.	🟥 Dikes are unnatural, disturbing for the natural ecological river functions . (Trying) to control nature to a large extend is inherently wrong.	🟨 Dikes are in general old fashioned and do not offer inhabitants additional living enjoyment. Some dikes can be preserved to protect economical hot spots, but more innovative solutions are preferred. Climate dikes may offer opportunities for self development and innovation.
Dike 1:1000			
Dike 1.5 times			
Room for the River large	🟥 In general, unnecessarily dangerous. People inside and outside the winter bed should be protected for floods and high discharges.	🟩 Preferred policy option, as it provides space for water and natural development and decreases human interferences within the natural system. The more space is reserved for natural processes, the better.	🟨 Wasting valuable space that may become particularly important if the population grows and more space be needed for living and building areas. Besides, it is lacking innovation and may be characterized as old fashioned. On a small scale this could be interesting if combined with floating houses.
Room for the River small	🟨 This may be acceptable if it is used to let the excessive discharge flood in a controlled way and if it is combined with dikes that protect the landside.		
Upstream Cooperation	🟩 It is good to put efforts in a properly controlled river outside our own country borders. However, safety and drinking water supply should be guaranteed regardless of the actions taken by upstream areas.	🟩 As we share the responsibility of river management with the entire catchment area we should strive for one natural management strategy shared by the entire catchment area	🟨 It is important to stay independent and therefore we should not make too may concessions. Because it is a relatively cheap way to adapt to problems, it is acceptable.
Floating Houses	🟨 Potentially very dangerous, as protection from drowning can not be guaranteed, and inconvenient. Effects on health (water quality) should also be investigated. Too expensive to guarantee government responsibility.	🟨 It is positive that water will gain more space (also in the winter bed) but not very keen on innovative technologies. Besides disturbing effects on the natural discharge and biodiversity are hard to prevent.	🟩 Preferred, as it approaches water as offering opportunities and it combines climate adaptation with maximizing living enjoyment and innovation.
Fort around Cities	🟨 A potentially good strategy. However, in the current time, attention needs to be paid to the vulnerability for damage and terroristic attacks. The 'bathtub" effect should be prevented. Implementing and testing a good working evacuation and emergency plan.	🟥 Rejection of controlling measures as it interferes too much in the natural dynamics.	🟨 Old fashioned, but in some cases acceptable to protect for example economic hot spots.
Houses on mound	🟩 Could be acceptable, but instead of dealing with the consequences of a flood, prevention of floods is preferred.	🟩 Acceptable if these mounds are natural elevations in the landscape; otherwise unacceptable, as it damages and interferes with nature	🟩 Traditional mounds are too old fashioned. New, larger mounds with possibilities to adapt infrastructures to it may offer opportunities
Low flow management policy options			
Small boats	🟨 A transformation of our navigation fleet is not considered to be a core responsibility of the government. However, subsidies could be a way to achieve small or medium ships and to assure a durable continuation of transport	🟩 As dredging may have negative impacts on ecology, this strategy is acceptable. The smaller the boats, the less damaging for ecological values. Navigation is less damaging than transport along the road.	🟨 Small boats are an inherently inefficient way of transportation, but considerable if traffic jams increase due to pressure on space and non navigable time increases.
Medium boats			🟨 Medium boats decrease the efficiency of transportation. Only considerable if the non navigable time increases sharply
Small scale dredging	🟩 A way to control the discharge and river depth and hence preferred. However, as the main focus is on drought issues, flood prevention should not be neglected.	🟨 Dredging is contra-natural and disturbs wild life values and ecology along the river bed. Only acceptable on a very local and small scale to restore natural river values.	🟩 Especially if private companies are responsible for dredging, this may offer good opportunities to combine profit making gravel extraction with controlling the river depth to guarantee large scale navigation.
Large scale dredging	🟩 See small scale dredging including attention to the effects of large scale dredging on other river functions that should not get disturbed too much (recreation, cooling water, fishing, etc.)	🟥 Too damaging for nature and ecological values and too much focus on the willingness to control water and nature. Rejected.	

Table 18: View of each Perspective on the policy options. Green indicates preferable option, yellow an acceptable option, and red is unacceptable for this Perspective.

C

APPENDIX TO CHAPTER 6

EQUATIONS USED TO CALCULATE THE DISCHARGE CAPACITY FROM LAKE IJSSELMEER TO WADDEN SEA.

$$Q = W \times d \times c \left(2g \left(H_{\text{IJsselmeer}} - H_{\text{Wadden Sea}}\right)\right)^{0.5} \tag{1}$$

Where:

Q = discharge across one of the orifices $[m^3/s]$

W = crest width $[m]$

d = opening height = opening level - crest level $[m]$

c = discharge coefficient

g = gravity acceleration $[m/s^2]$

$H_{\text{IJsselmeer}}$ = IJsselmeer water level $[m]$

$H_{\text{Wadden Sea}}$ = Wadden Sea water level $[m]$

EQUATIONS USED TO CALCULATE SALT CONCENTRATION AT GOUDA INLET.

$$\text{Salt} = 17{,}000 + (90 - 17{,}000) \times \frac{\exp^{\text{Fact}}}{1 + \exp^{\text{Fact}}} \tag{2}$$

$$\text{Fact} = \left(\frac{Q_{\text{Lobith}} - 600}{2.211}\right)^{0.309} \tag{3}$$

Where:

Q_{Lobith} = discharge at Lobith $[m^3/s]$

Salt = salt concentration at Gouda inlet $[mg/l]$

EQUATIONS USED IN THE WATER DEMAND MODULE

$$\text{Epot}_t = \text{Eref}_t \times \text{CropFactor}_t \tag{4}$$

$$\text{Qdr}_t = \text{Hsurf}_{t-1} - \frac{\text{Hgrnd}_{t-1}}{\text{Rout}} \tag{5}$$

$$\text{Qin}_t = \text{Hsurf}_{t-1} - \frac{\text{Hgrnd}_{t-1}}{\text{Rin}} \tag{6}$$

$$\mathrm{Perc}_t = \max\left(\mathrm{Sm}_{t-1} + P_t - \left(\mathrm{Po} \times \mathrm{Dr}_t\right), 0\right) \tag{7}$$

$$\mathrm{CapRise}_t = \mathrm{CapRiseMax} \times \mathrm{CapFact}_t \tag{8}$$

$$\mathrm{CapFact}_t = \mathrm{CapFact\_grnd}_t \times \mathrm{CapFact\_root}_t \tag{9}$$

$$\mathrm{Capfact\_grnd}_t = \begin{cases} 0 & \text{for } H\_grnd \geqslant \mathrm{Dc} \\ 1 - \dfrac{-\mathrm{Hgrnd}_t - 0.5 \times \mathrm{Dr}_t}{\mathrm{Dc} - 0.5 \times \mathrm{Dr}_t} & \text{for } \frac{1}{2}\mathrm{Dr} < \mathrm{H\_grnd} < \mathrm{Dc} \\ 1 & \text{for } \mathrm{H\_grnd} < \frac{1}{2}Dr \end{cases} \tag{10}$$

$$\mathrm{CapFact\_root}_t = \max\left(0, \left(1 - \frac{\mathrm{Sm}_{t-1}}{\mathrm{Po} \times \mathrm{Dr}_t}\right)\right) \tag{11}$$

$$\mathrm{RootVol}_t = \frac{\mathrm{Sm}_{t-1}}{\mathrm{Dr}_t} \times 100 \tag{12}$$

$$\mathrm{pF} = f\left(\mathrm{RootVol}_t, \mathrm{pFcurve}, \mathrm{Soiltype}\right) \tag{13}$$

$$\mathrm{RedFact} = \begin{cases} 0 & \text{for } \mathrm{pF} < pF_{red} \\ \dfrac{\mathrm{pF} - \mathrm{pFred}}{\mathrm{pFmax} - \mathrm{pFred}} & \text{for } \mathrm{pF}_{red} < \mathrm{pF} < \mathrm{pF}_{\mathrm{max}} \\ 1 & \text{for } \mathrm{pF} > \mathrm{pF}_{\mathrm{max}} \end{cases} \tag{14}$$

$$\mathrm{Eact} = \min\left(\mathrm{Sm}_{t-1} + P_t + \mathrm{CapRise}_t - \mathrm{Perc}_t, \left(1 - \mathrm{RedFact}_t\right) \times \mathrm{Epot}_t\right) \tag{15}$$

$$\mathrm{Sprink}_t = \mathrm{Sfrac} \times \left(\mathrm{Epot}_t - \mathrm{Eact}_t\right) \tag{16}$$

$$\mathrm{SM}_t = \mathrm{SM}_{t-1} + P_t + \mathrm{CapRise}_t - \mathrm{Perc}_t - \mathrm{Eact}_t + \mathrm{Sprink}_t \tag{17}$$

$$\text{Runoff} = \begin{cases} \text{Sm}_t - (\text{Po} \times \text{Dr}_t) & \text{if Sm} > \text{Po} \times \text{Dr}_t \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

$$\text{Hgrnd}_t = \text{Hgrnd}_{t-1} + \frac{\text{Delta\_h}_t - \text{CapRise}_t + \text{Perco}_t + \text{S}}{\text{Po}} \tag{19}$$

Where:

Eact = actual evapotranspiration [m/10d]
Epot = potential evapotranspiration [m/10d]
Eref = reference evaporation according to Makkink [m/10d]
CapRise = capillary rise [m/10d]
Delta_h = change in groundwater level due to drainage or infiltration [m]
Dc = depth at which CapRise equals zero [m]
Dr = rootzone depth [m]
Hgrnd = groundwater level below surface level [m]
Hsurf = surface water level below surface level [m]
Perco = percolation [m^3/10d]
P = precipitation [m/10d]
pFmax = pF at wilting point
pFred = pF at wich actual evaporation decreases linearly
Po = porosity [–]
Qdrain = drainage [m/d]
Qinfil = infiltration [m/d]
RootVol = rootvolume [%]
Rout = resistance for drainage to streams and canals [d]
Rin = resistance for flow from streams and canals to groundwater [d]
S = seepage [m/10d]
Sfrac = fraction of area with possibility of sprinkling [–]
SM = soil moisture [m]
Sprink = Sprinkling [m]
t = timestep

EQUATIONS USED TO CALCULATE CROP DAMAGE IN THE DROUGHT IMPACT MODULE

$$\mathrm{DF_t} \quad = \begin{cases} 0 & \text{for } \frac{\mathrm{Eact}}{\mathrm{Epot}} \geqslant 1 \\ \mathrm{RS_t} \times \dfrac{1 - \frac{\mathrm{Eact}}{\mathrm{Epot}}_t}{1 - \mathrm{RP_t}} & \text{for RP} < \frac{\mathrm{Eact}}{\mathrm{Epot}} < 1 \\ \mathrm{RS_t} + (\mathrm{MS_t} - \mathrm{RS_t}) \times \dfrac{\mathrm{RP_t} - \mathrm{ratio}}{\mathrm{RP_t} - \mathrm{SP_t}} & \text{for SP} < \frac{\mathrm{Eact}}{\mathrm{Epot}} < \text{RP} \\ \mathrm{MD_t} & \text{for } \frac{\mathrm{Eact}}{\mathrm{Epot}} \leqslant \text{SP} \end{cases} \tag{20}$$

Where:

DF	=	Damage fraction [–]
MD	=	Maximum damage [–]
RS	=	Reduction damage [–]
RP	=	Reduction point [–]
RY	=	remaining yield [–]
SP	=	Death point [–]
SF	=	Survival fraction [–]
t	=	timestep
TDF	=	total damage fraction [–]

EQUATIONS USED TO CALCULATE DAMAGE FOR INLAND TRANSPORT

$$\mathrm{Lfact_{t,s}} = \frac{\mathrm{Dc} - \mathrm{De}}{\mathrm{Dm} - \mathrm{De}} \tag{21}$$

$$\mathrm{Load_{t,s}} = \begin{cases} \mathrm{Lfact} \times \mathrm{MaxLoad} & \text{for Lfact} \geqslant \mathrm{C} \\ 0 & \text{for Lfact} < \mathrm{C} \end{cases} \tag{22}$$

$$\mathrm{DLoad_{t,s}} = \begin{cases} \mathrm{MaxLoad} & \text{for Lfact} < \mathrm{C} \\ 0 & \text{otherwise} \end{cases} \tag{23}$$

$$\mathrm{TotL_t} = \Sigma\,(\mathrm{Load_{t,s}}) \tag{24}$$

$$\mathrm{Ex} = \mathrm{TotMaxL} - \mathrm{TotL_t} - \mathrm{TotDL_t} \tag{25}$$

$$Pa_t = \frac{TotMaxL - TotDL_t}{TotL_t} \times P \tag{26}$$

$$Costs = \frac{MaxLoad \times P + MaxLoad \times Pa_t}{365} \tag{27}$$

Where:

C = critical load factor below which navigation will be delayed $[-]$
Costs = costs $\left[10^6 euros/year\right]$
Dm = water depth needed for ship with maximum load $[m]$
Dc = water depth at critical location $[m]$
De = depth of the ship without load $[m]$
$DLoad_{t,s}$ = delayed load at timestep t $[day]$ for ship type s $[tonne]$
Ex = load transported with extra ships $[tonne]$
$Lfact_{t,s}$ = load factor at timestep t for ship type s
$Load_{t,s}$ = load at timestep t for ship type s
MaxLoad = maximum load per ship type
Pa_t = adapted price
P = price per tonne load
$TotL_t$ = total load
TotMaxL = total maximum load
TotDL = total delayed load

D

APPENDIX TO CHAPTER 7

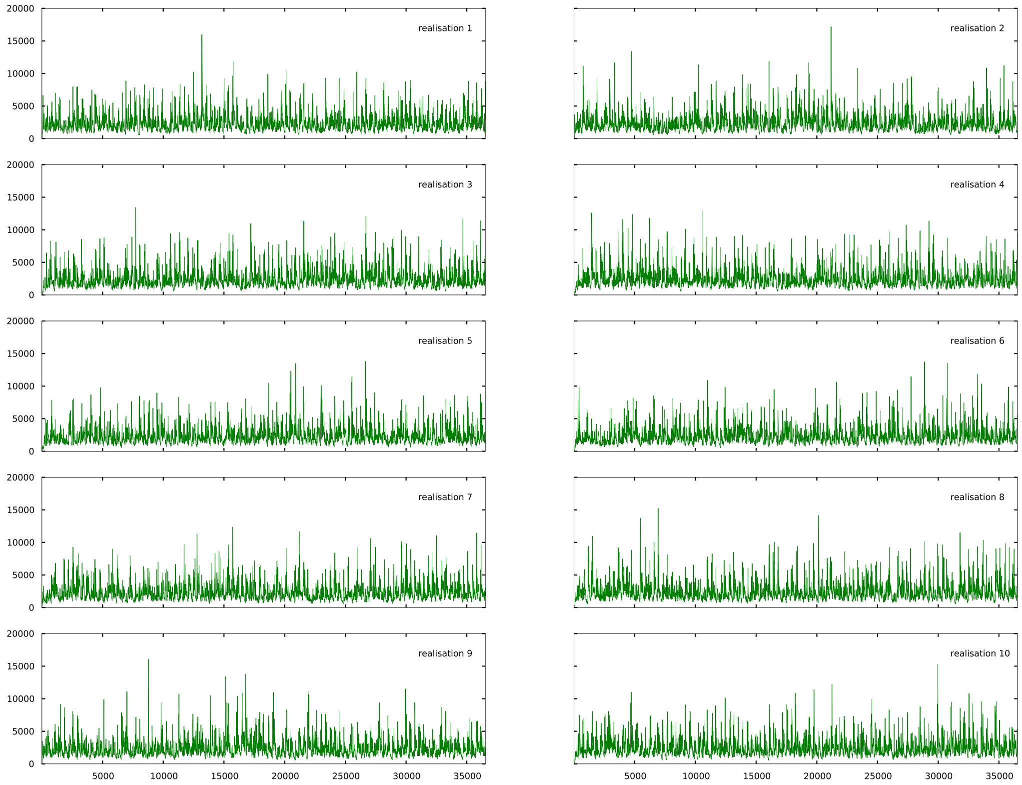


Figure 52: 10 realisations of discharges at Lobith for the No Change scenario

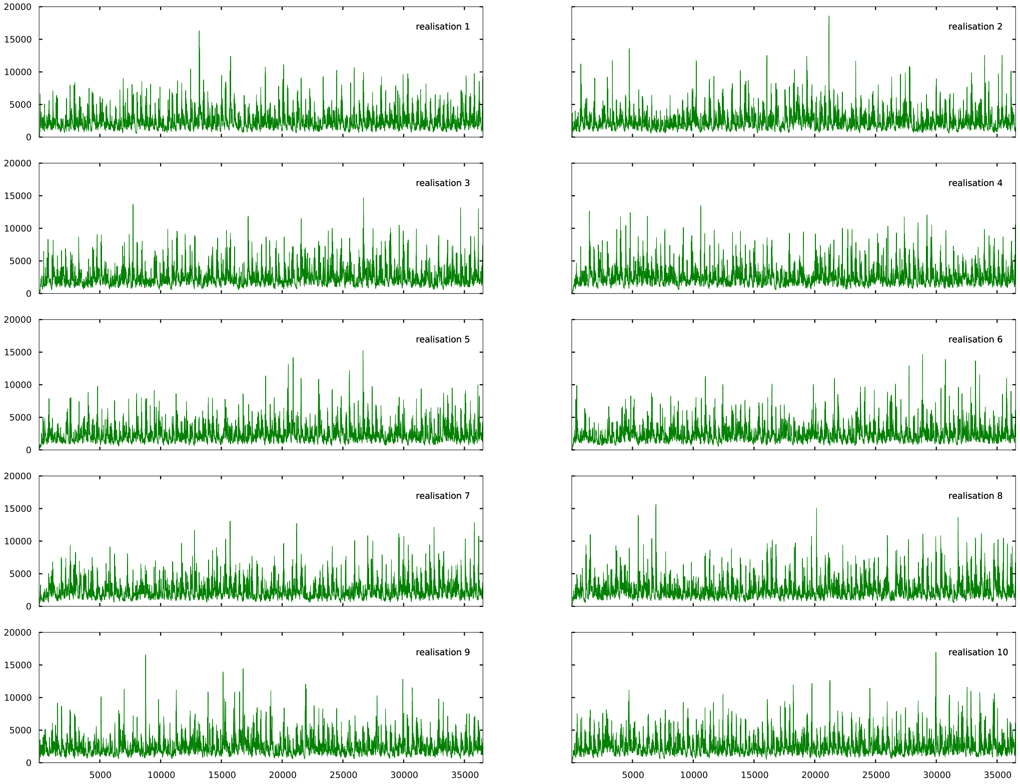


Figure 53: 10 realisations of discharges at Lobith for the G climate change scenario

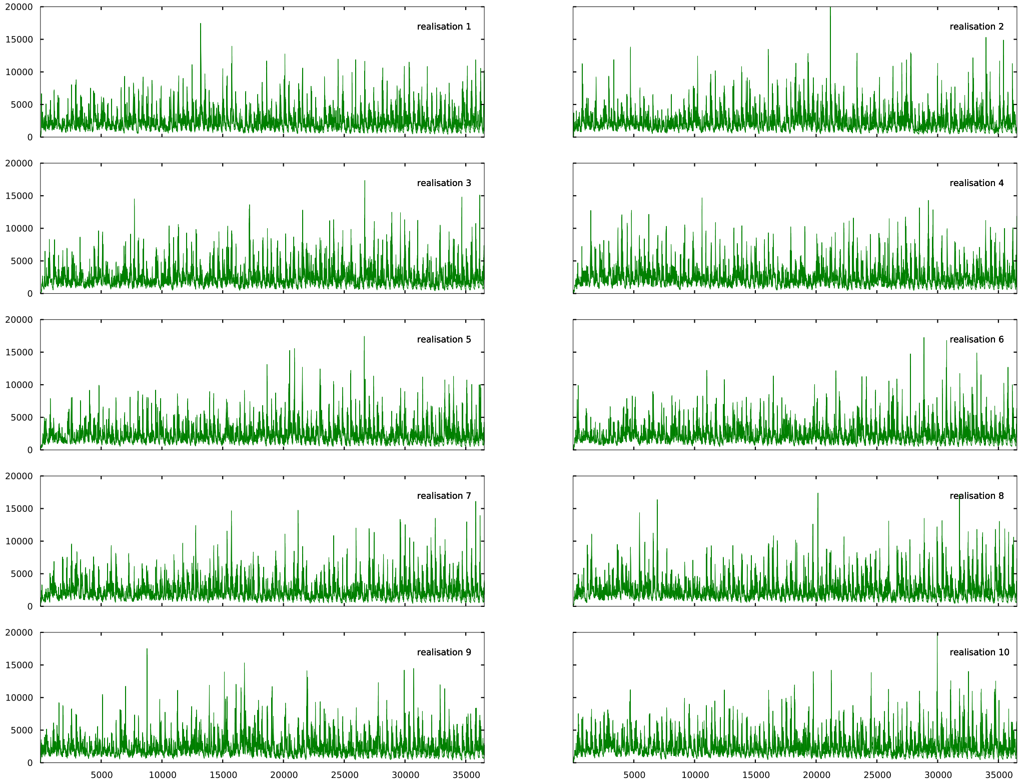


Figure 54: 10 realisations of discharges at Lobith for the Wp climate change scenario

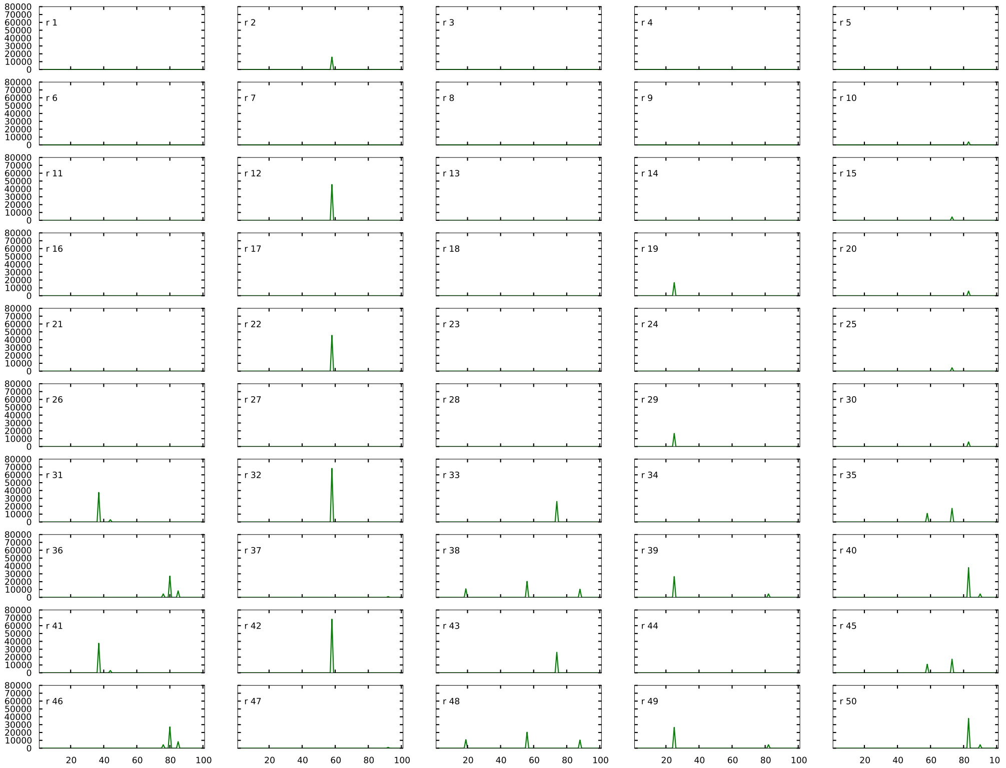


Figure 55: Flooding damage for the reference situation without policy actions for all 50 climate realisations.

Figure 56: Number of 10-day periods that water level in the IJsselmeer drops below threshold values during the summer half year for reference situation without policy actions for all 50 climate realisations. Green -0.2 - -0.25m MSL, Blue -0.3- -0.4m MSL, Red > -0.4 m MSL.

Figure 57: Number of ten-day periods that the water levels in the IJsselmeer are above threshold values in the winter half year for all 50 climate realisations in case a additional pump capacity of 500 m^3/s is implemented at the Afsluitdijk. Green 0.1-0.3 m MSL and > 0.3 m MSL

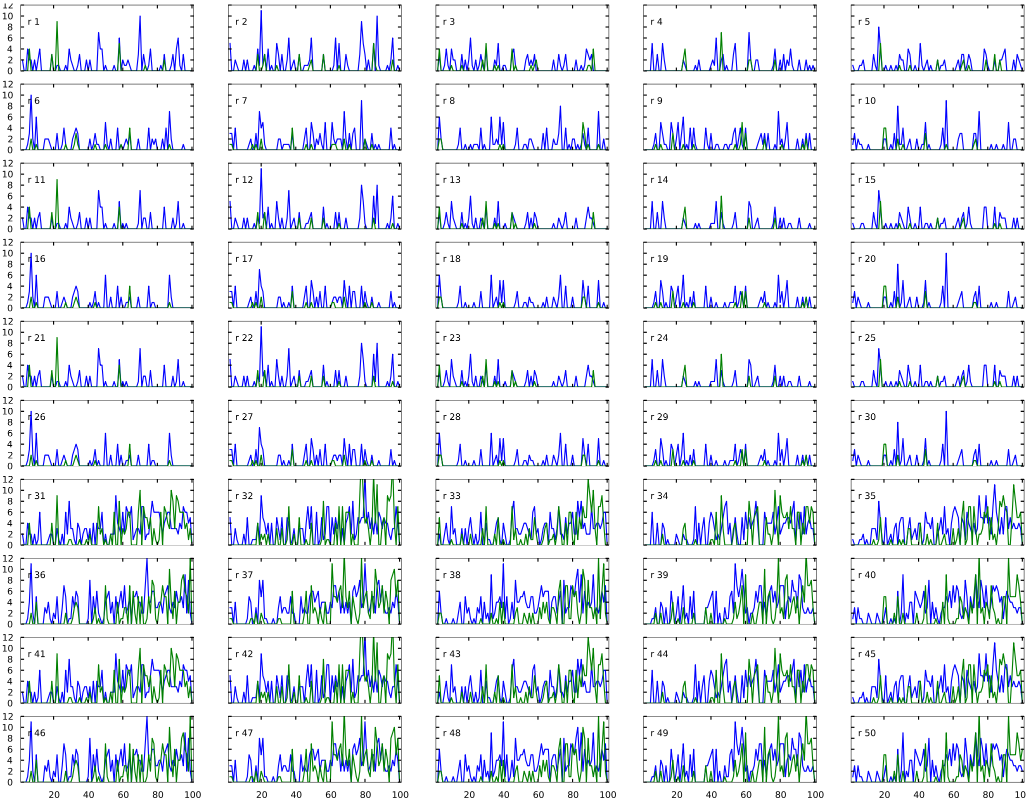


Figure 58: Number of ten-day periods with a salt concentration of 200-400 mg Cl/l (blue) or larger than 400 mg Cl/l (green) for the reference situation without policy actions for all 50 climate realisations.

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GLOSSARY AND ABBREVIATIONS

GLOSSARY

Adaptation pathway	Sequence of policy actions over time that are able to achieve (a set of) specified objectives.
Adaptation tipping point	Conditions under which a particular policy action performs unacceptably.
Adaptation (pathways) map	Visualisation of a set of adaptation pathways showing options for transferring from one pathway to an other, and the timing and/or conditions under which an adaptation tipping point of a policy action occurs.
Flexible actions	Actions can be adapted (e.g intensification of the action), abandoned (switch to a different action) or extended (add an action) at low cost or having small societal impact. Flexible actions do not result in lock-ins and have little influence on potential future options (i.o. have less path-dependencies).
Lock-in	Situation where the some future action in a pathway can only be implemented against high costs or high societal impact.
No regret actions	Actions that are robust or have additional benefits.
Path-dependency	Extent to which a policy action (in a pathway) is limited by actions implemented in the past or by actions planned anterior in the pathway
Policy pathway	See adaptation pathway.
Robust actions	Actions that result in acceptable indicator values under a wide variety of futures.
Scenario	Coherent descriptions of alternative hypothetical futures that reflect different perspectives on past, present and future developments, which can serve as a basis for action (Van Notten, 2005). In this study, scenario is used for 'external context' scenarios that describe developments that can not be influenced and are thus policy-free.
Sell-by date policy action	The timing of an adaptation tipping point of a policy action. This may differ per scenario, realisation, and threshold value of acceptable performance.
Signposts	Information that should be tracked in order to determine whether implementation of action or reassessment of the plan is needed.

Storyline	A story of a possible future over time, and include both natural and socio economic events (e.g. floods, droughts; economic crisis), trends (e.g. climate change; changing public perception of safety or nature) and interactions between the water system and society (e.g. flood impacts; flood mitigation measures). In contrast to (transient) scenarios, storylines are not policy free.
Transient scenario	Time-series into the forthcoming future that describe developments over time, that can not be influenced and are thus policy free.
Triggers	Critical values of signpost variables beyond which additional actions should be implemented.

ABBREVIATIONS

ADM	Adaptive Delta Management
ATP	Adaptation Tipping Point
G	KNMI'06 G scenario of +2°C in 2100
IAM	Integrated Assessment Model
IAMM	Integrated Assessment MetaModel
PSIR	Pressure State Impact Response
Ref	Reference situation without policy actions
Wp	KNMI'06 Wplus scenario of +4°C in 2100

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ABOUT THE AUTHOR

Marjolijn Haasnoot was born on June 9th, 1975 in Haarlem, The Netherlands. After completing secondary school in 1993, she pursued a Master's Degree in Environmental Sciences at the then Faculty of Biology of the Free University of Amsterdam. She specialised in Hydrology and completed a Master's dissertation about the eco-hydrological model DEMNAT. Marjolijn obtained the degree in 1998.

After graduation, Marjolijn worked for the National Institute for Inland Waterways and Wastewater Treatment (RIZA). While at RIZA, she researched the effects of climatic change and land subsidence on agriculture, water management and nature. In 2001, she went to work with Delft Hydraulics (which has since merged into Deltares). Here, she initially researched and consulted on eco-hydrological models. She became product manager of the HABITAT eco-hydrologic modeling suite, for which she introduced the *Dare To Share* principle (inspired by Soekijad 2005). In addition, she worked on projects related to water resources management and the implementation of the Water Framework Directive (notably in Cyprus and Romania).

From 2002 through 2008, Marjolijn has been a member of the Board of GAIA, a network for female earth scientists. She co-initiated the GAIA Ambassador's Network, which aimed to empower female beta researchers and consultants. Since early 2013 she has been a member of the Supervisory Board of Femconsult, a not-for-profit organisation that aims to further gender perspective in development programmes and projects.

In 2008, Marjolijn commenced working on a PhD research at Deltares, Utrecht University and the University of Twente. The research focused developing sustainable water management strategies taking into account uncertainties about the future.

Currently, Marjolijn continues to work for Deltares. She lives in Delft with her partner Jan and her son Nils.

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