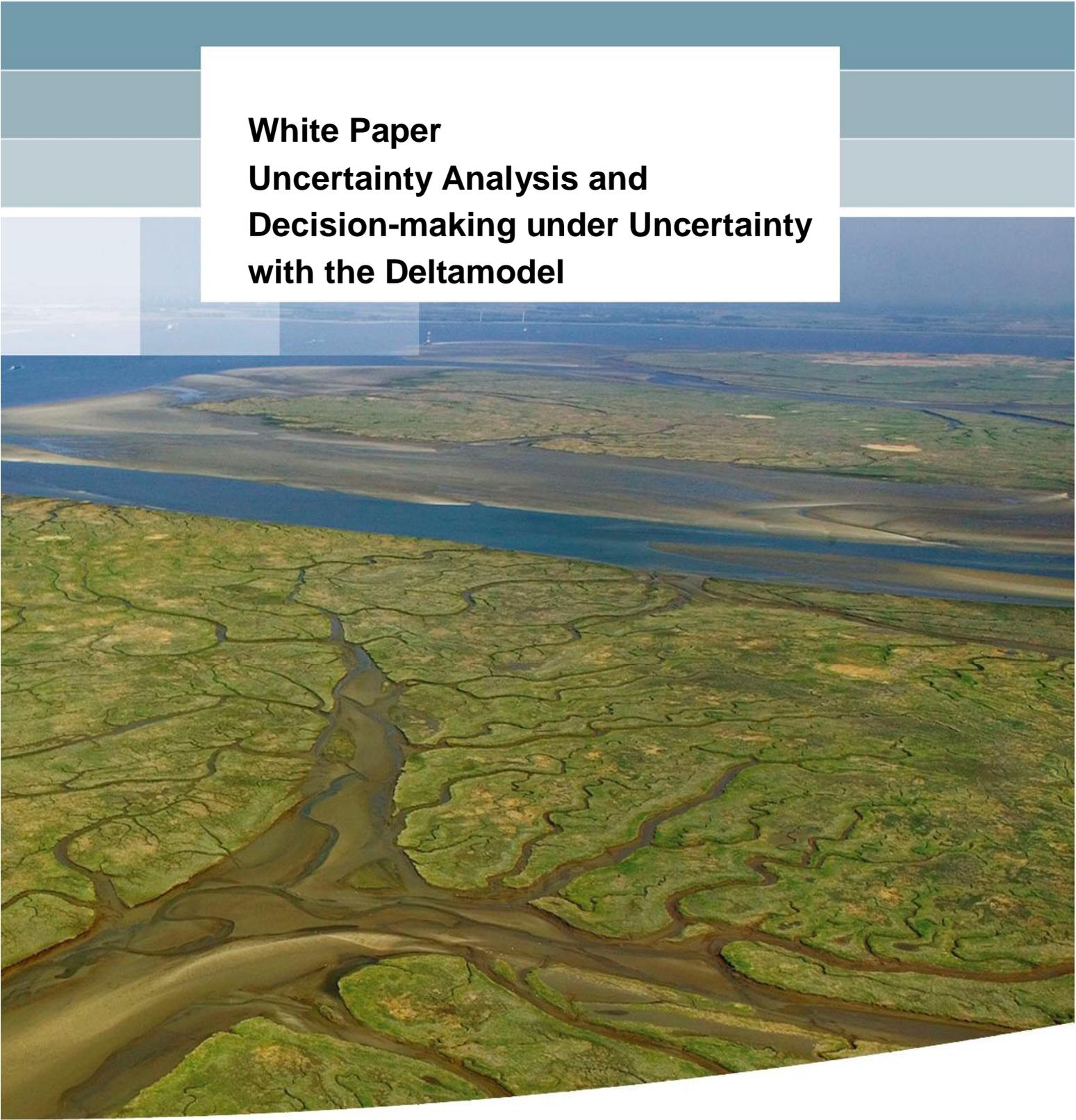


**White Paper
Uncertainty Analysis and
Decision-making under Uncertainty
with the Deltamodel**



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making under Uncertainty with the
Deltamodel

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1204151-014

Title

White Paper Uncertainty Analysis and Decision-making under Uncertainty with the Deltamodel

Client

Rijkswaterstaat Waterdienst

Project

1204151-014

Reference

1204151-014-ZWS-0003

Pages

16

Keywords

Deltamodel, uncertainty, decision-making

Summary

The purpose of the Deltamodel is to establish a reliable and accepted basis for decision-making in the Delta Programme, with a particular emphasis on Delta decisions. This White Paper presents our overview of the various types of uncertainty and how the Deltamodel can be used to support decision-making under uncertainty. In using the Deltamodel for decision-making, policymakers need to deal with uncertainties about the future, the model, the outcomes from the model, and the (future) weights on the outcomes.

Any specific uncertainty can be assigned a level that falls somewhere in the range from complete determinism to recognized ignorance. There are different methods for dealing with the different types of uncertainty. The Deltamodel and Delta Programme involve uncertainties that can be dealt with in a probabilistic way, as well as deep uncertainties that need new approaches that can support the development of adaptive policies. The Delta decisions are related to deep uncertainty, which can be dealt with through adaptive policymaking. The White Paper provides brief descriptions of various approaches for dealing with the different types of uncertainties in both the analysis and decision-making processes.

Decision-making under uncertainty and the (design and use of the) Deltamodel to support decision-making under uncertainty are intimately related. We are strongly in favor of the idea of having both a screening tool, which should be fast enough for policymakers to use to identify promising strategies, and an analysis tool that researchers can use for a more detailed analysis of the performance of promising strategies. Good decision support does not stop at the development of an appropriate model. Appropriate use of the model is also important to assure 'good' decision-making.

Version	Date	Author	Initials	Review	Initials	Approval	Initials
	feb. 2011	Marjolijn Haasnoot		Erik Ruijgh		Jaap Kwadijk	

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1 Introduction

The government is currently working on the Delta Programme¹. The aim of the Programme is to develop an effective, decisive, and integrated approach to the major water challenges facing the Netherlands in the coming decades. Deltares is involved in many activities for the Delta Programme. One of these activities is the development of the 'Deltamodel'. The Deltamodel comprises the water management models to be used for the Delta Programme. The model aims to establish a reliable and accepted basis for decision-making in the Delta Programme, with a particular emphasis on Delta decisions relating to water systems and consistency among the sub-programmes.

The International Advisory Commission on the Deltamodel has stated the following:
"..the degree in which the information (Deltamodel) can be used and applied depends on understanding uncertainties. We highly endorse accomplishing a comprehensive uncertainty analysis. This is important to understand the magnitude and sources of uncertainty. The error itself is of lesser importance...The uncertainty analysis will guide users with regard to the types of decisions that the Deltamodel results can inform, and those that it can not...The uncertainty analysis should also be informed by a profound understanding of the role uncertainties may play in the decision-making processes."

A lot of work is being undertaken to develop the model, so that the results are as accurate and meaningful as possible. Furthermore, scenarios are being developed that will enable the exploration of possible futures. However, uncertainties about the results remain, since there are limits to the data, a model is always a simplification of reality, and the future is inherently uncertain. Uncertainty is something we need to deal with.

Consequently, we need to develop a framework to cope with all of the uncertainties related to the Deltamodel. The following questions will need to be addressed:

- What do we mean by uncertainty and uncertainty analysis regarding the Deltamodel?
- Which types of uncertainty are there in the Deltamodel?
- What are the sources of uncertainty in the Deltamodel?
- Which uncertainties are relevant for the results and decision-making on the big five Delta decisions?
- How should these uncertainties be dealt with in using the Deltamodel for decision-making on the big five Delta decisions?
- How should the relevant uncertainties be presented to the various actors?

This objective of this White Paper is to provide a partial answer these questions and to propose a method to proceed. It has two main components. Part 1 will reflect on uncertainty analysis, and Part 2 will reflect on decision-making with the Deltamodel, given the uncertainties.

¹ www.rijksoverheid.nl/onderwerpen/deltaprogramma

Delta Programme and Delta Decisions (adapted from Summary Workplan Deltamodel)

The Delta Programme is a national programme involving the national government and regional government authorities, with contributions from organisations in society as a whole. The partners have a single common goal: "The Delta Programme sets out interlinked measures, the goal of which is to bring about sustainable flood protection and freshwater supplies in the light of expectations relating to climate change, socio-economic developments and changes in public thinking. The aim of the programme is an effective, decisive and integrated approach to the major water challenges facing the Netherlands in the coming decades".

Developments in different fields affect one another: decisions in one area may limit decision options in other areas. It is important in the Delta Programme to see regional decisions in conjunction so that coordinated decisions can be taken at the national level. In order to provide this process with direction and to flesh it out, the Delta Programme Ministerial Steering Committee decided, on 4 March 2010, to develop the principle of National Delta Decisions. These are decisions of a political nature that provide structure and boundary conditions; they set out the direction for the development of the Delta Programme in the Netherlands. There are five Delta Decisions (Deltaprogramma 2010). Four of them pertain to water management:

- *A decision in principle about flood protection standards.* In 2011, a Delta Decision will be taken about the nature and level of flood protection standards for the dike rings. These standards set out the quality standards for protection and therefore constitute a framework for proposed measures in the sub-programmes.
- *A strategy for freshwater supplies in 2014.* The urgency and importance of this Delta Decision result from its impact on the sub-programmes, above all for the IJsselmeer, Rhine Estuary, and Southwestern Delta.
- *Protection of the Rhine Estuary in 2014.* This Delta Decision is very urgent because it has a major impact upon elaboration in the other sub-programmes: for example, the level of dike reinforcement in the Delta of South Holland and along the banks of the Waal, the need to store excess river water in the Southwestern Delta, and freshwater supplies.
- *Management of the levels of the IJsselmeer for the long term.* In 2014, a Delta Decision will be taken for the IJsselmeer about water-level management in the long term. This will include: (1) Allowing the water level to rise in line with rising sea levels, so that the water can be discharged into the sea under gravity; (2) the size of the freshwater buffer in the IJsselmeer. This Delta Decision is urgent because measures are required for the outflow of fresh water to the sea and to safeguard the freshwater supplies, both for other parts of the Netherlands and for a range of user functions.

Deltamodel (adapted from Summary Deltamodel)

The Deltamodel comprises the water management models to be used for the Delta Programme. The model aims to establish a reliable and accepted basis for decision-making in the Delta Programme, with a particular emphasis on Delta Decisions relating to water systems and coherency among the sub-programmes. The Deltamodel is the "toolbox" for sound decisions about the preparation and implementation of the Delta Programme.

In addition to the actual computation core, the Deltamodel includes a consistent, validated, and accepted set of input data, such as Delta scenarios and the measures that are expected to be considered in the sub-programmes. The outcomes of the Deltamodel are available for use in the sub-programmes and for decisions on the national scale. Plans have therefore been made for the development of the "Delta Portal". This interface provides access to information about measures or combinations of measures, and to Delta scenarios, including the results of calculations in the Deltamodel.

The target group of Deltamodel users is the Delta Programme, and in the first place the sub-programmes, as well as the Delta Commissioner and his staff, the ministries, and other stakeholders. Naturally, other initiatives (for example from other government organisations) may also draw on the products generated by the Deltamodel project.

The reports of the Deltamodel distinguish between the tools for safety and the tools for water supply. Furthermore, the following purposes are identified (see figure below) (Ruijgh et al. 2010).

subject \ part	 <i>implementation</i>	 impact assessment (analysis)	 policy analysis (screening)
	<i>Regionaal model</i>	Deltamodel	
Water safety	<i>Sobek-Rural</i>	Waqua	Sobek-River
Fresh water supply	<i>Sobek-Rural</i> <i>Regionale modellen 25 m</i>	Sobek-River NHI 250 m	Sobek-River (stationair) NHI-light 1000 m

2 Uncertainty analysis

The notion of uncertainty has taken different meanings and emphases in various fields, including the physical sciences, engineering, statistics, economics, finance, insurance, philosophy, and psychology. In general, uncertainty can be defined as limited knowledge about future, past, or current events. In spite of profound and partially irreducible uncertainties and serious potential consequences of a wrong decision, policy decisions have to be made. Models aim to provide assistance to policymakers in developing and choosing a course of action, given all of the uncertainties surrounding the choice.

That uncertainties exist in practically all policymaking situations is generally understood by most policymakers, as well as by the scientists providing decision support. But there is little appreciation for the fact that there are many different dimensions of uncertainty, and there is a lack of understanding about their different characteristics, relative magnitudes, and available means for dealing with them.

2.1 Definition in the context of model-based decision support

Walker et al. (2003) define uncertainty as any departure from the unachievable ideal of complete determinism. Uncertainty is not simply the absence of knowledge. Funtowicz and Ravetz (1990) describe uncertainty as a situation of inadequate information, which can be of three sorts: inexactness, unreliability, and border with ignorance. However, uncertainty can prevail in situations in which ample information is available (Van Asselt and Rotmans 2002). Furthermore, new information can either decrease or increase uncertainty. New knowledge on complex processes may reveal the presence of uncertainties that were previously unknown or understated. In this way, more knowledge illuminates that our understanding is more limited or that the processes are more complex than we previously thought (Van der Sluijs 1997).

To aid in the policymaking process, applied scientists are frequently called upon to assess the outcomes of alternative policies. We refer to this as decision support. A common approach to decision support is to create a model of the system of interest that defines the boundaries of the system and its structure – i.e., the elements, and the links, flows, and relationships among these elements (Walker 2000). In this case the analysis is referred to as being model based. For this purpose, system models are used. A system model is an abstraction of the system of interest – either the system as it currently exists, or as it is envisioned to exist for purposes of evaluating policies in a different (e.g., future) context. The model helps to consider the effects of alternative policies under a range of conditions, which is a must in complex systems. This is exactly the aim of the Deltamodel. The role of the system model within the policymaking process is illustrated in Figure 2.1. Within this analytical process, different uncertainties can be identified.

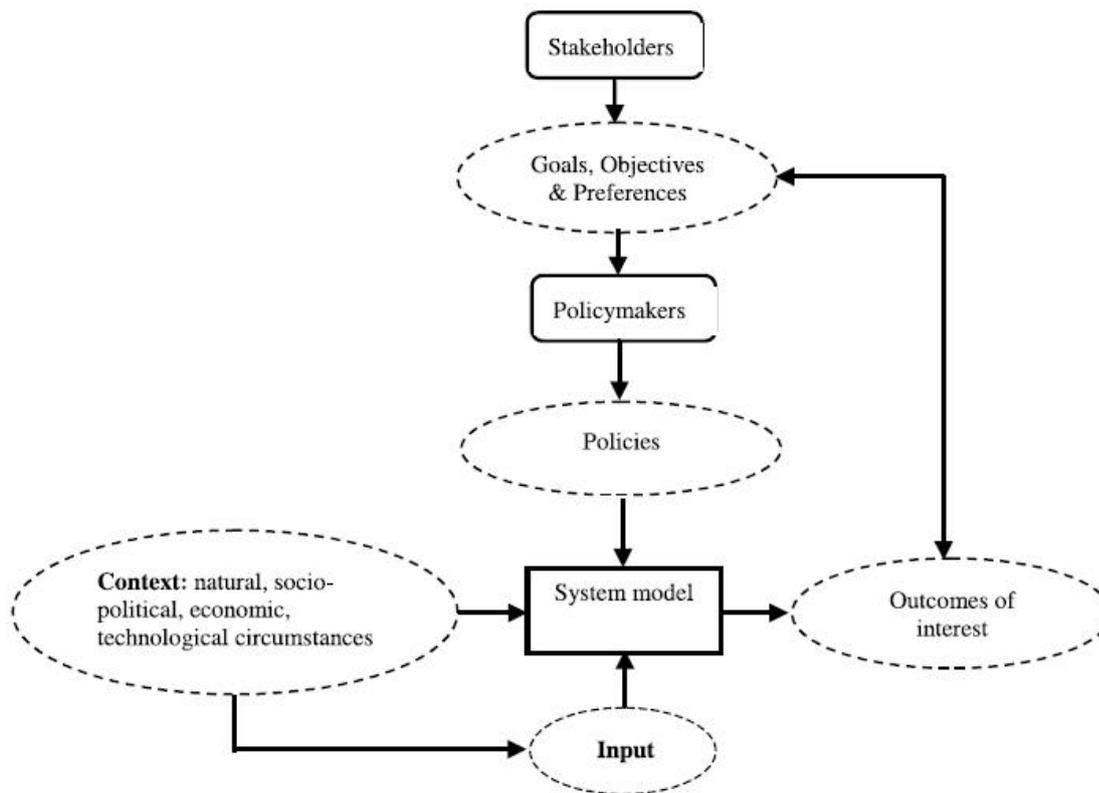


Figure 2.1 The role of the system model within the policymaking process (Walker et al. 2003).

2.2 Location, Level, and Nature of Uncertainties

Based on the framework in Figure 2.1, a classification of uncertainties with respect to policymaking can be made. Such a classification has recently been developed by Walker et al. (2003) and further expanded upon by Kwakkel et al. (2010). This framework integrated previous research on uncertainty (e.g. (Funtowicz and Ravetz 1990; Van Asselt 2000; Van der Sluijs 1997)). The classification has two fundamental dimensions:

- *Location*: where the uncertainty manifests itself within the framework.
- *Level*: the magnitude of the uncertainty, ranging from deterministic knowledge to total ignorance.

This produces a two-dimensional matrix of uncertainty types. With respect to Figure 2.1, uncertainty can manifest itself in several *locations* (specifically, in the context, the system, and the goals, objectives and preferences). And the uncertainty found at each location can be any one of the *levels*. The explanation of uncertainty within each cell of this matrix can be distinguished by what Walker et al. call its *nature*. According to Walker et al., the nature of an uncertainty can be due to the imperfection of our knowledge or to the inherent variability of the phenomena being described. Dewulf et al. (2005) add a third nature of uncertainty: ambiguity, which is defined as ‘*the simultaneous presence of multiple equally valid frames of knowledge*’. For example, uncertainty about whether a dike fails due to a structural defect is a knowledge uncertainty; uncertainty about the next peak discharge along the river Rhine is uncertainty due to natural variability; ambiguity arises when there are many interpretations of a situation (e.g., by different stakeholders). In the knowledge case, the uncertainty can be reduced (by collecting more information, or by waiting until the future becomes known).

In the variability case, some uncertainty must remain (although in some cases it can be reduced by additional observations and/or experiments).

Ambiguity can be reduced to a certain extent, but some will probably remain, since there are likely to always be different views or beliefs on how the system works.

2.2.1 The Location of Uncertainty

In terms of the policy analysis framework of Figure 2.1, one can identify four primary locations of uncertainty that affect the choice of an appropriate policy:

- (1) uncertainty about the *context*, which are external forces causing changes in the system;
- (2) uncertainty about the *system* response to the external forces and/or policy, which can be caused by model structure uncertainty;
- (3) system *model parameter uncertainty*;
- (4) uncertainty about the *relative importance placed on the outcomes* by the participants in the policymaking process (i.e., the weights they place on the outcomes, based on their *goals, objectives, and preferences*).

Uncertainty about the context, which is not under the control of the policymakers and that produces changes within the system (the relevant scenario variables), is of particular importance to policy analyses, especially if these changes are likely to produce large changes in the outcomes of interest. These are the variables that should be included in the scenarios used during the policy analysis process.

Uncertainty about the system model includes: (1) *model structure* uncertainty, and (2) *parameter* uncertainty. *Model structure uncertainty* arises from a lack of sufficient understanding of the system (past, present, or future) that is the subject of the policy analysis, including the behaviour of the system and the interrelationships among its elements. Uncertainty about the structure of the system that we are trying to model implies that any one of several model formulations might be a plausible representation of the system, or that none of the proposed system models is an adequate representation of the real system. We may be uncertain about the current behaviour of a system, the future evolution of the system, or both. Model structure uncertainty involves uncertainty associated with the relationships between inputs and variables, among variables, and between variables and output, and pertains to the system boundary, functional forms, definitions of variables and parameters, equations, assumptions, and mathematical algorithms. It also involves the processes included (or not). Parameters are constants in the model, supposedly invariant within the chosen context and scenario. *Parameter uncertainty* arises e.g. from calibration, which is performed by comparison of model outcomes with data series or through the definition of a certain value for a parameter.

Model outcome uncertainty is sometimes called *prediction error*, since it is the discrepancy between the true value of an outcome and the model's predicted value. If the true values are known (which is rare, even for scientific models), a formal validation exercise can be carried out to compare the true and predicted values in order to establish the prediction error. However, practically all policy analysis models are used to extrapolate beyond known situations to estimate outcomes for situations that do not yet exist. For example, the model may be used to explore how a policy would perform in the future or in several different futures. In this case, in order for the model to be useful in practice, it is necessary to (1) build the credibility of the model with its users and with consumers of its results (see, for example, (Bankes 1993)), and (2) describe the uncertainty in the model outcomes (e.g., using a typology of uncertainties such as that presented in (Walker et al. 2003)).

Model outcome uncertainty is the accumulated uncertainty caused by the uncertainties in the context and system locations that are propagated through a model and are reflected in the resulting estimates of the outcomes of interest. So, there are two major sources of model outcome uncertainty: uncertainty about the external forces, and uncertainties about the new system (and, therefore, the system model) that results from these external forces.

The fourth location of uncertainty in model-based policy analysis refers to uncertainty about the relative importance placed on the outcomes by the participants in the policymaking process (the *weights*). One can distinguish uncertainty about the *current stakeholders' configuration and their current weights* as well as the *future stakeholders' configuration and their future weights*. Even if the people who are affected by a policy are clear, there might still be uncertainty about how each of these stakeholders currently values the results of the changes in the system. The uncertainty about current values is related to different perceptions, preferences, and choices the system's stakeholders currently have regarding outcomes. And, even if the outcomes are known and there is no uncertainty about the current stakeholders' configuration and their valuation of outcomes, in time, new knowledge may become available, new stakeholders might emerge, and the values of the current stakeholders may change over time in unpredictable ways, leading to different weights placed on the outcomes than those placed on them in the present (Haasnoot et al. 2009; Offermans et al. 2009). For instance, the occurrence of a specific event (e.g. extreme weather), unexpected cost increases (e.g., in construction costs), or new technologies (e.g., floating buildings) can lead to changes in values. These changes in values can affect policy decisions in substantial ways.

2.2.2 The Level of Uncertainty

In order to manage uncertainty, one must be aware that an entire spectrum of different levels of knowledge exists, ranging from the unachievable ideal of complete deterministic understanding at one end of the scale to total ignorance at the other. Policy analysts have different methods and tools to treat the uncertainties at the various levels. The range of levels of uncertainty, and their challenge to decision-makers, was acknowledged by Donald Rumsfeld, who famously said:

*"As we know, there are known knowns – these are things we know we know. We also know there are known unknowns – that is to say we know there are some things we do not know; but there are also unknown unknowns – the ones we don't know we don't know.... It is the latter category that tends to be the difficult one."*²

For purposes of determining ways of dealing with uncertainty in developing public policies or business strategies, Courtney (2001) and Walker et al. (2003) have distinguished two extreme levels of uncertainty (determinism and total ignorance) and four intermediate levels. In Table 2.1, the four levels are defined with respect to the knowledge assumed about the various locations of a policy problem: (a) the context, (b) the model of the relevant system for that future world, (c) the outcomes from the system, and (d) the weights that the various stakeholders will put on the outcomes. The levels of uncertainty are briefly discussed below.

Determinism is the situation in which we know everything precisely. It is not attainable, but acts as a limiting characteristic at one end of the spectrum.

² Donald Rumsfeld, Department of Defense news briefing, Feb. 12, 2002.

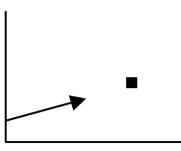
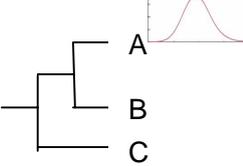
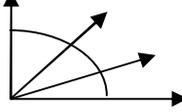
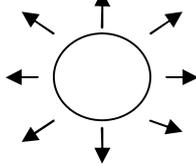
Level 1 uncertainty is any uncertainty that can be described adequately in statistical terms (e.g., historical weather patterns and river flows). In the case of uncertainty about the future, Level 1 uncertainty is often captured in the form of a (single) forecast (usually trend based) with a confidence interval. An example of Level 1 uncertainty might be the *measurement uncertainty* associated with observed data. Many measurements include stochastic noise that prevent them from ever precisely representing the “true” value of what is being measured.

Level 2 uncertainty represents the situation in which one is able to enumerate multiple alternatives and is able to rank the alternatives in terms of perceived likelihood. That is, in light of the available knowledge and information there are several alternative, trend-based futures, different parameterizations of the system model, different conceivable sets of weights, and alternative sets of outcomes. Some estimate can be made of the likelihood (e.g., probability) of each of the alternatives. In the case of uncertainty about the future, Level 2 uncertainty about the future world is often captured in the form of a few scenarios based on alternative assumptions about the driving forces (e.g., three scenarios for sea-level rise, based on three different assumptions about climate change). The scenarios are then ranked according to their likelihood.

Level 3 uncertainty represents the situation in which one is able to enumerate multiple plausible alternatives without being able to rank the alternatives in terms of how likely or probable they are judged to be. This inability can be due to a lack of knowledge or data about the mechanism or functional relationships that is being studied, but this inability can also arise due to the fact that the decision-makers cannot agree on the rankings. As a result, analysts struggle to specify the appropriate models to describe interactions among a system’s variables, to select the probability distributions to represent uncertainty about key parameters in the models, and/or how to value the desirability of alternative outcomes (Lempert et al. 2003).

Level 4 uncertainty implies the deepest level of recognized uncertainty; in this case, we know only that we do not know. We recognize our ignorance. Recognized ignorance is increasingly becoming a common feature of our existence, because catastrophic, unpredicted, surprising, but painful events seem to be occurring more often. Taleb (2007) calls these events “Black Swans”. He defines a Black Swan event as one that lies outside the realm of regular expectations (i.e., “nothing in the past can convincingly point to its possibility”), carries an extreme impact, and is explainable only after the fact (i.e., through retrospective, not prospective, predictability). One of the most dramatic recent Black Swans is the concatenation of events following the (2007) subprime mortgage crisis in the United States. The mortgage crisis (which some had forecast) led to a credit crunch, which led to bank failures, which led to a deep global recession (in 2009), which was outside the realm of most expectations.

Table 2.1 The progressive transition of levels of uncertainty from determinism to total ignorance (Walker et al. 2010).

Location	Level 1	Level 2	Level 3	Level 4
Context	A clear enough future 	Alternate futures (with probabilities) 	A multiplicity of plausible futures 	Unknown future (know we don't know) 
System model	A single system model	A single system model with a probabilistic parameterization	Several system models, with different structures	Unknown system model; know we don't know
System outcomes	A point estimate and confidence interval for each outcome	Several sets of point estimates and confidence intervals for the outcomes, with a probability attached to each set	A known range of outcomes	Unknown outcomes; know we don't know
Weights on outcomes	A single estimate of the weights	Several sets of weights, with a probability attached to each set	A known range of weights	Unknown weights; know we don't know

Total ignorance is the other extreme on the scale of uncertainty. As with complete determinism, total ignorance acts as a limiting case.

After Lempert et al. (2003), we call Level 4 uncertainty 'deep uncertainty', which is "the condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system's variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes."

2.3 Uncertainty framework for the Deltamodel

Based on the above described levels, locations, and nature of uncertainty, a matrix can be constructed (Walker et al. 2003). We refer to this as the uncertainty framework. The matrix can aid in classifying the uncertainties and in describing how uncertainty is to be treated in different parts of a specific study. This can support the identification of methods to deal with the various types of uncertainty in the study Table 2.2 presents the matrix and fills it in with examples of the different types of uncertainty related to the Deltamodel. The following section elaborates on methods that can be used to deal with the different types of uncertainty.

Table 2.2 *Uncertainty matrix of (Walker et al. 2003) for classifying uncertainty, with examples for the Deltamodel.*

Location	Level				Nature		
	Level 1	Level 2	Level 3	Level 4	Ambiguity (perspectives)	Epistemology (imperfection of knowledge)	Ontology (natural variability)
Context	Single forecast for the future: e.g., single estimates of future water demand for drinking, industry, and agriculture	Scenarios with probabilities: e.g., three climate change scenarios with probabilities	Scenarios for plausible futures without probabilities: - Climate change, Sea level rise - Socio-economic developments	Scenarios with surprises and dynamics: - Credit crunch resulting in less money for water - Dike collapse - Include interaction of the water system with society (e.g. autonomous adaptation of water users: self-supply in response to dry conditions)	Different perspectives (expectations) about the future, the system, the problem, etc.	- Lacking information on potential climate change - Too few monitoring locations (for e.g. land subsidence river discharge)	Time series of discharges of the river Rhine
System model	- One Deltamodel - Assuming current q-h relation ($q=\alpha h$) - Assumed strength of dikes	- One model structure with different (probabilistic) parameterizations - $q=\alpha h$, with $\alpha \sim N(\mu, \sigma^2)$	- Several model structures: WAQUA, SOBEK-1d for the river system - $q=f(h), g(h), k(h)$?	- Explore alternative models - $q=??$	Different processes in the model based on different 'beliefs' on how the system works	Several model structures describing the same process	
System outcomes	A point estimate and confidence interval for each outcome (e.g., groundwater level); a single scorecard with results for various (static) policy options	Several sets of point estimates and confidence intervals for the outcomes, with a probability attached to each set (e.g., water levels based on different sets of assumptions); a scorecard for each set of assumptions (e.g., for each scenario) with results for various (static) policy options	Ensembles of water levels and other outcomes; a scorecard for each set of assumptions (e.g., for each scenario and/or for each different model structure) with results for various (static) policy options	Water levels and other outcomes for the full range of scenarios, models, and other assumptions for various (dynamic or static) policy options	Different interpretations of what the outcomes mean		- Probability distribution of results - frequency of exceedance - frequency of low flows
Weights on outcomes	A single set of weights	Several sets of weights, with a probability on each set	Several sets of weights, with no probabilities on the sets	Explore policy implications under a range of assumptions about weights	Different weights for different stakeholders	Different stakeholder configurations in the future	

3 Dealing with uncertainties in decision-making with the Deltamodel

3.1 Approaches for dealing with uncertainties

Most of the quantitative analytical approaches for dealing with uncertainty are focused on Level 1 and Level 2 uncertainties. In fact, most of the traditional applied scientific work in the engineering, social, and natural sciences has been built upon the supposition that the uncertainties result from either a lack of information, which “has led to an emphasis on uncertainty reduction through ever-increasing information seeking and processing” (McDaniel and Driebe 2005), or from random variation, which has concentrated efforts on stochastic processes and statistical analysis. However, most of the important policy problems currently faced by policymakers are characterized by the higher levels of uncertainty (i.e., Levels 3 and 4), which we have labelled ‘deep uncertainty’.

The same development is seen in the way national policy documents treat uncertainty (Haasnoot and Middelkoop in prep). With the implementation of the Delta works, the probabilistic approach was introduced. Policymakers looked at the future and determined the accepted chance of failure of a structure in case of an event. For this purpose, prognoses based on autonomous developments were used. These ‘predict and act’ studies slowly shifted to an ‘explore and anticipate’ approach. Scenario analysis played an important role in this shift. However, there is a paradox in these studies: they explore several possible futures, but use a single scenario to determine design conditions and develop strategies. Recently, new approaches have emerged in water management research studies, taking into account the dynamics of the system or looking at the system’s vulnerabilities (see further in this section). These approaches are related to the increasing recognition of deep uncertainty.

Deep uncertainties cannot be dealt with through the use of probabilities and cannot be reduced by gathering more information, but are basically unknowable and unpredictable at the present time. And these higher levels of uncertainty can involve uncertainties about all locations of a policy problem — external or internal developments, the appropriate (future) system model, the parameterization of the model, the model outcomes, and the valuation of the outcomes by (future) stakeholders.

In this section, we summarize traditional ways of dealing with uncertainty about the future in conducting a policy analysis study, including when they are appropriate and when they are not. We then discuss ways of dealing with deep uncertainty, since these involve approaches less well known and rarely practiced yet. We describe the approaches for different levels of uncertainty (see also Table 3.1). Van der Sluijs et al. (2004) have done this thoroughly for an uncertainty matrix similar to the one described in Sec. 2.4.

Table 3.1 Different approaches and types of policies for each level of uncertainty.

Level	Analytic approach	Policy	Result
1 	Deterministic (optimization, sensitivity)	Forecast and act	Action
2 	Probabilistic (sensitivity, expected value, confidence intervals)	Predict and act	Workplan
3 	Scenario analysis	Robust, static policy	Policy document with policy options
4 	Exploratory (scenario) analysis, adaptive pathways	Robust, adaptive (dynamic) policy	Policy document with adaptation pathways, triggers, and options

Approaches to deal with Level 1 uncertainty

Approaches best suitable for this level assume that the current system is well known and that the future is clear. They base the policy on that assumption or on a single forecast. In this case, it is possible to use a single (perhaps, optimization) model to find the ‘best’ policy. Sensitivity analysis studies the influence of variation in the model parameters and initial values on the model outcomes. It can be used to explore how sensitive the policy results are to the assumptions. This approach is sometimes called the ‘predict-and-act’ approach. The resulting policy is ‘optimal’, but is fragilely dependent on the underlying assumptions.

Approaches to deal with Level 2 uncertainty

These approaches assume that the context, the system, and the weights are so well understood that the analysis can be completely based on probability functions. For example, they assume that there are only a few alternative futures, that they can be predicted well enough, and that probabilities can be assigned to them. In this case, a model for each future can be used to estimate the outcomes of policies for these futures. A preferred policy can be chosen based on the outcomes and the associated probabilities of the futures (i.e., based on ‘expected outcomes’ and levels of acceptable risk). Monte Carlo simulation, Ensembles analysis, and Decision Analysis are among the many approaches used to deal with Level 2 uncertainties. Ensembles are used in climate forecasting to take into account the chaotic nature of the atmospheric dynamics. Probabilistic approaches, such as Bayesian statistics or 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 the uncertainties can be represented probabilistically (see, e.g., (Bedford and Cooke 2001)). For decision-making under uncertainty, they are used in combination with utility curves.

The current evaluation of safety from flooding in the Netherlands is an example of Level 2 uncertainty. It is described in terms of the accepted failure of a structure per year. For this purpose, the chance of a specific event (storm or discharge) per year corresponding to a given climate is used (De Waal 2010). This is done using the Hydra models. PC-ring is an alternative method, which also includes knowledge uncertainty at Level 2. Note that models such as the ‘Hydras’ can use different climate scenarios as input to take into account Level 3 uncertainty.

Approaches to deal with Level 3 uncertainty

Approaches dealing with Level 3 uncertainties identify a policy that is robust (i.e., works fairly well) across a range of plausible futures (or different plausible understandings of the working of the current system). These approaches assume that, although the likelihood of the future worlds is unknown, the plausible futures can be specified well enough to identify a (static) policy that will produce acceptable outcomes in most of them. We call this *static robustness*; it is more often called *scenario planning* (Van der Heijden 1997). Most long-term water management studies have adopted scenario analysis (sometimes in combination with one of the methods for dealing with Level 1 and Level 2 uncertainties mentioned above) as adequate instruments to explore uncertain aspects of the future, the potential implications of future global change, and possible strategies.

To deal with uncertainty in the model structure of climate models, the IPCC uses results of different climate models for different emission scenarios to determine the potential temperature range. This potential temperature range is used by KNMI to develop climate scenarios for the Netherlands, such as the KNMI'06 scenarios describing possible futures for the climate in the Netherlands. 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 2009).

The Info-Gap method explores different simulations with increasing uncertainty of parameters to examine the performance of strategies in relation to the uncertain parameters ((Ben-Haim 2001, 2006); cf. (Hall and Harvey 2009) for water management examples). Robust Decision-making (Lempert et al. 2006; Lempert et al. 2003) and Exploratory Modeling (Agusdinata 2008; Bankes 1993) use modelled effects of strategies for different plausible uncertain input parameters and interpret this as an instance of traditional Bayesian decision analysis. By carrying out a large number of simulations, the performance of a strategy under this huge range of uncertainties can be determined, to estimate its robustness and to identify conditions under which the strategy would fail (i.e., the 'vulnerabilities' of the strategy).

Rotmans and De Vries (1997), Hoekstra (1998), and Middelkoop et al. (2004) used the Perspectives Model, based on cultural theory, to explicitly consider uncertainties about the future resulting from differing perceptions of values and objectives. These studies allowed identification of mismatches between the 'world view' of society and water management and the management strategies being used. Indeed, such shifts in societal perceptions of flood risk, ecological values, and cultural awareness have in the past led to changes in river management. Examples are river rehabilitation projects undertaken along several European rivers (see, e.g., (Buijse et al. 2003)). Perspectives can also be used to describe the different weights placed on the outcomes of the results by different (future) stakeholders (Offermans et al. 2009).

Approaches to deal with Level 4 uncertainty

In this level, it is recognized that there are things that we do not know, but that can have large impacts on decisions and the effectiveness of decisions. Thinking about possible surprising events can influence our thinking about the current and future system, and thus influence our decisions. Although some events have a short-term impact, the memory from such events can last for a long time.

Events such as the storm surge of 1953 and the high discharges of 1993 and 1995 can be catalysts for the implementation of existing plans, but can also change our strategies. Level 4 uncertainties pertain not only to events in the water system, but also to events in the social system, such as the credit crunch.

Approaches for dealing with Level 4 uncertainties assume a dynamic future. Instead of assuming a static future (or a future at a given point in time), these approaches include pathways towards an end point, and consider the possibility that unexpected events may drastically change such pathways, or may even change societal perspectives on what is considered to be the desired end-point situation (Haasnoot et al. 2009, submitted). Adaptive policies that depend on the evolution of the pathway are one way of dealing with these uncertainties. Thus the end-point is not only determined by what is known or anticipated at present, but also by what will be learned as the future unfolds (Yohe, 1990). This approach assumes that we learn, adapt, and change. Natural variability has a large influence on these dynamics. An experiment with transient scenarios (time-series) has shown that climate variability may be at least as important for decision-making as climate change, especially for the mid to long term (Haasnoot et al. submitted).

Broadly speaking, although there are differences in definitions, and ambiguities in meanings, the literature offers three (overlapping, not mutually exclusive) strategies for dealing with Level 4 uncertainties in making policies (see, for example, (Leusink and Zanting 2009)):

- *Resistance*: plan for the worst possible (predicted) case or future situation
- *Resilience*: whatever happens in the future, make sure that you have a policy that will result in the system recovering quickly
- *Adaptive robustness*: prepare to change the policy, in case conditions change

The first approach is still based on predictions, is likely to be very costly (Raad voor Verkeer en Waterstaat 2009), and might not produce a policy that works well, because of surprises (called 'Black Swans' by (Taleb 2007)). Furthermore, the policy may not be flexible, and it is probably difficult to hold on to this approach the longer no unexpected event happens. The second approach accepts short-term pain (negative system performance), but focuses on recovery. In case of a large frequency of events, it may be possible that the total damage is large or there is not enough time to recover. The third approach appears to be the most appropriate strategy for dealing with Level 4 uncertainties, since it includes the dynamics of the future in which the strategy will be adapted to changes and/or new insights.

Characteristic for the third approach method is the identification of both robust and flexible strategies, some of which will be implemented in the short term and others that are left as options for later. Triggers are identified to determine if and when the implementation of additional strategies is needed. Triggers can be based on information on the past or current situation (such as monitoring results), but also information about the future, such as scenarios on future climate, or new estimates of the Dutch population (e.g., 20 million instead of the currently planned for 16 million).

These approaches are currently under development. But there are examples from some research studies. For example, Walker et al. (2001) describe a process, now called Dynamic Adaptive Policymaking (DAP), to develop policies for an uncertain future that respond to changes over time and make explicit the possibility of learning. During the policymaking process, a definition of policy success is formulated and the vulnerabilities of the policy (in terms of potential adverse consequences or policy failure) are identified.

From this analysis, mitigating actions (to be implemented immediately) and hedging options (to diversify or reduce exposure) are developed. Furthermore, the conditions for success are translated into signposts to monitor progress toward or away from the objectives and to trigger the adaptive responses.

Haasnoot et al. (2010) use many integrated transient scenarios to identify 'adaptation pathways'. Their approach includes the response in terms of water management and society (e.g. change strategy and/or social values in response to event). With their adaptation maps it is possible to identify opportunities, no-regret strategies, threats (dead-ends), and when and how to change a strategy, all of which can be used by policymakers to develop water management roadmaps into the future. An adaptation pathway is a sequence of water management strategies over time that is robust under many futures and flexible enough to adapt when the future unfolds in an unexpected way.

A related way of dealing with deep uncertainty about the future is to focus on the vulnerabilities of the system; e.g., answering the question: How much climate change can the current strategy cope with? Kwadijk et al. (2008, 2010) answer this question with the Adaptation Tipping Point (ATP) approach. The moment in the future at which an ATP occurs depends on the climate scenario. An ATP is reached if the magnitude of change is such that the current management strategy can no longer meet its objectives. After a tipping point is reached, a change in strategy is needed. Scenarios are used to determine the timing of an ATP, much like what is done in DAP.

The Raad voor Verkeer en Waterstaat (2009) recently recommended such an adaptive approach. In its advice to the Ministry, it wrote: "a fundamentally different approach to the uncertainties associated with climate change must be adopted in policy-making and in government. A change of outlook is needed: the pursuit of certainty should be replaced by the acceptance of and allowance for uncertainty. Instead of basing policy on what is or appears to be certain, uncertainties should be explicitly covered by the policy analysis and proactively accommodated in the policies that are formulated. We need what academics describe as 'planned adaptation' or 'adaptive policy-making'."

3.2 Decision-making with the Deltamodel under uncertainty

3.2.1 Uncertainty in the Deltamodel and Delta Programme

The Delta Programme has two parts: (1) to improve the current flood safety strategy based on new knowledge, and (2) to prepare a strategy for the future (Deltaprogramma 2010). For the future, changes in climate and a relative increase in sea levels are foreseen. These changes require a sound analysis of the options open to the Netherlands for coping with them. In that sense, the Delta Programme and Deltamodel do not differ from policy problems described generically at the beginning of the previous section.

The purpose of the Deltamodel is to support the decision-making process in the Delta Programme. The Deltamodel can be seen as the "toolbox" to supply substantive information for sound decisions about the preparation and implementation of the Delta Programme (Ruijgh and Dijkman 2010). More specifically, the Deltamodel should assess the effectiveness of adaptation strategies for sustainable flood protection and freshwater supply under uncertain developments, such as climate change, socio-economic developments, and changes in public thinking. This involves the two highest levels of uncertainty, which can manifest themselves at all locations (context, model, and outcomes).

The principles of flood protection in the Netherlands are currently based on a probabilistic approach. These principles play an important role in the decision-making on strategies for safety. One of the Delta decisions is to decide on how to modify these principles. Consequently, the Deltamodel will be used to address issues involving the lower levels of uncertainty. These involve, for example, uncertainties due to natural variability, such as the occurrence of extreme discharges and storms, and uncertainties about parameters, such as the strength of a dike. These uncertainties manifest themselves mainly in the system model.

The Delta Programme introduces the term 'adaptive deltamanagement', which is in fact a way of dealing with uncertainties. It involves the process of defining policy options for the short and long term and adapting them in case new information becomes available (Deltaprogramma 2010). Short-term strategies should increase both the flexibility to adapt and the robustness against extreme events in order to extend the time frame for possible tipping points in the water system, while in the meantime insights into climate change can be increased and innovative solutions can be developed. This approach has elements from Level 3 and Level 4 uncertainty.

The Delta Commissioner mentions so-called 'basic values' in his report – namely solidarity, flexibility, and sustainability (Deltaprogramma 2010). Although these words are subject to different interpretations, some features related to uncertainty can be identified. Flexibility refers to leaving options open in case the future turns out to be different from what was expected. This suggests taking into account the dynamics of the system, and thus refers to Level 4 uncertainty.

In our view, uncertainties related to the Deltamodel involve uncertainties that are not only about the model structure and the parameters of the model, which can be analysed through sensitivity analysis and the results presented as confidence intervals or bands around an average. But, the uncertainties related to the Deltamodel also involve uncertainties about the context and outcomes: the possible futures that are simulated using the model, and how the results are interpreted. Thus, in the end, it is all about using the Deltamodel in decision-making under uncertainty.

Good decision support does not stop at the development of an appropriate model. Appropriate use of the model is also important to assure 'good' decision-making. To facilitate the decision-making process, a framework of analysis can be used (Loucks and Van Beek 2005; Walker 2000). A framework of analysis describes the different steps in a policy analysis study and identifies where and how in the process the model can be used. Examples of steps are: identification of the problem, specification of objectives, screening of strategies, analysis of strategies, evaluation of strategies, and choice of a strategy to implement.

Making good decisions is important, because decisions are made about large investments (Hulme and Dessai 2008) and can have large implications for the population. One way to evaluate the quality of the decision-making process is to consider whether a wide variety of relevant uncertainties have been considered to provide information to make either robust decisions for many relevant futures or flexible decisions in case the future unfolds in a way that is different from what was expected (Haasnoot and Middelkoop in prep; Hulme and Dessai 2008b). The justification for framing the criterion in this way emerges from a view of decision-making summarized by Groves and Lempert (Groves and Lempert 2007): "Robust decision-making proceeds from the observation that decision-makers often manage deep uncertainty by choosing strategies whose good performance is relatively insensitive to poorly characterized uncertainties."

Anticipation and preparing for the future has been seen more and more in water management since the 1970s. However, history has shown that it is difficult to maintain such a long-term view. Flood and drought events, or periods with no events, influence public opinion, and thus can change the support for water management strategies (Offermans 2010; Van der Brugge et al. 2005). Monitoring and evaluation of the implemented strategy are thus important requirements for achieve the original objectives. (If the objectives change, the strategy might need to be changed.)

For different types of analysis, different types of models are needed. For the development of the Deltamodel, at least three different purposes have been identified: screening, analysis, and implementation (Ruijgh et al. 2010). For the screening of possible strategies, a large number of runs are needed, since there are many possible futures, many possible strategies, and many possible combinations of strategies. For this purpose, the ‘screening tool’ needs to be fast enough to be able make these runs in a short amount of time. Once a strategy appears promising, its performance can be analysed in more detail with the ‘analysis tool’, and, for fine-tuning, in order to prepare to really implement the strategy at local scale, the ‘implementation tool’ can be used. The implementation tools refer to the regional models available at the water boards; they are not part of the Deltamodel (Ruijgh et al. 2010). The analysis and screening tools are part of the Deltamodel. These tools differentiate among the scales (spatial, time), processes, and amount of detail included; i.e., the screening tool is a simplification in time, space, process, and detail compared to the analysis tool.

3.2.2 Characteristics of a model for policymaking

There are some general characteristics that can be defined for policy models. Since the Deltamodel is designed to support decision-making on the policy options in the Delta Programme, a lot of these characteristics also apply to the Deltamodel. Once delivered in late 2012, the Deltamodel will serve as the new model for, at the least, policy preparations for the main water system. We, therefore, elaborate on some important characteristics of policy models (for screening and analysis) in this section.

Policy analysis models are fundamentally different from most other types of models that scientists and engineers build. Scientists and engineers usually build models to try to obtain a better understanding of one portion of the real world. The better the match between the model and the real world, the better the model is considered to be. Scientific and engineering models can be validated using empirical data. By contrast, policy models are built to provide information to policymakers who are trying to develop policies intended to solve real world problems, usually for a future situation. They are designed to give policymakers information that can help them develop insights into their problem situation and on which they can base their policy decisions. The models serve as laboratory environments, to test alternative policies and compare their performance without having to actually implement them to see how they would perform.

The quality of a policy analysis model is judged not by how accurately it reflects the real world, but by how well it is able to provide information that enables a decision-maker to make knowledgeable choices among policy options – i.e., how well the model can help construct and defend an argument about the relative pros and cons of alternative policy options. A relatively crude model that can clearly demonstrate that alternative A performs better than alternative B under both favorable and unfavorable assumptions will probably lead to a better decision than a complex model that can perform only a detailed expected value estimation.

Policy analysis models trade off rigor for relevance. In many cases they are intended to be used for screening large numbers of alternative policy options, comparing the outcomes of the alternatives, and/or designing strategies (packages of policy options). This means that they should include a wide range of factors (e.g. technical, financial, social), but not a lot of detail about each of the factors. The outcomes are generally intended for comparative analysis (i.e., relative rankings), so approximate results are sufficient. They must provide sufficient information to map out the decision space – the ranges of values of the various input parameters (policy variables and scenario variables) for which each of the various policy options would be preferred. Implementation planning, engineering, and scientific models are needed for examining fewer alternatives according to a smaller number of factors. However, they are used in situations where absolute values are needed (e.g., water levels, economic damage), which requires more accurate estimation of the results for each factor (and more fully validated models). Therefore, designing a policy analysis model is a balancing act. There is a tradeoff between breadth and depth. Adding too much depth is a pitfall in developing a policy analysis model. Instead of aggregating, approximating, and simplifying, the modeler includes every factor that s/he thinks might have an influence on the results. But to make the model manageable, the boundaries (reduce breadth) are pulled in. When the boundaries are too narrow, the model cannot address all the relevant issues. Figure 3.1 illustrates the scope and level of detail of a policy analysis model in relation to that of a scientific or engineering model.

A policy analysis model is developed to analyze policies that have not yet been chosen. They have not been (and may never be) implemented, and the impacts cannot be observed directly. Often, though, the theory is suspect, the data have much variation, and even the design of the policy is uncertain. Under such circumstances, it makes no sense to expect to estimate the impacts accurately. Instead, the analyst can use a model to explore the issue. A scientific or engineering model will almost always attempt to provide a single estimate of an outcome, perhaps with an error band. A policy model needs to support exploration of possibilities instead of only point predictions.

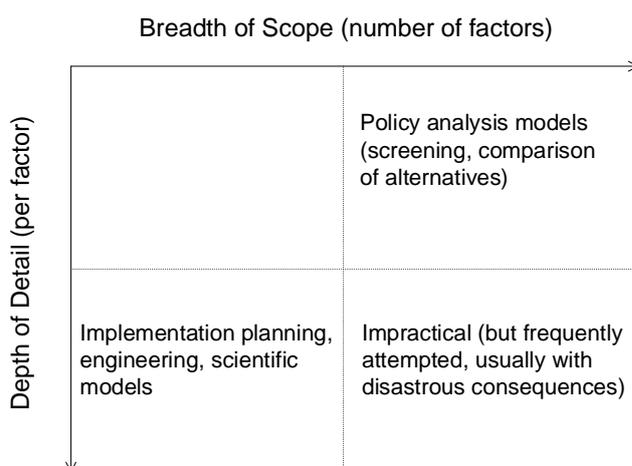


Figure 3.1 Different types of models have different scopes and levels of detail.

A model designed for policymaking should produce outcomes that describe the impacts of policy options on the outcome indicators used for evaluation of the results; in other words the model should give results that can then be placed in a scorecard. A scorecard is a table in which each column represents an impact and each row represents a policy option (Walker 2000). An entire row shows all of the impacts of a single option; an entire column shows each option's value for a single impact. Numbers or words appear in each cell of the scorecard to convey whatever is known about the size and direction of the impact in absolute terms, i.e. without comparisons among cells. In comparing the policy options, each stakeholder and decision-maker can assign whatever weight he/she deems appropriate to each impact. This way the focus will be on the decision about the policy options and not on the weights that should be placed on each criterion. For the Deltamodel, the Assessment Framework Background Document describes which criteria and effects (which should be quantitative when possible) need to be supplied by the Deltamodel (Marchand 2010). The effects in the Deltamodel will be presented in a non-aggregated form as much as possible, in order to give users the option of selecting the aggregation or evaluation method. The latter assures that each stakeholder and decision-maker can assign his/her own weights.

4 Conclusions and potential activities for the Deltamodel

Dealing with uncertainties – especially uncertainties about the future – is a challenge water managers need to face, since the future is inherently uncertain. The updating of scenarios is something that water managers also need to deal with (Hulme and Dessai 2008a). Scenarios are a reflection of the knowledge and world view at a specific moment and are based on the context in which the scenarios are developed.

To establish views on the current and future states of the water system, models are used, which describe the natural environment and the socio-economic system. Models, such as the Deltamodel, can support decision-making on adaptation strategies. However, uncertainties limit our understanding of the system as well as our ability to predict its future state. In using the Deltamodel for decision-making, policymakers should thus deal with uncertainties about the future, the model, and the (future) weights on the outcomes. There are different levels of uncertainties, ranging from determinism to recognized ignorance. The Deltamodel and Delta Programme involve uncertainties that can be dealt with in a probabilistic way, as well as deep uncertainties that need new approaches and that can support the development of adaptive policies. They also involve many types of uncertainties at different locations and different levels with different natures. We described different approaches of dealing with for these different types of uncertainties in both the analysis and decision-making processes. So, uncertainties about the current and future system need not be used as a reason for not developing adaptation strategies for water management (see also (Dessai et al. 2009)).

Decision-making under uncertainty and the (design and use of the) Deltamodel for this purpose are intimately related. As explained above, it is important that the Deltamodel be designed so that it can be used efficiently and effectively in designing policies under all types of uncertainty. For different purposes, different tools are needed. We support the idea of having both a screening and analysis tool in the Deltamodel, which can have different purposes and users, and, consequently, different requirements.

The screening tool can be used by policymakers (e.g. the members of the Deltacommissioners team and policymakers in the *deelprogramma's*) for a policy analysis – to explore different futures and assess the effects of the *deltascenarios*, identify policy options, and assess the effectiveness of these options under different possible futures. The use of a policy analysis framework can support this process (see, for example, Loucks and van Beek (2005) and Walker (2000)). Given these requirements and users, the screening tool should be fast enough (minutes, not hours or days) to perform a lot of runs in order to be able to analyse many combinations of futures and measures. The spatial and temporal detail should be large enough to enable the analysis of the most important impacts for the Delta decisions. This way, it will be possible to develop adaptation pathways and dynamic adaptive policies for adaptive *deltamanagement*. It would be useful to present information on the model and parameter uncertainty of the outcomes from this tool; this will be able to be done using the analysis tool. By 'outcomes', we mean the relevant indicators in the scorecard on which the Delta decisions will be based.

The analysis tool will be able to be used by researchers who are advising the policymakers in the Delta Programme. They could use the Deltamodel to understand the working of the system in terms of the most relevant processes (which should then be included in the analysis tool), and to investigate in more detail the effectiveness of measures under the deltascenarios. Given these requirements and users, the calculation time can be larger (days) and the spatial and temporal schematization should contain more detail.

Once the high level policy measures have been decided upon, implementation requires even more detailed models for the design of specific measures, for example by water boards and companies supporting the water boards. These models should be able to represent the current situation with much more detail (spatial, temporal, and process), and can have much longer run times. These models are not necessary for the Delta decisions.

The next steps for dealing with uncertainties in decision-making with the Deltamodel could be:

- Construct an uncertainty matrix for the Deltamodel.
- Identify the relative importance of the uncertainties qualitatively, based on expert judgement and existing model runs. The uncertainties can be presented in an impact-uncertainty matrix, such as has already done for the developments in the study for the Deltascenarios (Bruggeman et al. 2010).
- Identify the relative importance of the uncertainties quantitatively, based on sensitivity analysis. This can result in a table describing the effect of a change in input x on output y.
- Determine approaches (both probabilistic and adaptive) for dealing with the uncertainties, based on the filled in uncertainty matrix for the Deltamodel.
- Clearly communicate and disseminate the uncertainties, assumptions, and limitations of the Deltamodel and Deltascenarios, and how to use the model for decision-making.

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