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An Integrated Assessment Metamodel for Developing Adaptation Pathways for Sustainable Water Management in the Lower Rhine Delta

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Abstract: Water management is increasingly challenged by pressures from population growth, sea level rise and potential climate change. Moreover, these developments are highly uncertain and change over time. The challenge is to develop strategies that are either robust - insensitive to the future - or flexible enough to adapt to changing conditions. Adaptation is not only determined by what is known or anticipated at present, but also by what will be experienced and learned while the future unfolds, and by policy responses to social and water events. As a result, an *adaptation pathway* emerges. Exploring adaptation pathways into the future will provide indispensable support to decisionmaking in achieving sustainable water management. For a structured exploration of the various adaptation pathways, we are developing a computational model of the Rhine Delta in the Netherlands. With this model, we will simulate an evolvement of the system wherein pressures influence the water system state, and impacts on flood risk and water services such as agriculture and nature, which may then trigger a policy response. The result of this dynamic simulation is an adaptation pathway. The model should run fast enough to calculate many 100-year transient scenarios, representing the dominant processes and natural variability, and be able to implement various policy options. To enable such dynamic modelling we are developing an Integrated Assessment MetaModel (IAMM) using the technique of metamodelling. Metamodels are simple aggregated models that approximate the behaviour of complex and detailed models. The IAMM is simple in terms of process and spatial information, but complex in terms of time-series and policy response. The challenge is to capture enough detail and process information ensuring an adequate model behavior for policy analysis. We present the concept and describe for which situations - policy options and effects - the model can be used to support decisionmaking under uncertainty.

***Keywords**:* metamodel; adaptation pathways; water management; uncertainty

1 INTRODUCTION

Decisionmaking on water management is increasingly challenged due to pressures from population growth, sea level rise and climate change. Adaptation to such pressures is not only determined by what is currently known or anticipated, but also by what will be experienced and learned while the future unfolds, and by policy responses to events. As a result, an adaptation pathway emerges.

Adaptation pathways describe a sequence of water management actions needed to achieve defined targets. Exploring pathways into the future can support decisionmakers in achieving sustainable water management in a changing environment. An adaptation pathway map shows the adaptivity and flexibility of a plan by indicating available possible actions, potential lock-ins and path-dependence. In recent papers, we presented a method for exploring adaptation pathways, and illustrated this for a hypothetical case (Haasnoot *et al.*, accepted, Haasnoot *et al.*, 2011, Kwakkel and Haasnoot, 2012). As such analysis can become quite complex, our approach comprises a computational model to dynamically simulate alternative transient scenarios, their impacts and a variety of policy responses.

The current generation of simulation tools have limited ability to explore alternative futures and policy responses in a dynamic way. One of the reasons is that the existing tools for quantifying impacts are becoming increasingly complex and require too much computing time. To explore pathways for water management in the lower Rhine delta, we are developing an Integrated Assessment Metamodel (IAMM). This model is a simplification or a model of complex detailed models. Such metamodels are also referred to as ‘low-resolution models’ (Davis and Bigelow, 2003) or ‘Fast Simple Models’ (Grol *et al.*, 2006, Kwakkel *et al.*, 2010).

In this paper we describe a metamodel for the lower Rhine delta, and the possibilities of such a model for dynamic policy making in a changing environment. After a short explanation of the concept of adaptation pathways, section 3 presents the IAMM’s requirements. In Section 4, we present the preliminary implementation of the model. Closing remarks are presented in section 5.

2 CONCEPT OF EXPLORING ADAPTATION PATHWAYS

The adaptation pathways approach is summarised in Figure 1. Multiple pathways are developed using 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. Management responses can be a priori entered into the model, or can be derived from single or multiple users, such as policymakers in a game setting (participatory modelling).

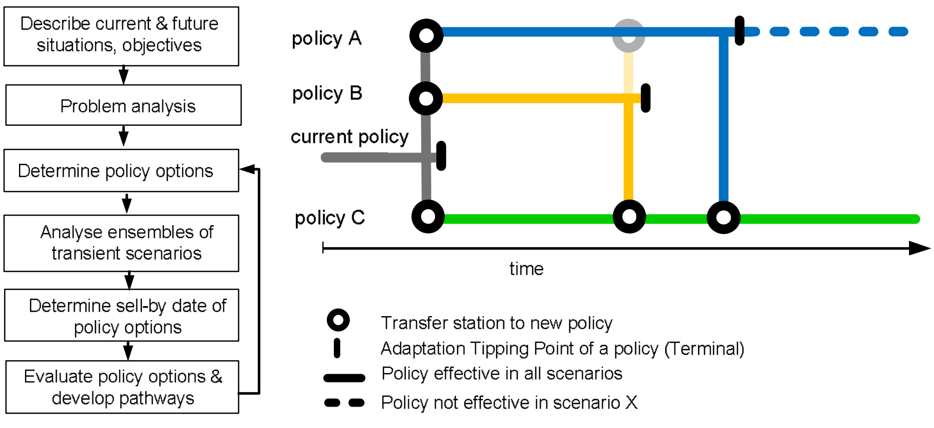

Figure 1: Stepwise policy analysis to construct adaptation pathways (left) and an example of an adaptation pathways map (right). Policy options are based on the objectives and problem analysis. The pathways are generated from the performance of each individual policy option for an ensemble of transient scenarios. After an Adaptation Tipping Point is reached (when a policy action fails to meet the objectives), all other options are considered. Similar to a Metro map, the map presents different routes to get to a desired point in the future. Also, the moment of an ATP (terminal station), and the available policy options are shown (transfer stations). Some routes are only available in part of the scenarios (dashed line). Options which add little to the performance of a route are shown transparently.

For the development of pathways, first the effects of each individual policy option are analyzed for the complete set of transient scenarios (all possible realizations of the climate and socio-economic scenarios), and for each climate or socio-economic scenario separately. These results are then used to determine the 'sell-by date' of each policy option. The 'sell-by date' specifies the moment in the future at which an option no longer meets its objective. This 'sell-by date' varies for different policy options or transient scenarios. The conditions under which a policy option no longer meets its objective is also called an adaptation tipping point (ATP) (Kwadijk *et al.*, 2010). With the IAMM all relevant policy options after an ATP has been reached, can be explored. From this information, different adaptation pathways can be derived. These pathways can then in turn be analyzed on their performance. The adaptation pathways map, manually drawn based on all model results, presents an overview of relevant pathways (Figure 1). With this map it is possible to identify opportunities, no-regret strategies, lock-ins, and timing of a strategy, to support decisionmaking in a changing environment.

3 MODEL REQUIREMENTS FOR EXPLORING ADAPTATION PATHWAYS

For the development of the IAM model we first address the model requirements. A computational model for developing adaptation pathways can be considered as a policy model. Policy models are built to give policymakers information that can help them to get insights in their (future) problem situation on which they can base their decisions (Walker *et al.*, forthcoming). The models serve as laboratory environment, to test alternative policies, and compare their performance without actually implement having to implement them to see how they would perform. This type of models is different from the models established in the scientific and engineering community to obtain a better understanding of a limited domain in the physical part of the water system. The better the match between the model and the real world, the better the model is considered to be.

The main purpose of the model is (similar to a policy model) to assess a large number of alternative policy options under different possible futures, and – along with that - designing adaptation pathways. The purpose of the model is *not* to provide *the* solution, but to provide information supporting policymakers.

Ideally, a computational model for adaptation pathways would be ***fast enough to be able to dynamically simulate transient scenarios for all policy options, and provide credible outcomes of interest with sufficient detail and accuracy****.* More concretely, the model should be able to implement individual ***policy options***, reflecting a wide range of perspectives in such a way that users can choose the preferred management response, and that decisionmakers can take into account the interests of other stakeholders. At the same time, the model should be ***fast*** enough to dynamically simulate 100-year scenarios and a large number of policies in a limited period of time. Preferably, the model should be fast enough, to be able to use the model interactively or participatorily in a game-like setting. The ***outcomes*** from the model should be such that policymakers and stakeholders can assess the relevant indicators, which they each use for decisionmaking, and that they can understand these outcomes. Additionally, the performance of strategies should be quantified by measures of sustainability as we seek for sustainable water management under changing conditions.

The ***accuracy*** of the model refers to the sense that decisions based on the results are justified. To achieve enough accuracy and clear results, the model should represent the key areas, dominant processes and natural variability, but without unnecessary details (Booij, 2003). As the model is intended for comparative analysis, such as ranking of policy options and drawing adaptation pathways, approximate results are sufficient. Moreover, the policy options have not been (and may never be) implemented, making observation of the impacts impossible. It must, however, provide sufficient information to map out the decision space (the relevant range of outcomes for various scenarios and policies) (Walker *et al.*, forthcoming). If necessary, a few selected policies could be examined in more detail using other (generally much slower) models.

For ***acceptation*** of the model, users need to be convinced that the model is credible. It helps if the model is not a black box, but if it tells a story about how things work in the relevant portion of the world (Walker *et al.*, forthcoming). Therefore, the model must express a set of logical relations and cause-effect mechanisms. To gain trust in the model ***validation*** and ***calibration*** are used. In contrast to scientific and engineering models, policy models can not be validated using empirical data as it simulates situations which can not be observed (futures and not yet implemented policy options). Hodges (1991), calls such models 'unvalidatable models', and emphasizes that any particular model can be used for specific purposes. These purposes should be made clear, and use of the model should be limited to these purposes (Walker *et al.*, forthcoming).

To fulfil the model requirements, we use the technique of metamodelling. Metamodels, or models of models, can be obtained purely statistically 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 will be build up by a set of small metamodels describing parts of the cause-effect chain, which will then be fully integrated.

In the development of metamodels, special attention should go to aspects related to ***time-steps, spatial resolution*** *and* ***aggregation*** *of processes*. Simple (and thus fast) solution schemes work reasonably well, if the inherent time-step of the process is an order of magnitude different from the model time-step. For example, we can create a reliable metamodel of rainfall-runoff relations in a large catchment with large time-steps (e.g. ten days or monthly). Using these large time-steps, we do not have to consider the dynamic behaviour of the wave travelling through the river network, as we can assume that all water entered and left the network within one time-step (and thus aggregate the wave-travelling process). Once we get in the domain of time-steps of one day, one hour or even smaller, this assumption is no longer valid. In this case, our simple hydrology-based model becomes a complex hydraulics-based model.

4 A METAMODEL FOR THE LOWER RHINE DELTA

The process of building a metamodel is similar to building any other model.

- *Purpose*: define objectives, boundaries, outcome indicators, policy actions.
- *Design*: identify key processes and areas, and determine level of aggregation, time-step and spatial resolution.
- *Implementation*: build the model in a way that can be executed by a computer.
- *Calibration and validation*: calibrate parameters and build confidence in the model and identify questions it will be able to address.

In the lower Rhine delta habitation is enabled through a comprehensive water management system, with dams, dikes and an extensive network of ditches and canals. However, for coping with future changes adaptation may be needed. Currently, the Dutch Government's main water management project is a nationwide programme, called the Delta Programme. The main task is "*to protect the Netherlands from flooding and to ensure adequate supplies of freshwater for generations ahead*." (Deltaprogramma, 2010). The model, therefore, focuses on safety against flooding and fresh water supply.

The water system of the lower Rhine Delta, has several characteristics that should be incorporated in the metamodel for allowing the pathway development (see also figure 2). After the Rhine enters the country, the water is distributed over the branches Waal, Nederrijn, IJssel by means of a weir. The IJssel supplies the

IJsselmeer and Markermeer with fresh water. The Afsluitdijk dam protects its adjacent areas from flooding, and enables water storage in the lakes. The levels of the lakes are carefully maintained with sluices at the dam, to ensure safety in the winter and enough fresh water in the summer. As in other countries, safety from flooding is expressed in standards of a probability per year that a critical water level will occur, e.g. 1:1,250 years. The standards are laid down by law for every dike ring area, and depend largely on the economic activities, the number of inhabitants and flood characteristics. The Haringvliet sluice gates and the Maeslantkering protect the Rhine estuary from (mainly coastal) flooding. The Haringvliet also limits salt intrusion into the river, a main source of fresh water in the Midwestern part the delta.

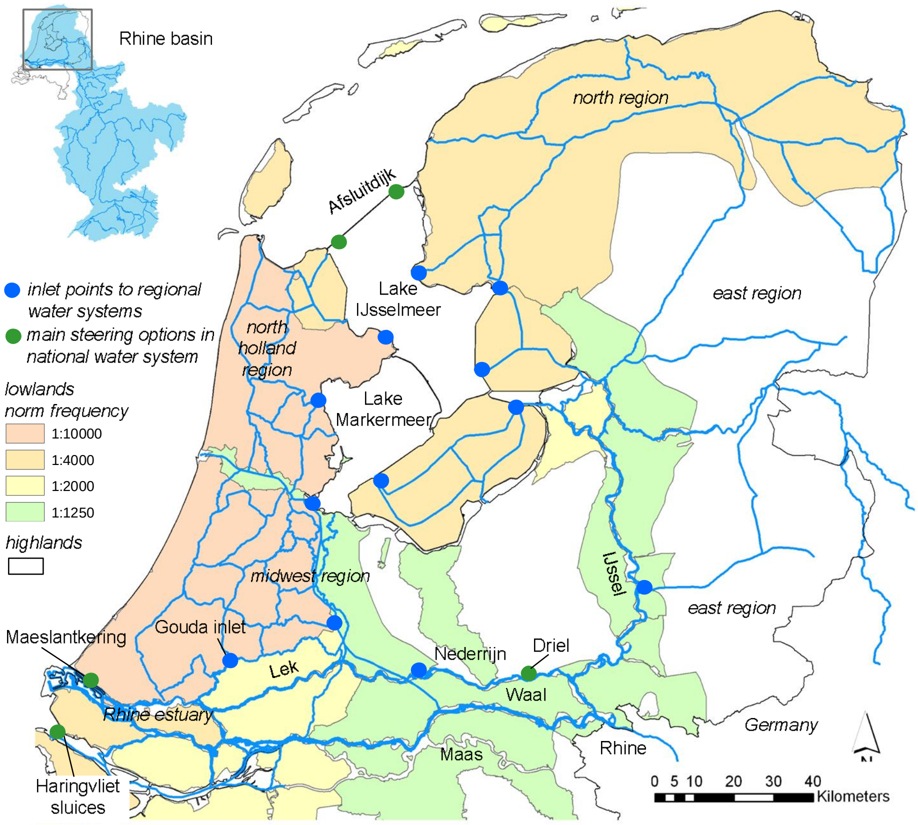

Figure 2. Study area

The IJsselmeer and Markermeer are the main water reservoirs in the lower Rhine Delta. 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. The major uses of water are for agriculture (for irrigation), for flushing (to mitigate adverse impacts for agriculture and drinking water due to salt upward seepage 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.

In the future, climate change and socio-economic developments may result in a 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; lower water availability in the summer due to less rain and lower river discharges, and more salt intrusion in the rivers; and an increase in flood risk due to sea level rise, higher river discharges, and population and economic growth.

Based on the water system characteristics and a problem analysis, we identified three key areas representing the strategic decisions for long-term water management in the lower Rhine Delta: Rijnmond area, IJsselmeer area and the main rivers (Nederrijn, Waal, IJssel). For building of the model the main alternative policies should be incorporated. These `corners of the playing field of policies' are:

- Rijnmond area: open, closure, temporarily closure of dams.
- IJsselmeer area: increase level + dike raising, decrease level + pumping.
- River area: dike raising, room for the river, climate dikes, evacuation plans, adapting land use (e.g. floating houses), dredging, changing ship types.
- Generic policies: more efficient water use, change of crops, land use changes.

The objectives, water system and policy actions determine the model design in terms of processes, time and spatial resolution. Figure 3 presents a diagram of the (intended) modules, which we shortly explain below:

- *Water distribution module*: describes the transport of water from the Rhine through the main water channels and regional areas. This includes distributions over the three main Rhine branches, the inlets from the IJsselmeer to the Northern, Noord-hollland and Midwest region, the inlet via Twentekanaal to the Eastern region, the inlets near Gouda and Amsterdam Rijnkanaal to the Midwest region, and the main channels in the regional systems.
- *Water demand module*: is a simple two layer groundwater model with a resolution of 1000 m grid cells, taking into account a limited amount of land use and soil types. The cells are aggregated over a district area linking the regional areas to the distribution network. This module results in water demands for sprinkling and water level control. Quantities needed for flushing are fixed values.
- *Drought impact module*: determines 1) impacts of low flows on navigation using a relation between water depth and suitability for different ship types. 2) agricultural damage due to lack of fresh water; and 3) the impact of water level change in the IJsselmeer area on nature in terms of ecotope areas.
- *Salt intrusion module*: simulates the salt intrusion in the surface water of the lower Rhine in relation to river discharge, sea level rise and tide. This determines the potential use of the inlet at Gouda.
- *Flooding module*: describes the possibility of flooding based on cause-effect relations of the Rhine discharge, the sea level and the water level in the river for several points along the river, and a relation between the water level and dike fragility.
- *Flood impact module*: based on the flooding module the probability of dike failure and overtopping of the dikes are used to calculate flood damage, using relations between water depth and land use type. Moreover, casualties are assessed using water depth, land use, and flood alarms triggered by the probability of dike failure. Also, the ecotope areas along river are calculated.

The metamodel will be based on the models of the PAWN and NHI study to build for the water demand and water distribution modules (Arnold and van Vuuren, 1988, Delsman, 2008, Wegner, 1981), the Damagesanner to simulate flood damages (De Bruijn, 2008, Haasnoot *et al.*, 2009), HABITAT to similate effects on nature in the large lakes and rivers (Haasnoot et al., 2009), and model results on salt concentrations and water levels with SOBEK schematisation of the rivers. Floodmodule and part of the Drought impact modules have already been implemented for a hypothetical area inspired by the Waal (Haasnoot *et al.*, accepted). The model is implemented using the object oriented programming language PYTHON and the spatial environment module PcRaster.

Given the goal of the model, a policy model for exploring adaptation pathways in the lower Rhine delta, we focus the ***validation*** on how the model can (not) be used. The model will be validated against the results of previous studies that used more detailed models, and with monitoring results. We will compare the model behaviour with the behaviour of these models. In addition, we will test the model structure through testing of equations and extreme conditions tests (Barlas, 1996).

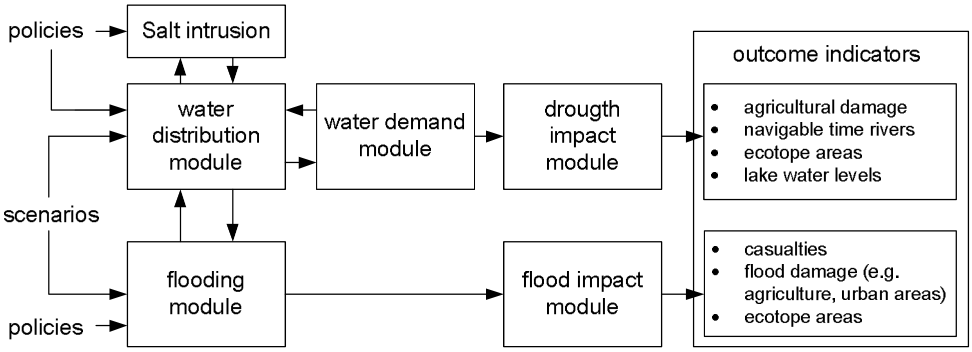

Figure 3. Model diagram

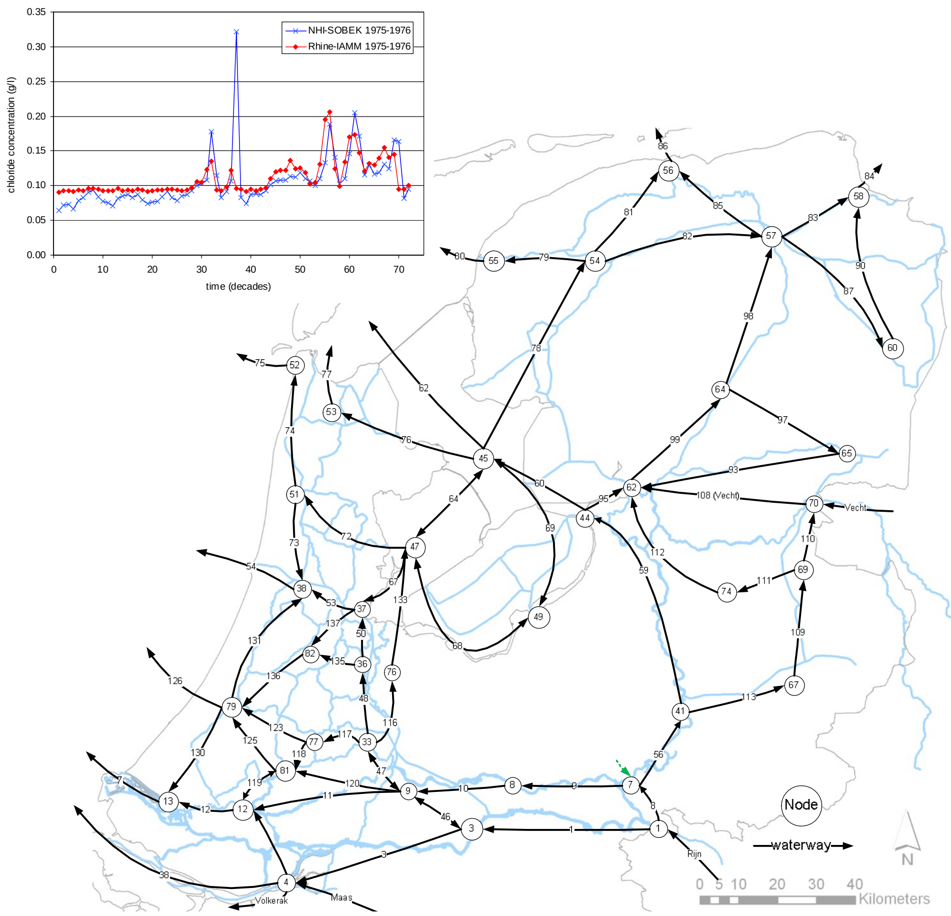

Figure 4. Network of the water distribution module (figure) and preliminary results of the IAMM for the salt concentration near the Gouda inlet for a dry period (1975-1976), and results of a complex detailed model NHI-SOBEK are presented.

5 NEXT STEPS

There is a need for a new generation of water policy models that are suitable for exploring policy actions sequentially over time to develop adaptation pathways. Adaptation pathways provide insights into options, lock-in possibilities, and path dependencies, and can thus be a valuable starting point for a discussion on short term policy actions, while keeping options open and avoiding lock-ins. Moreover, the pathways can be used to develop a plan for transitioning to a more sustainable system. To build adaptation pathways the dynamic interaction between water system, society and policy response needs to be analysed over time for a set of multiple plausible futures describing the natural variability and environmental changes. Such an analysis can become quite complex. A fast and simple model can support this analysis. A complex model can subsequently be used to obtain more detailed information about the performance of the most promising options resulting from the policy exploration using the IAMM.

We are developing such a fast and simple model, namely an Integrated Assessment Metamodel, for the lower Rhine delta in the Netherlands to explore adaptation pathways by using transient scenarios and taking into account the dynamic interactions between the pressures, state and impacts and water policy response. The model has different modules as presented in figure 3. Currently, the water distribution, salt intrusion and the impact modules are ready for use. Designing the model is a balancing act, between model completeness (in terms of considering all policy-relevant components), model credibility (in terms of physical detail and validity) and flexibility and calculation time of a simulation. To make the model manageable, simplifications in time scale, spatial scale and processes are needed. Simple (and thus fast) solution schemes can work well if the time-step of the process is an order of magnitude different from the model time-step. Consequently, the model will be good for some purposes, but not for other. Therefore, It should be clearly communicated what the model is able to do and what not. For example, the model we are developing will be able to assess impacts of strategic decisions such as the order of magnitude of the salt intrusion, the available amount of fresh water, and the potential impact on water users, but the model will not be able (and does not need to) to perform well in assessing detailed groundwater levels. Still, we should be aware that oversimplification may result in a model that cannot address all the relevant issues. Next steps are further elaboration of the model, and comparison of the model behaviour with the outcomes of complex models and past events. Finally, the model will be used to develop adaptation pathways, such as done for a hypothetical case (Haasnoot *et al.*, accepted). Additionally, the model will be coupled to a policy model to include policy dynamics in the generation of pathways (Wijermans and Vreugdenhil, 2012).

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