

## Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways



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### ARTICLE INFO

#### Article history:

Received 11 December 2013

Received in revised form

23 May 2014

Accepted 26 May 2014

Available online 1 July 2014

#### Keywords:

Integrated assessment

Metamodel

Water management

Uncertainty

Climate change adaptation

Rhine

### ABSTRACT

Exploring adaptation pathways is an emerging approach for supporting decision making under uncertain changing conditions. An adaptation pathway is a sequence of policy actions to reach specified objectives. To develop adaptation pathways, interactions between environment and policy response need to be analysed over time for an ensemble of plausible futures. A fast, integrated model can facilitate this. Here, we describe the development and evaluation of such a model, an Integrated Assessment Metamodel (IAMM), to explore adaptation pathways in the Rhine delta for a decision problem currently faced by the Dutch Government. The theory-motivated metamodel is a simplified physically based model. Closed questions reflecting the required accuracy were used to evaluate the model's fitness. The results show that such a model fits the purpose of screening and ranking of policy options and pathways to support the strategic decision making. A complex model can subsequently be used to obtain more detailed information.

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### 1. Introduction

Decision makers from governments, NGOs, and businesses sometimes face deep uncertainties associated with the future conditions against which policies must be developed. Deep uncertainties are severe uncertainties that can arise (i) from multiple possible futures without knowing relative probabilities (Lempert et al., 2003), for example due to climate change, population growth, and economic developments; (ii) from multiple world-views including different values to evaluate the system (Rotmans and De Vries, 1997); and (iii) from policy responses to environmental events and trends (Haasnoot et al., 2012) that cannot be considered independently (Hallegatte et al., 2012). Despite these deep uncertainties, decisions need to be taken.

To address deep uncertainties, literature suggests to use adaptive policies that can be changed over time (e.g. Walker et al., 2001;

Albrechts, 2004; Hallegatte, 2009; Ranger et al., 2010; Walker et al., 2013). Adaptive management has been adopted in various policy domains, including water management (Swanson and Bhadwal, 2009; Walker et al., 2010). Adaptive policy plans are currently being developed for the water management of New York City (Rosenzweig et al., 2011), and the Rhine Delta (Delta Programme, 2012), and have been established for the Thames Estuary (Reeder and Ranger, online; Ranger et al., 2013). Development of such adaptive plans requires exploration of different futures and assessments of impacts of these futures and adaptation actions, which is generally done by means of scenario analysis (e.g. Carter et al., 2007).

Exploring adaptation pathways (Haasnoot et al., 2012, 2013) constitutes a novel approach to develop a dynamic adaptive policy plan. An adaptation pathway describes a sequence of policy actions over time that aim to achieve (a set of) specified objectives. A pathway emerges from a set of time-varying boundary conditions of the water system, their impact, and the policy responses in terms of actions. An ensemble of such pathways provides insight into the potential consequences of different policy actions, potential lock-

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ins and path dependencies of actions, and factors that dominate the emerging pathways. This may provide insight in which policy actions constitute a robust plan, being (almost) insensitive to uncertain future developments and events, and which actions are flexible for adequate adaptation to changing conditions (Haasnoot, 2013). To explore adaptation pathways for this purpose, a multitude of plausible futures and sequences of policy actions needs to be evaluated. Often, a computational model is used to support such an exploratory scenario analysis (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 *integrated* assessment is needed (Jakeman and Letcher, 2003; Welsh et al., 2012; Laniak et al., 2013; EEA, 2013; Kelly et al., 2013). Integrated Assessment has been defined as a ‘meta-discipline’ that integrates knowledge and makes it available for decision making processes (TIAS, 2011). In this study, *integrated* refers to the integrated treatment of social, economic and environmental issues and the integration of different systems and processes. The Integrated Assessment Model (IAM) needs to be applied to analyse the whole system including its state, impacts of changing boundary conditions and relevant feedbacks within the system or resulting from policy responses. IAMs have been applied to analyse climate change and the effects of emission mitigation strategies on global and regional scale (e.g. Rotmans and Van Asselt, 1996; Van der Sluijs, 2002; Van Vuuren et al., 2009; Carnevale et al., 2012; de Vos et al., 2013; Schwanitz, 2013) and to assess adaptation strategies on regional scale (e.g. Carmona et al., 2013; Catenacci and Giupponi, 2013). Giupponi et al. (2013) give an overview of successes, shortcomings, and new approaches of integrated global change modelling. In this study, we apply the IAM concept for adaptation analysis on a regional to local scale and to the river delta domain. Following the decision tree of Kelly et al. (2013) a knowledge-based model would be an appropriate model for this study as it can support decision making under uncertainty and the system processes are quite well understood.

Secondly, to execute large number of simulation runs, a limited execution time is required, which implies that the model should be *fast*. One knowledge-based approach for the development of a fast model is ‘metamodelling’. Metamodels are models intended to mimic the behaviour of complex models (Davis and Bigelow, 2003; Walker and Van Daalen, 2013). Metamodels are generally thought of as statistically inferred constructs. Davis and Bigelow (2003) introduced the term theory-motivated metamodel for a model of which the structure is motivated in part by phenomenological considerations and in part by statistical analyses. Metamodels have been built for simulating rainfall-runoff (Jakeman and Hornberger, 1993), analysing airport policies (Kwakkel et al., 2010), assessing flood risks (Ward et al., 2011; Kramer et al., 2012), and identifying promising flood management actions (Schijndel, 2005).

This paper 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 challenge is to make the model fast enough to do many calculations for long time-series (up to 100 years), while keeping sufficient mechanistic and spatial detail to represent the whole system (integrated model) for supporting strategic decision making.

We illustrate the development of a fast, integrated model by means of a case for the Rhine delta in the Netherlands. At the time of writing, the Dutch Government is working on a large study, 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 (Delta Programme, 2012).

In the process of building and evaluating a model for exploring adaptation pathways we adopted a step-wise approach similar to any other model (e.g. Jakeman et al., 2006; Gupta et al., 2012; Walker and Van Daalen, 2013; Bennett et al., 2013). This paper follows these steps.

1. *Definition of model purpose and context*: based on the objectives of the Delta Programme, the purpose of the model is defined in terms of the scenarios, policy actions, outcome indicators, and relevant processes that should be simulated with the model (Section 2).
2. *Conceptualization of the system*: the main characteristics of water management in the Rhine delta are described in a conceptual structure of the model (Section 3).
3. *Implementation in the model*: the model structure and parameters are described. To make the model fast and integrated, the model consists of theory-motivated metamodels describing the complete cause-effect chain, and is referred to as an Integrated Assessment Metamodel (IAMM) (Section 4).
4. *Evaluation of the model*: evaluation of IAMs has received more attention, but a common framework is lacking. Recently, Schwanitz (2013) proposed a framework for evaluation of IAMs on global change. We use the approach of closed questions. This was inspired by Guillaume and Jakeman (2012) who focused on the adequacy of the model in answering policy questions rather than on quantifying the models accuracy. This study's 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?* In cooperation with potential end-users appropriate performance metrics were defined for a set of sub-questions the model should be able to answer (Section 5).

## 2. Model purpose and context

The purpose of the model is to support the strategic decision making of the Delta Programme that runs from 2009 to 2014. The main objective of the *Delta Programme* is to propose a set of strategic decisions ‘to protect the Netherlands from flooding and to ensure adequate supply of freshwater for generations ahead’ (Delta Programme, 2010, 2011). This should result in a dynamic adaptive plan that contains short-term actions and a long-term vision for action to adapt to changing conditions, if necessary. The time horizon of the programme is 2100. After 2014 the details of the actions will further designed in follow-up studies. To prepare the decisions, the potential impacts of climate change, sea level rise, socio-economic developments and policy actions need to be assessed. Climate change and sea level rise may result in an increased flood risk during winter and lower water availability during summer (e.g. Delta Committee, 2008). In addition, water demands from the regional areas to the national water system may increase due to less rain, more salt intrusion, and/or changes in the agricultural sector. Socio-economic developments may change fresh water demands and potential flood damage and casualties.

The focus of this paper is on flood and drought risk management in the main lower Rhine river branches, IJsselmeer lakes, and rural areas (Fig. 1). In the Delta Programme the following questions for decisions on policy options have been identified for flood risk: What policy actions are needed to guarantee compliance with flood protection standards? How can the Rhine discharge distributed

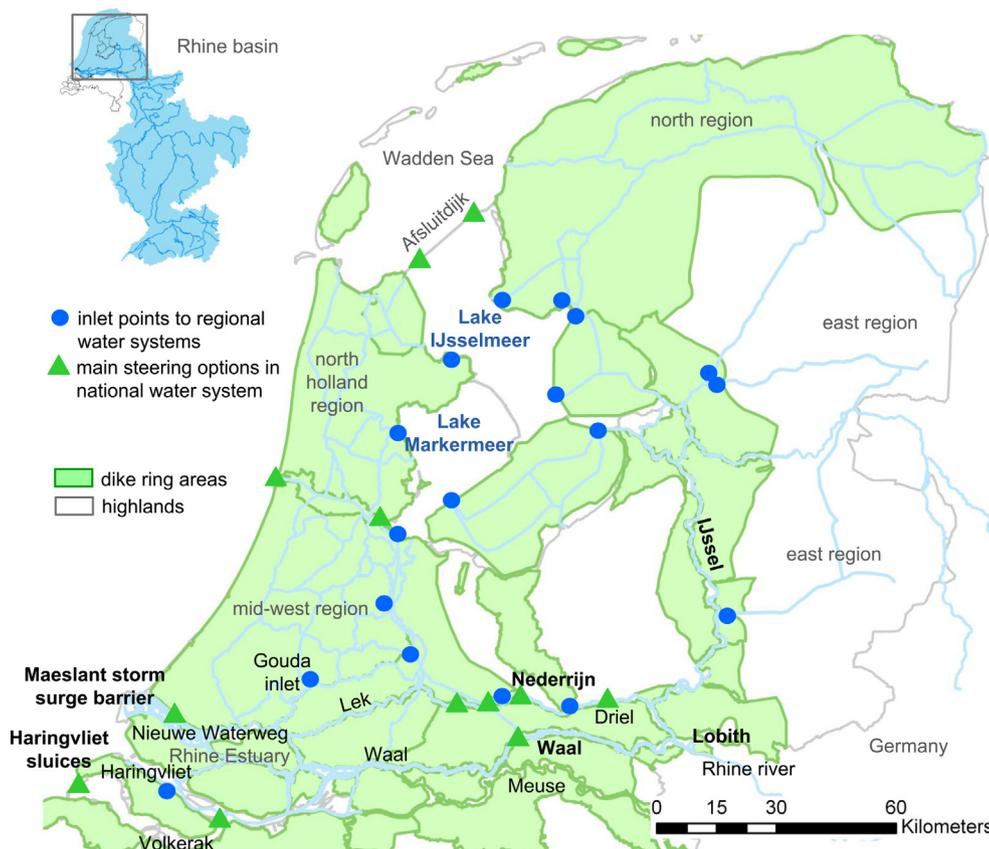


Fig. 1. Rhine delta and its characteristics.

over the river branches? What spatial planning actions can contribute to reduction of flood risk, and how can nonstructural actions reduce flood risk in existing flood prone areas? For drought risk they include: How can future water demands be fulfilled in a sustainable and economically effective manner? Should water levels in the IJsselmeer be raised to make use of energy efficient gravitational drainage, or should current water levels be maintained and pumping capacity increased accordingly?

The model should allow evaluation of the impacts of relevant pressures (climate change and socio-economic developments) and policy options that are being considered in the Delta Programme. Thereby, the model should support the analysis of trade-offs, which can be used to screen and select promising actions and rank these actions in order of performance for achieving the specified objectives. Furthermore, to support the development of a dynamic adaptive plan, the model should be fast enough to dynamically simulate long time-series (e.g. 100-year scenarios) and a large number of policy options and sequences thereof in a limited period of time; meaning that it should be able to carry out such a study within the time planned for the Delta Programme. The outcomes from the model should include the relevant indicators for the decision making in the Delta Programme.

The concept of *Adaptation Pathways* is summarised in Fig. 2 (Haasnoot et al., 2012, 2013). This example is the result of an assessment of the performance of actions over time for an ensemble of transient scenarios reflecting natural variability and different climate change scenarios. Central to this concept are adaptation tipping points (Kwadijk et al., 2010), which are the conditions under which an action no longer meets the a priori specified objectives. The timing of the adaptation tipping point for a given action, its 'sell-by date', is scenario dependent. After reaching

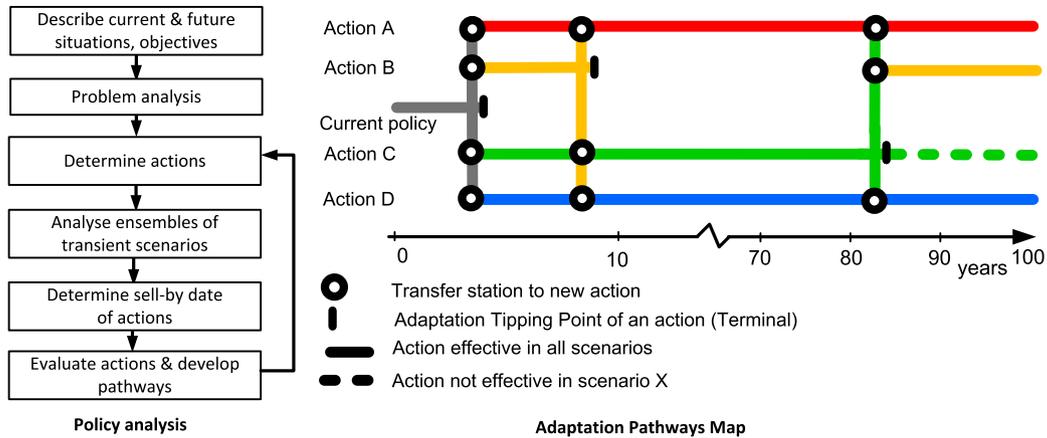
a tipping point, additional actions are needed to reach the defined objectives. As a result, a pathway emerges. An Adaptation Pathways map presents an overview of relevant pathways and policy options. Using this map, decision makers can make an informed decision about short-term actions, while keeping options open to adapt, if necessary.

### 3. Conceptualisation of the system

The water system of the Rhine delta has several key characteristics that were incorporated in the model as shown in the model diagram (Fig. 3).

The water distribution over the Rhine delta is represented in the *water distribution module*. 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 lakes with fresh water. From the rivers and lakes, water is distributed to other parts of the country through an extensive network of ditches and canals. Water flows can be bidirectional; drainage of excess water in winter and inlet of water during dry periods in summer.

To protect the country against flooding, flood prone areas are surrounded by dikes (embankments); these are referred to as dike ring areas. This is represented in the *flood mapping and flood impact module*. 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 completely open. The Haringvliet barrier regulates the amount of flow through the Nieuwe Waterweg at its specified maximum flow (1500 m<sup>3</sup>/s) for minimal disturbance of shipping. The Afsluitdijk



**Fig. 2.** 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, objectives 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 objectives for the next 100 years in all climate scenarios. If Action B is chosen after the first four years, within about five years a shift to one of the other three actions will 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 as in this scenario the performance of this actions was unacceptable after approximately 85 years (follow the solid green lines). In all other scenarios, the objectives will be achieved for the next 100 years (the dashed green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dam protects the adjacent areas of the IJsselmeer and Markermeer areas from coastal flooding. In the winter half year, the lake levels are carefully maintained with sluices at the dam at  $-0.4$  m MSL (Mean Sea Level) to store excess water in times of high river discharges.

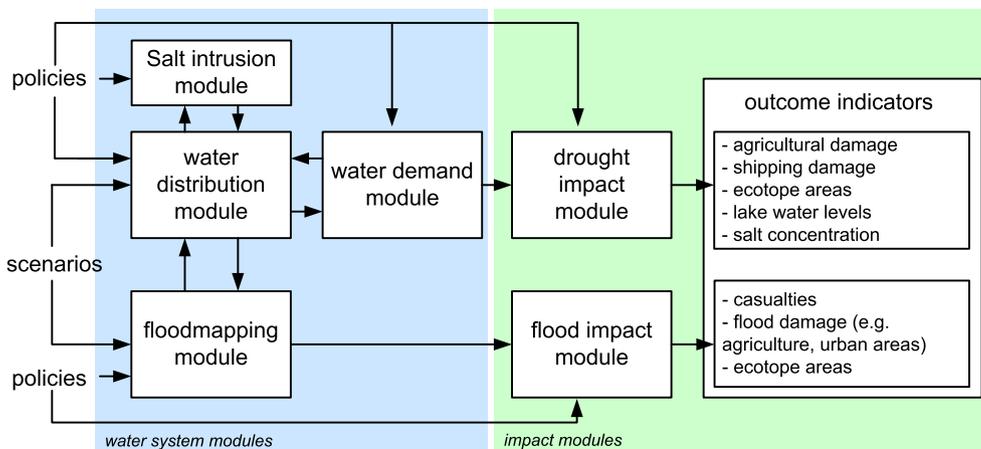
Salt intrusion, represented in the *salt intrusion module*, is another important pressure in the delta. At low Rhine discharges, the flow in the Nieuwe Waterweg is set as high as possible to limit seawater intrusion. This is achieved by reducing the flow through the Haringvliet barrier gates to its minimum required flow ( $10 \text{ m}^3/\text{s}$ ) for flushing.

There are multiple water demands in the delta (*water demand module*). The major demands are for agriculture (for irrigation and sprinkling), 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 ( $25 \text{ m}^3/\text{s}$ ) is supplied to the Nederrijn, and the flow in the Nieuwe Waterweg is set as high as possible.

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 at  $-0.2$  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, water supply can be insufficient. For the mid-western region the inlet of river water near Gouda is important. Occasionally, the Gouda inlet cannot be used due to a high salt concentration (current threshold used in the Delta Programme is  $250 \text{ mg Cl/l}$ ) as a result of the seawater intrusion in the Nieuwe Waterweg.

The model calculates the impacts of scenarios and policies on the water system and its water related functions in the flood impact and drought impact modules for a set of relevant model outcome indicators that are needed to support the decision making. The scenarios describe potential changes in climate, sea level, land use and economy, which are considered as external forcings that



**Fig. 3.** Model diagram. Section 3 describes the system characteristics. The modules are described in detail in Section 4.

cannot be influenced by water management. The policies include both flood and drought risk actions. Flood risk actions, include: dike raising, strengthening dikes, providing more room for the river, increasing drainage capacity at the Afsluitdijk, adapting target levels of the IJsselmeer, adaptive building in floodplains (e.g. floating houses), 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 by, for example, more efficient water use in the region or by using drought tolerant crops, increasing flow capacities, increasing irrigation for agriculture, and changing thresholds for allowed salt concentration at the Gouda intake.

**4. Model description**

The IAMM model is split into two main parts (Fig. 3): (1) modules describing the *water system* in terms of water availability and demand, and (2) modules describing the *impacts* of flooding and water scarcity. Appendices A–D.2 presents the model equations.

For building the IAMM modules for drought risk assessment, we used a set of complex models originating from a national assessment of the water systems in the Netherlands carried out in the 1980s (the PAWN project, e.g. Wegner, 1981; Abrahamse et al., 1982; Goeller et al., 1983, 1985), that were further elaborated by the institute for inland water management and waste water treatment (RIZA) (e.g. Vermulst et al., 1998) and subsequently by a consortium of Dutch research institutes (NHI Project Team, 2013; De Lange et al., 2014). These PAWN models comprise a multi-layer spatially distributed groundwater model that is connected to a regional surface water model, a water distribution model of the main branches and a hydraulic salt concentration simulation model. For flood management, the IAMM model contains a database with the results of a complex 2D hydrodynamic model that was used to determine inundation areas, depth and flood damage for flood-prone areas along the lower Rhine distributaries (De Bruijn and Van der Doef, 2011). The IAMM model is implemented using the programming language Python (Van Rossum and Drake, 1995) and the spatio-temporal modelling environment module PcRaster (Van Deursen, 1995).

The spatial scheme of the model 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 8–11 days period (2 periods of 10 days and the remainder of the month). The input of the model consists of transient scenarios on river discharges flowing into the system, precipitation and evaporation, and sea water levels at the Wadden Sea side of the Afsluitdijk. The output indicators reflect the information needed for the decision making and were derived from the existing complex model currently used in the Delta Programme, and consultation of potential end-users.

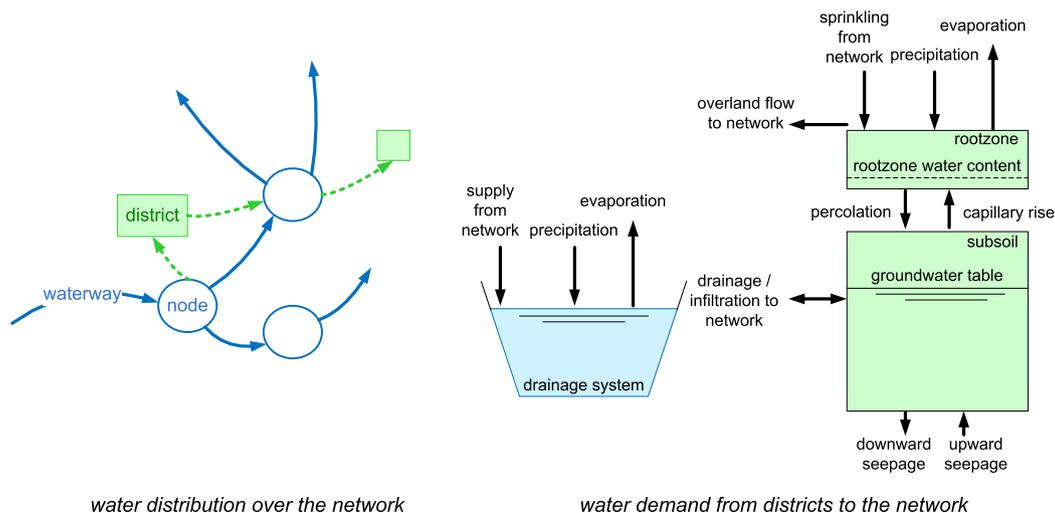
**4.1. Water system modules**

The *water distribution module* simulates the water flow from the Rhine at Lobith through 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 (Fig. 4 and Appendix E). The links represent the waterways that bring water into and across the country. The nodes represent the conjunctions of these waterways or the IJssel lakes. The nodes representing the lakes have a target level and can store water.

The distribution over the three main Rhine branches is represented by a discharge dependent curve derived from the complex model, which on its turn is partly based on observations (up to 12,000 m<sup>3</sup>/s). For most links the flow is calculated from the water balance at a certain node. For others and also for allocation to some of the watersheds, allocation factors 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 lakes together is calculated, resulting in an average level for each lake. The water level determines the discharge capacity from the IJsselmeer to the Wadden Sea, and the inlets from the lakes 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).

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



**Fig. 4.** Schematisation of the water distribution module (left), and the water demand module (right) that represents the local drainage system and the subsoil.

using stage-discharge curves based on observations (Rijkswaterstaat, 2013) for a selection of potential breach locations. 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; Haasnoot et al., 2012). Whether the dike fails or not depends on a random number selected between 0 and 1 (the seed is fixed to enable comparing the simulation results for different actions, without increasing the number of calculations enormously). 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 depending on river discharge and sea level. This module is based on empirical correlation between the Rhine discharge at Lobith and salt concentrations in the lower river reaches calculated using a 1D hydraulic model (SOBEK) (Van den Boogaard and Van Velzen, 2012).

The *water demand module* generates water demands for irrigation and water level control in rural areas and is a simple two layer grid base groundwater model with a resolution of  $1 \times 1$  km, taking into account a limited number of land use and soil types (Fig. 4). For each layer in each grid cell, the model calculates the water balance. 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 actual evaporation is a function of the potential evaporation, the available moisture in the root zone, and the soil moisture suction (pF value). 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 (Kabat et al., 1994; Oosterbaan, 2001). 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 runoff coefficient of 0.8 (Urbanas and Roesner, 1993). 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. The grid cells are aggregated over a watershed area (called district), linking the rural areas to the water distribution network. The water distribution module calculates whether the demanded water is available or not and supplies a requesting district with the available amount of water. For each time step, water demand and supply are calculated.

#### 4.2. Impact modules

The *flood impact module* estimates the damage, casualties and the number of 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 a dike fails, flood depth and consequent damages and casualties will be much larger when compared to flood depth caused by overtopping of a dike due to high water levels without breaching. 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 derived from 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 from 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 a 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) (Van Velzen, 2012). Increased navigation costs for other waterways within the Netherlands are very small relative to this, and are therefore not considered in the model. 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 on fresh water supply, the salt concentrations from 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 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. With this damage fraction, the survival fraction is calculated: the fraction of the crop that can still potentially grow and result in a specific yield, given the maximum crop yield under the weather circumstances. This is combined with the remaining yield of a time step to calculate the final damage fraction for each year.

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

## 5. Model evaluation

### 5.1. Evaluating the quality of IAMM models: metrics and closed questions

The purpose of the model is to support policy makers and stakeholders with the impact assessment of their decisions. That is, the model will be used to scan a large number of potential decisions, and help in selecting the right policy options for the right reasons. The question of the quality of the IAMM can thus be reformulated as: does the fast, integrated model lead policy makers to the same decisions as would be made if using the complex models? The target to be reached is thus a set of decisions, which corresponds to the decisions made on basis of the complex models. A good IAMM should yield the same set of decisions based on the same reasoning as the decisions made with the complex models.

Note that this is a different notion of quality than often used in validation of simulation models. We are not predominantly interested in the traditional notion of quality as expressed in metrics such as R2 or Nash–Sutcliffe coefficients, which assess the similarity of a simulated series of values with a measured series of values. In our case, we are not per se interested in similarities of series of continuous values, but are interested whether right decisions have been made at the right point in time and locations.

Another reason why we use additional criteria for assessing the quality of the model is that we have, by definition, no truth against which the model can be validated; the IAMM model is a policy model that simulates situations that have not existed or observed in the past (futures, and not yet implemented policy options) (Jakeman et al., 2006; Walker and Van Daalen, 2013). The only

validation set we have is the results of the complex models, and no independent source of ‘reality’ is available.

The performance of the IAMM was evaluated in different ways. First, the model structure was evaluated through extreme conditions tests (Barlas, 1996). Second, the output of the different model components was compared to the results of the complex models, and observations for pre-specified periods of interests within between 1975 and 2004. We compared model behaviour with the complex models and historical data in the sense that e.g. dry and wet periods should be reproduced at least with correct relative magnitude. The focus of our evaluation was however on the third step: a thorough evaluation of the model using a set of evaluation metrics expressed as closed questions. If needed, the purpose, design and implementation of the model were reassessed.

This section first presents the reference data selected, the evaluation approach using the closed questions, and then discusses the model performance based on the closed questions.

## 5.2. Reference data

For the evaluation of the model, we used data of periods of interests related to wet, dry and average hydrological years. Although a metamodel is usually compared directly with the complex model, we also compared the IAMM results with monitoring data to be able to evaluate them for longer time series and to analyse differences with the complex model.

In the Rhine delta, characteristic wet periods with high river flows occurred in the winters of 1976, 1985, 1993, and 1995; the year 1985 was especially wet in the rural areas. Characteristic 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 and 2003 (De Wit, 2004). 1995 and 1996 were both years with a greater than average precipitation shortage, and 1996 had also relatively low summer flows. 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.

For flood risk, we used results from the complex models (Deltares, 2012) for potential key dike breach locations. To evaluate the estimates of drought risk, output from the complex models was available for the years 1975, 1976, 1988, 1989, and 2003, which include some of the driest summers in recent decennia. These data included flows for river sections, water levels in the IJsselmeer, water demand from districts, the total agricultural damage for the whole of the Netherlands, and a map of the potential and actual agricultural yield.

## 5.3. Evaluation metrics expressed as closed questions

To define context-dependent criteria for acceptable model quality and determine appropriate model complexity, we built upon the idea of Guillaume and Jakeman (2012) of using closed questions to precisely specify the purpose of the model. Guillaume and Jakeman (2012) used this approach to enable decision makers to make a better choice in selecting models and techniques that are fit for purpose.

Here, decisions to be made are related to water distribution over the main branches, water allocation to the main users, and to water levels in the IJsselmeer. The impacts to be evaluated include flood and drought damage. The closed questions developed assess the quality of the IAMM in this domain, and are centered on the notion of ‘the right decision for the right reason’, complemented with a set of more traditional metrics. We established closed questions that do not leave wiggle room: the answer is either yes or no. Therefore, we aimed at using indifference threshold values indicating that a higher accuracy would not result in a different decision.

The questions were formulated iteratively in consultation with potential end-users. This potential end-user group comprised primarily policy advisors who are either currently involved in advising the Delta Programme directly, or currently developing a hydrological impact model – the Deltamodel – which is being used for

**Table 1**

Closed questions used for evaluating the model's performance, grouped per overarching question. The last question is related to all identified strategic decisions.

1. Can the model predict the occurrence of river flooding events and related damages? (Water distribution module, flood mapping module, flood impact module)
  - a. Does the model simulate a similar distribution of water (difference less than 200 m<sup>3</sup>/s) over the main Rhine branches for high flows (10,000 m<sup>3</sup>/s–16,000 m<sup>3</sup>/s) and/or for peak flows (<16,000 m<sup>3</sup>/s)?
  - b. Does the model simulate higher dike failure probabilities in high water situations than in case of low or moderate flows, and flooding events in case of peak flows?
2. Can the model predict the impact of low river flows on navigation? (drought impact module)
  - a. Can the model identify the occurrence and severity of drought damages for shipping in average and (extremely) dry years?
  - b. 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)?
  - c. Does the model simulate a correct distribution of water (difference less than 15 m<sup>3</sup>/s) over the main Rhine branches for low flows (<2,000 m<sup>3</sup>/s)?
3. Can the model predict how often the salt concentration of the fresh water supply in the mid-west exceeds the inlet norm? (Salt intrusion module)
  - a. Can the model discriminate the differences between salt concentrations in average and (extremely) dry periods?
  - b. Can the model simulate the number of 10-day periods that the salt concentration exceeds 250 mg Cl/l?
4. Can the model predict the IJsselmeer water levels in winter half year, and in the summer half year? (Water distribution module)
  - a. Can the model simulate whether the IJsselmeer water level drops below target level (–0.2 m MSL), below threshold value of –0.3 m MSL or –0.4 m MSL in summer half year?
  - b. Can the model simulate whether the IJsselmeer water level exceeds a threshold value of +0.1 m MSL in the winter half year?
  - c. Does the model adequately simulate IJssel discharges during low flow, which is that it does not cause an error in the calculated water levels in the IJsselmeer larger than <0.05 m?
5. Can the model predict the fresh water demands from rural areas? (Water demand module)
  - a. 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?
  - b. Can the model simulate the total water demand for these uses in summer half year with a difference of less than 5 m<sup>3</sup>/s?
6. Can the model predict drought damage for agriculture? (Drought impact module)
  - a. Can the model discriminate the damages in average and (extremely) dry years?
  - b. Can the model simulate credible actual and potential evaporation?
7. Can the model assess impacts of scenarios and policy actions on relevant outcome indicators? (All modules)
  - a. Are relevant variables and parameters included?
  - b. Do experts and potential end-users judge that the model provides credible results for impact assessment of scenarios and policy actions on relevant outcome indicators for the decision making?

assessing the effectiveness of policy actions considered in the Delta Programme. In light of the answer to a given question, we reconsidered whether we built the right model, used the right question, and used the right test.

The closed questions are grouped and answered per overarching (more ambiguous) question. Table 1 gives an overview of the questions, their relations with the strategic decisions to be made within the Delta Programme (Section 2) and the different parts of the model (Section 4).

#### 5.4. Model performance

In this section, we discuss the appropriateness of the model by answering the closed questions for evaluation (Table 1).

Q1. Can the model predict the occurrence of river flooding events and related damages?

The model should correctly simulate discharge distribution over the lower Rhine branches during peak flow under present and changed climate conditions. Subsequently, it should give high dike failure probabilities in case of high discharges, flooding events in case of peak discharges. Flood damages are directly derived from the complex model, and thus not questioned.

Q1a. Does the model simulate a similar distribution of water (difference less than  $200 \text{ m}^3/\text{s}$ ) over the main Rhine branches for high flows ( $10,000 \text{ m}^3/\text{s}$ – $16,000 \text{ m}^3/\text{s}$ ) and/or for peak flows ( $>16,000 \text{ m}^3/\text{s}$ )?

For answering this question, only a limited number of observations is available for high flows. After answering the question on low flows (question 2c in Table 2), the distribution function over the main Rhine branches was adapted, resulting in the same flows as the complex model. Comparing the predicted flows with observations for the high discharges of 1993 and 1995 ( $10,000$  and  $12,000 \text{ m}^3/\text{s}$ ) reveals the following: for the Nederrijn differences were  $\approx 200 \text{ m}^3/\text{s}$  ( $\approx 8\%$ ), for the IJssel  $\approx 220$ – $260 \text{ m}^3/\text{s}$  ( $\approx 13$ – $15\%$ ), and for the Waal  $\approx 250$ – $315 \text{ m}^3/\text{s}$  ( $\approx 3$ – $4\%$ ). Although the model appears to show these errors in the discharges among the different tributaries, it is still possible to evaluate the effect of policy actions such as an artificial change by  $400 \text{ m}^3/\text{s}$  or more at the bifurcation. In spite of the uncertainty in the absolute discharge, the model will result in a changed distribution as well.

Q1b. Does the model simulate higher dike failure probabilities in high water situations than in case of low or moderate flows, and flooding events in case of peak flows?

Yes, in 1993 and 1995 with observed high flows ( $\approx 10,000$  and  $12,000 \text{ m}^3/\text{s}$ ) but without floodings, the probability of dike failure was higher than in other years. The probability was still very low ( $0.05$ – $0.15\%$  compared to  $0$ – $0.02\%$  for other discharges), and no flooding occurred. Analysing a hypothetical time series of  $10,000$  to  $22,000 \text{ m}^3/\text{s}$  shows that the dike failure probability increases with discharge, and rises from  $1\%$  at  $13,000 \text{ m}^3/\text{s}$  to  $100\%$  at  $18,000 \text{ m}^3/\text{s}$  at Lobith (the design conditions), resulting in flooding events in case of peak discharges. The model did not simulate dike breaches for the period of 1975–2004, which corresponds with observations.

Q2. Can the model predict the impact of low river flows on navigation?

To be able to use the model for estimating the extra costs for navigation in case of low flows, the model must be able to discriminate between average and dry years, and be able to estimate the damages reasonably well.

Q2a. Can the model identify the occurrence and severity of drought damages for shipping in average and (extremely) dry years?

Yes, the model is able to discriminate the drought damages for navigation for (extremely) dry and wet years. To evaluate the model results for shipping damage, we used the discharge deficit. This is the difference between a threshold value ( $1800 \text{ m}^3/\text{s}$  at Lobith) and the average discharge in a 10-day period summed for the whole year if the discharge is below that threshold (instead of summer half year that has been used by (Beersma et al., 2004) we took the whole year as the whole year is relevant for shipping). The model results correctly reflect the years with a large discharge deficit over the past decades (Fig. 5; R2 is 0.99).

Q2b. Can the model simulate the annual ship damage with an error width that is lower than the differences between average and (extremely) dry years ( $\approx 1$  million euro)?

There is no reference data to answer this question. However, Van Velzen (2012) concluded that their discharge-water depth-damage relation, which 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 during which 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). This suggests, that the answer to this question is yes.

Q2c. Does the model simulate a correct distribution of water (difference less than  $15 \text{ m}^3/\text{s}$ ) over the main Rhine branches for low flows ( $<2000 \text{ m}^3/\text{s}$ )?

For the Waal and Nederrijn Rivers,  $89\%$  of the flows for each ten-days period fall within this range when compared to the results of the complex model for the years 1976 and 1989. For the IJssel River,  $100\%$  of the flows fall within this range when compared to the results of the complex model for 1989 (1976 is not available).

Q3. Can the model predict how often the salt concentration of the fresh water supply in the mid-west exceeds the inlet norm?

To assess whether the Gouda intake is more or less vulnerable for closing in case of climate change and policy actions, the model must be able to discriminate between the salt concentrations of average and dry periods, and assess the number of 10-days periods the salt concentrations exceeds a threshold value of  $250 \text{ mg Cl/l}$ .

Q3a. Can the model discriminate the differences between salt concentrations in average and (extremely) dry periods?

Yes, the IAMM and the complex model show roughly the same fluctuations in salt concentration at the Gouda intake point (Fig. 6). However, salt concentrations during peaks are much lower in the IAMM than in the complex model ( $200$ – $500 \text{ mg Cl/l}$ ). Comparing both model results with observations indicates that the IAMM underestimates the peaks and misses some, and the complex model overestimates the peaks and predicts peaks that are not there (R2 of the equation used in the IAMM is 0.99 in its original use for daily time-

steps). This could be caused by the fact that the IAMM uses the average discharge within a 10 to 12 days period for this module. It would be possible to use also the lowest discharge in this period (in addition to the average discharge for the water distribution module and the maximum discharge for the flood mapping module), but this would increase the runtime of the model. For both models, the simulated concentrations are also lower than observed concentrations during average conditions. This may be caused by the lower background concentrations used as boundary conditions in both models. These concentrations are based on maximum allowable salt loads in the Rhine River determined by international agreement instead of real concentrations.

Q3b. Can the model simulate the number of 10-day periods that the salt concentration exceeds 250 mg Cl/l?

For 1976 and 1989 the number of 10-day periods that the simulated concentration is above the critical level is 12 and 6 for the complex model, 8 and 2 for the IAMM, and 15 and 2 for the observations. Potential end-users of the Delta Programme found this difference acceptable for estimating whether the Gouda intake would be closed more (or less) under changing environmental conditions or after implementation of policy actions in comparison to the reference situation. Still, the user should be aware that the model underestimates the concentrations by 50–100 mg Cl/l. The model cannot be used to estimate the salt concentration per 10-day period.

Q4. Can the model predict the IJsselmeer water levels in winter half year, and in the summer half year?

For the summer half year, it is relevant to know whether water levels drop below approximately  $-0.3$  m MSL because in that case water intake may need to be limited and below  $-0.4$  m infrastructural damages start to occur. Therefore, the following question needs to be answered:

Q4a. Can the model simulate whether the IJsselmeer water level drops below target level ( $-0.2$  m MSL), below threshold value of  $-0.3$  m MSL or  $-0.4$  m MSL in summer half year?

From comparison with the observations and model results, we conclude that the model can simulate

whether the water level drops below target level or below a threshold of  $-0.3$  m MSL in the summer half year. The observations (grey lines, Fig. 7) 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 the summer target water level in both models, although the complex model shows a larger decrease (in 1976 this is approximately  $-0.4$  m versus approximately  $-0.3$  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 along the lake show a drop down to  $\approx -0.23$  m MSL (Hoogewoud et al., 2011) which fits better with the IAMM. Differences can be caused by changes in land use and water management, and ad-hoc regulation. Both model simulations used the current land use and flow capacities of drainage canals and the decision rules from water management agreements. In 1988 and 1989 the water level follows the summer target level in both models (not presented).

Q4b. Can the model simulate whether the IJsselmeer water level exceeds a threshold value of  $+0.1$  m MSL in the winter half year?

In winter, a temporary, wind-induced increase of the sea level can limit the discharge capacity at the Afsluitdijk. The complex model considered in this study does not account for these limitations. 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. The model results for the winter period should be used with care and only used indicatively for assessing effects of the limited discharge capacity as a result of sea level rise. This is a consequence of the time resolution of the

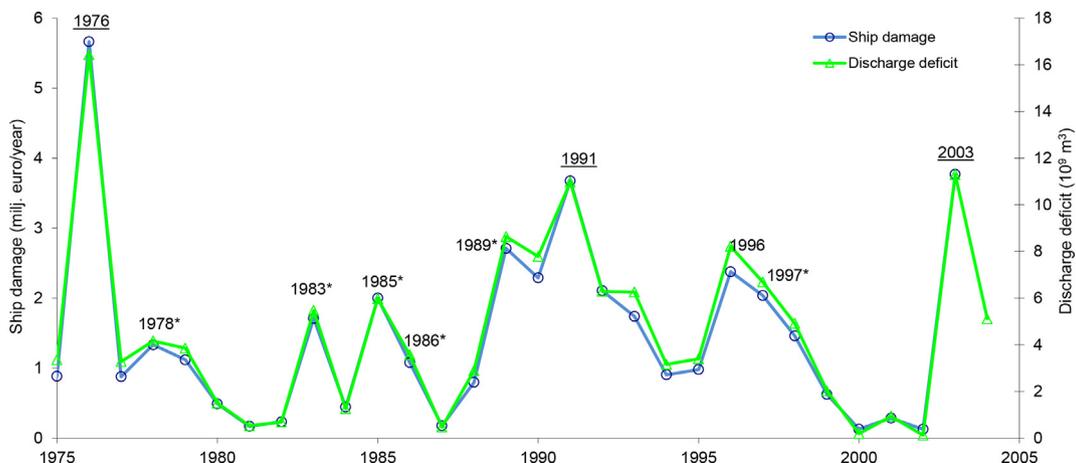


Fig. 5. Simulated total damage for navigation (million euros/year) and the observed discharge deficit ( $m^3/year$ ) for the summer half year. The years 1976, 1991 and 2003 are in the top-10 of low flows. Years with an asterisk (\*) have low flows outside of the summer half year, resulting in differences between the damage and discharge deficit.

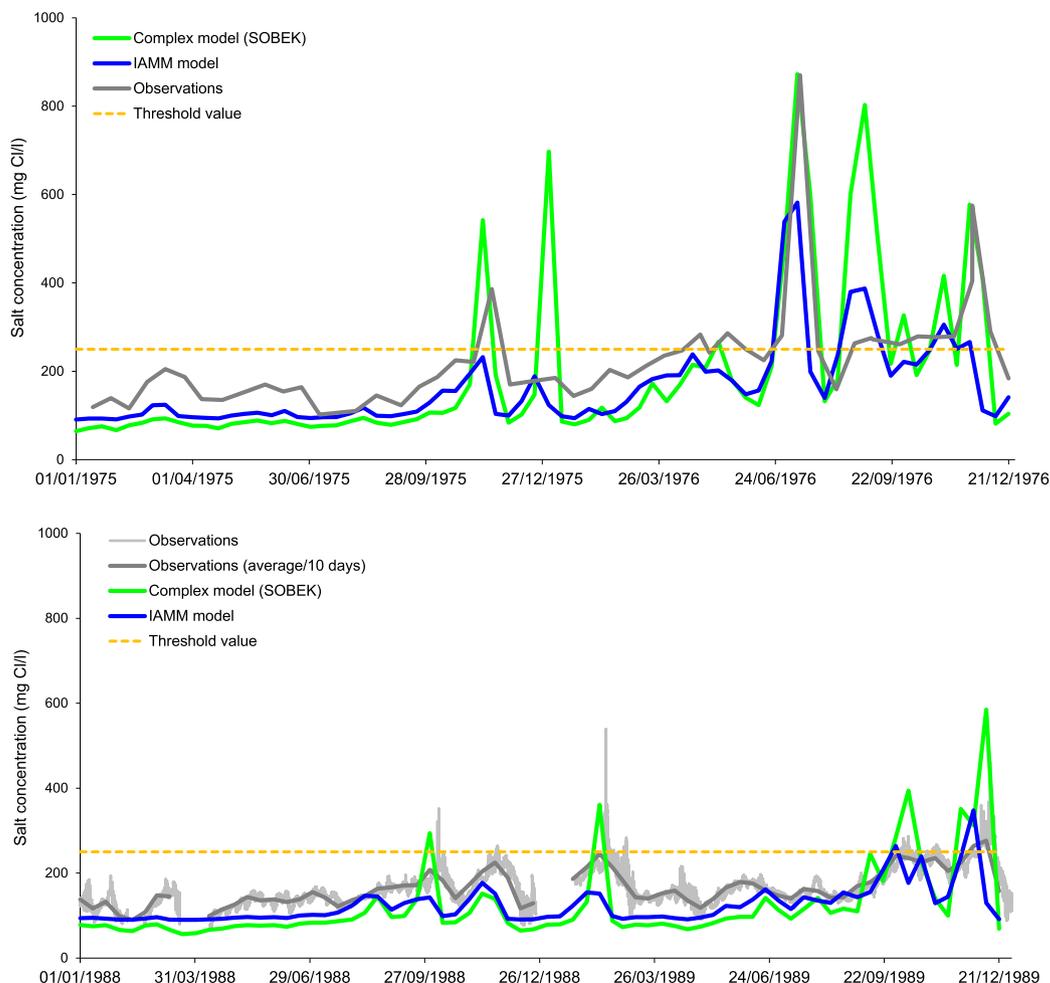


Fig. 6. Salt concentration at the Gouda intake (mg/l) for the complex model, the IAMM and observations.

model. To conclude, the model cannot assess short-lasting (daily) water level rises that may occur as a result of high wind speeds during storms.

As the inflow from the IJssel River into the IJsselmeer lake is an important variable for the water level, we assessed whether the model simulates these flows appropriately by answering the following question

Q4c. Does the model adequately simulate IJssel discharges during low flow, which is that it does not cause an error in the calculated water levels in the IJsselmeer larger than  $<0.05$  m?

For the year 1989 (with flows between 900 and 4000  $\text{m}^3/\text{s}$ ), differences vary between  $-37$  and  $+38$   $\text{m}^3/\text{s}$  with average of 9  $\text{m}^3/\text{s}$  in comparison with the observations (average value per 10-days period), which would result in a 0.006 m water level difference in the IJsselmeer (0.025 m at maximum). Differences with the results of the complex model for 1989 are even smaller and range between  $-36$  and  $+13$   $\text{m}^3/\text{s}$  with an average of 1  $\text{m}^3/\text{s}$ . For 1976, no observations were available for the IJssel river discharges. The differences with the complex model result at maximum in a 0.008 m difference in the lake level. These results can thus be considered as appropriate for the strategic decision making in the Delta Programme.

Q5. Can the model predict the fresh water demands from rural areas?

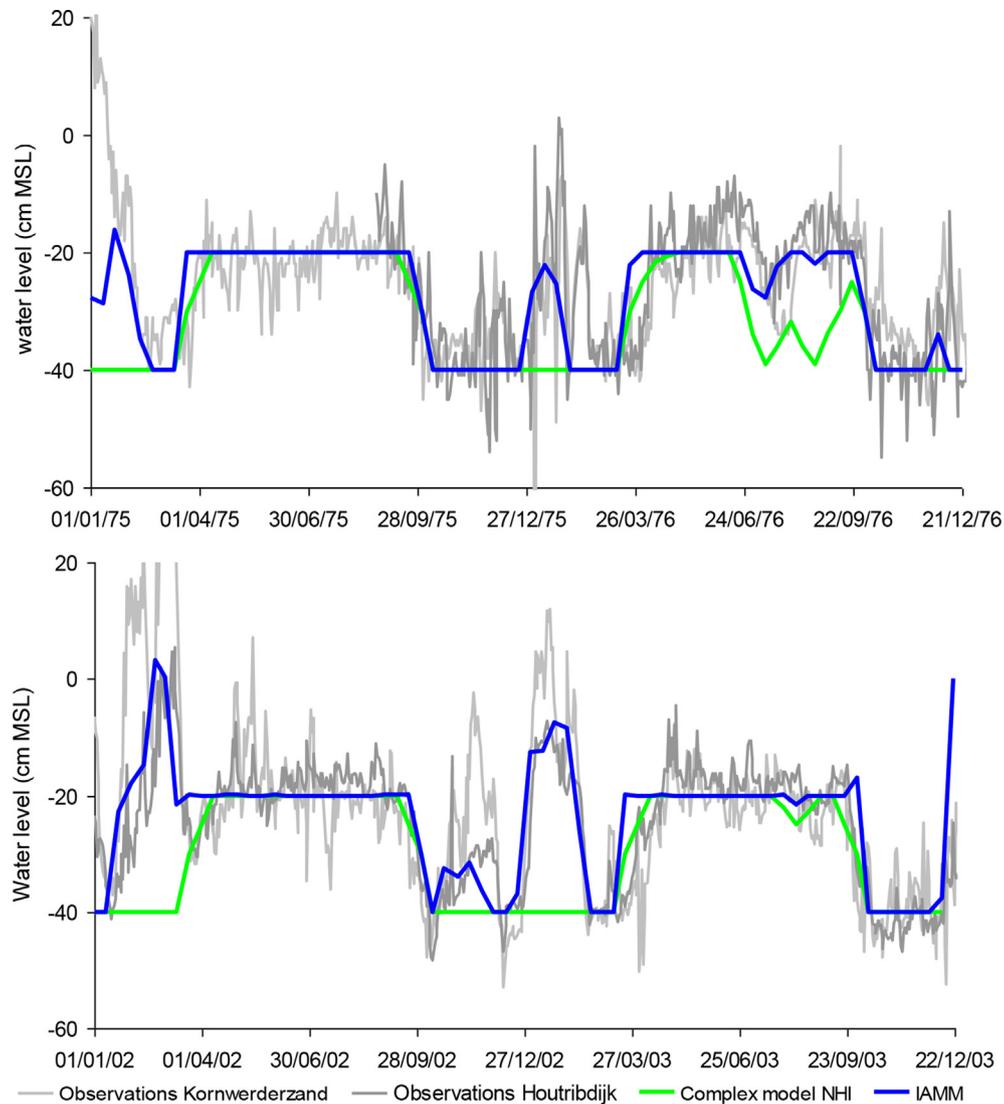
The fresh water demand of the rural areas from the main waterways is relevant for determining the IJsselmeer water levels and the agricultural damages. For this purpose, the model should be able to assess the seasonal and year-to-year variability in both demand and availability. Also, the total demand should be assessed reasonably well.

Q5a. 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?

Yes, the water demands for sprinkling and water level management show similar values and variations in time in both models (Fig. 8 shows results for Friesland in the north region).

Q5b. Can the model simulate the total water demand for these uses in summer half year with a difference less than 5  $\text{m}^3/\text{s}$ ?

Yes, for the sprinkling demand the differences are within this range. However, this is not always the case for the water demands for maintaining the water levels in the canals and ditches in the regional areas. The difference in the total water demand in the growing season varies per year and per district. In 1976 the total



**Fig. 7.** 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.

water demand is on average  $-1.6 \text{ m}^3/\text{s}$  ( $-4.5\%$ ) lower in the IAMM than for the complex model, for 1989  $-0.3 \text{ m}^3/\text{s}$  ( $-10\%$ ) while for 2003 the difference is  $5 \text{ m}^3/\text{s}$  ( $+36\%$ ). For the total water demand for water level management the differences are larger:  $-2.5 \text{ m}^3/\text{s}$ ,  $12.5 \text{ m}^3/\text{s}$ , and  $26 \text{ m}^3/\text{s}$  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. Increasing the model spatial resolution would increase the runtime, while a more detailed input on meteorology would improve the results with the same runtime, but this input was not available in the transient scenarios. 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, 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, the model performs adequately.

#### Q6. Can the model predict drought damage for agriculture?

To assess whether the scenarios and policy actions affect the agricultural drought damage, the model must be able to discriminate between average and dry years.

##### Q6a. Can the model distinguish discriminate the relative damages in average and (extremely) dry years?

Yes, 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. Fig. 9 shows the total damage for the Rhine delta in relation to the precipitation deficit based on observations in the mid-western area ( $R^2 = 0.86$ ). 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. The potential yield per crop type ranges between 8000 and 60,000 kg/ha. Comparing the maps of the potential and actual agricultural yield for the complex and IAMM model indicates that the IAMM

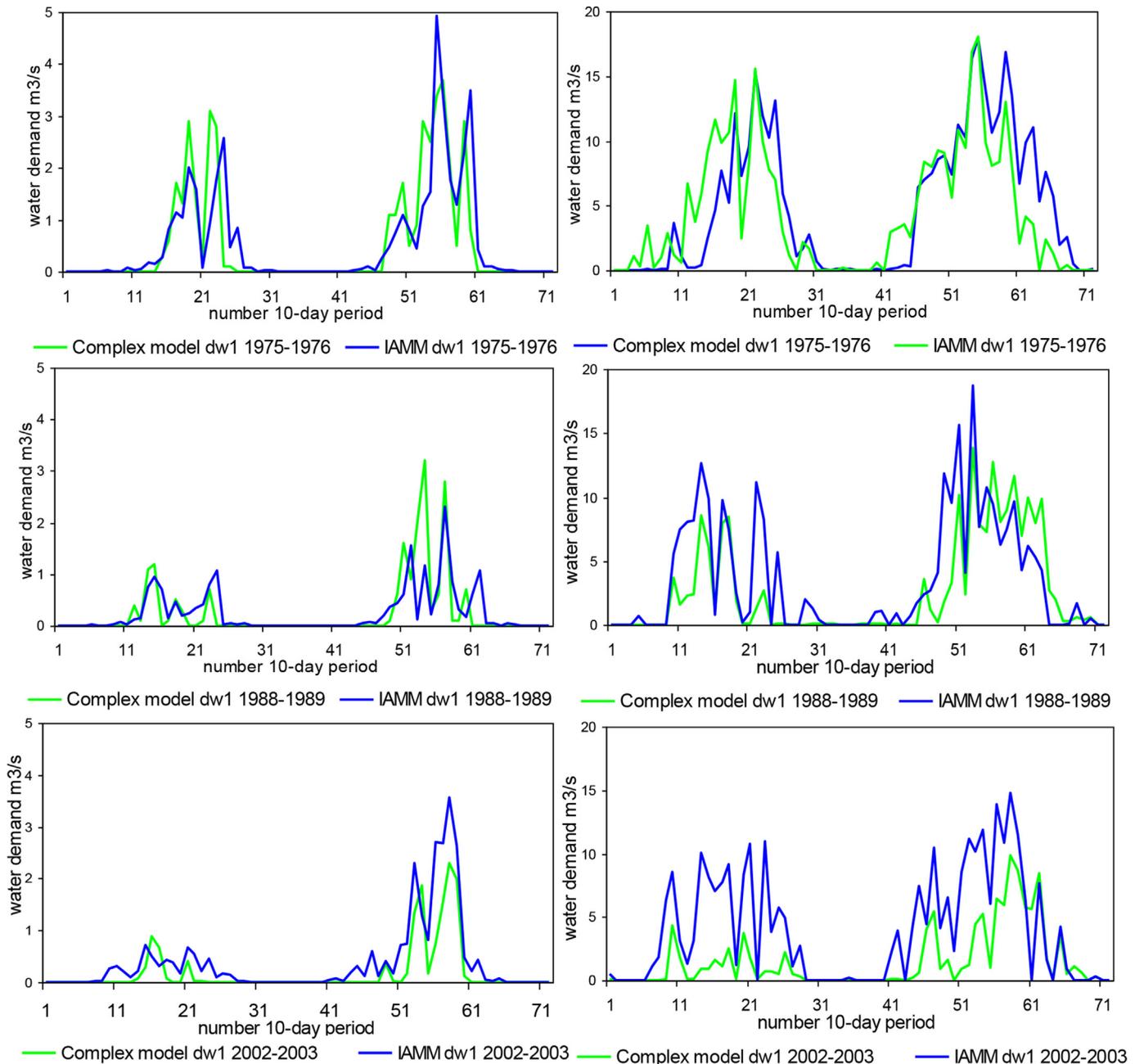


Fig. 8. Water demand for sprinkling (left figures) and for water level control (right figures) for district 1 Friesland for three dry periods (1975–1976, 1988–1989 and 2002–2003).

underestimates the potential yield by 1000–1500 kg/ha, and the actual yield by 2000–7000 kg/ha, resulting in an overestimation of the damages by 1000–6000 kg/ha (Appendix G presents the maps). To assess whether the model gives the right answers for the right reasons, and to find the cause of (spatial) differences, the actual and potential evaporation and their ratio were further analysed, as these are the basis for the calculation of the drought damage (see next question).

Q6b. Can the model simulate credible actual and potential evaporation?

Yes, the model produces credible outcomes for these variables: Actual and potential evaporation patterns produced by the IAMM are similar to those resulting from the complex model, although the IAMM shows a stronger response to drops in net precipitation

(Appendix H). The difference for the total potential evaporation in the growing season is 3–5% for most districts, but substantially larger for districts Friesland and Amstelland (20–70%). Differences are mainly due to different inputs in precipitation and evaporation, and secondarily to differences in the crop factors used. Total actual evaporation in the growing season differs by 3–43%. This difference is due to simplification of the processes in the model, and lower spatial and time resolution in the IAMM. Consequently, the ratio between the actual and potential evaporation is lower, resulting in a higher damage than the complex model. Therefore the model can be used to simulate changes in the total agricultural damage per year; the model is unable to provide reliable absolute damages or damages at a more detailed scale. Nevertheless, for ranking of

policy options for the Delta Programme this is sufficient as proposed actions apply to national to regional scale.

Q7. Can the model assess impacts of scenarios and policy actions on relevant outcome indicators?

Answering this overarching question with “yes”, requires that the model should include relevant variables and parameters, and should respond correctly to scenarios and policy actions.

Q7a. Are relevant variables and parameters included?

Yes: 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 be 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 model does not consider river bed morphology. All policy actions described in Section 2 can be implemented in the model.

Q7b. Do experts and potential end-users judge that the model provides credible results for impact assessment of scenarios and policy actions on relevant outcome indicators for the decision making?

To assess whether the models responds correctly to scenarios and policy actions, we simulated a climate change scenario and all policy actions, and 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.

The following model results were achieved: with increasing river discharge in winter (effect of climate change) flooding events occur more frequently and in more dike ring areas. If flood risk policy actions are implemented in the model, the occurrence of flooding events decreases. Raising the dikes to cope with a design discharge of 18,000 m<sup>3</sup>/s indeed leads to a higher discharge before flooding occurs. With decreasing river discharges in summer (effect of climate change), water levels in the IJsselmeer are falling more frequently below summer target level of -0.2 m MSL (down to -0.6 m m MSL). With increasing sea level, the water level in the IJsselmeer exceeds more frequently the threshold value of -0.1 m MSL in winter. Increasing the discharge capacity through the Afsluitdijk indeed leads to less frequent exceedance of the target lake levels in winter. A decrease of 30 % in water demand for both

agriculture and water level control (a policy action considered in the Delta Programme) lowers the IJsselmeer levels only by several cm, which is very small when compared to the the model errors, but end-users found it plausible as they did not expect such a policy action to have a strong effect. No impacts of climate change on agriculture emerged, because – likewise in the complex models – in the IAMM it is assumed that farmers will use other water sources to avoid damage. 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 water supply from the national network. Raising the summer target water levels in the IJsselmeer did sometimes increase water shortage, as the model reduces water inlet in case the water level dropped below target levels. We therefore adapted the model such that users can choose the priority: either the districts' water demand resulting in a drop of water levels or maintaining target water level, reducing water supply to rural areas to less than their demand. Increasing number of areas with sprinkling installations increases water demand for agriculture and reduces drought damage. Diverting more water to the IJssel River 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.

### 6. Discussion and conclusions

This paper describes a fast, Integrated Assessment Metamodel (IAMM) for exploring adaptation pathways to support the strategic decision making 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 models speed and transparent structure were appreciated, but also the possibility to use it as a tool to support discussions with stakeholders: it demonstrates the delta-wide effects of climate scenarios as well as of combinations of actions in an interactive way, and allows defining and rapid evaluation of alternative policy actions.

Using closed questions (Guillaume and Jakeman, 2012) that were iteratively formulated in consultation with end-users, proved to be valuable in specifying and evaluating the models capabilities for its purpose. We accepted a certain amount of inaccuracy in the IAMM output, as long as a state value of the system did not exceed an indifference threshold for decision making. It was not possible to include such thresholds in all closed questions. For example, for question 1a; the probabilities of dike failure associated with high

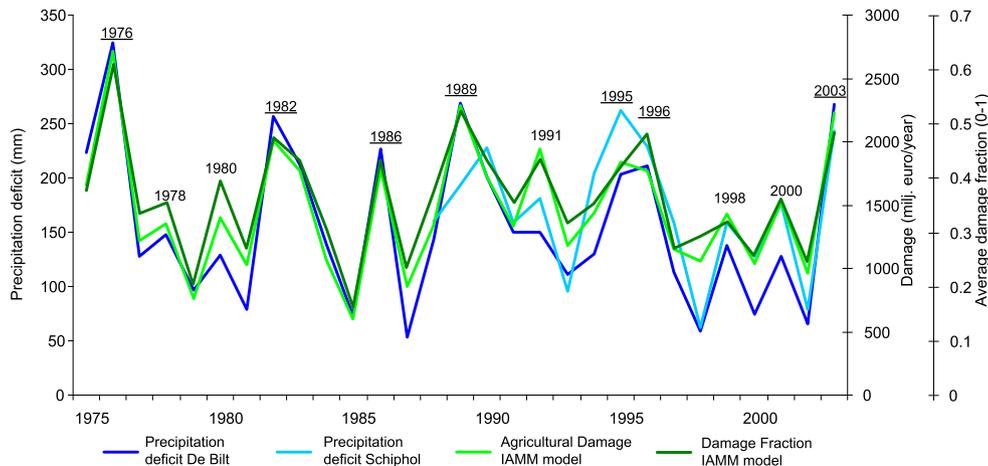


Fig. 9. Simulated total agricultural damage per year, the average damages fraction, and Standardised Precipitation Index based on observations for two locations (in the mid-western area).

discharges are unknown. Nevertheless, this is not a model error, but a lack of knowledge on this aspect.

Based on the answers to the questions, questions were sometimes reformulated to be more specific in what the model can(not) be used for. For example, the answer to question 3b ('...acceptable for estimating whether the Gouda intake would be closed more (or less) under changing environmental conditions.') suggests the question could be rephrased into: *Can the model simulate which of the scenarios has a greater number of 10-day periods with salt concentration exceeding 250 mg Cl/l?*

The results show that it is possible to build a model that fits the purpose of exploring pathways in the Rhine delta, and support the strategic decision making. The model can be used to predict the impacts of scenarios (climate change, sea level rise, land use) and effects of policy actions on the occurrence of flooding events and related damages, the possibility that IJsselmeer lake levels drop below or rise above threshold levels, impacts of low flows on navigation, changes in the vulnerability of the Gouda fresh water intake, changes in fresh water demand from rural areas, and drought damage for agriculture. The model cannot be used for assessing absolute values of flows in the main river branches (<200 m<sup>3</sup>/s), salt concentration at the Gouda intake, wind induced rise of water levels in the IJsselmeer, fresh water demands, and agricultural damage. When used for the purpose of predicting the absolute values, the model needs to be adapted.

The model is fast enough to assess impacts of transient scenarios and policy actions over time (simulation of a 100-year pathway takes approximately 1 hour) and performs adequately to screen and rank policy options to support the strategic decision making the Dutch Delta Programme is facing. The IAMM therefore forms an adequate instrument to establish multiple pathways, allowing to identify robust and flexible integrated water management actions for an adaptive policy plan at delta scale under deep uncertainties. Subsequent steps in the decision making process require more complex and detailed models giving more detailed information about the performance of the most promising options, worst-case scenarios or periods of interest arising from the exploration with the fast, integrated model. We will further test and apply the model for developing adaptation pathways for the Rhine Delta. Given the simple model set-up, we expect that this approach may also be exported to deltas elsewhere in the world.

## Acknowledgements

We thank Emiel van Velzen and Judith ter Maat for their input model requirements and model structure for the fresh water supply, Henk van den Boogaard for his input on salt module, Karin de Bruijn for her feedback on the flooding module, and Marjolein Mens for evaluating the water demand and drought impact module for the Rijnland area.

## Appendix A. Equations used in the water system module

On each node water balances are calculated based on in- and outflow branches, and for some node distribution keys determining the distribution among two or more branches. For the lakes also the net precipitation and the storage change is included.

Calculating the discharge capacity from Lake IJsselmeer to Wadden Sea

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

where:  $Q$ =discharge across one of the orifices [m<sup>3</sup>/s] output variable  $W$  = crest width [m] input parameter;  $d$ =open in

height = opening level – crest level [m] input parameter;  $c$ =discharge coefficient input parameter;  $g$ =gravity acceleration [ms]/[m/s<sup>2</sup>] input parameter;  $H_{\text{IJsselmeer}}$  = IJsselmeer water level [m] input variable;  $H_{\text{Wadden Sea}}$  = Wadden Sea water level [m] scenario input variable.

## Appendix B. Equations used in the salt intrusion module

Calculating the salt concentration at Gouda inlet

$$\text{Salt} = 17,000 + (90 - 17,000) \times \frac{\exp(\text{Fact})}{1 + \exp(\text{Fact})} \quad (\text{B.1})$$

$$\text{Fact} = \left( \frac{Q_{\text{Lobith}} - 600}{2.211} \right)^{0.309} \quad (\text{B.2})$$

where:  $Q_{\text{Lobith}}$  = discharge at Lobith [m<sup>3</sup>/s] scenario input variable;  $\text{Salt}$  = salt concentration at Gouda inlet [mg/l] output variable.

## Appendix C. Equations used in the water demand module

Calculating the potential evaporation

$$\text{Epot}_t = \text{Eref}_t \times \text{CropFactor}_t \quad (\text{C.1})$$

Calculating lateral in- and outflows

$$Q_{\text{dr}_t} = H_{\text{surf}_{t-1}} - \frac{H_{\text{grnd}_{t-1}}}{R_{\text{out}}} \quad (\text{C.2})$$

$$Q_{\text{in}_t} = H_{\text{surf}_{t-1}} - \frac{H_{\text{grnd}_{t-1}}}{R_{\text{in}}} \quad (\text{C.3})$$

Calculating vertical flow between soil and subsoil

$$\text{Perco}_t = \max(\text{Sm}_{t-1} + P_t - (P_o \times \text{Dr}_t), 0) \quad (\text{C.4})$$

$$\text{CapRise}_t = \text{CapRiseMax} \times \text{CapFact}_t \quad (\text{C.5})$$

$$\text{CapFact}_t = \text{CapFact}_{\text{grnd}_t} \times \text{CapFact}_{\text{root}_t} \quad (\text{C.6})$$

$$\text{Capfact}_{\text{grnd}_t} = \begin{cases} 0 & \text{for } H_{\text{grnd}} \geq D_c \\ 1 - \frac{H_{\text{grnd}_t} - 0.5 \times \text{Dr}_t}{D_c - 0.5 \times \text{Dr}_t} & \text{for } \frac{1}{2} \text{Dr} < H_{\text{grnd}} < D_c \\ 1 & \text{for } H_{\text{grnd}} \leq \frac{1}{2} \text{Dr} \end{cases} \quad (\text{C.7})$$

$$\text{CapFact}_{\text{root}_t} = \max\left(0, \left(1 - \frac{\text{Sm}_{t-1}}{P_o \times \text{Dr}_t}\right)\right) \quad (\text{C.8})$$

Calculating the actual evaporation

$$\text{RootVol}_t = \frac{\text{Sm}_{t-1}}{\text{Dr}_t} \times 100 \quad (\text{C.9})$$

$$pF = f(\text{RootVol}_t, pF_{\text{curve}}, \text{Soiltype}) \quad (\text{C.10})$$

$$\text{RedFact} = \begin{cases} 0 & \text{for } pF < pF_{\text{red}} \\ \frac{pF - pF_{\text{red}}}{pF_{\text{max}} - pF_{\text{red}}} & \text{for } pF_{\text{red}} \leq pF \leq pF_{\text{max}} \\ 1 & \text{for } pF > pF_{\text{max}} \end{cases} \quad (\text{C.11})$$

$$\begin{aligned} \text{Eact}_t &= \min(\text{Sm}_{t-1} + P_t + \text{CapRise}_t - \text{Perco}_t, (1 - \text{RedFact}_t) \\ &\quad \times \text{Epot}_t) \end{aligned} \quad (\text{C.12})$$

Calculating the amount of sprinkling

$$\text{Sprink}_t = \text{Sfrac} \times (\text{Epot}_t - \text{Eact}_t) \quad (\text{C.13})$$

Updating the soil moisture content and groundwater level

$$\text{SM}_t = \text{SM}_{t-1} + P_t + \text{CapRise}_t - \text{Perco}_t - \text{Eact}_t + \text{Sprink}_t \quad (\text{C.14})$$

$$\text{Runoff} = \begin{cases} \text{Sm}_t - (\text{Po} \times \text{Dr}_t) & \text{if } \text{Sm} > \text{Po} \times \text{Dr}_t \\ 0 & \text{otherwise} \end{cases} \quad (\text{C.15})$$

$$\text{Hgrnd}_t = \text{Hgrnd}_{t-1} + \frac{\text{Delta}_h_t - \text{CapRise}_t + \text{Perco}_t + S}{\text{Po}} \quad (\text{C.16})$$

where  $\text{Eact}$  = actual evapotranspiration [m/10d] output variable;  $\text{Epot}$  = potential evapotranspiration [m/10d] output variable;  $\text{Eref}$  = reference evaporation according scenario variable to Makink [m/10d] input;  $\text{CapRise}$  = capillary rise [m/10d] output variable;  $\text{Delta}_h$  = change in groundwater level [m] output variable due to drainage or infiltration [m] [m/10d];  $\text{Dc}$  = depth at which  $\text{CapRise}$  equals zero [m] input parameter;  $\text{Dr}$  = rootzone depth [m] input parameter per soil type;  $\text{Hgrnd}$  = groundwater level below surface level [m] output variable;  $\text{Hsurf}$  = surface water level below surface level [m] output variable;  $\text{Perco}$  = percolation [m<sup>3</sup>/10d] output variable;  $P_t$  = precipitation [m/10d] scenario variable input per soil type;  $\text{pFmax}$  =  $\text{pF}$  at wilting point input parameter per soil type;  $\text{pFred}$  =  $\text{pF}$  at which actual evaporation input parameter decreases linearly [m/10d] per soil type;  $\text{Po}$  = porosity [-] input parameter per soil type;  $\text{Qdrain}$  = drainage [m/d] output variable;  $\text{Qinfil}$  = infiltration [m/d] output variable;  $\text{RootVol}$  = rootvolume [%] output variable;  $\text{Rin}$  = resistance for flow from [d] input spatial parameter streams and canals to groundwater [m/10d];  $\text{Rout}$  = drainage resistance to streams and canals [d] inputspatial parameter;  $S$  = seepage [m/10d] input spatial parameter;  $\text{Sfrac}$  = fraction of area with possibility of sprinkling [-] input spatial parameter;  $\text{SM}$  = soil moisture [m] output variable;  $\text{Sprink}$  = sprinkling [m] output variable; and  $t$  = timestep.

## Appendix D. Equations used the drought impact module

### Appendix D.1. Calculating crop damage

Calculating damage fractions for drought

$$\text{DF}_t = \begin{cases} 0 & \text{for } \frac{\text{Eact}_t}{\text{Epot}_t} \geq 1 \\ \text{RS}_t \times \frac{1 - \frac{\text{Eact}_t}{\text{Epot}_t}}{1 - \text{RP}_t} & \text{for } \text{RP}_t < \frac{\text{Eact}_t}{\text{Epot}_t} < 1 \\ \text{RS}_t + (\text{MD}_t - \text{RS}_t) \times \frac{\text{RP}_t - \frac{\text{Eact}_t}{\text{Epot}_t}}{\text{RP}_t - \text{SP}_t} & \text{for } \text{SP}_t < \frac{\text{Eact}_t}{\text{Epot}_t} < \text{RP}_t \\ \text{MD}_t & \text{for } \frac{\text{Eact}_t}{\text{Epot}_t} \leq \text{SP}_t \end{cases} \quad (\text{D.20})$$

Calculating the survival fraction

$$\text{SF}_t = \text{SF}_{t-1} (1 - \text{DF}_t) \quad (\text{D.2})$$

Calculating the total damage fraction

$$\text{TDF}_t = \text{RY}_t (\text{SF}_{t-1} - \text{SF}_t) \quad (\text{D.3})$$

where  $\text{Eact}$  = actual evapotranspiration [m/10d] output variable;  $\text{Epot}$  = potential evapotranspiration [m/10d] output variable;  $\text{DF}_t$  = Damage fraction [-] output variable;  $\text{MD}_t$  = Maximum damage per crop [-] input parameter;  $\text{RS}_t$  = Reduction damage, damage fraction per crop at reduction point [-] input variable;  $\text{RP}_t$  = Reduction point, point before moderate damage occurs [-] output variable;  $\text{RY}_t$  = Remaining yield for a crop reflecting the growing season [-] input parameter;  $\text{SP}_t$  = Death point, point after which maximum damage occurs [-] input parameter;  $\text{SF}_t$  = Survival fraction [-] output variable;  $t$  = timestep;  $\text{TDF}_t$  = total damage fraction [-] output variable.

### Appendix D.2. Calculating damage for inland transport

Calculating load factor and potential load based on ship type and water depth

$$\text{Lfact}_{t,s} = \frac{\text{Dc}_t - \text{De}_s}{\text{Dm}_s - \text{De}_s} \quad (\text{D.4})$$

$$\text{Load}_{t,s} = \begin{cases} \text{Lfact} \times \text{MaxLoad} & \text{for } \text{Lfact} \geq C \\ 0 & \text{for } \text{Lfact} < C \end{cases} \quad (\text{D.5})$$

Calculating the delayed load per ship type

$$\text{DLoad}_{t,s} = \begin{cases} \text{MaxLoad} & \text{for } \text{Lfact} < C \\ 0 & \text{otherwise} \end{cases} \quad (\text{D.6})$$

$$\text{TotL}_t = \Sigma(\text{Load}_{t,s}) \quad (\text{D.7})$$

Calculating load that needs to be shipped with extra boats

$$\text{Ex}_t = \text{TotMaxL} - \text{TotL}_t - \text{TotDL}_t \quad (\text{D.8})$$

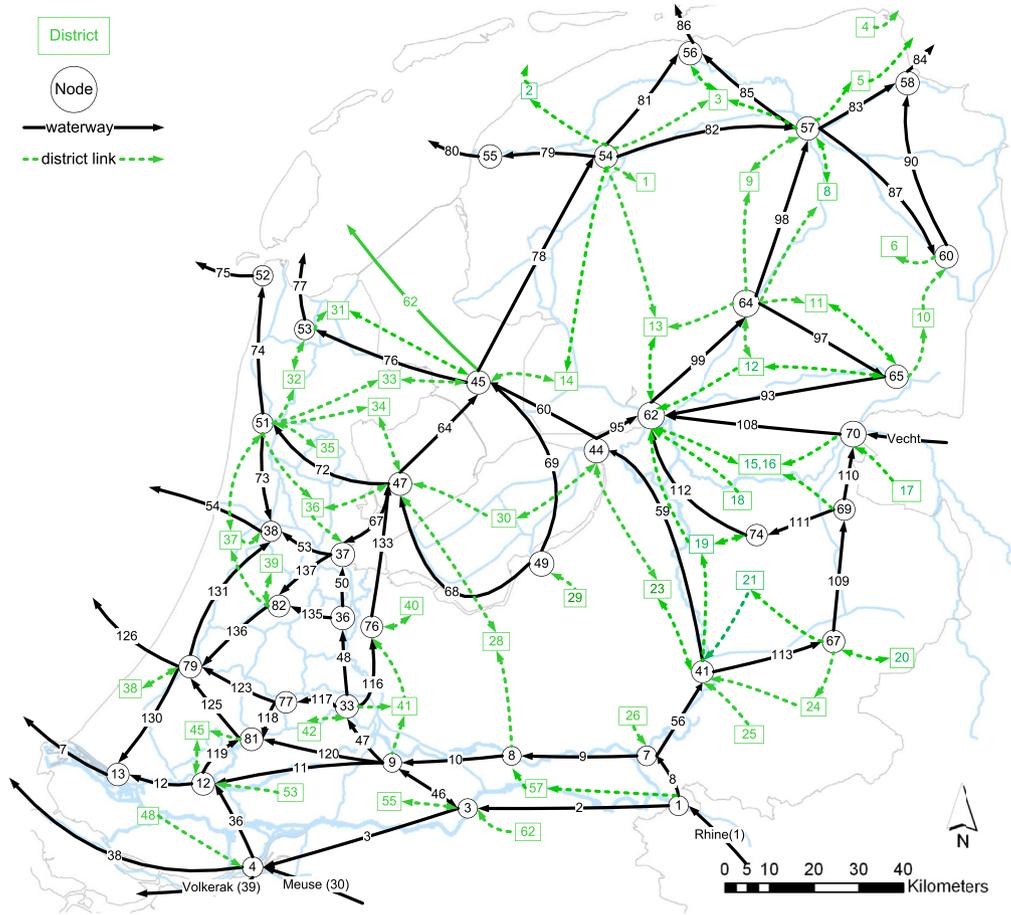
Calculating shipping costs

$$\text{Pa}_t = \frac{\text{TotMaxL} - \text{TotDL}_t}{\text{TotL}_t} \times P \quad (\text{D.9})$$

$$\text{Costs}_t = \frac{\text{MaxLoad}_s \times P + \text{MaxLoad}_s \times \text{Pa}_t}{365} \quad (\text{D.10})$$

where:  $C$  = critical load factor below which navigation will be delayed [-]  $c$ ;  $\text{Costs}_t$  = costs [10<sup>6</sup> euros/year] output variable;  $\text{Dc}_t$  = water depth at critical location [m] input variable;  $\text{De}_s$  = depth of the ship without load [m] input parameter;  $\text{Dm}_s$  = water depth needed for ship with maximum load [m] input parameter;  $\text{DLoad}_{t,s}$  = delayed load at timestep  $t$  [day] for ship type  $s$  [tonne] output variable;  $\text{Ex}_t$  = load transported with extra ships [tonne] output variable;  $\text{Lfact}_{t,s}$  = load factor at timestep  $t$  for ship type  $s$  output variable;  $\text{Load}_{t,s}$  = load at timestep  $t$  for ship type  $s$  output variable;  $\text{MaxLoad}_s$  = maximum load per ship type input parameter;  $\text{Pa}_t$  = adapted price output variable;  $P$  = price per tonne load input parameter;  $\text{TotL}_t$  = total load output variable;  $\text{TotMaxL}$  = total maximum load output variable;  $\text{TotDL}_t$  = total delayed load output variable.

**Appendix E. Schematisation of the water distribution network**



**Fig. 10.** Schematisation of the water distribution network. 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 water demand from regional areas is summed for sets of small watersheds – districts (squares) – that are linked to the distribution network via the nodes (dashed line).

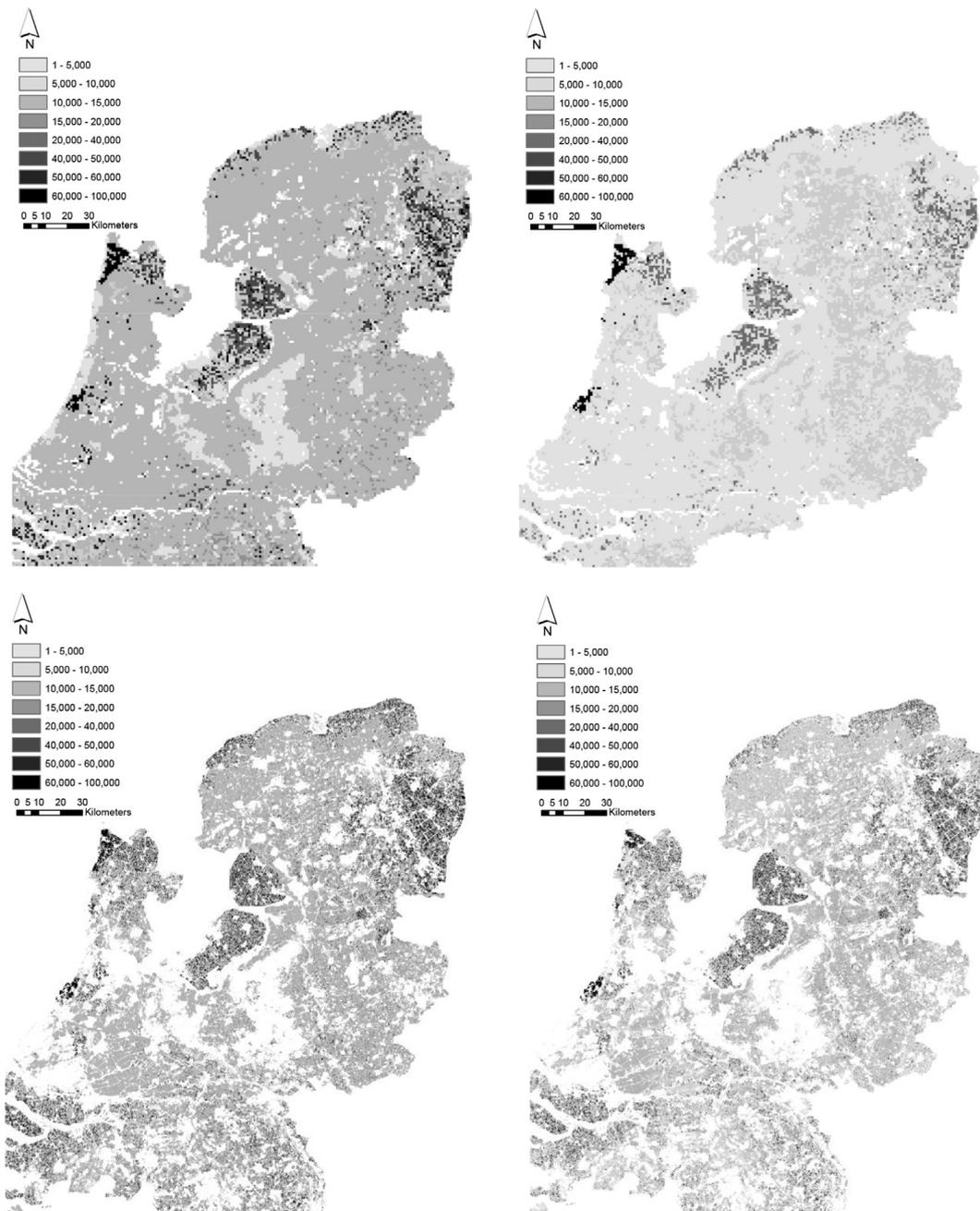
## Appendix F. Overview of the main characteristics of the IAMM and the complex models

**Table 2**

Overview of the simplifications made in the IAMM in comparison to the complex models to make the model fast and integrated.

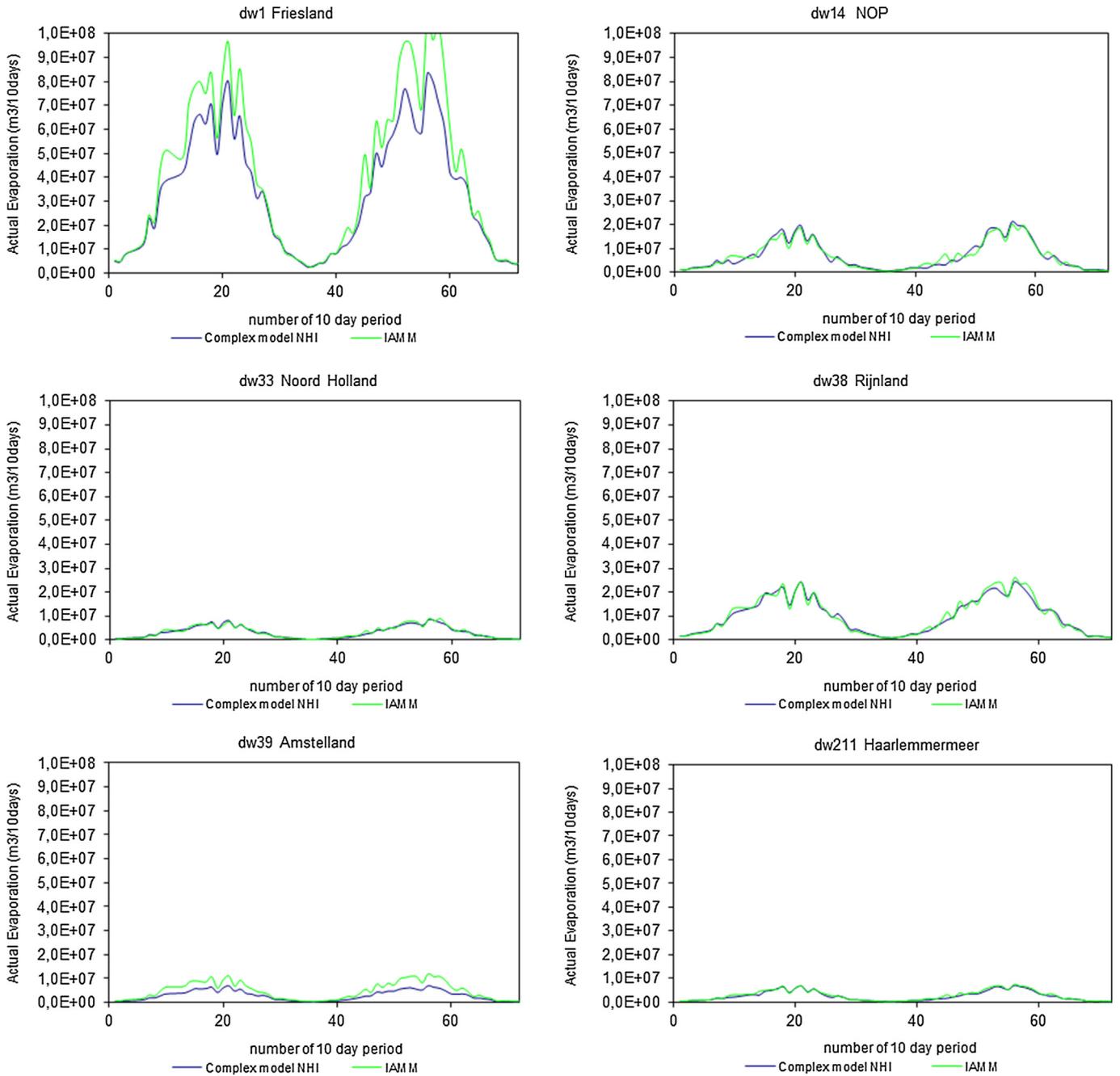
Aspect	IAMM	Complex models
<i>Flood risk assessment modules</i>		
Temporal resolution	10 days	Hours
Spatial resolution	Damage per dike ring area, 2–3 breach locations per dike ring	Damage per 100 m grid cells, 3–6 breach locations per dike ring
Input	Maximum Rhine discharge at Lobith,	Rhine discharge 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
Run time	One hour for 100 years for calculating flood and drought risk	Three hours for 2d flood and flood damage modelling per combination of breach location, river flow and sea level (500 in the Rhine delta), days for modelling river water levels
<i>Drought risk assessment modules</i>		
Temporal resolution	10 days	1 day, water distribution 10 days
Spatial resolution	1000 m grid cells, 69 links, 45 watersheds (districts), 38 nodes, 2 layer groundwater module	250 grid cells, 140 watersheds (districts), subdivided into 8750 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, and 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
Simulation speed	One hour for 100 years for calculating flood and drought risk	Approximately 24 h for 1 year

### Appendix G. Comparison results for agricultural damage



**Fig. 11.** Potential (left) and actual yield (kg/ha) for agriculture simulated with the IAMM (upper figures) and the complex model (lower) for the extreme dry year of 1976.

**Appendix H. Comparison results for the potential and actual evaporation**



**Fig. 12.** Potential evaporation simulated with the complex model and the IAMM model for districts Friesland, NOP, Noord-Holland, Rijnland, Amstelland and Haarlemmermeer for the period 2002–2003.

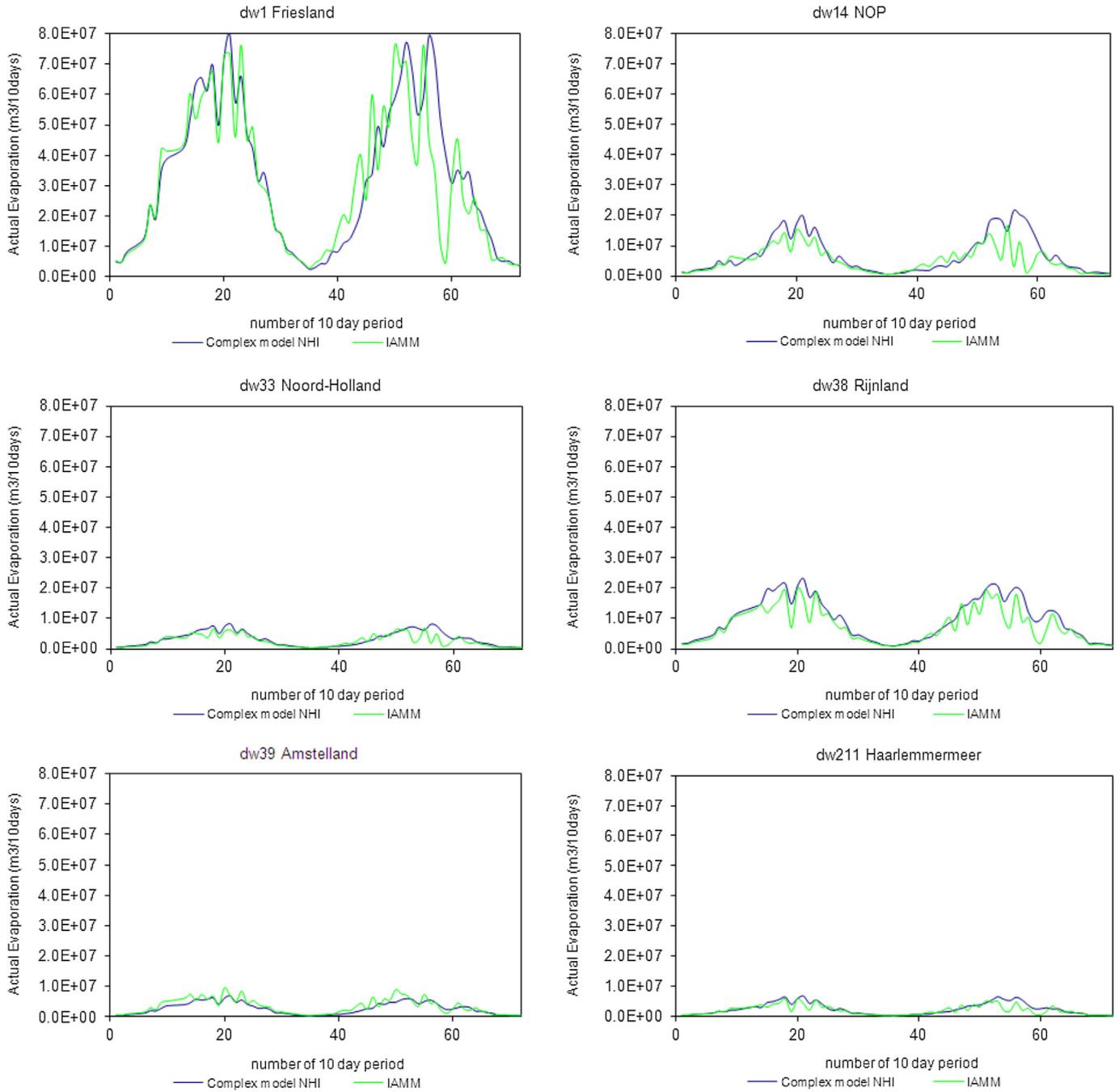


Fig. 13. Actual evaporation simulated with the complex model and the IAMM model for districts Friesland, NOP, Noord-Holland, Rijnland, Amstelland and Haarlemmermeer for the period 2002–2003.

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