The Dutch Delta model to support national policy analysis

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Abstract

Within the framework of the Dutch Delta Programme a long term water management plan is prepared to cope with the effects of climate change and socio-economic developments on flood risk management and fresh water supply in the Netherlands. The Delta model has been developed as the tool to support the national policy analysis for the Delta Programme. The Delta model combines a range of models to address issues related to flood risk management and fresh water supply. All models have been integrated in the Delta model - using Delft-FEWS - to enhance the consistency in computations for the Delta Programme.

The Delta model includes both existing and new models. The existing models were calibrated and validated in earlier stages, and are applied within other projects as well. Although these models were not developed for the national policy analysis in the framework of the Delta Programme, they were selected to gain acceptance and support among the scientific community and the water managers. In addition, new (regional) models were developed using the same software to allow for a consistent approach throughout the Netherlands. The acceptance of the models and the consistency of the approach were considered as key requirements for the successful implementation of the results of the Delta Programme. Flexibility and robustness were added as requirements as well. This paper describes the choices made in the development of the Delta model, to make it appropriate for the use in the preparation of the Delta programme.

The Delta model has been used extensively during the preparation of the Delta Programme. The temporal and spatial resolution of some of the models appeared to be higher than technically necessary for policy analysis. The paper presents some lessons learned and suggestions for future enhancements, based on the experiences during the development and application of the Delta model in the framework of the Delta programme.

Key words: Delta Programme, Delta model, integrated model, policy analysis, flood risk management, fresh water supply, Delft-FEWS, acceptance, consistency, resolution.

1. Introduction

The Netherlands are located in north-west Europe, at the border of the North Sea and in the delta of the rivers Rhine, Meuse, Scheldt and Ems. Over many centuries water management in the Netherlands has been – and still is – a crucial part of daily life (RWS, 2011 and Van de Ven, 1993). Infrastructure, like storm surge barriers, dikes, pumping stations, canals, sluices, dams and weirs is designed, build, operated and maintained in order to protect the country from floods and droughts.

Until recently the development of water related infrastructure, as well as the related water management plans, was initiated after a serious disaster, in order to assure "this never to happen again". In view of the challenges ahead due to the possible change in climate and socio-economic conditions, the Dutch government launched a policy analysis to address these issues from now onwards in advance: the Dutch Delta Programme (see also: www.deltacommissaris.nl). The objective of the Delta Programme was to develop a safe and attractive Netherlands, now and in the future, where fresh water supply, flood risk management and spatial planning are organised effectively (Van Alphen 2012 and 2014).

The Delta Programme is a national programme, in which national, regional and local authorities prepare key decisions, develop strategies and implement measures, in close cooperation with the public, stakeholders and research institutes (Van Alphen, 2014). The Delta Programme has been organised in 9 sub-programmes, 3 national (flood risk management, fresh water supply and spatial planning) and 6 regional sub-programmes (see Figure 1). Each of these sub-programmes has taken into account the 4 Delta scenarios representing the "corner flags of the playing field of plausible futures", by combining climate change (rapid or moderate) and socio-economic development (growth or squeeze), for both 2050 and 2100 (Figure 1).

The results of the Delta Programme are presented to the Dutch Parliament in September 2014 (Delta Programme Commissioner, 2014). The final results of the Delta Programme are formulated in 6 Delta decisions:

- Water Safety Delta Decision
- Freshwater Strategy Delta Decision
- IJsselmeer Region Delta Decision
- Rhine-Meuse Delta Decision
- Spatial Adaptation Delta Decision
- Decision on Sand

Background information on these Delta decisions is available on www.deltacommissaris.nl.

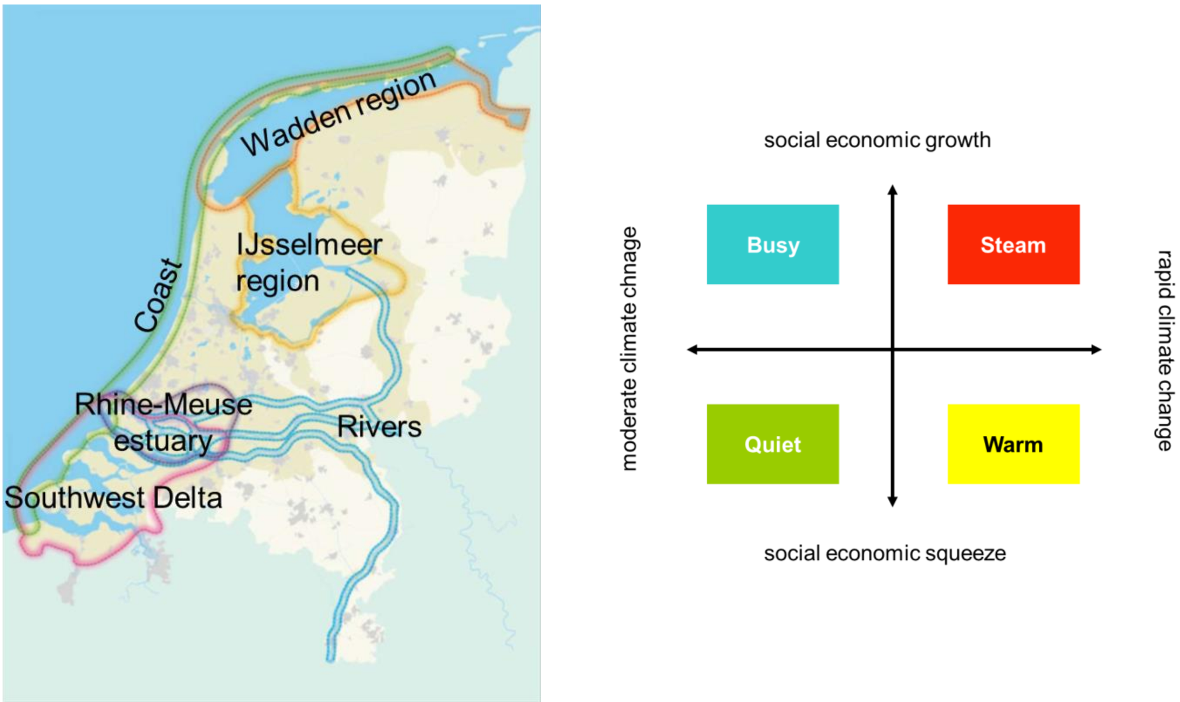

Figure 1. *The location of the 6 regional sub-programmes in the Netherlands (left) and the outline of the 4 Delta scenarios (right) (Delta Programme Commissioner, 2011).*

The Delta Programme required a quantification of the severity of water related problems in order to set priorities and identify the main tipping points and their timing (Kwadijk et al. 2010; Haasnoot et al. 2012). To this end, it was decided to develop a multi-disciplinary modelling system – the Delta model – that allows for climate and socio-economic scenario analysis as well as exploration of possible adaptation strategies (Kroon and Ruijgh, 2012). The Delta model is one of the first model suites that (1) covers a nationwide water system (both surface and subsurface) to study flood risk management and fresh water supply; (2) integrates multiple use sectors - i.e. agriculture, navigation, drinking water, industry, ecology, energy, and flood protection - ; (3) enables scenario analysis and the exploration of adaptation options; and (4) is supported and accepted by modellers, (regional) water managers and policy makers (Prinsen et al. 2014).

The key objectives of the development of the Delta model were to provide a consistent and accepted set of models, in a robust and flexible environment, to support the policy analysis of the Delta Programme for flood risk management and fresh water supply. In this paper we will discuss the development of the Delta model as an integrated computer modelling system that meets these requirements.

The version of the Delta model (version 1.1) described in this paper has been released by December 2013. A well organised support & maintenance organisation is active for the Delta model (see http://www.helpdeskwater.nl), providing updates and new releases including bug-fixes, minor additions and improvements.

2. Consistency of models

When the development of the Delta model started in 2010, a range of different models was available and used throughout the Netherlands. These models appeared to vary in terms of scope, resolution, geographical distribution etc. The status of documentation and version management, as well as the implementation of support & maintenance organisations, varied. Several of these models were coupled whereas isolated models existed as well. Some of the models were implemented for the entire Netherlands, other models only covered a specific water system. Figure 2 (left) presents the original situation back in 2010 schematically.

For the Delta Programme it was required to develop a consistent set of models for flood risk management and fresh water supply, in order to be able to perform comparable calculations in the entire country and to integrate the results in the national policy analysis. As illustrated in Figure 2 (right), the Delta model combines a range of consistent models, databases, scenarios, measures and impact assessment tools. Delta model - version 1.1 includes models for flood risk management and fresh water supply; models for spatial planning might be added in future as well.

The development of the Delta model primarily focussed on the enhancement of the consistency of all included models. Our approach to achieve the consistency was to select first – in close communication with the involved stakeholders – from all available models the most suitable ones. We specified for these selected models both the version of the software and the version of the schematisation. Secondly, the selected version of the software was implemented systematically nationally; this included for some regions an upgrade of the (selected) version of the software and in other regions the development of new applications (schematisations) of the software. Moreover, we compared the various existing schematisations and harmonised (as much as possible) the spatial resolution of the models. Finally, we stimulated the owners of the software to provide the proper documentation and to implement support & maintenance. Section 4 and 5 of this paper include more detailed information on the selected software and schematisations for flood risk management and fresh water supply.

For the coupling of all selected models (software plus schematisations) in the Delta model a dedicated implementation of Delft-FEWS has been developed. This choice was made as Delft-FEWS could contribute to the implementation of the required consistency. For instance, standardised workflows have been implemented in Delft-FEWS, to assure that all calculations are performed along the same (consistent) procedures, including the use of (exact) the same Delta Scenarios in each of the sub-programmes. A client-server application was deployed to provide a central accessible platform for all calculations and presentations. This platform has been implemented and hosted by NMDC, the National (Dutch) Modelling and Data Centre. Moreover, as Delft-FEWS is also used in several other applications of the Ministry of Infrastructure and Environment in the Netherlands, the consistency of the Delta model with those applications could be enhanced as well. Verseveld et al (2015, in prep.) provide more details on the coupling of all models within Delft-FEWS.

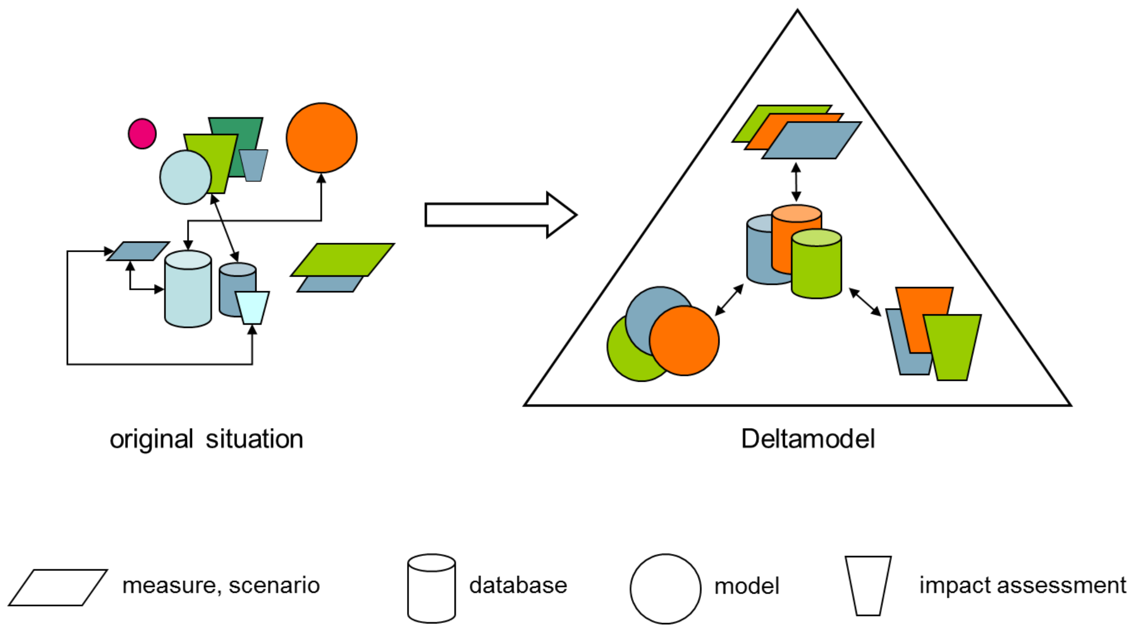

Figure 2. *The development of the Delta model from the original situation to a consistent set of measures, scenarios, databases, models and impact assessment tools for (in different colours) flood risk management, fresh water supply and spatial planning (Prinsen et al, 2014).*

3. Acceptance by various stake-holders

In addition to the consistency discussed in the previous section, the Delta Programme required the Delta model to be accepted by the scientific community, (regional) water managers, as well as the policy makers. During the development of the Delta model it became clear that all involved stake-holders participated in the discussions from their own perspective and responsibility (see Figure 3).

Scientists and researchers were very interested in the development of the Delta model as they were keen to include (new) techniques and tools. The Delta model served for them as an ideal platform to apply (and test) their knowledge and software, and to reduce the uncertainty in the available knowledge and software. Consequently, they argued to include the very latest versions of software (or even to wait for new releases), and to enhance the spatial and temporal resolution of the models.

(Regional) water managers participated in the development of the (national) Delta model as the results of the Delta Programme would likely be relevant for them. Their key-priority was to include the existing models currently used in regional water management, as these models are accepted by their stakeholders. These models are developed for the analysis of near-time effects and the preparation of implementation of specific measures, and they typically include high resolution in time and space. The regional water managers focussed on the comparison of the results of the models, once implemented in the Delta model, with the results of the existing models to make sure that results the Delta Programme remained in line with previous studies.

The perspective of the policy makers on the Delta model was quite different as well: they focussed on the long term effects to analyse the possible implications of scenarios (on climate change and socio-economic developments). Rather than uncertainty or accuracy, the keen interest of the policy makers was the sensitivity of the modelled water system for changed conditions. In order to facilitate the decision making process, the policy makers preferred the calculation results to be aggregated in time and space as seasonal - year totals on a regional - national scale.

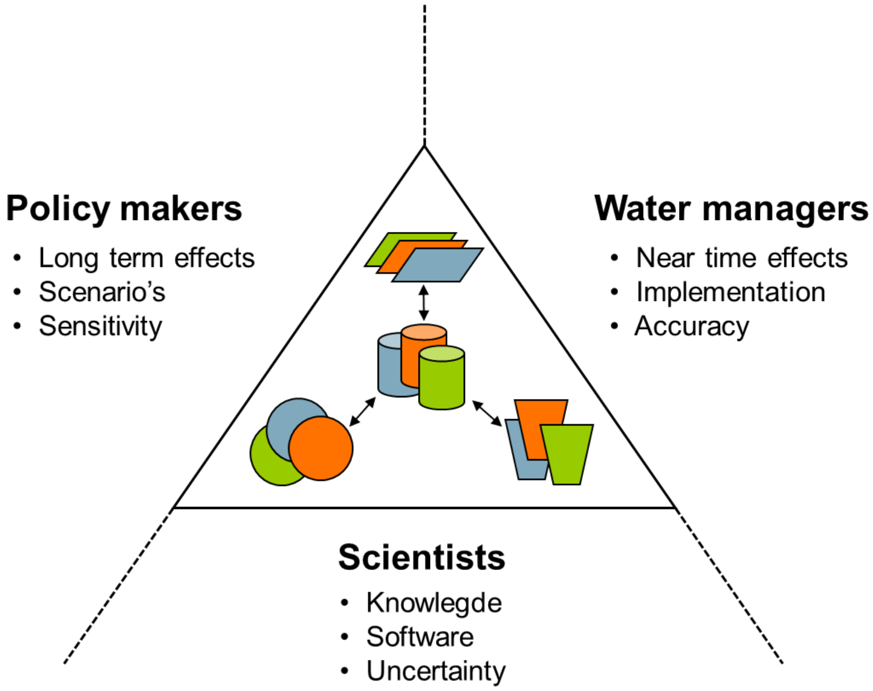

Figure 3. *Various perspectives from water managers, scientists and policy makers on the Delta model.*

As discussed above, a major challenge of the development of the Delta model was to obtain the acceptance of all involved stakeholders, and at the same time to ensure the consistency within the modelling instrument. To gain the acceptance we maintained an open approach to include in the Delta model the software and schematisations as preferred by the scientists and water managers. Their choices and suggestions were implemented as much as possible within the requirements for consistency. The results of the calculations are aggregated up to the level relevant for the policy makers and presented in the Delta portal, as depicted in Figure 4, to gain acceptance from them as well.

The Delta portal is (www.deltaportaal.nl) is a web-based geographical presentation tool dedicated to the use by the policy makers, as well as by the general public. It combines the summarised results of the (detailed) calculations in the Delta model with information from various other sources.

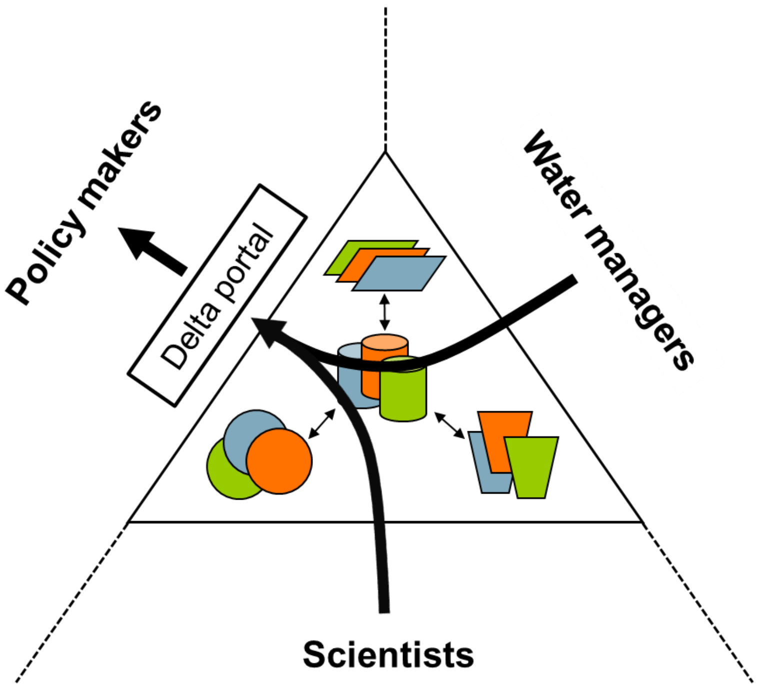

Figure 4. *Approach in the development of the Delta model to achieve acceptance from water managers, scientists and policy makers.*

Following this open approach to all involved stakeholders, most of their specific requirements could be fulfilled. The downside of the approach was that the calculation time of some of the (detailed) models did only allow for a limited number of calculations. Both the scientists, water managers and policy makers indicated that they would have preferred to perform more calculations.

To compensate for the long calculation times the available hardware has been optimized as much as possible (given the financial limitations), and ample attention was given to tune the hardware and the software. We will address this issue in more detail in the discussion of this paper.

4. Flood risk management

The Delta Programme on flood risk management focussed on the flood protection and the development on new risk-based standards (Van der Most et al, 2014). Flood risk management has been implemented in the Delta model for 4 regions; the Rhine branches, the Meuse river, the Rhine-Meuse estuary and the Lake IJssel area, including the IJssel-Vecht estuary (Slomp et al, 2014). To enhance the consistency within the Delta Programme, a similar approach has been implemented in the Delta model for each of these 4 regions. Figure 5 presents the approach schematically, and Table 1 includes detailed information on the selected (version of) software and schematisations.

The hydrodynamic calculations form the basis of the approach. In 3 regions a 2D-hydrodynamic (Waqua) model has been implemented, whereas in the Rhine-Meuse estuary a 1D-hydrodynamic (Sobek) model was selected. The same version of the hydrodynamic-software has been implemented in the Delta model for each of the 3 regions. Moreover, the schematisation for the Reference-case for each of the 4 regions was developed following the same considerations (using the latest (2012) data-inquiry available and assuming on-going measures to be implemented in 2015). These choices contributed substantially to the internal consistency of the Delta model.

From the point of consistency it would have been preferred to include the same software package for each of the 4 regions. However, the regional water managers for the Rhine-Meuse estuary preferred to use a 1D-hydrodynamic model, whereas the regional water managers for the other 3 regions preferred a 2D-hydrodynamic model (amongst others, because for these 3 regions a suitable 1D model was not yet available). In this situation, maintaining acceptance by all stakeholders was considered more valuable than the additional consistency of using the same kind of software in each region. The coupling between the models for the 4 regions has been standardised using stage-discharge relations at specific locations, in order to allow for country wide calculations.

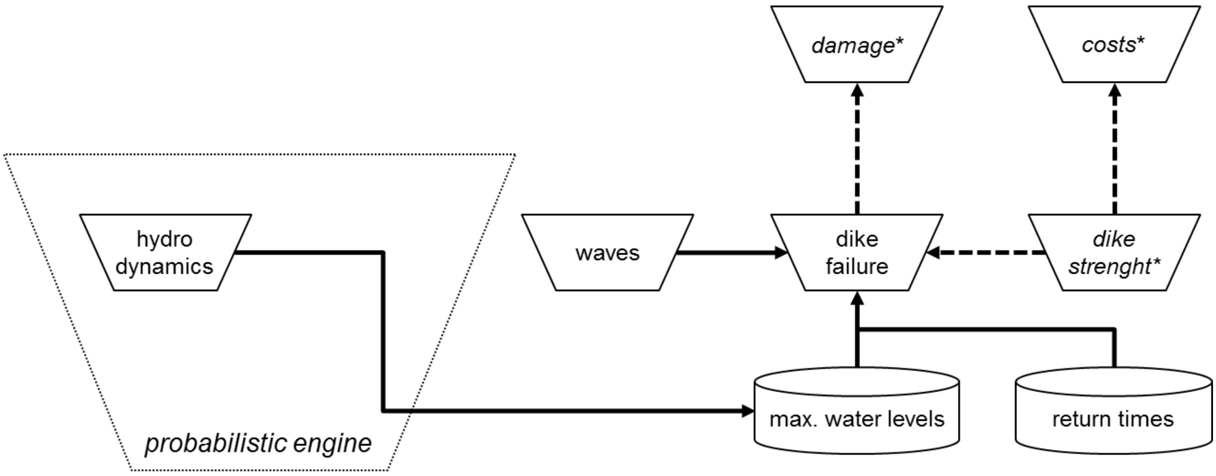

Figure 5. *Overview of Delta model – 1.1 components, and coupled components (marked with *), for the Delta Programme on flood risk management.*

The calculations for flood risk management in the Delta model follow a probabilistic approach. A number of hydrodynamic calculations (that each covers a period of several days) combine a range of river discharges, storm surges and wind fields, as well as failure of storm surge barriers, each with a related probability based on historic data. Table 2 summarizes the composition of the probabilistic calculations for the various sub-systems in the Delta model. These probabilistic calculations are organised (following a similar approach) within the Delft-FEWS configuration of the Delta model, again to support the internal consistency. The resulting maximum water level in each calculation, at a pre-selected number of locations, is included in a dedicated database (Figure 5).

Table 1. *Overview of the selected versions of software and schematisations included in Delta model – 1.1 for the Delta Programme on flood risk management.*

DP-Flood risk management	Software	version	Schematisation version	OS
DP-Rivieren				
Rhine branches				
Hydrodynamics	Waqua	Simona-2011 (patch 16)	Waqua-Rijn-DMref12_5-v1	Linux
Probabilisatic engine	Delft FEWS	FEWS 2012.02 (build 40125)	Deltamodel-1.1	Windows
Waves (Brettschneider)	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
Dike failure	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
Meuse				
Hydrodynamics	Waqua	Simona-2011 (patch 16)	Waqua-Maas-DMref12_5-v1	Linux
Probabilisatic engine	Delft FEWS	FEWS 2012.02 (build 40125)	Deltamodel-1.1	Windows
Waves (Brettschneider)	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
Dike failure	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
DP-Rijnmond Drechtsteden				
Rhine-Meuse estuary				
Hydrodynamics	Sobek-RE	2.52.007	Sobek-RMM-ReferentieDPR2015	Windows
Probabilisatic engine	Delft FEWS	FEWS 2012.02 (build 40125)	Deltamodel-1.1	Windows
Waves (Brettschneider)	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
Dike failure	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
DP-IJsselmeer				
IJssel-Vecht estuary				
Hydrodynamics	Waqua	Simona-2011 (patch 16)	Waqua-IJVD-DMref12_5-v3	Linux
Probabilisatic engine	Delft FEWS	FEWS 2012.02 (build 40125)	Deltamodel-1.1	Windows
Waves (Brettschneider)	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows
Dike failure	Hydra-Zoet	1.6.3	Deltamodel-1.1	Windows

Table 2. *Overview of the composition of the probabilistic calculations in Delta model-1.1 per sub-system.*

	river discharge	storm surge level	wind speed	wind direction	status barriers	number of calculations
Rhine branches	9	1				9
Meuse	9	1				9
Rhine-Meuse estuary	9	6		1	2	108
IJssel-Vecht estuary	5	5	4	5	2	1025

The database with maximum water levels serves as input for the module on dike failure Hydra-Zoet (Slomp et al, 2014). The same version of Hydra-Zoet is implemented in each of the regions. Hydra-Zoet combines this database with the statistical return times associated with each probabilistic calculation, as well as information on waves and (external) data on dike strength. The effect of wind on waves for each location is currently included in Hydra-Zoet using a Brettschneider approach. In future, the consistency might be enhanced by transferring the calculation of the effects of wind on waves from Hydra-Zoet into the probabilistic engine.

The results of Hydra-Zoet provide information on the possible dike failure (following various dike failure mechanisms). These results can be used subsequently to estimate the possible damage due to flooding. The Delta model exports the required data for the damage module. An external module to evaluate the costs related to dike strengthening is also available (Slomp et al, 2014), to allow the analysis of costs and benefits (=reduced damage).

A dilemma during the development of the Delta model was that – especially for flood risk management – the results from the policy analysis were required to be consistent with the results of previous studies. As these previous studies merely focussed on water management, the spatial resolution of these models was very high. From the point of view of policy analysis models with less spatial resolution could be used. The high resolution models have been selected though for the Delta model, for reasons of acceptance by the regional water managers. Although the calculation times of these detailed models were substantial, the upside is that the results of the present calculations can also be used for the preparation of the implementation of the measures.

To compensate for the long calculation times of the 2D-hydrodynamic calculations a Linux cluster has been implemented. The cluster allowed for 8 parallel calculations, directly managed from Delft-FEWS, to reduce the calculation time of the probabilistic calculations by a factor of 8.

The calculation of Hydra-Zoet for the Rhine Meuse estuary takes more than 4 days, and relies on the total number of selected output locations. In the present version of the Delta model for national policy analysis, the same number of output locations is included as used by the regional water managers (1145 locations). The spatial resolution of these output locations might be reduced in future to a level more appropriate for national policy analysis, to reduce the calculation time of Hydra-Zoet.

5. Fresh water supply

The Delta Programme on fresh water supply focussed on water demand, allocation and distribution during droughts. It covered the entire Netherlands, with special attention to the water demands in the regions, including the various functions using the water. To study fresh water supply a nation-wide hydrological model (NHI) is available in the Netherlands (De Lange et al, 2013). NHI is coupled in the Delta model to a range of various impact assessment tools, including agriculture, nature, navigation, drinking water and cooling water. The hydrological model and the impact assessment tools are described in Prinsen et al (2014), and presented here in Table 3 and Figure 6.

One of the results of the development of the Delta model is that the hydrological models and impact assessment tools have now been coupled into one integrated system. This allowed the Delta Programme on fresh water supply to make calculations without requiring input of all the individual developers of the various models and tools. Moreover, as these models and tools are included in the Delta model, support and maintenance of each of them is taken care of, and version control is established (allowing for consistency and reproducibility).

Calculations with the Delta model for fresh water supply typically covered a time series of 30 years, using the combination of (historical) meteorological monitoring data and (future) climate change scenarios as external forcings on the boundaries. In addition, calculations covering 1 characteristic hydrological year have been made for quick scan of possible effects of measures. Socio economic scenarios were included based on the possible (relative) changes in land-use, as well as demands on available water for cooling water, drinking water and navigation. Possible measures have been implemented in the models by adjusting the input data such as pumping station capacity, changes in irrigation/drainage, water intakes etc. It should be noted that the level of detail in data for the Delta scenarios was merely national to regional, whereas the measures are often implemented on a local scale.

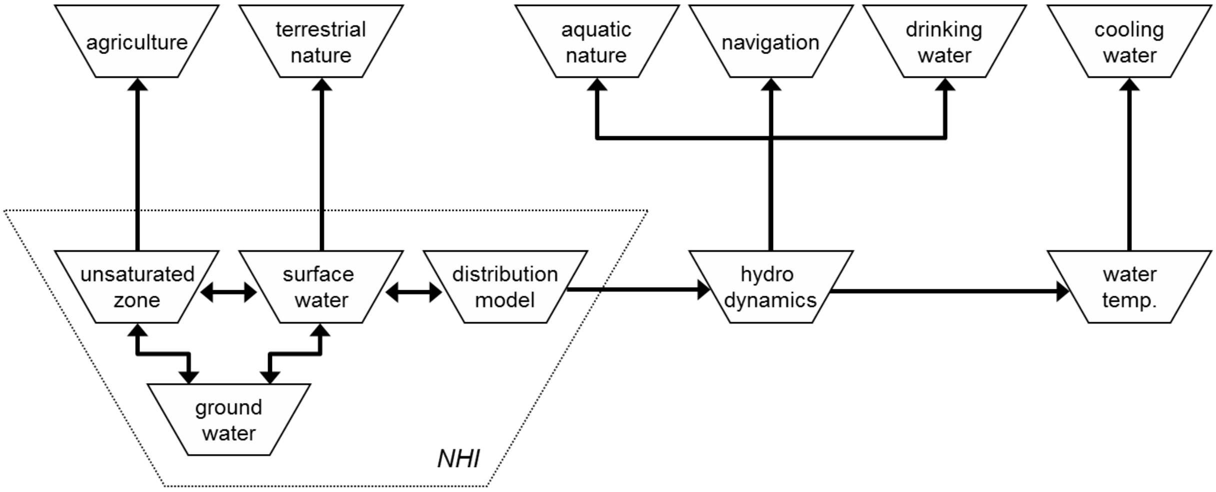

Figure 6. *Overview of Delta model – 1.1 components for the Delta Programme on fresh water supply (Prinsen et al, 2014).*

Table 3. *Overview of the selected versions of software and schematisations included in Delta model –1.1 for the Delta Programme on fresh water supply.*

DP-Fresh water supply	Software	version	Schematisation version	OS
Groundwater	Modflow	NHI-3.01	NHI-3.01	Windows
Unsaturated zone	Metaswap	NHI-3.01	NHI-3.01	Windows
Regional surface water	Mozart	NHI-3.01	NHI-3.01	Windows
Distribution model	DM	NHI-3.01	NHI-3.01	Windows
Hydrodynamics	Sobek-River	2.12.004	LSM-1.1	Windows
Hydrodynamics	Sobek-River	2.12.004	LSM-*Light* -1.1	Windows
Water temperature	Sobek-Waq	2.12.004	LTM-1.0	Windows
Agriculture	Agricom	1.06	1.06	Windows
Terrestrial nature	Demnat	3.0	3.0	Windows
Aquatic nature	Habitat	PCRaster	PCRaster	Windows
Navigation	Bivas	2.7.5	2.7.5	Windows
Drinking water supply	Drinkwat	FEWS 2012.02 (build 40125)	Deltamodel-1.1	Windows
Cooling water supply	Koelwat	FEWS 2012.02 (build 40125)	Deltamodel-1.1	Windows

The main dilemma in the implementation of the models and impact assessment tools for fresh water supply was to find the proper balance between the use of detailed models (necessary for acceptance by regional water managers and the implementation of local measures) and the long calculation times (resulting from these detailed models, and the selected time span of 30 years). During the development of the Delta model the software was tuned as much as possible (given the financial limitations) to limit the calculation time. For instance, several unused output files of NHI (hydrology) and BIVAS (navigation) are no longer produced and a 'light' version of the hydrodynamic LSM model (surface water) is included. Despite these improvements, one complete calculation for fresh water supply, including all hydrological models and impact assessment tools and covering 30 years, takes some 15 days calculation time. These long calculation times clearly limited the possible number of calculations.

An option to reduce the calculation time might be to reduce the spatial and/or temporal resolution. This might hamper the acceptance by the regional water managers, as well as the possibility to implement local measures. Another option to reduce the calculation time might be to reduce the time span from 30 years to several hydrological events. As this would have limited the climate variability in the analysis, a calculation of 1 year is only implemented to allow a quick scan of measures. We recommend for future applications to evaluate how the calculation time of the models can be reduced, to improve the applicability of the models for fresh water supply.

In the present version of the Delta model, the detailed models are included and the long calculation times are accepted by all participants. The results of the calculations with these detailed models are aggregated to a spatial and temporal resolution that is used for policy analysis.

6. Robustness and flexibility

The Delta model has been implemented as a dedicated application of Delft-FEWS (Werner et al, 2012, www.delft-fews.nl). Verseveld et al (2015, in prep.) describe in detail how all selected models were included in Delft-FEWS for the Delta model, and how the coupling of all models has been implemented. Section 2 above describes how the implementation of Delft-FEWS contributed to the required consistency of the Delta model. In this section we discuss two other requirements of the Delta model in relation to Delft-FEWS: robustness and flexibility.

As Delft-FEWS is originally developed for operational forecasting, the robustness of Delft-FEWS is one of the crucial aspects (Werner et al, 2012). With applications of Delft-FEWS implemented in operational forecasting systems all over the world, the robustness of Delft-FEWS can be considered as ‘proven technology’.

During the initial stages of the development of the Delta model the robustness of the system was discussed several times. For instance, it appeared that due to memory leaks in some of the models included in the Delta model, the resilience of the entire system was hampered. It should be noted that these models were developed and maintained independent from Delft-FEWS. After discussions with the model-owners and software developers, the memory leaks in these models could be solved and the robustness of the Delta model was repaired.

Another issue related to the robustness of Delft-FEWS arose when the graphical display function was used by some of the early users by mistake to export huge amounts of data. This issue could be tackled by adding a dedicated export function and limiting the dimensions of the graphical display function.

Once these start-up issues were solved, no further issues related to robustness of Delft-FEWS and the Delta model evolved.

With respect to the flexibility of the system a lot of discussion has taken place during the development and the application of the Delta model. These discussions revealed that consistency and flexibility seem to be opposite requirements and difficult to combine. For instance, several stake-holders asked for flexibility to adjust the workflows in order to define specific calculations for each scenario and/or measure. At the same time, the requirements of the Delta Programme were to apply consistently the same workflows for all calculations and regions in the Netherlands. This issue could be solved in Delft-FEWS by separating the selection of the input data from the actual calculation. The requirements of the stake-holders (for flexibility to specify their input data) and the requirements of the Delta Programme (for consistency in the calculations) could both be fulfilled in this way.

The remaining point of discussion with respect to the flexibility was related to the time-span required to implement updates of the Delta model. Policy analysts often demand high flexibility to update the system with new data and/or functionality. From a technical point of view these updates could be implemented in most cases rather quick in the Delft-FEWS configuration for the Delta model. However, due to the requirements related to the hosting of the (client-server) system it was necessary to go through a phase of external testing before these updates in the Delta model were made available for the policy analysts. The flexibility of the Delta model was several times hampered by the time constraints of these procedures, rather than the technical limitations of Delft-FEWS. For future projects we recommend to take into account the various time constraints in the governance of the hosting.

7. Discussion

One of the two key objectives of the development of the Delta model was to obtain a consistent modelling system for policy analysis on flood risk management and fresh water supply. As we presented in this paper, in Delta model – 1.1 the required consistency has been implemented successfully within the models for flood risk management, as well as within the models for fresh water supply. Throughout (most of, see section 4) the Netherlands the same software (versions) and same modelling concepts are being used now within these two domains.

A consecutive step to enhance the consistency between flood risk management and fresh water supply might be to further integrate the modelling system. For instance, at present flood risk management uses a 2D-hydrodynamic model for policy analyses (for 3 out of 4 regions), whereas fresh water supply is using a 1D-hydrodynamic model. From the perspective of consistency it is preferable to implement in future the same hydro-dynamic model for both flood risk management and fresh water supply. Based on the discussions on calculation time, we recommend to implement a 1D model for policy analysis on both flood risk management and fresh water supply.

Another possible consecutive step might be to evaluate whether or not, and if yes – how, the analysis methods used for flood risk management and fresh water supply can be integrated further. As described in section 4 and 5, flood risk management uses a probabilistic approach of flood events whereas fresh water supply is based on the deterministic analysis of a time series of 30 years. Although it is not yet clear at this moment how these 2 methods can be integrated, using a similar analysis method for flood risk management and fresh water supply would clearly contribute substantially to the overall consistency of the policy analysis.

The second key objective of the development of the Delta model was to achieve acceptance among the scientific community, (regional) water managers and policy makers in the Netherlands. The acceptance of the scientific community and water managers was gained by maintaining an open approach to all available models and model-components in the Netherlands. Using one of the strong features of Delft-FEWS to couple various models, it was possible to create an integrated system based upon the models supported by scientists and water managers. The results of these (rather detailed) models are aggregated in the Delta model (and presented in the Delta portal) up to a level that is accepted by policy makers as well.

It should be noted that in future more detailed data will become available, and regional water managers and scientists will likely include more detail in their models. Cleary this would result in longer calculation times. At the same time policy makers tend already to prefer substantial shorter calculation times, in order to analyse many different alternatives and scenarios. The introduction of exploratory modelling (Walker et al, 2013) and the research on adaptation pathways (Haasnoot, 2013) in policy analysis would strengthen the demand of policy makers for shorter calculation times.

In time, the performance of the available hardware will probably improve and allow for faster calculations. The demands for more details and more calculations are likely to increase even faster though. Consequently it will be necessary in future to discuss with all stakeholders how the calculation times can be reduced, whilst the consistency and acceptance of the models can be maintained. An option might be to shift the discussion on acceptance from the models to the underlying data. Once the data would be accepted by all stakeholders, models (based on the same software) with different spatial and temporal resolutions might be developed by water managers, scientist and policy makers without losing mutual acceptance of the calculation results. As an example, the spatial resolution of Hydra-Zoet for the Rhine-Meuse estuary might be reduced from 1145 locations in the application for regional water management to 25-50 locations in policy analysis. This might reduce the calculation time of Hydra-Zoet for this region from 4 days to approximately 1 hour.

A reduction of the calculation time is also required with respect to the models for fresh water supply, as a calculation time of 15 days does (clearly) hamper the analysis. As NHI and LSM take the larger part of the overall calculation time for fresh water supply, we recommend to focus on these models first. A reduction of the spatial resolution of the groundwater models (in NHI), as well as a reduction of the spatial distribution of the surface water model (as included in LSM-*light*) might be useful to reduce the calculation times. Further analysis is recommended though to formulate a proper strategy to reduce the calculation time.

Robustness and flexibility were also formulated as requirements for the development of the Delta model. As described in section 6, we selected Delft-FEWS as platform to implement the Delta model because it added to the robustness and flexibility of the system, in addition to the consistency. The choice for Delft-FEWS has proven to be successful in this respect (see section 6). It should be noted though that the present Delft-FEWS configuration for Delta model-1.1 includes quite a lot of different workflows, related to the various scenarios and strategies (see also Van Verseveld, in prep.).

The maintenance of all these workflows may become a burden on the long run, due to the complexity of the configuration.

Recently, 'templates' have become available within Delft FEWS (www.delft-fews.nl). The objective of these templates is to facilitate the organisation of the workflows within a configuration. We recommend to apply the templates in due time to the configuration of the Delta model to reduce the complexity of the configuration and hence allow for maintenance.

Delta model-1.1 has been used extensively during the policy analysis related to the Delta Programme. With the presentation of the conclusions of the Delta Programme in September 2014, the scope of the application of the Delta model has changed from policy analysis to the implementation of measures. Other applications may be expected in future as well, as the Delta model is appreciated widely as the consistent and accepted basis for hydrological and hydrodynamic calculations in the Netherlands. The requirements for the Delta model will probably be adjusted to tune them to these new applications.

An interesting point of discussion in this context is the position of the impact assessment tools. The present version 1.1 of the Delta model includes impact assessment tools for fresh water supply (see Figure 6). Within the limitations of time and budget, we managed not yet to include all impact assessment tools for flood risk management in the Delta model (see Figure 5). For policy analysis it was considered useful to include all impact assessment tools in the Delta model, as this facilitated the management of the calculations with various model-components.

Future applications of the Delta model are expected to include the same hydrological and hydrodynamic models (although new versions of these models will become available), with different or additional impact assessment tools. In this context it might be considered to consolidate the hydrological and hydrodynamic models in the Delta model and provide (OpenData) exports of the results for (off-line) applications with impact assessment tools.

8. Conclusions and recommendations

The development of the Delta model to support the national policy analysis in the framework of the Dutch Delta Programme was very successful. The consistency of the selected models used in the analysis was improved by using the same (version of) software throughout the country as well as schematisations based on similar basic data. The acceptance of all stake-holders could be gained by maintaining an open approach to include the software and schematisations preferred by (regional) water managers and scientists (keeping in mind the requirements on consistency), and aggregating the results of the calculations up to the level required by policy makers.

The Delta model has been implemented as a dedicated application of Delft-FEWS, which contributed to the consistency as well as the robustness of the system. As a result, the development of the Delta model supported the process within the Netherlands to achieve commitment on the measures to be taken to cope with climate change and socio economic developments. A similar approach might also prove to be successful in other countries.

Based on the experiences gathered during the development and application of the Delta model, several recommendations are formulated for further improvements, as discussed in this paper. It is anticipated that in the near future several of these recommendations will be implemented, in close coordination with the Ministry of Infrastructure and Environment in the Netherlands. Most of the recommendations are related to the reduction of the complexity of the Delta model. In addition, it is recommended to facilitate the coupling of the Delta model to other modelling instruments. Currently, the coupling of the Delta model with water quality models is being implemented.

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