Environmental Modelling and Software 143 (2021) 105100

Contents lists available at ScienceDirect

Environmental Modelling and Software

journal homepage: www.elsevier.com/locate/envsoft

Dilemmas in developing models for long-term drought risk management: The case of the National Water Model of the Netherlands

Marjolein Mens[a,*], Bennie Minnema[a], Koen Overmars[b], Bart van den Hurk[a]

[a] Deltares, Boussinesqweg 1, 2629, HV, Delft, the Netherlands
[b] Rijkswaterstaat, Zuiderwagenplein 2, 8224, AD, Lelystad, the Netherlands

ARTICLE INFO

Keywords:
National water model
Large-scale integrated modelling
National policy-making
Regional stakeholder support
Risk-based decision-making
Drought risk management
Dutch delta programme
Climate change
Model requirements
Meta-modelling
CPU-Time

ABSTRACT

Strategic decision-making on long-term drought risk management can be supported by integrated assessment models to explore uncertain future conditions and potential policy actions. Such models have to meet many – sometimes conflicting – requirements posed by policy-makers, model developers, and stakeholders. This paper discusses the case of the National Water Model (NWM) that is applied for national policy-making on drought risk management in the Netherlands. The case demonstrates that the chosen assembled model set-up (in which several existing models are combined) is cost-effective and increases stakeholder acceptance, but also leads to high model complexity and computation time. To be effective for policy-making, integrated assessment models need to produce relevant model outcomes that are accepted by stakeholders, within acceptable time and cost limits. For this, the model set-up must support simulations at different aggregation levels (allowing both detailed analysis and exploratory analysis of many scenario/strategy combinations) while maintaining internal consistency.

1. Introduction

Strategic decision-making on long-term drought risk management is a complex process in which a large range of relevant system processes and impacted sectors is involved, and uncertainty about future changes in climate and in the environmental and socio-economic system is large. Integrated assessment models are indispensable tools in support of a decision-making process, as they provide a framework to systematically and transparently understand the system, including linkages and feedbacks between system components, explore scenarios and policy actions, and communicate with stakeholders (Hamilton et al., 2019; Loucks and van Beek, 2005). The trade-off between model complexity and computing time needs to balance the need to cover a required number of calculations and scenarios, while keeping sufficient mechanistic and spatial detail to represent the elementary functioning of the system (Haasnoot et al., 2014; Booij et al., 2003).

Many requirements play a role in the development of integrated assessment models. Common requirements for an effective decision support model, reviewed and clustered by Hamilton et al. (2019), include credibility, relevance, legitimacy, model accessibility, end-user satisfaction, timeliness, and costs for maintenance and computing. The prioritization of these criteria may be subject of debate among the model developers, decision-makers and other stakeholders. From a decision--maker's perspective, model outcomes should be relevant for the decision at hand, accepted by the stakeholders, and produced in time to be useful in the decision process. From a modeller's perspective, the model should be scientifically and technically valid, sufficiently representing the system dynamics, and accessible (including availability of user-friendly and well-documented software and data). Dilemmas in the model development may arise from conflicting requirements, for example the desire to include more detailed processes at the cost of computational efficiency.

There is a growing interest in quantitative risk analysis to inform drought risk management policies, similar to the approach taken for other natural hazards such as floods and earthquakes (Hall and Leng, 2019). Drought risk is understood as the combination of the probability of drought occurrence and the associated impact on society, appreciating different meteorological, hydrological, soil moisture and/or groundwater drought typologies (Van Loon, 2015). Risk analysis involves considering the full range of (drought) conditions to which a system might be exposed and forms the basis for cost-benefit analysis of investments by governments and water users (such as drinking water companies, the agricultural sector and industries). Because droughts

* Corresponding author.
E-mail addresses: Marjolein.Mens@deltares.nl (M. Mens), Bennie.Minnema@deltares.nl (B. Minnema), Koen.Overmars@rws.nl (K. Overmars), Bart.vandenHurk@deltares.nl (B. van den Hurk).

https://doi.org/10.1016/j.envsoft.2021.105100
Accepted 24 May 2021
Available online 1 June 2021

develop slowly over time and various hydrological processes (soil moisture, groundwater, river discharge) impact a variety of sectors, the construction of the full range of plausible and relevant conditions with statistical or empirical methods is far from straightforward (Mishra and Singh, 2011). Therefore, simulation of long time series of meteorological conditions with a coupled hydrological and hydrodynamic model representing natural variability at different time scales is considered to be a necessary prerequisite for a reliable mapping of relevant drought conditions and their frequency. Furthermore, sufficient spatial and temporal detail is necessary to be able to assess and compare a variety of risk management options, for example the implementation of more efficient irrigation techniques may significantly reduce dependency on the water supply system when implemented on a large scale. Multiple scales thus need to be integrated in the model to better understand drought propagation through the socio-hydrological system.

To improve our understanding of the dilemmas in the development and application of integrated assessment models and ways to overcome these, this paper discusses the role of the National Water Model (NWM)) in support of drought risk management in the Netherlands. Over the past decades, the NWM has been frequently updated to meet gradually changing requirements. Despite its importance in national policy-making, the model is increasingly perceived by stakeholders as being 'too slow and too complex'. In other words: policy-makers, model experts and stakeholders question: is the model still 'fit-for-purpose'? We analyse how the NWM has evolved in response to the requirements and how dilemmas arise, based on the authors' collective experience and in-depth interviews with scientists and policy advisors for the Delta Programme. We focus on three aspects that determine whether a model is fit-for-purpose from a decision-maker's perspective: relevance of the model outcome, stakeholder acceptance and timeliness in the decision-making process. Relevance of the model outcome relates to the processes that are modelled and their level of detail, as well as the number of strategy/scenario combinations that can be simulated. The resulting model requirements in terms of spatial and temporal resolution may vary throughout the policy process. Stakeholder acceptance relates to the agreement between model output results and observed (or perceived) status of the water system at the regional scale addressed by the stakeholder. Timeliness refers to whether the desired model outcomes can be published at a convenient and opportune time for the policy process. These aspects are a condensation of the criteria reviewed by Hamilton et al. (2019), and play an important role in the fit-for-purpose discussion that is taking place in practice. Insights from this paper will be used as input for the ongoing debate about the future of the NWM instrument in support of the next policy cycle of the Delta Programme (2022–2027). These insights can provide inspiration for other practitioners who design, maintain and apply integrated assessment models in support of long-term policy-making for drought risk management.

2. Description of the National Water Model

2.1. Role and history

The National Water Model (NWM) plays an important role in the Netherlands' national *Delta Programme* on fresh water supply (Glas, 2019), addressing the national strategy to manage the risk of water shortage due to droughts under climate change and socio-economic change. In support of this decision-making process, the National Water Model integrates hydrological, hydrodynamic and water allocation models for all physical processes that are relevant for drought risk analysis. The model has a long history; some of the submodels have been first developed in the 80s as part of the Policy Analysis for the Water management of the Netherlands (PAWN) study (see Wegner, 1981; Abrahamse et al., 1982; Goeller et al., 1983; Goeller et al., 1985), which provided model-based decision support for the 2nd national policy on water management (Rijkswaterstaat, 1984). In this PAWN project, more than 50 models were developed to quantitatively describe all relevant aspects of drought risk management, including impacts on agriculture, shipping, industry, and drinking water. This pioneered the application of cost-benefit analysis for the Netherlands policy interventions in water management. Various model concepts from PAWN have been integrated in the current national hydrological model (LHM), which now forms one of the submodels of the NWM. Since the 1990s, the LHM has been further developed (see Vermulst et al., 1998), currently by a consortium of Dutch research institutes.[1] In different forms, LHM has supported strategic decision-making on water management in the Netherlands over the past decades, for example the Delta Programme strategy for the period 2016–2021 (Kuijken, 2014) and currently for the upcoming Delta Programme strategy for the period 2022–2027.

2.2. Physical processes

In the Netherlands, drought is defined as a period of precipitation deficit, a period of low river discharge, or a combination of both. Drought impacts include soil moisture deficit, decline in groundwater levels, shortage of surface water supply (for irrigation, water level management, navigability, and flushing of polders), salt water intrusion in coastal areas, reduced water levels in the main transportation waterways, and water temperature increase in rivers and canals. The National Water Model assembles several submodels that each simulate a subset of these relevant physical processes. For a full understanding of drought risk, economic and societal impacts of droughts are quantified with impact modules that are available as post-processing tools.

In the NWM various processes are considered at different spatial scales. For example, surface water allocation of Rhine river water in periods of drought takes place on a national scale, the groundwater system is of crucial importance primarily in the Southeast and East of the Netherlands, and water shortage in the North of the Netherlands depends on water allocation schemes and reservoir management of lakes IJssel and Marker. Furthermore, drought impacts in the West are caused by salt water intrusion from sea, and salinization of groundwater determines water availability for agriculture in all coastal areas. These processes are all integrated in one national model, in order to be able to understand water shortage issues at a national scale and compare various types of measures with feedback effects between processes and regions.

The input data of the NWM include time series of precipitation, evapotranspiration, and discharge from the main rivers Rhine and Meuse at national entry points. Output of the NWM includes groundwater levels on 250 × 250 m resolution, daily and 10-daily time series of river discharge within the national domain, and water demand and supply for various users (irrigation, water level control, flushing of polders, drinking water, industry) on several inlet points of the distribution network (Fig. 1).

2.3. Submodels

The following submodels are incorporated in the NWM (Fig. 2):

- LHM - A national hydrological model of the Netherlands
- LSM-light - A national one-dimensional hydrodynamic model
- Sobek-NDB – A regional one-dimensional hydrodynamic model of the South-West of the Netherlands, including salt water simulations
- LTM-light – a national surface water temperature model based on LSM-light.

A detailed technical description of each underlying model can be found in Prinsen et al. (2014) and De Lange et al. (2014). The groundwater model MODFLOW is derived from Modflow-2005 (Harbaugh,

[1] http://nhi.nu/nl/index.php/organisatie.

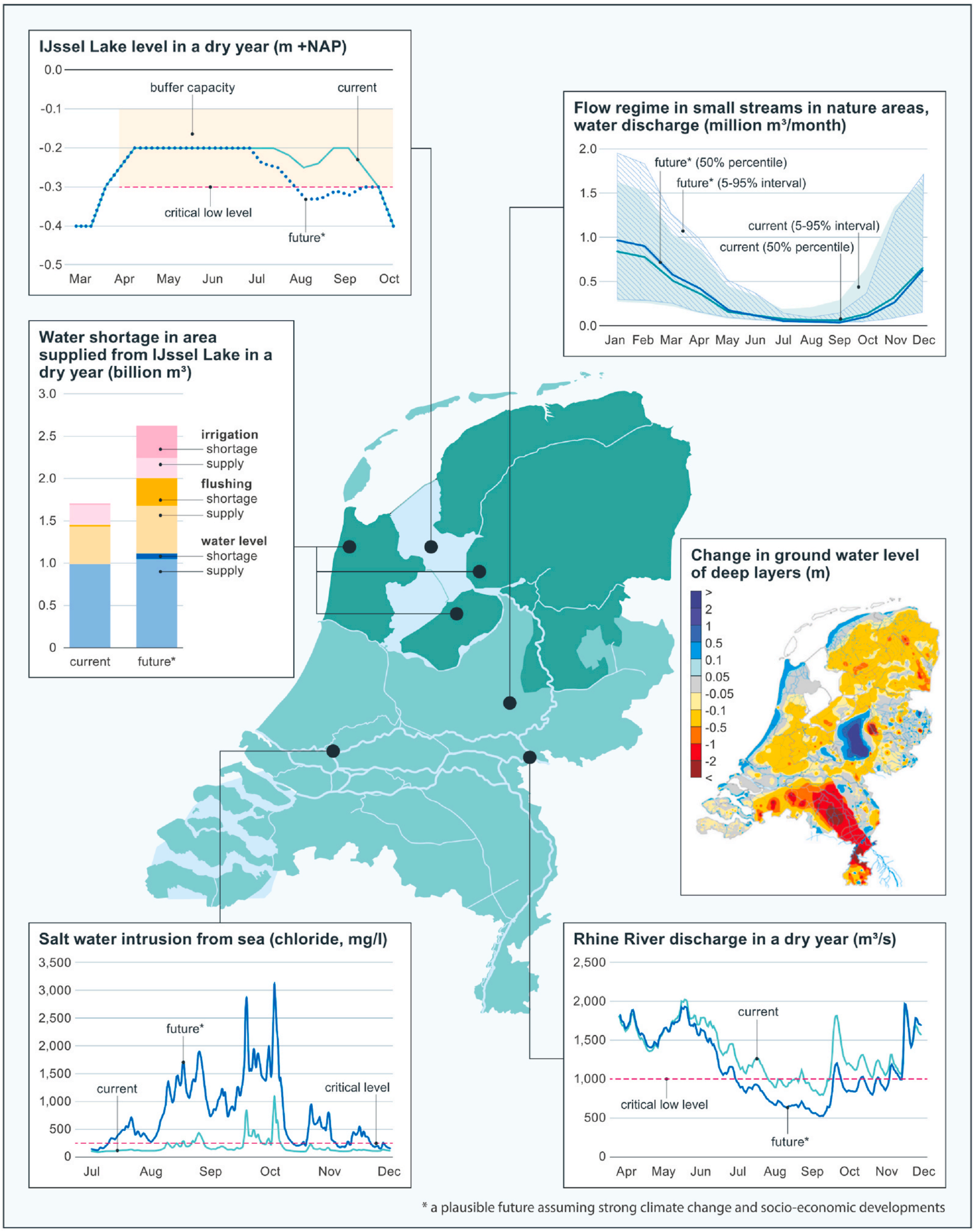

Fig. 1. Example output of (the submodels of) the National Water Model showing the various processes that are included: level of lake IJssel (upper left), flow regime in small water streams (upper right), water shortage (middle left), aquifer pressure head (middle right), salt intrusion (lower left) and Rhine discharge (lower right).

2005) and coupled with the unsaturated zone model MetaSWAP (Van Walsum and Groenendijk, 2008), which in turn is based on the physics of the SWAP model (Kroes et al., 2008). The regional surface water distribution is modelled using MOZART (Bos et al., 1997), and the Distribution Model (DM) is used to describe the water distribution in the large rivers and distribution canals. LSM-light (Prinsen and Wesselius, 2015) is a one-dimensional (1D) hydrodynamic surface water model of the major rivers and canals of the Netherlands. Sobek-NDB (Van der Linden and van Zetten, 2002) is a 1D hydrodynamic model for calculating salt water intrusion from the sea in the coastal rivers and canals in the mid-western parts of the Netherlands. Finally, LTM-light (Meijers and Boderie, 2004) simulates the depth-average (1D) surface water temperature in the major rivers and canals. The computational framework Delft-FEWS (Werner et al., 2013) takes care of the model coupling, data exchange, and feedbacks between the submodels.

2.4. NWM governance and stakeholder groups

The NWM project is guided by a steering committee, an advisory board, and a scientific committee. The steering committee consists of national and regional water managers and policy advisors, who decide on which model developments should be prioritised. The advisory board includes experts from national research institutes, who advise on long-term developments. Furthermore, the scientific committee advises on the scientific quality of the models and model structure of the NWM. The underlying submodels of the NWM are developed, validated, and maintained in separate projects, each with its own governance structure. The stakeholders in the steering committees of these submodels partly overlap with those in the NWM committees. The development of LHM, the largest submodel of NWM, is a continuous process in interaction with stakeholders, including hydrologists and policy advisors from all

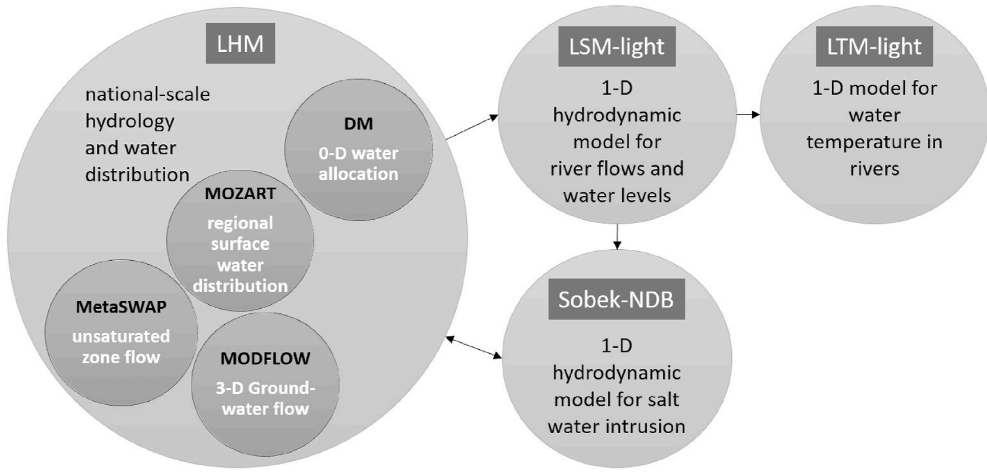

Fig. 2. Schematic overview of the submodels that are assembled in the National Water Model.

regional water authorities and the national water management authority (Rijkswaterstaat) in the Netherlands. The LHM model has its own set of requirements with respect to the model concept, model accuracy, parameterization of physical processes, simulation time, data, etc.

2.5. The NWM project

NWM is an example of a modular assemblage approach to integrated modelling, in contrast to a single integral model representing the whole system (see Voinov and Shugart, 2013). In an assemblage approach, existing models are reused that are developed and tested by specialists in that particular area. 'Integrated' particularly refers to the consistent treatment of input data and the time synchronization across all processes and regions. For example, the exploration of the effect of long-term changes in climate and land use requires model input data for the future scenario to be developed consistently for all regions and submodels. A major advantage of an assemblage approach is that it reduces model development cost, time, and effort. On the other hand, investments are needed in the interfacing, interoperability, information exchange, and governance of the development of the components (Rizzoli et al., 2008). The NWM project started in 2010 (then labelled as the Delta Model) with key objectives to provide a consistent and accepted set of models, in a robust and flexible modelling environment, to support policy analysis within the Delta Programme (Prinsen et al., 2014; Ruijgh et al., 2015). To ensure consistency and reproducibility, a selection of the most appropriate subset of models from a large ensemble of existing candidate models with varying spatial resolutions and scopes was made. The Delft-FEWS framework enabled the utilization of standardized boundary conditions and data exchange between the models. Furthermore, the submodel developers are required to provide proper documentation and support and maintenance to enhance uptake of the models in the NWM framework. Choices regarding the level of detail and upscaling of regional data to the national scale were negotiated between the scientific community, (regional) water managers and policy-makers. From 2010 onwards, in view of the first phase of the Delta Programme, additional submodels were coupled (first Sobek-NDB and later LSM-light; see Fig. 2), and the exchange of data between these submodels was improved. The salt water intrusion model (Sobek-NDB) was coupled to dynamically calculate the salt-dependent closure of one of the main fresh water inlet points in the West of the Netherlands. Because feedbacks exist between salt concentration and water distribution, an iteration loop of both LHM and LSM-light was required. Furthermore, in 2015, the choice was made to start simulating 100-year time-series of (historical and future) precipitation, evaporation, river discharge and sea level, based on historical measurements (Kroon et al., 2015). With this approach the observed temporal and spatial correlations between the various variables are included, thereby allowing a proper estimation of the probability distribution of drought impacts. In parallel, the submodel LHM was updated with regional data provided by regional stakeholders, such as measured time series of surface- and groundwater levels, detailed data on the surface water elements, and on the vertical discretization of the subsurface. For example, the number of soil types was tripled, thereby refining the unsaturated zone parameterization. To increase computational efficiency, parallelization of the computational cores has been developed (see e.g. Verkaik et al., 2021). The current activities of the NWM project mainly consist of integrating updated versions of the underlying submodels and data streams, in combination with hardware upgrades, improving model coupling and data exchange, and improving the consistency of boundary conditions between the submodels, for example related to future scenarios.

2.6. NWM quick scan tool

Over the past years, a quick scan tool (QWAST; Gijsbers et al., 2017) has been developed to allow the quick and rough exploration of measures that are aimed at water demand or water allocation on the national scale. The temporal and spatial resolutions of the water allocation network are similar to that of the Distribution Model, one of the NWM submodels. In the policy process, QWAST serves as a first order evaluation of the effectiveness of measures with the aim of developing a water allocation strategy. QWAST simulates water allocation given pre-calculated and time-dependent water demands (taken from NWM) of various users in all regions that are connected to the main water distribution system, considering prioritization over users and regions. The quick scan model does not cover the full range of potential risk management actions, since it only includes surface water processes and water allocation, excluding rainfed agriculture, salt water intrusion, and groundwater processes.

3. Discussing the key requirements of the National Water Model

The NWM aims to support a decision-making process for which questions about system behaviour, effects of external developments (climate change, socio-economic change), and effectiveness of drought risk reduction measures need to be answered in a timely manner. This section first describes the modelling goals and model complexity in relation to the policy process, and then discusses the extent to which the NWM is able to meet the three key requirements: relevance, timeliness, and stakeholder acceptance.

3.1. Modelling goals in relation to the policy process

In the context of water resources management, modelling activities are designed to provide useful and timely information to all stakeholders involved in the decision-making process, which typically consists of the following phases, including feedback loops (Loucks and van Beek, 2005): (I) inception, (II) situation analysis, (III) strategy building, and (IV) action planning, implementation, monitoring, and evaluation. Modelling takes place in support of the situation analysis (phase II) and strategy building (phase III), in order to analyse the problem under current and future conditions through scenario analysis, and to assess (a collection of) alternative policy actions.

Within phase II and III, four modelling goals can be distinguished (Fig. 3). The first goal is to understand the natural and human system with all relevant processes and feedbacks and identify the main characteristics of the problem. For drought risk management this involves the identification of the probability of water shortage due to drought as well as the impacts on a range of water users. Major drought characteristics may vary across the different regions. The second goal is to explore potential emergence or development of future problems (‘explore future scenarios’). Such scenario analysis includes mapping the uncertainty of future climate change and potential response of water users to this (for example, changing time-varying water demands). The third goal is to explore various policy actions to reduce drought risk and help the stakeholders develop a preferred strategy from a long list of potential measures. These include operational, tactical, and strategic measures focusing on water demand reduction and/or water supply increase (e.g Buurman et al., 2017). Finally, the fourth goal is to assess several strategies on their effectiveness, i.e. the ability to reduce (the impact of) water shortage due to drought, against acceptable societal costs.

Integrated assessment with the purpose of supporting long-term policy-making (50–100 years ahead) involves taking into account many types of (deep) uncertainty arising from multiple plausible future developments, multiple views on system evaluation, various responses to events and trends, natural variability, and limited knowledge of the system processes and functioning (Marchau et al., 2019; Walker and van Daalen, 2013; Hallegatte et al., 2012; Haasnoot et al., 2012, Lempert et al., 2003). To ensure consistency and optimize model management, one integrated assessment model is preferably used to analyse the whole system, and to explore the interaction between future scenarios and policy actions, while additional (detailed) models may be used subsequently to perform in-depth analyses for a certain region, sector or measure. In the current policy cycle leading to an updated national strategy to deal with climate change (Delta Programme, 2022–2027), NWM is used for three of the four described goals (Fig. 3). To explore water shortage in the future, four scenarios were used for two future time periods (2050 and 2100). These so-called Deltascenarios (Wolters et al., 2018) combine two climate change scenarios (KNMI, 2015) with two socio-economic scenarios (Manders and Kool, 2015), resulting in four different storylines for climate change and the response of the human system for different socio-economic configurations. Land use, irrigation, and drinking water demand are examples of scenario-specific human responses. Additionally, one scenario-variant was developed to explore the effect on water demand of implementing drainage systems in peat areas to reduce CO2 emissions according to the Paris-agreement. All scenarios were translated into consistent model input and boundary conditions by Hunink et al. (2018). A total of 11 model experiments (1 x reference + 5 scenarios for 2050 + 5 scenarios for 2100) were thus carried out to understand the drought risk system and explore drought risks in the future.

The meta-model QWAST has been used to quickly explore a large set of policy actions (third goal). The choice for a separate quick scan tool was made because, at least currently, the NWM is not fast enough to support the iterative process of moving from a long list of potential measures to a short list of promising measures. About 60 model experiments were conducted with QWAST: 20 individual measures and 10 strategies (combinations of measures) were simulated for 2 scenarios encompassing a 100-year times series. Each 100-year QWAST run takes a few hours to simulate.

NWM was finally used again to compare priority strategies in order to choose the preferred strategy (fourth goal). However, because of the simulation time and cost constraints (both following from model complexity), only 4 scenario/strategy combinations were explored: 2 strategies for 2 scenarios in 2050, each for the 100-year time series. The subsequent interviews with policy-advisors revealed that this collection was not sufficient to address all relevant policy questions. For example, the relative impact of drinking water and agricultural water extraction on declining groundwater levels under future conditions remained unresolved.

3.2. Model complexity

In terms of model complexity, it is generally accepted that for the purpose of decision support and exploration of future developments, spatially and temporally less-detailed models are required than, for instance, operational models to forecast system behaviour in response to weather predictions. Fig. 4 displays a conceptual overview of model applications with respect to three model dimensions: the required conceptual detail of the processes that are modelled (model complexity), the level of acceptable model uncertainty, and the time range of the analysis. Three types of model application can be identified: (1) prediction (estimating the value of a system variable given a change in system inputs or boundary conditions), (2) forecasting (predicting the value of

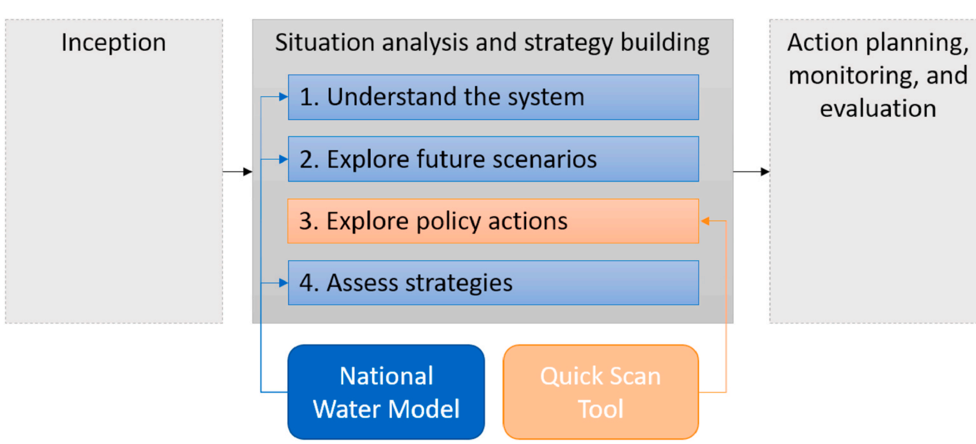

Fig. 3. The role of the National Water Model in the policy-making cycle.

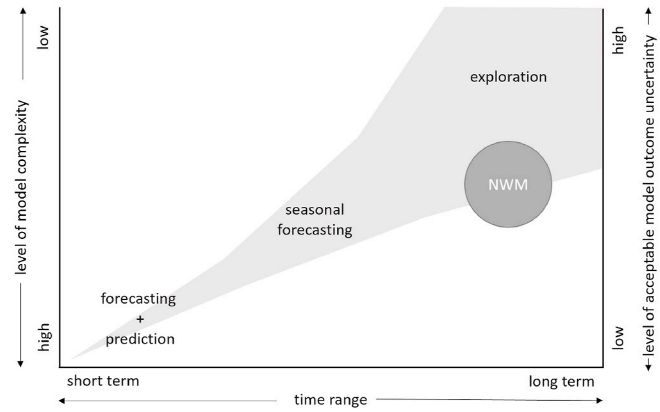

Fig. 4. Three model applications in relation to dimensions of model complexity, time range and uncertainty. NWM is located schematically in this conceptual diagram.

system variables in the near future on the basis of varying system forcings) and, (3) exploration (estimating model variables in the future given changes in a combination of model inputs, parameters, and boundary conditions). While for prediction and forecasting historical accuracy is an important characteristic of model approaches, exploring long-term future (30–100 years ahead) requires model outcomes to be plausible given assumed conditions (see Kelly et al., 2013). Many scenarios are needed to explore the interactions between processes and impacts of interrelated changing conditions including feedbacks, and how this can be adapted by policy actions. For this type of application, models used should be fast enough to allow large numbers of calculations for long time series, while keeping sufficient detail to represent all relevant processes and their interactions (Haasnoot, 2013; Booij et al., 2003). A comparison of models with different levels of complexity is needed to determine the configuration that would be sufficient for answering policy questions (Guillaume and Jakeman, 2012).

Determination of an optimal model configuration is difficult when the model will be used for different applications simultaneously (in a so-called unified modelling concept, see e.g. Clark et al., 2015). Also, the LHM is used for purposes other than long-term assessments, e.g. as a predictive model for regional hydrological studies, as a component in the national operational drought management system, and for simulating and forecasting the real-time drought situation and expected water shortage in the short term. These multiple purposes imply that choices in temporal and spatial resolution require a trade-off between high accuracy versus high computational efficiency. Interestingly, many (particularly regional) policy advisors consider the current version of LHM not detailed enough for regional (groundwater) studies. Since the multi-purpose model LHM is a major component of NWM, the NWM is placed in the middle of the vertical axis in Fig. 4, reflecting a compromise between exploring the future and forecasting.

The steering committee considered it necessary that NWM contains groundwater and surface water interaction, because 1) large parts of the subsurface of the Netherlands consists of highly permeable river sediments, causing the surface water and groundwater systems to act as one system (Winter et al., 1999) with mutual feedback mechanisms, especially when simulating dry conditions, and 2) the Netherlands partly consists of large areas with deeper groundwater levels that react slowly (¿ 20 years) to changes in hydrological boundary conditions, causing adjacent connected areas to react also slower than other areas, and 3) the central Veluwe area with deep groundwater levels directly connects with the Lake IJssel via the deeper subsurface, which is relevant when performing simulations for long time periods (Gehrels, 1999).

3.3. Relevance of the model outcomes

The required level of detail in an integrated assessment model directly follows from its purpose in the policy process – in this case to understand the system, explore scenarios, and assess strategies to deal with (potential future) problems (see Fig. 3). Relevant system processes must be included at the right temporal and spatial scale, and their response to changing climate and land use conditions need to be assessed as well. For the exploration of drought risk and mitigation strategies, the NWM should provide a realistic representation of natural variability and extremes of main drivers and internal dynamics of droughts, which determines the frequency and intensity of major drought impacts (Van Loon, 2015). This in turn gives guidance to the policies addressing the balance between water demand and supply under current and potential future climate and socio-economic conditions. The relevant performance indicators for drought risk assessment in the Netherlands include:

- Frequency and severity of soil moisture deficit (which may change due to climate change, land use change and water management actions)
- Average summer groundwater levels (which may change due to the combination of climate change and extractions for drinking water production, industrial use, and irrigation)
- Frequency, level, and duration of salt water intrusion (which may change due to the combination of changing river flows and sea level rise and affecting fresh water inlets)
- Level and frequency of water shortage from the main rivers, canals, and lakes (which may change due to a combination of temperature change, change in river flows, land use change, and farmers' response to climate change).
- Duration and frequency of low water depths along the main waterways that impact inland shipping

This set of variables reflect the many physical processes related to drought. Furthermore, the computational framework allows long time series to represent climate variability, many combinations of measures and scenarios can be simulated, and output is easily connected to economic impact models. The model outcome is thus considered relevant for the decision-making process.

3.4. Timeliness

To be useful in the decision-making process, model results should be published at a convenient and opportune time (Hamilton et al., 2019). Timeliness is not only related to the net simulation time (computation time) of the model, but also to the time it takes to prepare model inputs and schematisations (e.g. derived from scenarios and proposed policy actions) and the analysis of the outcomes. Complex models are more difficult to schematize and interpret, thereby increasing the duration of the modelling exercise, which poses a risk for the timeliness of the outcomes. Available budget to carry out the computations clearly play a role as well, which may limit the efficiency of the simulations. For example, the more model runs that are carried out in parallel, the higher the use cost of processing units. Over the past decade, the simulation time of NWM has significantly increased, due to the addition of sub-models and the simulation of long time series, despite developments in computation architecture that allow parallelization of model runs (see Section 3.2). This increased the simulation time of the full model train from a few weeks to 2–3 months for one 100-year run, making it increasingly challenging to synchronize with the policy-making process and significantly increasing the project costs. In practice the deadlines of the Delta Programme policy-making process are met by limiting the number of NWM-runs and the use of QWAST to explore potential policy actions. This shows that the NWM's ability to simulate a sufficient number of scenario/strategy combinations to answer relevant policy questions is limited.

3.5. Stakeholder acceptance

To increase acceptance of model outcomes, the decisions that are supported by these outcomes, and commitment to its implementation, stakeholders must be engaged in the model design process (Hamilton et al., 2019; Voinov and Bousquet, 2010). Furthermore, model outputs must be scientifically justified and developed without a bias towards a desirable outcome or interpretation (Hamilton et al., 2019; Cash et al., 2003). A range of techniques is available to evaluate the scientific performance of an environmental model (see Bennett et al., 2013), including quantitative comparison with observed data (model validation). Since model behaviour under future conditions cannot be directly derived from model validation, additional (qualitative) evaluation methods are often used based on e.g. theoretical reasoning, extrapolation to future conditions, or finding analogues in different locations or time ranges (Jakeman et al., 2006). Furthermore, trust in model outcomes is also gained by discussions on their plausibility with stakeholders with high expertise in the functioning of the system they manage in practice. Quantitative and qualitative model validation is not carried out as part of the NWM project, but is carried out as part of the projects that maintain and develop the submodels. Although the submodel LHM has been significantly improved over the past 10 years (by including more processes and updating underlying data), full model validation is not applied routinely but undertaken in irregular dedicated projects (such a project is running in 2021; the former validation took place in 2013). Similarly, the submodel LSM has been improved by merging several regional models but has hardly been validated with observed low flow data. Besides model validation, other activities have contributed to the trust in model outcomes. Stakeholders in the LHM project not only advise about model developments, but also share local and regional data about their water system. For example, the groundwater model of LHM is based on upscaled data from the underlying regional high-resolution (25×25 m) groundwater models (e.g. Hoogewoud et al., 2013). Acceptance of the results of national analysis by regional stakeholders is promoted by the ability to compare results with their own regional model outcomes. Also, the periodic discussion of model outcomes with an independent expert group facilitates this acceptance. Such discussions were facilitated in the previous Delta Programme policy cycle as well as in the PAWN study, during which the model-based analysis was reviewed by a group of independent (model) experts from national and regional authorities (Goeller et al., 1985).

Summarizing, because the submodels are developed and validated in a continuous process in close interaction with regional stakeholders, the NWM is accepted as 'state-of-the-art'.

4. The main NWM dilemma

Over the past 10 years, the National Water Model (NWM) has developed into a well-documented and structured, integrated model instrument with interconnected models that are accepted by stakeholders. Its outcomes are used in the drought risk management process, because it describes all relevant drought-related physical processes, it allows long time series to represent climate variability, and it connects to economic impact models. Its computational framework (FEWS) allows transparency and reproducibility of model simulations. Because continuous investments in development and validation of the submodels occur in a parallel process and in close interaction with regional water managers and model experts, these submodels are considered 'state-of-the-art' for national-scale analyses.

The NWM thus meets many of the key requirements. However, the multi-purpose design of some components (particularly the LHM submodel) inevitably lead to trade-offs in the configuration that is not fully optimized for its specific use as integrated assessment model for national policy-making. The subsequent heavy computational burden of the NWM limits its usefulness for the national Delta Programme, because the number of scenario/strategy combinations that can be (afforded to be) simulated in time for the policy process is (too) limited. This demonstrates the main dilemma: an assemblage approach limits development costs and increases stakeholder acceptance, but it also increases the model complexity and computation time, compromising timeliness in and knowledge for the policy-making process. The NWM case shows that policy analysts come up with practical solutions to overcome the dilemma, for example by limiting the number of NWM simulations which increased timeliness but reduced the model outcome relevance, because not all policy questions were answered. Another example is that the length of the time series for some of the scenario runs with NWM was reduced from 100 to 30 years, at the expense of a reduced insight into natural variability and extreme drought events. Another choice that was made to overcome the dilemma was to develop a quick scan model (QWAST) for water demands and water allocation. The QWAST served the purpose of quickly providing insight into the performance of several (combinations of) policy options under a range of scenarios. However, its relevance to the policy process is still limited, because several relevant processes are left out, and it heavily depends on the NWM for input on climate change and land use scenarios. Also, a systematic comparison between the performance characteristics of QWAST and NWM is not executed, limiting the consistency between the two models.

Clearly, the choice of NWM as an integrated assessment model was well-justified for its status as state-of-the-art repository of accepted submodels, but it is currently not fit-for-purpose to explore the desired scenario uncertainty range and the range of policy options in a timely manner. Its computational costs are too large, and its complexity requires considerable time and effort to translate storylines about future development, policy actions and model uncertainty into model schematizations and boundary conditions, and to analyse the model output to provide valuable model outcomes.

For future development and application of the NWM, the following is recommended:

1. Increase the flexibility of the NWM modelling framework and the submodel software, allowing to switch between spatial scales, resolution, and degree of conceptual complexity. For example, in regions where groundwater is less important, the LHM model could be used to simulate surface water allocation with a semi-static groundwater boundary condition. Flexibility may also be introduced by adding the ability to alternate between the national scale and a regional scale using multi-resolution modelling concepts (Davis and Bigelow, 1998; Rabelo et al., 2015). Specific to the NWM case, an upgrade to MODFLOW6 (Langevin et al., 2017) would allow for more flexibility in groundwater modelling, facilitating detailed analysis for a certain region while maintaining connection and consistency with the rest of the model domain;
2. Derive and periodically update a meta-model version of NWM that includes all relevant processes in a less-detailed way than currently done in the NWM submodels. A meta-model or fast-and-simple model mimics the behaviour of complex models by using simplified cause-effect relationships (Davis and Bigelow, 1998; Van Grol et al., 2006; Walker and van Daalen, 2013; Haasnoot et al., 2014). Such a meta-model can be used to explore many combinations of scenarios and policy options, and to assess adaptation strategies. The more detailed NWM and/or its submodels may be used subsequently to perform in-depth analyses for a certain region, sector, and/or measure.

To ensure the acceptance and uptake of meta-model outcomes by all stakeholders, a standardized procedure is required to preserve consistency between the simple meta-model and the institutionalized NWM. Furthermore, stakeholders must be engaged in the model development process (Hamilton et al., 2019; Van Delden et al., 2011; Voinov and Bousquet, 2010). In view of the varying model requirements in terms of spatial and temporal resolution throughout the policy process, the future NWM should not be considered a single integrated model, but instead a collection of detailed, connected submodels and a less-detailed meta--model. Depending on the policy phase and resulting requirements, many scenario/strategy combinations can be explored with the meta-model, or more detailed insights can be obtained with submodels for specific regions, processes, and/or measures (see also Haasnoot et al., 2014).

To move forward with the NWM project, it is recommended to organize a continuous conversation about fit-for-purpose between policy advisors, model experts, and stakeholders. The literature provides useful frameworks to structure and formalize such a conversation (Bennett et al., 2013; Guillaume and Jakeman, 2012). Furthermore, a comparison of models with different levels of complexity is needed to determine the configuration that would be sufficient for answering upcoming drought risk management policy questions.

5. Conclusion

The Netherlands' National Water Model (NWM) is an integrated assessment model that allows exploring and assessing various adaptation measures, long-term strategies, and future scenarios on a national scale in support of policy-making on drought risk management. The model's outcomes are considered relevant and are accepted by stakeholders, but its simulation time is considered too long to respond quickly to policy questions. Also, its complexity requires considerable effort in schematization and analysing the model simulations, which reduces timeliness and increases project costs.

The NWM case has illustrated a clear dilemma that occurs when submodels are used as a basis for developing an integrated assessment model in support of policy-making. Such an assemblage approach limits development costs and increases stakeholder acceptance, but also implies trade-offs when multi-purpose submodels are used. This poses a risk of increased model complexity and computation time, compromising timeliness in and knowledge for the policy-making process. To deal with this dilemma, two recommendations were made: 1) Increase the flexibility of the NWM modelling framework and the submodel software, allowing to switch between spatial scales, resolution, and degree of conceptual complexity; this is known as multi-resolution modelling, and 2) derive and periodically update from this institutionalized complex model a meta-model - i.e., a fast simple model (FSM) - that includes all relevant processes to quickly explore many scenario/strategy combinations.

The insights from the NWM case can be valuable for others that are involved with developing and maintaining integrated assessment models in support of long-term policy-making for water resources management. The fit-for-purpose conversation between policy advisors and model developers deserves formalization and should be continuous in view of changing requirements and ongoing submodel developments. When integrated assessment is supported by a meta-model, a standardized procedure is required to assure consistency between the meta-model and the institutionalized complex model.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We greatly acknowledge the following people, who contributed to this paper by sharing their valuable experience as policy advisor in the first and/or second phase of the Delta Program or as expert in the field of integrated assessment modelling: Bas de Jong, Eelco van Beek, Erik Ruijgh, Jeroen Ligtenberg, Judith ter Maat, Marjolijn Haasnoot, Mark Bruinsma, Neeltje Kielen, Sharon Muurling-Van Geffen, Timo Kroon, and Wim de Lange. We also thank the three anonymous reviewers for their valuable feedback on previous versions of this paper. The research was partly funded by the Dutch Ministry of Infrastructure and Water Management.

References

Abrahamse, A., Van Beek, E., Baarse, G., 1982. Policy Analysis of Water Management for the Netherlands. Techreport in: Model for Regional Hydrology, Agricultural Water Demands and Damages from Drought and Salinity, vol. XII. The Rand Corporation, S anta Monica, California, and Delft Hydraulics, Delft. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref1.

Bennett, N.D., Croke, B.F.W., Guariso, G., Guillaume, J.H.A., Hamilton, S.H., Jakeman, A.J., Marsili-Libelli, S., Newham, L.T.H., Norton, J.P., Perrin, C., Pierce, S. A., Robson, B., Seppelt, R., Voinov, A.A., Fath, B.D., Andreassian, V., 2013. Characterising performance of environmental models. february 2013 Environ. Model. Software 40, 1–20. https://doi.org/10.1016/j.envsoft.2012.09.011. Environmental Modelling & Software 40, 1–20.

Booij, M., Bloschl, G., Franks, S., Kumagai, M., Musiake, K., Rosbjerg, D., 2003. Decision support system for flood control and ecosystem upgrading in the red river basin. IAHS Publ. 281, 115–122.

Bos, H., van Ek, R., Hoogeveen, J., Kors, A., de Lange, W., Vermulst, H., Arnold, G., Kroon, T., 1997. Water onder land, tussen regen en plant – Ofwel: landelijke modellen voor verdrogingsbestrijding (in Dutch). techreport RIZA rapport 97.062. Rijkswaterstaat, RIZA, Lelystad.

Buurman, J., Mens, M.J.P., Dahm, R.J., 2017. Strategies for urban drought risk management: a comparison of 10 large cities. Int. J. Water Resour. Dev. 33, 31–50. https://doi.org/10.1080/07900627.2016.1138398.

Cash, D.W., Clark, W.C., Alcock, F., Dickson, N.M., Eckley, N., Guston, D.H., Jäger, J., Mitchell, R.B., 2003. Knowledge systems for sustainable development. Proc. Natl. Acad. Sci. Unit. States Am. https://doi.org/10.1073/pnas.1231332100.

Clark, M.P., Nijssen, B., Lundquist, J.D., Kavetski, D., Rupp, D.E., Woods, R.A., Freer, J. E., Gutmann, E.D., Wood, A.W., Brekke, L.D., Arnold, J.R., Gochis, D.J., Rasmussen, R.M., 2015. A unified approach for process-based hydrologic modeling: 1. modeling concept. Water Resour. Res. 51, 2498–2514. https://doi.org/10.1002/2015WR017200.

Davis, P.K., Bigelow, J.H., 1998. Experiments in Multiresolution Modeling. MR-1004-DARPA. RAND Corporation, Santa Monica.

De Lange, W.J., Prinsen, G.F., Hoogewoud, J.C., Veldhuizen, A.A., Verkaik, J., Oude-Essink, G.H.P., van Walsum, P.E.V., Delsman, J.R., Hunink, J.C., Massop, H.T.L., Kroon, T., 2014. An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands hydrological instrument. Environ. Model. Software 59, 98–108. https://doi.org/10.1016/j.envsoft.2014.05.009.

Gehrels, J.C., 1999. Groundwater Level Fluctuations; Separation of Natural from Anthropogenic Influences and Determination of Groundwater Recharge in the Veluwe Area. Ph.D. thesis. Vrije Universiteit Amsterdam. PhD Thesis. Research VU, graduation VU.

Gijsbers, P.J.A., Baayen, J.H., Maat, G.J.T., 2017. Quick scan tool for water allocation in The Netherlands. In: Hřebíček, J., Denzer, R., Schimak, G., Pitner, T. (Eds.), Environmental Software Systems. Computer Science for Environmental Protection. ISESS 2017, pp. 97–109. https://doi.org/10.1007/978-3-319-89935-0_9.

Glas, P., 2019. Delta Programme 2020 - Continuing the Work on the Delta: Down to Earth. alert, and prepared. Published by: Ministry of Infrastructure and Water Management, Ministry of Agriculture, Nature, and Food Quality and Ministry of the Interior and Kingdom Relations. https://english.deltacommissaris.nl/delta-programme/documents/publications/2019/09/17/dp2020-en-printversie.

Goeller, B.F., Abraham, S.C., Abrahamse, A., Bigelow, J.H., Bolten, J.G., DeHaven, J.C., Jaquette, D.L., Katz, N.A., Kirkwood, T.F., Petruschell, R., Repnau, T., Stucker, J.P., Walker, W., Wegner, L.H., Vaiana, M.E., 1983. Policy Analysis of Water Management for the Netherlands. techreport Report R-2500/1-NETH. The Rand Corporation, Santa Monica, California, USA. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref22.

Goeller, B.F., Abraham, S.C., Abrahamse, A.F., Bigelow, J.H., Bolten, J.G., de Ferranti, D. M., Haven, J.C.D., Jaquette, D.L., Katz, N.A., Kirkwood, T.F., Petruschell, R.L., Repnau, T., Stucker, J.P., Walker, W.E., Wegner, L.H., Pulles, J.W., Dorsman, W.A., Groen, H., Sprong, T.A., van de Watering, B.G.M., Veen, M.A., Baan, P., Baarse, G., van Beek, E., Dijkman, J.P.M., van Gameren, J., Los, F.J., Koenis, J., Miedema, G., Smits, J.G.C., de Rooij, N.M., 1985. Planning The Netherlands' water resources. Techreport Interfaces 15 (1), 3e33. The Rand Corporation, Santa Monica, California, USA. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref23.

Guillaume, J., Jakeman, A., 2012. Providing scientific certainty in predictive decision support: the role of closed questions. In: Sixth International Congress on Environmental Modelling and Software (iEMSs), July 1e5, 2012, Leipzig, Germany. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref24.

Haasnoot, M., 2013. Anticipating Change: Sustainable Water Policy Pathways for an Uncertain Future. Ph.D. thesis. University of Twente Enschede. https://doi.org/10.3990/1.9789036535595.

Haasnoot, M., Middelkoop, H., Offermans, A., Van Beek, E., Van Deursen, W.P.A., 2012. Exploring pathways for sustainable water management in river deltas in a changing environment. Clim. Change 115, 795–819. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref26.

Haasnoot, M., van Deursen, W.P.A., Guillaumee, J.H.A., Kwakkel, J.H., van Beek, E., Middelkoop, H., 2014. Fit for purpose? Building and evaluating a fast, integrated

model for exploring water policy pathways. Environ. Model. Software 60, 99–120. https://doi.org/10.1016/j.envsoft.2014.05.020.
Hall, J., Leng, G., 2019. Can we calculate drought risk… and do we need to? Wiley Interdiscipl. Rev.: Water. https://doi.org/10.1002/wat2.1349.
Hallegatte, S., Shah, A., Brown, C., Lempert, R., Gill, S., 2012. Investment Decision Making under Deep Uncertainty. Technical Report Policy Research Working Paper 6193. The World Bank. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2143067.
Hamilton Serena, H., Fu, B., Guillaume, J.H.A., Badham, J., Elsawah, S., Gober, P., Hunt, R.J., Iwanaga, T., Jakeman, A.J., Ames, D.P., Curtis, A., Hill, M.C., Pierce, S.A., Zare, F., 2019. A framework for characterising and evaluating the effectiveness of environmental modelling. Environ. Model. Software 118, 83–98. https://doi.org/10.1016/j.envsoft.2019.04.008.
Harbaugh, A.W., 2005. MODFLOW-2005, the U.S. Geological Survey Modular Ground-Water Model — the Ground-Water Flow Process. software 6-A16. U.S. Geological Survey.
Hoogewoud, J., Hunink, J., Prinsen, G., Veldhuizen, A., Verkaik, J., 2013. Veranderingsrapportage NHI 3.0. Beschrijving van de veranderingen in versie 3.0. Technical Report Report number 1206107-000-BGS-0012, 17 april 2013, definitief.. Deltares, Wageningen Environmental Research. http://nhi.nu/nl/files/8114/2651/1956/1206107-000-BGS-0012-DEF-Veranderingsrapportage_NHI_3.0.pdf.
Hunink, J., Delsman, J., Prinsen, G., Bos–Burgering, L., Mulder, N., Visser, M., 2018. Vertaling Van Deltascenario's 2017 Naar Modelinvoer Voor Het Nationaal Water Model. Technical Report Deltares rapport 11202240-009-ZWS. Utrecht, oktober 2018. Deltares.
Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environ. Model. Software 21, 602–614. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref33.
Kelly, R.A., Jakeman, A.J., Barreteau, O., Borsuk, M.E., Hamilton, S.E.S.H., Henriksen, H. J., Kuikka, S., Maier, H.R., Rizzoli, A.E., van Delden, H., Voinov, A.A., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environ. Model. Software 47, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005.
Kroes, J.G., van Dam, J.C., Groenendijk, P., Hendriks, R.F.A., Jacobs, C.M.J., 2008. SWAP Version 3.2. Theory Description and User Manual. Software Alterra-Report 1649. Alterra, Research Institute, Wageningen, The Netherlands, p. 262. http://edepot.wur.nl/39776.
Kroon, T., Prinsen, G., Hunink, J., Visser, M., van den Boogaard, H., 2015. 100 Jaar reeks LHM en LSM; beschrijving van de invoer. Technical Report. Deltares.
Kuijken, W., 2014. Delta Programme 2015 - Working on the Delta. The Decisions to Keep the netherlands Safe and Liveable. Published by: The Ministry of Infrastructure and Environment, The Ministry of Economic Affairs. https://english.deltacommissaris.nl/delta-programme/documents/publications/2014/09/16/delta-programme-2015.
Langevin, C.D., Hughes, J.D., Banta, E.R., Niswonger, R.G., Panday, S., Provost, A.M., 2017. Documentation for the MODFLOW 6 Groundwater Flow Model. software U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197 pp.. U.S. Geological Survey. https://doi.org/10.3133/tm6A55.
Lempert, R.J., Popper, S., Bankes, S., 2003. Shaping the Next One Hundred Years: New Methods for Quantitative, Long Term Policy Analysis. techreport Technical Report MR-1626-RPC. The Rand Corporation, Santa Monica, California. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref41.
Loucks, D.P., van Beek, E., 2005. Water Resource Systems Planning and Management. An Introduction to Methods, Models, and Applications. Springer, Cham. https://doi.org/10.1007/978-3-319-44234-1.
Manders, T., Kool, C., 2015. Toekomstverkenning Welvaart en LeefomgevingNederland in 2030 en 2050: twee referentiescenario's. Technical Report. Planbureau voor de Leefomgeving en Centraal Planbureau.
Marchau, V.A.W.J., Walker, W.E., Bloemen, P.J.T.M., Popper, S.W., 2019. Decision Making under Deep Uncertainty: from Theory to Practice. Springer, Boston, MA.
Meijers, E., Boderie, P., 2004. Sobek Landelijk Temperatuurmodel. Software Q3861. WL | Delft Hydraulics, Delft, The Netherlands.
Mishra, A., Singh, V., 2011. Drought modeling - a review. J. Hydrol. 157–175. https://doi.org/10.1016/j.jhydrol.2011.03.049.
Prinsen, G.P., Wesselius, C., 2015. LSM Achtergronddocument, KPP 2016 Hydraulica Schematisaties – Zoet. Techreport 1220072-015. Deltares, The Netherlands.
Prinsen, G.P., Sperna Weiland, F.C., Ruijgh, E.F.W., 2014. The delta model for fresh water policy analysis in The Netherlands. Water Resour. Manag. https://doi.org/10.1007/s11269-014-0880-z.
Rabelo, L., Kim, K., Park, T., Pastrana, J., Marin, M., Lee, G., Nagadi, K., Ibrahim, B., Gutierrez-Franco, E., 2015. Multi resolution modeling. In: Yilmaz, L., Chan, W.K.V., Moon, I., Roeder, T.M.K., Macal, C., Rossetti, M.D. (Eds.), Proceedings of the 2015 Winter Simulation Conference, pp. 2523–2534. https://doi.org/10.1109/WSC.2015.7408362.
Rijkswaterstaat, 1984. National Policy Memorandum on Water Management (De Waterhuishouding Van Nederland), 2nd PWN. Technical Report. Rijkswaterstaat.
Rizzoli, A.E., Donatelli, M., Athanasiadis, I.N., Villa, F., Huber, D., 2008. Semantic links in integrated modelling frameworks. Math. Comput. Simulat. 78 (2–3), 412–423. https://doi.org/10.1016/j.matcom.2008.01.017.
Ruijgh, E.F.W., Kroon, T., Snippen, E., 2015. The Dutch Delta Model to Support National Policy Analysis. World Water Congress XV. International Water Resources Association (IWRA), Edinburgh, Scotland. 25-29 May, 2015. https://www.iwra.org/member/congress/resource/2982897.pdf.
Van Delden, H., van Vliet, J., Rutledge, D.T., Kirkby, M.J., 2011. Comparison of scale and scaling issues in integrated land-use models for policy support. Agric. Ecosyst. Environ. 142, 18–28. https://doi.org/10.1016/j.agee.2011.03.005.
Van der Linden, M., van Zetten, J.W., 2002. Een SOBEK-model van het Noordelijk Deltabekken: bouw, kalibratie en verificatie. techreport RIZA rapport 2002.002. RIZA, ISBN 903695 420 7.
Van Grol, R., Walker, Warren, de Jong, G., Rahman, A., 2006. Using a Meta-Model to Analyse Sustainable Transport Policies for Europe: the Summa Project's Fast Simple Model.
Van Loon, A.F., 2015. Hydrological drought explained. WIREs Water 2, 359–392. https://doi.org/10.1002/wat2.1085.
Van Walsum, P.E.V., Groenendijk, P., 2008. Quasi steady-state simulation on of the unsaturated zone in groundwater modeling of lowland regions. Vadose Zone J. 7, 769–778. https://doi.org/10.2136/vzj2007.0146.
Verkaik, Jarno, Hughes, J.D., Walsum Van, P.E.V., Oude Essink, G.H.P., Lin, H.X., Bierkens, M.F.P., 2021. Distributed memory parallel groundwater modeling for the Netherlands Hydrological Instrument. Environ. Model. Software. In press.
Vermulst, J.A.P.H., Kroon, T., de Lange, W.J., 1998. Modelling the hydrology of The Netherlands on a nation wide scale. In: Wheater, H.K.C. (Ed.), Hydrology in a Changing Environment. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref63.
Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Model. Software 25, 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007.
Voinov, A., Shugart, H.H., 2013. 'integronsters', integral and integrated modeling. Environ. Model. Software 39, 149–158. http://refhub.elsevier.com/S1364-8152(13)00115-1/sref228.
Walker, W.E., van Daalen, C.E., 2013. System models for policy analysis. In: Thissen, W., Walker, W. (Eds.), Public Policy Analysis. International Series in Operations Research & Management Science. Springer, Boston, MA, pp. 157–184. https://doi.org/10.1007/978-1-4614-4602-6_7.
Wegner, L., 1981. techreport In: Policy Analysis of Water Management for the Netherlands. Water Distribution Modelling Technical Report, vol. XI. The Rand Corporation, Santa Monica, California, USA. http://refhub.elsevier.com/S1364-8152(14)00159-5/sref69.
Werner, M., Gijsbers, P., Schellekens, J., van Dijk, M., van den Akker, O., Heynert, K., 2013. The delft-fews flow forecasting system. Environ. Model. Software 40, 65–77. https://doi.org/10.1016/j.envsoft.2012.07.010.
Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M., 1999. Ground Water and Surface Water: A Single Resource. Technical Report Circular 1139. United States Geological Survey. https://doi.org/10.3133/cir1139.
Wolters, H.A., van den Born, G.J., Dammers, E., Reinhard, S., 2018. Deltascenario's voor de 21e eeuw, actualisering 2017. Technical Report. Deltares. Wageningen Environmental Research, Planbureau voor de Leefomgeving.