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Featured Article

An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument.

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ABSTRACT

Water management in the Netherlands applies to a dense network of surface waters for discharge, storage and distribution, serving highly valuable land-use. National and regional water authorities develop long-term plans for sustainable water use and safety under changing climate conditions. The decisions about investments on adaptive measures are based on analysis supported by the Netherlands Hydrological Instrument NHI based on the best available data and state-of-the-art technology and developed through collaboration between national research institutes. The NHI consists of various physical models at appropriate temporal and spatial scales for all parts of the water system. Intelligent connectors provide transfer between different scales and fast computation, by coupling model codes at a deep level in software. A workflow and version management system guarantees consistency in the data, software, computations and results. The NHI is freely available to hydrologists via an open web interface that enables exchange of all data and tools.

Software availability

All model data are freely available (http://www.nhi.nu/) and the NHI-specific software is free and open. The model-codes are partly open-source and partly in transition to the open domain.

1. Introduction

For over a millennium, people living in the territory that is today the Netherlands have been both battling against and enjoying the benefits of water from the sea, the major rivers Rhine and Meuse, precipitation and seepage of groundwater (Van de Ven, 1993). As a result of their need to maintain habitable, arable and pasture land in deep, reclaimed polders close to the sea and in peaty areas around higher-lying sandy infiltration areas, a sophisticated water management system has evolved (Huisman et al., 1998). The economic developments over the last five centuries have resulted in a dense and highly efficient network of canalized rivers, large canals, lakes, local and regional water storage systems, dams, weirs and sluices, by means of which almost throughout the country, surface water can be manipulated in virtually any direction (Huisman et al., 1998). Nowadays, the surface water is managed according to whether there is a surplus or shortage of water, and in light of its salt content, nutrient load or temperature, the aim being to ensure optimal use with respect to safety, agriculture, nature, shipping, drinking water supply, cooling water for power plants, and recreation (Anonymous, 2009).

The drought of 1976 focused national attention on water shortage and triggered the idea of constructing a national water modeling instrument (Abrahamse et al., 1982) for use in the Policy Analysis for Water in the Netherlands: PAWN (Pulles, 1985). Since then, PAWN has been regularly improved in light of the national water management plans, which have been published at intervals of 3–5 years. During periods of drought, PAWN has been used to optimize the distribution of water throughout the country. The distribution depends on the water availability, the type of demand

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(e.g. drinking water, agriculture, inland navigation, cooling) and on the transport capacity of the system. The actual water distribution is governed by consensus among the national and regional water managers.

Around the year 2000, numerous regional and national models for both groundwater and surface water simulation existed that were based on different technologies, schematizations and data. The different models generated different results that had impact on the strategic and applied water management of national and regional authorities. In response to the problems arising from these different results, the scientific/technical and policy/water management communities in the Netherlands started activities to achieve consensus on technologies, schematizations and data.

In 2005, the national research institutes and national and regional water authorities pooled their water expertise and finances (about 1M€/y) in order to construct and maintain an enhanced national water modeling instrument: the Netherlands Hydrological Instrument NHI (http://www.nhi.nu) (Van der Giessen, 2005). After a significant effort to consolidate available data and technologies, a major consensus–driven activity started in 2010, which resulted in improvement of data, concepts and validation of results. In 2013, a consensus-based NHI was achieved, thanks to the cooperation of virtually all the national and regional water management organizations in the Netherlands. The cooperation of many parties in sharing different data and models has resulted in the development of appropriate tools and data management systems for both surface water and groundwater in the Netherlands.

There are few comparable instruments for integrated water management and policy making issues. Compared with the NHI, however, those that do exist describe the water system less comprehensively, are less embedded in a sustainable data management system, or are not directly applied both to support long-term policy analysis and for daily water management during drought. For instance, (Højberg et al., 2013) presented an instrument for water management in Denmark, based on MIKE-SHE (Abbott et al., 1986a, 1986b) and focus on the sustainable management of hydrogeological datasets that were built consensually by regional and national authorities. Another example is the model for climate change effects in the basin of the river Elbe (Hattermann et al., 2011).

Unlike other comparable instruments, the NHI consists of five physically different models for different water domains with different concepts and different temporal and spatial scales that are explicitly connected using scaling, transformation, implicit iteration and single-to-many and many-to-single coupling. The chain from basic data to model data to results comprises differently-owned national and regional databases and is embedded in an appropriate data management system. In addition, all model data, results and software are intended to be open access and free of charge, while the costs of maintenance and development are intended to be shared by organizations representing all the water authorities in the Netherlands.

This paper presents an overview of the NHI after its most recent overhaul and recent use in policy analysis for adaptive long-term measures to climate change. The overview starts by describing the five hydrological models. The connectors linking these models are described, together with the data management systems. An extensive set of results is presented, and their calibration and validation are described. The long-term management of the instrument and the impact of the NHI in the consensus on long-term decisions on adjusting the water system in light of climate change are discussed.

The present work adds to the increased interest for multi-user, integrated models for water management e.g. under climate change conditions (Carmona et al., 2013; Hattermann et al., 2011; Højberg et al., 2013; Welsh et al., 2013) as well as to the development of open source modeling tools (Knapen et al., 2013; Werner et al., 2013, *water.usgs.gov/ogw/modflow/MODFLOW.htm*) and developments on open data (http://www.globalopendatainitiative.org).

2. The five hydrological models in the NHI

2.1. General description

Typical aspects of subsurface and surface water in the Netherlands (see also Huisman et al., 1998) are sketched in Fig. 1 together with the domains encompassed by the models of NHI. The surface water domain is classified at three levels of operation: at national level few large canals, rivers and lakes with large weirs are available to manage the major transport and storage capacity both during water surplus and shortage. The major resources of water are the river Rhine and the precipitation (850 mm/y) from the maritime climate. At regional level, a large number of intermediate surface water bodies provide regional water distribution. Along the coast in the west and north of the country sub-catchments consist of polders (reclaimed lakes) with abrupt changes of several meters in elevation at short distances. In the rest of the country, most of the brooks and streams have been canalized and seepage zones have been drained to improve the economic value of the land. At local scale, numerous dense drainage pipe systems and ditches operate as the major interaction with the groundwater domain.

The major groundwater domain consists of Pleistocene sands and is overlain by fluvial and marine Holocene peat and clay deposits in the lower-lying areas and by glacial and Aeolian sands in the higher areas. The ice-pushed ridges merely occurring in the center of the country, include steeply sloping layers that cause anisotropy in groundwater flow. In the south-eastern region, faults generate discontinuities in aquifers. The low-permeable base of the groundwater system rises from about 600 m below sea level in the north-west to the surface in the south-east. In a wide zone (50 km) along the entire west and north coast seawater intrusion in the past has caused a wide variation in the salt concentration of groundwater (Fig. 1).

The vegetation on top of the groundwater system merely consists of crops and pasture with forest mainly in the higher areas and designated nature reserves mainly in the lower areas. Local relief affects the presence and amount of infiltration and seepage which, in turn, results in differences in the water quality in the root zone.

A core task of the NHI national model is to optimize the distribution of water throughout the Netherlands during periods of shortage. This task is performed by the Surface Water model for Optimized Distribution (SWOD, Fig. 2) which comprises the main, national surface water system and the major regional surface waters. The water availability and demand from the hinterland is derived from the Surface Water model for Sub-Catchments (SWSC, Fig. 2) and are based on the water balance including surface water and sub-surface water. The sub-surface water flow is simulated by two models: the Soil Vegetation Atmosphere model for the Transfer of water (SVAT, Fig. 2) and the GroundWater (GW, Fig. 2) model. The model for Surface Water Flow and Transport (SWFT, Fig. 2) computes changes in the salt concentration and temperature distribution of the surface water for operational water management under circumstances of water shortage.

The model ID's used in the present paper (Table 1, column on left) are different from the names of operational models (Table 1, column on right) because the NHI is continuously being refined and improved to account for the best available standards in software and modeling concepts.

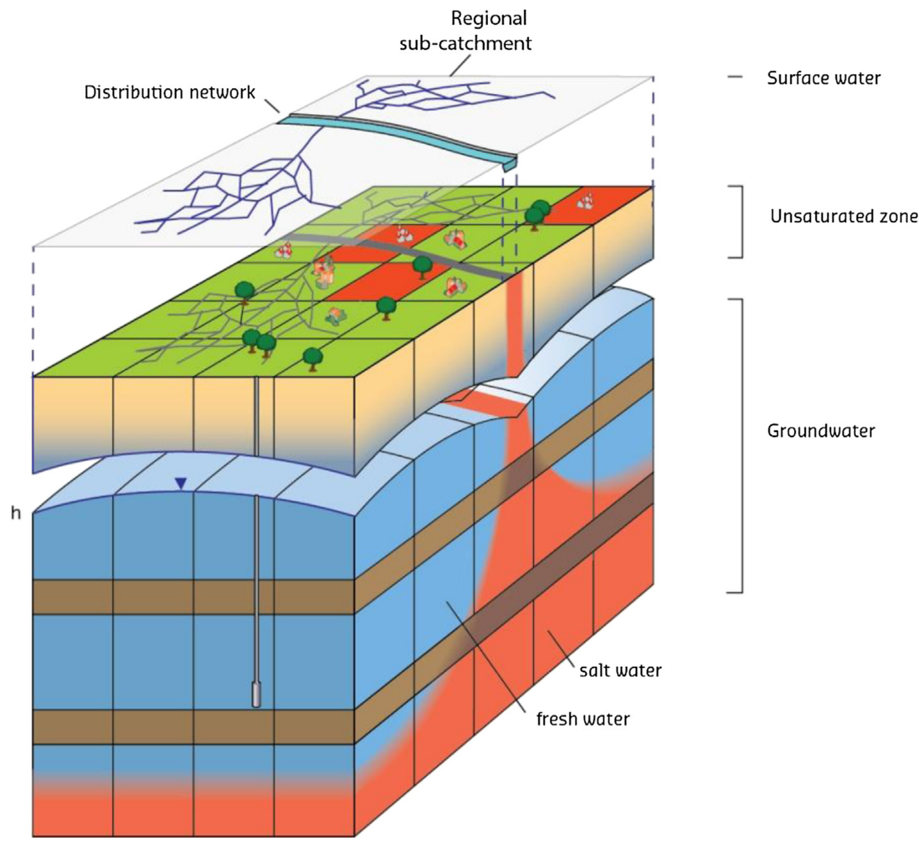

Fig. 1. The water domains covered by the five hydrological models in NHI.

The flow in the different domains is governed by different physical processes and occurs at different spatial and temporal scales. The five models of NHI adapt to these differences by using different computational units (line, polygon, cell) and different scales (Table 2). To achieve NHI functioning as a single working system, connectors have been built to calculate temporal and spatial scaling of parameters and variables between the models (section 3 see below).

Salt is accounted for in all model domains but in different ways. Transport of salt is computed in SWFT (1-D), SVAT (1-D) and GW (3-D), while SWOD and SWSC apply a salt balance approach. Computation of salt is fully integrated in SWOD, SWFT and SWSC and is calculated by additional models for SVAT and GW.

The exchange of water between the five models enables a complete water balance to be derived for the entire country and for each region. Table 3 shows the major input and output flows between the models and across the national borders. A brief overview of each model is presented in the following sections.

2.2. The model for optimized distribution of surface water SWOD

The SWOD model allocates water on the basis of conditional optimization of the demands for water quantity and quality (salt and temperature) from various water users and the availability of water revealed by the water balance of groundwater and surface water computed by the SWSC model. The water distribution network of the Netherlands is schematized as a network of connected nodes, with maximum flows as constraints of the optimization model. The system allows for alternative routing of water, e.g. if the salt concentration of intake water is too high.

The conditions in the optimization come from user priorities and distribution rules. At national level, the highest category of use

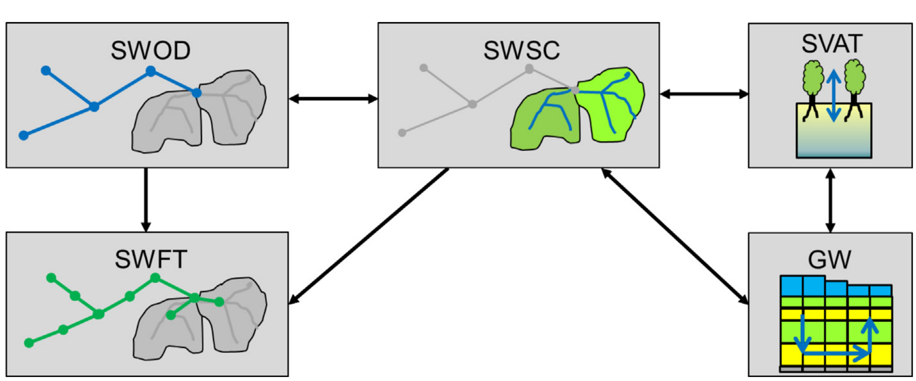

Fig. 2. The relations between the five hydrological models in NHI, see text for abbreviations.

Table 1
General characterization of the models in the NHI.

ID	Domain	Purpose	Scale of process	Present name (www.nhi.nu)
SWOD	**S**urface **W**ater	**O**ptimization of **D**istribution	Nationwide	DM
SWFT	**S**urface **W**ater	**F**low and **T**ransport	Nationwide	LSM
SWSC	**S**urface **W**ater	Distribution to users of groundwater & surface water	**S**ub-**C**atchment	Mozart
SVAT	**S**oil **V**egetation **A**tmosphere	**T**ransfer of water in root zone, soil water deficit	Plot, column	MetaSWAP
GW	**G**round**W**ater	Flow and transport	Regional	MODFLOW

is the maintaining of surface water levels to prevent irreversible damage, e.g. to dikes on peat land or to nature areas. The second category of use concerns the availability of surface water for drinking water and for cooling water for electricity generation. Categories 3 and 4 contain the other water users such as agriculture, industry, navigation and recreation as formalized in regional water agreements. The optimization is done heuristically, allocating water first to the highest priority water users and then stepwise to lower priorities while accounting for discharge capacity limitations. Use of a formal optimization algorithm is foreseen in the near future.

2.3. The model for surface water flow and transport SWFT

The SWFT model computes changes in flows, water levels, salt concentrations and temperature in the national surface waters and is based on SOBEK, a package for 1D and 2D modeling of hydrodynamics, water quality, salt intrusion and morphology (http://www.deltares.nl/en/software-alg).

The SWFT model incorporates branches, nodes and parameters of the national network of the SWOD model and of other existing SOBEK models from regional and national water authorities. The detailed, regional models have been scaled up for use at national level (Prinsen et al., 2013a). The SWFT model uses water allocation fluxes from the SWOD model. The results of SWFT are used to compute how changes in temperature, cooling water, water quality, salinization and water depth for navigation will impact on operational management during periods of water shortage and on policy analysis (Klijn et al., 2012).

2.4. The model for surface water in sub-catchments SWSC

The distribution of surface water computed by the SWSC model is based on the water balance per sub-catchment, which includes

Table 2
Computation units, dimensions and processes.

Model ID	Computation unit	Unit size	Time step	Essential process in computation
SWOD	Node–node	1–25 km	1–10 day	Conditional optimization in response to demands, allocation with rerouting
SWFT	Line	0.5 km	1 day	1D horizontal flow
SWSC	Polygon	0.5–5 km^2	1–10 day	Q-h relations, balance of sub-catchment, gathering demands, allocation with routing
SVAT	Grid cell	250 m	1 day	Unsaturated transfer, evapotranspiration
GW	Grid cell	250 m	1 day	3D saturated flow, salt: density driven

Table 3
Overview of input and output water flows and levels.

ID	Input water flows and levels	Output water flows and levels
SWOD	River discharges across national border, priorities and fluxes of water demands at nodes from SWSC	Allocated fluxes from/to SWSC; discharge to sea, discharges and levels at nodes
SWFT	River discharges across national border, fluxes of water at nodes from SWOD	Discharge to sea, discharges and levels at nodes
SWSC	(Available) fluxes from/to SWOD and from/to adjacent sub-catchments SWSC, drainage from GW inside sub-catchment	Water demand of sub-catchment to SWOD, surface water level change to GW, amount for sprinkling in SVAT
SVAT	Precipitation and evapotranspiration from atmosphere, vegetation type, phreatic level from GW,	Recharge to GW, root zone water deficit to SWSC
GW	Recharge from SVAT, negligible flux across national borders	Phreatic level to SVAT; drainage discharge to SWSC

groundwater fluxes from the GW model and precipitation and evaporation from the SVAT model. In the low-lying (coastal) area of the Netherlands, the polygons encompassing the sub-catchments follow the shape of the polders (flat areas in which target surface water levels are maintained); in the higher areas, the polygons are GIS-determined zones based on the national available shapes of local surface water catchments. The routing of water across sub-catchments consists of discharge-level relationships for the regional surface waters in hilly regions and volume within time step in the polder regions. The water demand and allocation volumes per time step are calculated to provide constant water levels, flushing and abstraction for drinking water, industrial use and sprinkler irrigation. The salt concentration of the surface water is computed per time step from the salt loads and water volumes of surface water and groundwater.

The SWSC model combines all relevant salt loads; from the surface water in the national distribution network, from shallow groundwater discharged by tile drains and ditches, and from the deeper groundwater exfiltrating through boils (De Louw et al., 2010).

2.5. The model for soil–vegetation–atmosphere water transfers SVAT

The SVAT model computes the vertical water transfers in a column between saturated groundwater and the atmosphere, via root zone and vegetation. The evapotranspiration is modeled with a crop coefficient approach, including interception evaporation, plant transpiration and soil evaporation (Van Walsum and Supit, 2012). The flow in the unsaturated zone is based on the Richards concept for 1D uniform flow, as yet not accounting for hysteresis, preferential flow or cracks.

A meta model (MetaSWAP, Van Walsum and Groenendijk, 2008) is used to reduce the computational effort needed in NHI to much less than required when applying a classical Richards type column model (SWAP, Kroes et al., 2008). The partial differential equation of Richards equation is replaced by two ordinary differential equations; one for the variations in the vertical column (using the steady state flow equation) and the other for the variations in time. At preset time steps in the calculation process, the separate solutions are combined in the final result.

The steady-state solution comprises a database of pre-computed profiles of the water saturation at discrete intervals of soil moisture status and depth to the groundwater level covering the full range of possible situations by smart combinations. These profiles are used in a non-steady model by conversion into up to 18 aggregation boxes, starting with the root zone and ending with a box extending into the saturated groundwater. The meta model computes through time by means of a 'quasi-steady' state concept that uses the available profiles in the database flexibly in such a way that each box has its own dynamics, with varying intensity of the vertical flux (percolation or capillary rise). The boxes are linked as a chain of reservoirs. At the pre-set time steps in the calculation process, each stage of saturation is updated at the aggregation level of the boxes. Via a reversal of the aggregation procedure, the associated detailed saturation profiles are derived from the database to calculate the moisture stress factor needed for the computing the actual transpiration that is fed back into the aggregated model. The detailed profiles are also used in the additional salt model (section 2.1) and in water quality modeling (section 9).

The soil of the Netherlands is characterized by 72 units given in Wösten et al. (2013). The meta concept has been verified for these soil units by comparing the results of non-steady state simulations to the results of the SWAP model from which the meta concept has been derived (Van Walsum and Van der Bolt, 2013).

2.6. Model for saturated groundwater GW

The GW model computes semi-3D (Strack, 1984) flow in a model with 1.6 M cells of 250 × 250 m, using MODFLOW 2005 (http://water.usgs.gov/nrp/gwsoftware/modflow2005/modflow2005.html). Seven aquifers and aquitards represent the more than fifty hydrogeological layers distinguished in the national hydrogeological database REGIS (http://www2.dinoloket.nl/nl/about/modellen/regis.html). Large amounts for drinking water and industry are abstracted from the deeper aquifers, while sprinkler irrigation mainly comes from the upper aquifers.

The surface water levels in the GW model are adjusted by the SWSC model during the NHI's computations. The phreatic storage coefficient, phreatic head and flux to or from the unsaturated zone are determined during iteration (section 3) with the SVAT model.

Groundwater discharges from and to surface water change during seasons and, in terms of boundary conditions, can be highly non-linear with respect to differences between the levels of groundwater and surface water. Surface water networks in the country vary from densely-distributed discharge systems (including tile drains) to extensive systems that fall dry during summer. After being classified (mainly by wet perimeter), these different discharge systems are translated into a set of parameter values in the RIVER package of MODFLOW by using a uniform upscaling procedure (De Lange, 1999, 1996).

A separate version of the GW model computes full-3D variable-density groundwater flow and coupled salt transport. To account for groundwater density effects, this model contains forty layers instead of seven (e.g., Oude Essink, 2001; Oude Essink et al., 2010). The model is currently being overhauled; this entails transfer to a SEAWAT setting (Langevin and Guo, 2006) and extension to parallel computation e.g. of temporal changes in the density (salt) distribution.

3. The connectors between the hydrological models

3.1. Technical description

The data shared between the models described in section 2 are exchanged by connectors as presented in Table 4, in which the terminology applies to the hydrological purpose of the models. Each connector is specific to the two adjacent models it links and, in some cases, also to the direction of the transfer. Many connectors include data transformation by simple or complex calculations that can be both a many-to-one combination of data and a change of data type (line, polygon, cell). The connectors provide spatial and temporal scaling and maintain consistency of fluxes and heads between the models. In effect, they form the "intelligence" of the NHI by describing our physical understanding of how the different hydrological systems act and are connected.

An example is the connector between the SVAT and GW models (Van Walsum and Veldhuizen, 2011), with the phreatic head as a 'shared state variable' for providing a seamless integration of two models. The basic idea is that the phreatic head is updated alternately by the SVAT model and the GW model. In the implementation of the method, the SVAT model prepares its update of the GW model by first computing an unsaturated-to-saturated flux and also a non-linear storage-head relationship; together they form a non-linear boundary condition of the third kind for the GW model. This boundary condition is then used in a within-time-step iteration to a single head at the phreatic surface in both models, while exchanging the variables summarized in Table 4.

The basic principle in the software code behind the connectors is that a single, main driver program is used, in which all connectors

Table 4
Description of connectors between the hydrological models.

Connector	Concept of connection	Coupling level	Exchange variables	Transformations
SWSC ↔ SWOD	Surface water routing and regional assignment based on national priorities	Straightforward data transmission	Surface water flux, salt load	Spatial: aggregation from polygons to encompassing polygon
SWOD → SWFT	Surface water flow and routing based on national priorities	Straightforward data transmission	Surface water flux, salt load	None
SWSC ↔ GW	Drainage levels depend on the regional surface water routing process for water demand and allocation	Straightforward data transmission	GW tot SWSC: salt load by seepage from deep aquifer SWSC to GW: change in surface water level	Temporal: 1 day ↔ decade (10 days)
SWSC ↔ SVAT	Regional irrigation resources from surface water depends on the national surface water allocation and the available groundwater seepage	Straightforward data transmission	SVAT to SWSC: surface water irrigation demand (at start of allocation), salt load SWSC to SVAT: water availability for surface water irrigation	Spatial: aggregation of cell values within polygon
SVAT ↔ GW	(Non-linear) connection where the groundwater head is a function of recharge and phreatic storage, and recharge/storage is a function of phreatic head	Internal iteration (Picard)	GW to SVAT: Phreatic head SVAT to GW: unsaturated-to-saturated flux, storage coefficient	None

are managed. Each model code (section 2) is split into parts (initialization, do time step, do iteration, finalize, etc.), similar to what occurs in the code of HECRAS-MODFLOW (Fenske et al., 2008). This splitting at the deepest level in software enables the complex computation process to be managed in great detail. It supports understanding of the numerical and physical processes within the NHI as a whole. The splitting also enables connectors and model codes to be updated independently. A few minor adjustments are needed for the software to comply with the Open-MI standard (Gregersen et al., 2007).

3.2. Operation of connectors during water allocation in periods of scarcity

A major task of connections in the NHI is to transfer and translate data throughout all models when calculating water demand and water allocation (and salt concentrations) during a period of water scarcity (Fig. 3). The water demands are specified either as pre-described input (e.g., a timetable of desired lake water levels, or desired discharges for flushing to combat salt intrusion) to the SWOD model, or are computed by the SWSC model interacting with the SVAT model and GW model.

From a computational point of view, the demand and allocation come down to modeling a non-linear process of interactions in groundwater and surface water. The national distribution or allocation (Fig. 3, green arrows) follows from the water demand in all sub-catchments in the country (Fig. 3, blue arrow). The water demand per sub-catchment (SWSC, Fig. 3) is compared with the water volume available through the distribution network (SWOD, Fig. 3), taking into account the available surface water and groundwater and the needs of the users in each sub-catchment. If there is a shortage of fresh water, the water allocation is optimized (Fig. 3, green arrows) while accounting for the demands of different user categories (section 2.2). The optimization occurs in a decade time period, which is 10 days, except for the last period of each month, which ranges from 8 to 11 days. The scaling to 36 decades per year generates acceptable computation times and enables a water balance approach to be used instead of a full-scale 1D surface water flow model.

4. Data and workflow management

The data sets involved are usually very large. Many developers and users work with these tools, and all have their own field of interest. In order to manage all the activities consistently, it is essential to have a version management system for the data and computer codes. All the tools in this system have been constructed to perform well with very large data sets. The basic principle of the data management in the NHI is to decouple data in files into metadata and bulk data. The metadata is stored in SubVersion (Collins-Sussman et al., 2004) and the bulk data is stored read-only in a file server that is reachable by the File Transfer Protocol (FTP). The metadata describes the file content and the file access protocol and location.

The data management system is schematized in Fig. 4. The workflow management tool is based on the open software VisTrails (Bavoil and Callahan, 2005) and applies to all activities in the schematization phase and the post-processing (Fig. 4). The actions performed in the run phase are formalized in a Python run script. This combined workflow tool is integrated with the new version control tool called FileSync, which handles all data in the run phase, the schematization phase and the post-processing phase.

Access to the input and output data of the NHI is open and free to any person after registration. The access (purple area in Fig. 4) consists of a Web-based viewer directly linked to an OpenDAP (Cornillon et al., 2003) server with a (one-way) link to the NHI data. On the OpenDAP server the NetCDF (Rew and Davis, 1990) file format is used, following the Climate Forecast convention (Gregory, 2003).

5. Pre and post-processing

Pre-processing tools produce model-specific input data from data in external databases (Fig. 4, green box). Major external databases comprise data on daily weather, land use (e.g. agriculture), surface water levels, topography and land elevation, subsoil type and abstractions. A key pre-processing tool is used to compute the parameters in the interaction between surface water and groundwater in the GW model. Certain model input (e.g. surface water level, drainage parameters) are used in several models and require different transformation for the different models.

Post-processing tools (Fig. 4, box on lower right) transform the results into formats for visualization and interpretation. Recently, Delft-FEWS (http://www.deltares.nl/en/software/479962/delft-fews) has been applied to analyze the results of the NHI in support of national, strategic decisions to adapt the water management system for climate changes (Prinsen et al., 2013b). Post-processing models have been developed for the same application to assess the cost and benefit for agriculture (Ruijgh and Kroon, 2014) and the impact on nature (Haasnoot and Van de Wolfshaar, 2009). During periods of water shortage, Delft-FEWS is used to obtain daily predictions of levels of groundwater and surface water that are used to support operational decisions on national water distribution.

6. Sharing data with stakeholders

Since its inception in 2006, a major aim of the NHI has been to achieve stakeholder participation. The national government, regional water authorities, drinking water companies and the participating research institutes have supported the development

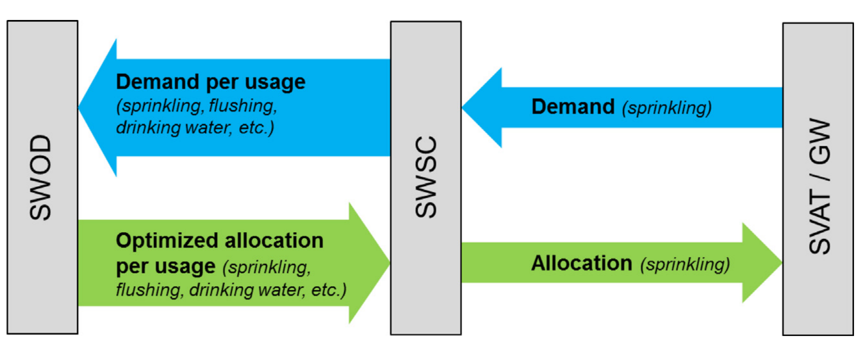

Fig. 3. Connectors transferring water demand and allocation (green and blue arrows) in periods of water scarcity.

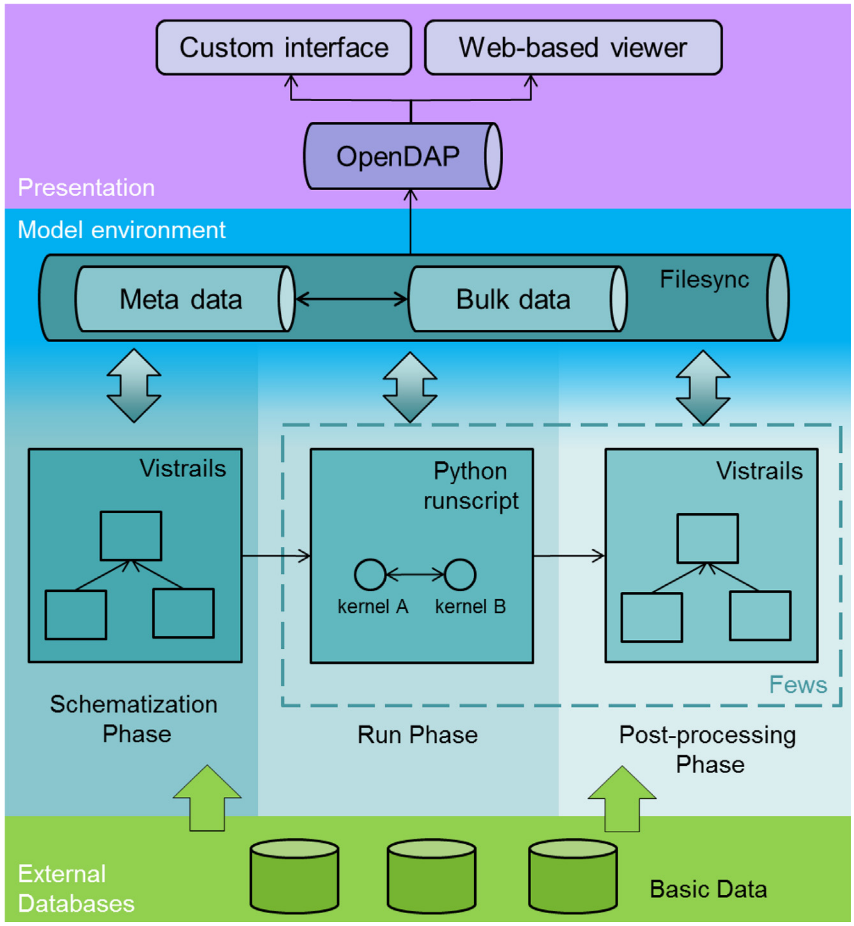

Fig. 4. Data flow and management in the NHI.

of NHI both financially and in kind, with the aim of achieving a set of sustainable data and state-of-the-art tools for use nationally and regionally. In 2011 and 2012, significant effort was put into the exchange of knowledge on concepts and data in surface water and groundwater models, in order to secure regional consensus about the national instrument. Workshops were given, and were attended by hydrologists from almost all the water-related organizations in the Netherlands. The consensus-generating process will be repeated periodically. As a result of discussions during the workshops, it has been agreed that the responsibility for keeping input data up to date should be set at the lowest possible organizational level (local, regional or national). At national level, consistency is maintained in the entire process of model building. Below, we give some examples of data sharing with stakeholders from the consensus process sketched above, grouped per model in the NHI.

The SWFT model has been expanded to the major regional surface water systems, which are based on the existing calibrated regional models of the water authorities. The aim of all parties is to derive a consistent set of national and regional schematizations by using consensus-based transformation (e.g. scaling, condensing) procedures. The representation of sub-catchments in the SWSC model has been improved with input from the field hydrologists of the water authorities. The priorities for water usage in sub-catchments during drought are specified by regional water authorities and are used directly in the SWOD model.

The SVAT model has been improved by field hydrologists visually inspecting maps of input data region by region. Farmers have been recognized as stakeholders by incorporating into the model the status of agricultural land-use (including the presence of drainage pipes and information on sprinkling) from a statutory annual internet-based survey of farmers. Participation in the survey is mandatory, prescribed by laws on national environmental responsibilities.

The GW model has been compared with existing calibrated regional groundwater models, each built by different groups of stakeholders. To deal with existing differences in the number of aquifers and aquitards, tools (www.imod.nu/downloads/Deltares_Flyer_NL.pdf) have been developed as part of the national Groundwater Model Data Base GMDB (www.gmdb.nhi.nu), in which all models used in the comparison are stored and can be visually compared. For the national schematization, regional and national geohydrologists have determined the best available parameter values and extents of layers based on comparison at the finest distinction of hydrogeological units from the REGIS national hydrogeological database (see section 2.6). Large abstractions are administered by authorities and drinking water companies; this entails the issuing of statutory permits. Their locations and abstraction rates are made available in the GMDB, insofar as they are needed by the GW model.

7. Calibration and validation

In 2012, a limited number of parameters on the interaction between surface water and groundwater in version 3.0 of the NHI were manually calibrated, to represent the dry year of 2003 as a typical dry year with known operational water management. It is not yet possible to calibrate by parameter optimization of the entire modeling system, but ideas have been advanced on how to do so, and expert meetings have been held on the topic. Automatic calibration of all parameters in the NHI is a huge task and will require expertise from many. At present, calibrated model data in the NHI come from existing regional models and apply merely to the surface water schematization in the SWFT model. Experience gained from calibrations in the regional groundwater models (e.g., parameter values and extents of separating layers) has been used to improve the consensus data set in the GMDB (section 6), which is used directly in the NHI.

Each major release of the NHI national model is validated against measurements selected from a period of 15 years that includes extremely wet and dry years. These comprise fluxes measured at about 25 sites in the main surface water system and 45 sites in regional surface waters and measurements of the phreatic surface and heads in deeper aquifers at thousands of locations. For about 20 sites, measurements of salt distributions in surface water are used in the validation. National and regional experts on integrated water management have set up a benchmark (Kroon and Ruijgh, 2011) that gives the permissible percentages of deviations allowed between the measured and computed values of a major output variables used for national policy making, such as surface water discharges, water deficit in the root zone during drought, typical highs and lows in the phreatic heads, and salt concentrations in surface water in the coastal zone.

The NHI national model of 2013 does not entirely satisfy the benchmark for two recent years (2003 and 2006) with significant periods of drought (Hoogewoud et al., 2013). However, it has been accepted for use in national policy analysis, largely as a result of involving stakeholders and experts in building a consensus input dataset. The recent policy analysis in the Netherlands (Klijn et al., 2012) is mainly intended to predict water demand in future scenarios under climate change conditions. It was found that a limited number of output variables accounts for the decisions and are computed sufficiently accurate for policy decisions to be made (Marchand and De Lange, 2013).

8. Overview of output of the NHI

In Fig. 5 we present different types of results in three different regions, selected from nationwide covers of the 2013 version of NHI. These results are applied in national policy making as described in section 9. The description follows the four panes (A, B, C, D) shown in Fig. 5.

8.1. Upper left corner

Between the nodes in the distribution network for this region (map on right, bold nodes and lines) of the SWFT and SWOD models, the surface water fluxes over time are calculated in accordance with the water balance (top-left figure). The light blue (dotted) line in the lower left figure represents the calculated surface water flux in 2003 and the black line represents the measured fluxes.

Each node in the network is connected to a group of sub-catchments (map on right, groups of sub-catchments in shades of blue, linked by light arrows to and from a bold node). In each sub-catchment, the water balance (top left-hand figure, mm/day water averaged over the entire area) is evaluated, resulting in water allocation in response to the water demand and taking account of groundwater seepage (pane C).

8.2. Upper right corner

The transport of salt is computed in the surface water network (left-hand figure, colored lines). The chloride concentration in the surface water is calculated in each sub-catchment (right-hand figure, colored domains) from the salt balance in the surface water and includes salt from groundwater seepage (pane D).

8.3. Lower left corner

The water volume per sub-catchment allocated by the SWOD and SWSC models is distributed per 250 × 250 m cell as presented in the top grid (cover 1). Major components in the water balance per cell are (top – down order in pane C): The water demand (cover 2) for agriculture comes from the soil water deficit for crops and other vegetation calculated by the SVAT model, and includes the evapotranspiration (cover 3). The surface water is fed by groundwater seepage (cover 4) and drainage (cover 5) computed by the GW model, which supplies the flux across the upper aquitard (cover 6) and head distribution (cover 7) to the connector between the SVAT and GW models.

8.4. Lower right corner

In each sub-catchment, the chloride concentration of the surface waters (pane B) and the flux and concentration of the groundwater seepage (middle cover) result in the salt load (top cover) in kg/ha. The groundwater seepage comes from direct flow into ditches as well as from leachate into drains in the unsaturated zone. The salt concentration in the groundwater model is described by a fully 3D distribution (bottom figure) based on approximately 65,000 measurements.

9. Discussion

The NHI serves two major aims, the first being a model for long-term national policy making and real-time forecasting for daily water management (Berendrecht et al., 2009), the second being a state-of-the-art toolbox and a source of sustainably managed data available for all hydrologists in the Netherlands. Although developed for the Netherlands, the experience, tools and management system are considered valuable for many applications in other parts of the world.

The national model for policy analysis by the Dutch government has been developed according to the four phases in DTAP: Development – Testing – Acceptance – Production (http://en.wikipedia.org/wiki/Development,_testing,_acceptance_and_production). In practice, this means that computations are carried out only with the tested and accepted version that runs in a separate production environment. This was found to be important for stable and continuous computations of runs that may take up to several weeks of computation time using parallel computing and that generate several terabytes of output data each run.

The applications described in this paper are examples of integrated water system analysis. As a first example, the national model computes all the hydrological effects that are needed for post-processing tools that translate these results for use in cost – benefit analysis for agriculture, shipping, cooling water, etc. (Fig. 5, left-hand side). A second example is the assessment of the effects of climate change on salt intrusion in surface water as well as in groundwater. The NHI computes the salt load on the water system and the subsoil, which can be translated into the effects on the availability of fresh water for drinking water, irrigation, natural vegetation, etc. (Fig. 5, right-hand side). A third example is the application for operational water management during water scarcity, by using Delft-FEWS to obtain daily predictions of heads and fluxes in groundwater and surface water. Output – in terms of fluxes per layer – of the NHI national model is planned to be used in models for the leaching of nutrients (Wolf et al., 2003) and

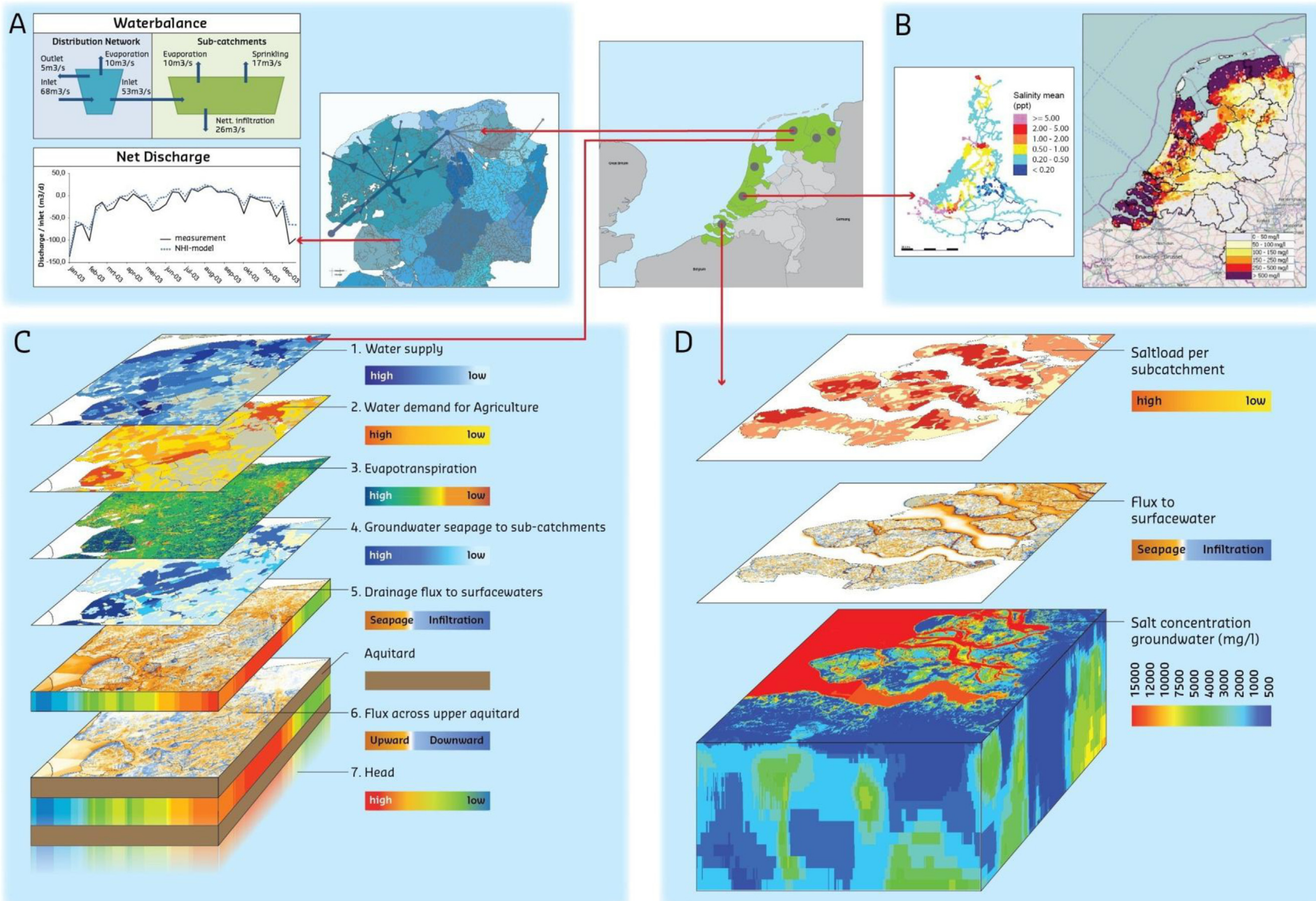

Fig. 5. Overview of results of the NHI, in four panes: A) water balance of subcatchments and main surface waters, B) salt in surface water system, C) fluxes and heads in unsaturated and saturated groundwater, D) salt concentration in saturated groundwater and salt flux to surface water. Detailed description in section 8.

pesticides (Tiktak et al., 2012, 2002) to the groundwater and surface waters. The purpose of these models is to support policy evaluation and pesticide registration.

The connectors, the version management system, the workflow and data management (section 3) and the model codes (section 2) can be seen as a set of tools that can also be applied in less complex situations and with smaller datasets. The use of different model codes enables the physically relevant processes to be modeled at appropriate scales. The smart operations between model codes by the connectors, including the scaling in time and space, can also be used in combination with other model codes available elsewhere. In addition, the model codes in The NHI will soon become open-access software, which will enable universities to participate in the development of the NHI by supplying state-of-the-art technology and will also allow commercial users to provide feedback that can be applied to improve NHI's applicability.

The experience of sharing data with stakeholders (section 6) has shown that when jointly building an integrated model instrument, it is crucial for regional and national water authorities to have the same focus and share the same challenge at all levels of water management. The development of joint rules for the upscaling of surface water schematizations has enabled one-to-one comparison of results from regional models and the national model. In addition, the boundary conditions of regional models have been improved on the basis of the two-sided consistency of the national model at these boundaries. The result of the collaboration is a tool for comparing groundwater models with different schematizations and different numbers of aquifers. Using this tool, calibrated results from regional models have been translated into improvements in the national model. Consensus on the schematization and parameterization of the subsoil has been obtained successfully by open discussion between experts.

10. Concluding remarks

We have presented an overview of a comprehensive instrument that is the outcome of 35 years of development and collaboration between water-related governmental and private organizations. Given the support of the water authorities in the Netherlands, it is envisioned that the NHI will become *the* hydrological instrument and toolbox (tools and data) for model-based solutions to surface water and groundwater issues at national, regional and local scale. Many aspects of the NHI have only been mentioned briefly in the present paper and will be elaborated in future publications.

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