Development of an Operational Drought Forecasting System Using Coupled Models for Groundwater, Surface Water and Unsaturated Zone

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ABSTRACT: During periods of drought the National Coordinating Committee for Water Distribution of the Netherlands has to decide how the available surface water is used and allocated between different functions. To support decision making, real-time information is needed about the availability of surface water, groundwater levels, saturation of the root zone, etc. This real-time information must give insight into the current state of the system as well as into its state in the near future.

For this purpose an operational drought forecasting system has been implemented. This system runs on a daily basis and provides distributed model estimates and forecasts of hydrological variables for the whole of the Netherlands. The model consists of a nationwide distribution model and surface water model coupled with a MODFLOW-MetaSWAP model of the saturated-unsaturated zone (250x250 m^2). Model forcing includes radar data of actual precipitation and point measurements of actual evaporation.

Model forecasts are driven by precipitation and evaporation from the Ensemble Prediction System. Each day 50 model runs are performed in parallel to calculate 10-day forecasts based on the ensemble members of the EPS. The system is operationalized within Delft-FEWS, which is an operational forecasting system to manage data and models in a real-time environment.

1 INTRODUCTION

1.1 *Drought and Water Shortage*

During periods of drought many sectors and societal interests may experience difficulties as a result of water shortage. Water shortages occur when water demand exceeds the availability. Every sector has its own specific demands concerning the availability of water. Agriculture for example, demands a good management of water levels and an abundant quantity of water for irrigation. Energy and industrial sectors require access to sufficient quantities of surface water with a relative low temperature. And the navigation sector has an interest in high water levels in the waterways. For all these sectors water shortages lead to extra costs, limited production, lower profits and/or decrease of quality.

Water shortages in the Netherlands manifest themselves mainly in the soil and therefore in groundwater levels. In dry periods soil moisture deficits occur. These result in suboptimal growing conditions for plants. In extreme cases plants will die but normally water shortages manifest themselves in reduced growth and thus yield reductions. Water shortages can also occur in surface waters, resulting in difficulties to control and maintain water levels in the primary and secondary water systems for navigation and to safeguard the stability of dikes, dams and other flood defense structures. It could also lead to insufficient water for drinking water, industrial and irrigation purposes or flushing of the local and regional water systems.

1.2 *Operational Drought Forecasting*

In case of water shortage the National Coordinating Committee for Water Distribution of the Netherlands has to decide how the available surface water is used and allocated between different sectors. Real-time information on the current and forecasted demands and availability of water is then essential. For that purpose an operational drought forecasting system has been developed. This system runs on a daily basis and provides distributed model estimates and forecasts of hydrological variables for the whole of the Netherlands. The model consists of a nationwide distribution model and surface water model coupled with a MODFLOW-MetaSWAP model of the saturated-unsaturated zone (250x250 m^2). The model is driven by radar data of actual precipitation, point measurements of actual evaporation and measurements of discharges and water levels.

The operational system runs within Delft-FEWS. This operational forecasting environment manages all data and models, which means that it collects all relevant data, prepares model input, runs the models, and processes all essential model output.

1.3 *Overview*

This paper presents the drought forecasting system as implemented for operational use in the Netherlands. Chapter 2 gives an outline of the model. It describes the basic principals of the models that are applied to provide daily estimates and forecasts of water availability and water shortage. Chapter 3 describes the operational forecasting system as being implemented within Delft-FEWS. Finally, chapter 4 contains a short discussion and some topics for further research.

2 MODEL OUTLINE

2.1 *Introduction*

The Netherlands Hydrological modeling Instrument (NHI) aims at modeling the complete interconnected hydrological system on a nation scale. The model was set up with several requirements in mind. A key requirement of the model building process was consensus among the participating institutes, all with different historical backgrounds in hydrological modeling. Furthermore, model building had to be completely transparent and reproducible, to allow for transparent policy analysis. The model was set up using the model codes MODFLOW (saturated groundwater flow), MetaSWAP (unsaturated zone) and MOZART/DM (surface water).

The Netherlands Hydrological modeling Instrument makes full use of available national databases. Nationwide data is becoming increasingly available at ever finer resolutions. The NHI uses, amongst others, topographical data, elevation data, soil data, land use data water management data, and data on the subsurface. Several data sources have been specifically refined for the NHI, such as data on hydraulic soil properties, vegetation development, vegetation evapotranspiration, and data on local and regional water management.

2.2 *Model concepts*

Saturated groundwater flow in the Netherlands Hydrological modeling Instrument is modeled using a MODFLOW model (Harbaugh et al, 2000). The model area covers the entire mainland of the Netherlands, excluding only the southernmost part. This area has a distinctly different geological build-up, consisting of hardrock instead of the unconsolidated sediments in the remaining part of the Netherlands. The horizontal resolution of the model is 250 meters. Including a buffer area to minimize boundary effects, the model area consists of 1300 x 1200 cells. For consistency reasons with existing national groundwater models, the NHI opted for a four-layer vertical discretization of three aquifers, three aquitards and the phreatic surface.
The unsaturated zone is modeled using an on-line coupling of MODFLOW with the MetaSWAP model. The MetaSWAP model (Veldhuizen et al., 2006) has recently become available as a meta-model of the SWAP model. The SWAP (Soil Water Atmosphere Plant) model is a deterministic column-model of the unsaturated zone, and the interaction of the soil with its supported vegetation and the atmosphere. Comparison of MetaSWAP with the original SWAP model shows excellent agreement, while calculation times have been reduced by several orders of magnitude (Van Walsum and Groenendijk, 2008). The MetaSWAP model operates on the same spatial resolution as the MODFLOW model.
Surface water flow is accounted for in the coupled box-models MOZART and DM. The regional surface water system is schematized in MOZART using drainage basins of, on average, 2 km^2. The model accounts for drainage, precipitation and evaporation and local water management including level control, water distribution and flushing. Topographical and elevation data have been combined with information on weirs to calculate discharge-stage relationships in an automated procedure. Local water boards were interviewed for information on local water management rules. The DM model calculates water distribution at the nation scale. The model allows for the simulation of water allocation to drought-affected areas. Water management rules are based on current practice by the Ministry of Transport, Public Works and Water Management.

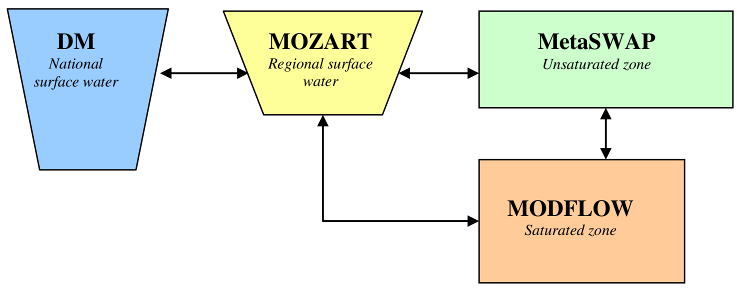

Figure 1 Model components and their interconnections in the Netherlands Hydrological modeling Instrument

3 OPERATIONAL FORECASTING SYSTEM

3.1 *Concept of DELFT-FEWS*

DELFT-FEWS is an operational forecasting system developed over several years at Deltares. The main philosophy underlying the system is to provide an open shell tool, that allows integration of arbitrary hydrological models with meteorological data and numerical weather forecasts. In its actual form DELFT-FEWS constitutes a collection of platform-independent software modules, linked to a central database. The database is used to store historical data from gauging stations, and meteorological data from local and synoptic meteorological stations. These can be updated on-line through direct access to national weather services, weather forecast centres and hydro-meteorological services. In addition, the platform is designed to import and convert numerical weather forecasts produced by weather agencies, and interface them with the database. The system incorporates a wide range of algorithms for data verification, interpolation, model updating and data assimilation. These can be employed for data verification and reconstruction of missing values, as well as for preprocessing of meteorological data, such that are made ready for use in hydrological models. The various hydrological models are included into the system via appropriate model adapters, that convert data in the database to specific model data formats and vice versa. In this manner a concatenation of various operational and already tested models into model cascades is facilitated within a single and consistent computational framework.
This chapter gives a brief overview of the configuration of the Netherlands Hydrological modeling Instrument in DELFT-FEWS. The next sections describe the import of necessary data, the process of running the model and, finally, the post processing of model output.

3.2 *Data Import*

Precipitation and evaporation are among the main driving forces of the Netherlands Hydrological modeling Instrument. Several types of precipitation data are being imported from KNMI (Royal Netherlands Meteorological Institute), including radar image data of the accumulated daily precipitation amount (resolution of 1 km^2) and precipitation amount from stations in the climatic rain measuring network (325 stations). An example of a radar image projected on the model domain in given in Figure 2. Evaporation is derived from observation data of a limited amount of meteorological stations spread all over the country.
Surface water levels and discharges are imported from the Water Monitoring System for the river Rhine and Meuse. Deterministic and ensemble are forecasts of discharge and water levels of the Rhine and Meuse are imported from the operational flood forecasting system of the Rhine and Meuse.
At several locations in the Netherlands groundwater level data is available in real-time. This data is imported into the operational system and can be used to verify model output.
Model forecasts are driven by deterministic and ensemble forecasts of precipitation and evaporation (derived from temperature) from the Ensemble Prediction System (EPS) of the European Centre for Medium Range Weather Forecasts (ECMWF) in Reading, UK. The forecast horizon is 10 days. Each day 1 deterministic model run plus 50 ensemble runs are performed to calculate an ensemble forecast of groundwater level, surface water level and soil moisture content.

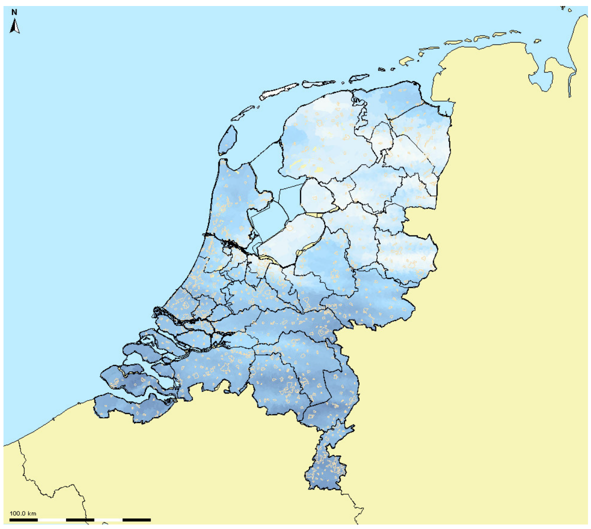

Figure 2 Radar image data

3.3 *Model Adapters and Workflows*

Model adapters transform imported data (stored in the DELFT-FEWS database) into model input files, After a model run, the adapters read data from the model output files and store these data in the DELFT-FEWS database. In this way, an adapter can be seen as the connection between DELFT-FEWS and the models.
Each day, a model run is performed to calculate the actual state of the system. For the coupled MODFLOW-MetaSWAP model, this means that precipitation and evaporation are read from the database and written as input files for MetaSWAP. Surface water discharges are take from the database as input for the MOZART/DM model. At this moment, other time-varying driving forces such as groundwater extractions for industrial and drinking water purposes, are based on historical data.
After the actual state of the system has been calculated, the 10-day ensemble forecasts are calculated using the 51 ensemble members of precipitation, evaporation and ensemble forecasts of river discharges. The model forecasts are computed in parallel.

3.4 *Model Output and Visualization*

All model output is post-processed by the adapters and stored in the DELFT-FEWS database. Users can visualize relevant output data within DELFT-FEWS. For drought forecasting, water demand and water shortage are essential parameters. As an illustration, Figure 3 shows a forecast of the water demand and water shortage. The left figure shows that there is a high water demand in several western and northern districts. The right figure shows that only for some districts, this will result in a water shortage. Based on this information, the National Coordinating Committee for Water Distribution can advise on the water distribution and, for example, can suggest to reallocate water.

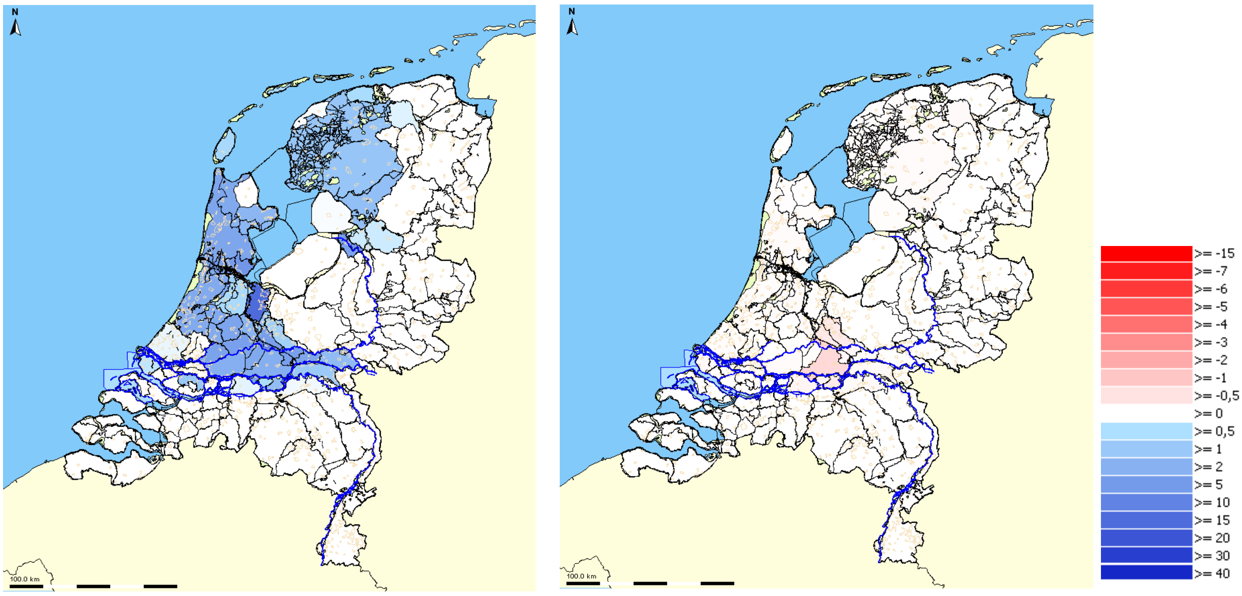

Figure 3 Forecasted water demand (left) and shortage (right) in mm/decade for districts. Red districts in the right figure indicate water shortage.

4 DISCUSSION

An operational drought forecasting system has been developed to support the National Coordinating Committee for Water Distribution of the Netherlands during periods of drought. The system runs the Netherlands Hydrological modeling Instrument on a daily basis to estimate the actual state of the system and to provide a 10-day forecast. The model produces an overview important hydrological variables, including groundwater level, soil moisture conditions, surface water levels, water demand, water supply and – as a result – water shortage per district.

Further research will focus on verification studies using ECMWF re-forecasts, addition of damage modules, introduction of scenarios and seasonal forecasting. Furthermore, additional measurements (including remote sensing data) will be included. Data assimilation techniques will then be applied to update model estimates and, consequently, improve model forecasts. The forecasting system may also serve as a supplier of boundary conditions for more detailed local forecasting systems run by the water boards.

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