Deltares

Enabling Delta Life

Hindcast of water levels for the Rhine branches and the Meuse for 2006 & 2007

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Prepared for:

Waterdienst

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Report

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Contents

1 Introduction

1.1 General Introduction

The Centre for Water Management (WMCN) and Deltares are working on the development of FewsNL Rhine & Meuse, which will ultimately be used for forecasting of discharges and water levels along the Meuse and the Rhine branches in the Netherlands. There are three major uses of FewsNL envisaged: daily water level forecasts for shipping, flood prediction and mitigation, and planning of river maintenance.

The model cascade in FewsNL Rhine & Meuse consists of an inter-linked hydrological rainfall runoff model (HBV-96) and a hydrodynamic model (SOBEK-RE). This model chain runs in two principal operational modes; i) a historical mode and ii) a forecast mode. In the first mode the models are forced by hydrological and meteorological observations over a limited time period prior to the onset of the forecast. In the second mode, the models are run over the required forecast lead time, whereby the internal model states at the end of the historic run are taken as initial conditions for the forecast run. The models are forced using quantitative forecasts of precipitation and temperature. The forecasting lead-time may extend from 96 to 240 hours ahead depending on the forecast used (HIRLAM, DWD-LM, DWD-GME, ECMWF-DET).

The current operational system for the Rhine is the LobithW model which provides 1, 2, 3 & 4 day ahead water level forecasts at Lobith. This data driven (multiple linear regression) model is fed by instantaneous water levels and discharges and daily averaged precipitation measurements and forecasts upstream of Lobith. This model is used operationally since 1980 (Ronde, J.G. de, 1982). Currently, during flood events the ‘hoogwatergroep’ uses FloRIJN (Sprokkereef, E. 2001) or FloMAAS which is comparable to the model cascade used in FewsNL.

To evaluate the improvement in performance of the FewsNL system after major changes, a hindcast of the forecasted water levels will be carried out on a regular basis. The goal of the hindcast described in this report is to see how good the forecasts of the current system (version FewsNL 1.11, January 2008) are and to have a first benchmark to evaluate future changes/improvements in the configuration of FewsNL Rhine & Meuse. In a previous study, a hindcast with FewsNL (version May 2006) for the Rhine was performed for the period June 2002- June 2005 (Weerts and Kwadijk, 2006). For the Rhine, it is also interesting to see how well the model cascade within FewsNL Rhine is doing when compared with the operational forecasts issued by the operational service “Infocentrum Binnenwateren” of the Centre for Water Management. For the Meuse, this study is the first major hindcast to evaluate forecasts made with the FewsNL instrument.

1.2 Developments FewsNL Rhine & Meuse

In this hindcast use is made of FewsNL version 1.11 (January 2008). For the Meuse, no major changes have been implemented since May 2006 (Weerts and Van Mierlo, 2006). In FewsNL version 1.11, the SOBEK-RE model has been updated from version 2.01/2.02 to 3.01/3.02 (Van der Veen, 2007a). The Rur catchment developed by van Deursen (2006) has been added as HBV-96 model replacing the statistical relationship as implemented in the version of May 2006 (Weerts and Van Mierlo, 2006). Most other changes are in the area of additional exports, additional ensemble forecasts (COSMO-LEPS) and display of information.

For the Rhine, major changes have been realised since the version of May 2006 (Weerts and Van Mierlo, 2006). In FewsNL version 1.11, the SOBEK-RE model has been updated from version 2.01/2.02 to 3.01/3.02 (Van der Veen, 2007b). The amount of synop stations has increased from +/-200 to +/-500 (see Figure 1.1).

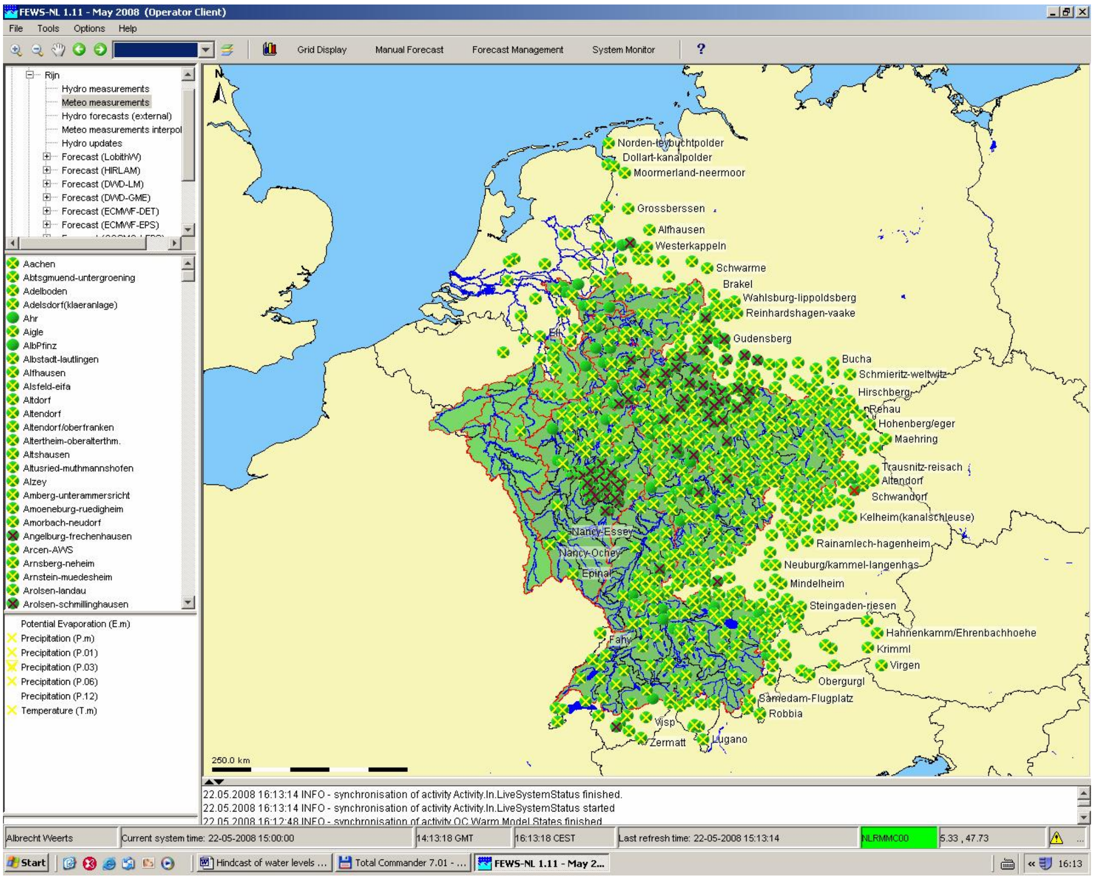

Figure 1.1 *Overview of all meteorological measurement stations in the Rhine basin (green dot indicating measurement station without missing data, red cross indicating no data at all, yellow cross indicating some data).*

Ensemble Kalman Filter has been implemented using DATools (Weerts, 2007). Measurements along the Rhine and its branches are now assimilated when running the model cascade in historical mode. This was strongly recommended after analysing the results of the hindcast performed for the period June 2002 - June 2005 by Weerts and Kwadijk (2006).

1.3 Outline Report

The report describes the results obtained with the hindcast 2006 & 2007. Chapter 2 describes the results for the Meuse at Borgharen and downstream of Borgharen. Chapter 3 describes the results for the Rhine at Lobith and up- and downstream of Lobith. Chapter 3 also provides the comparison of the operationally issued water level forecasts at Lobith with the results from the hindcast. Chapter 4 ends this report by a short summary and the final conclusions.

2 Hindcast Meuse

2.1 Introduction

The model cascade in FewsNL Meuse consists of an inter-linked hydrological rainfall runoff model (HBV-96) and a hydrodynamic model (SOBEK-RE). This model chain runs in two principal operational modes; i) a historical mode and ii) a forecast mode. In the first mode the models are forced by hydrological and meteorological observations over a limited time period prior to the onset of the forecast. In the second mode, the models are run over the required forecast lead time, whereby the internal model states at the end of the historic run are taken as initial conditions for the forecast run. The hydrological model is forced using quantitative forecasts of precipitation and temperature. The forecasting lead-time may extend from 48 to 240 hours ahead depending on the forecast used (HIRLAM, DWD-LM, DWD-GME, ECMWF-DET). Available discharge measurements of major tributaries are assimilated using output correction (Broersen and Weerts, 2005) to improve the inputs of the hydraulic model and as a consequence improve the predictions at Borgharen.

This hindcast for the Meuse is the first study into how good the performance of the forecast for the Meuse is. This study can therefore serve as a benchmark for future improvements to the forecasting system for the Meuse. Note that the flow regime of the Meuse is highly affected by human interference (weirs, controls etc). This is clearly visible in the water level and discharges measurements.

2.2 Material & Methods

2.2.1 Available data

The meteorological data available for the hindcast of the Meuse consist of multiple sources: Synop precipitation and temperature data, TTRR precipitation and temperature data, KNMI synoptic rainfall and temperature data, and Met-Sethy rainfall data. The water level gauging data in the Belgian part of the Meuse are available from Met-Sethy and along the Meuse in The Netherlands via MSW. For the downstream boundary of the SOBEK-Re model Keizersveer, the available astronomical water level and forecasted water levels at Keizersveer are used.

2.3 Results and Discussion

Figure 2.1a shows the Root Mean Squared Error (RMSE) of the forecasted water level and discharge at Borgharen determined over the two year hindcast period 2006&2007 obtained with HIRLAM NWP together with an example. The pattern that is visible is probably caused by the weirs/controls. The behaviour of the weirs/controls is not modelled in the version used for hindcast. To be able to see the behaviour of the system during a flood period and other periods some examples are given in Figure 2.1b, Figure 2.2 (winter 2006 & 2007) and Figure 2.3 (summer/spring 2006 & 2007). These figures show that the error in water level forecast during a flood period is probably less than the RMSE as determined over a two-year hindcast with a few flood periods. These figures also make clear that the weirs and their control is not well captured by the SOBEK-RE model.

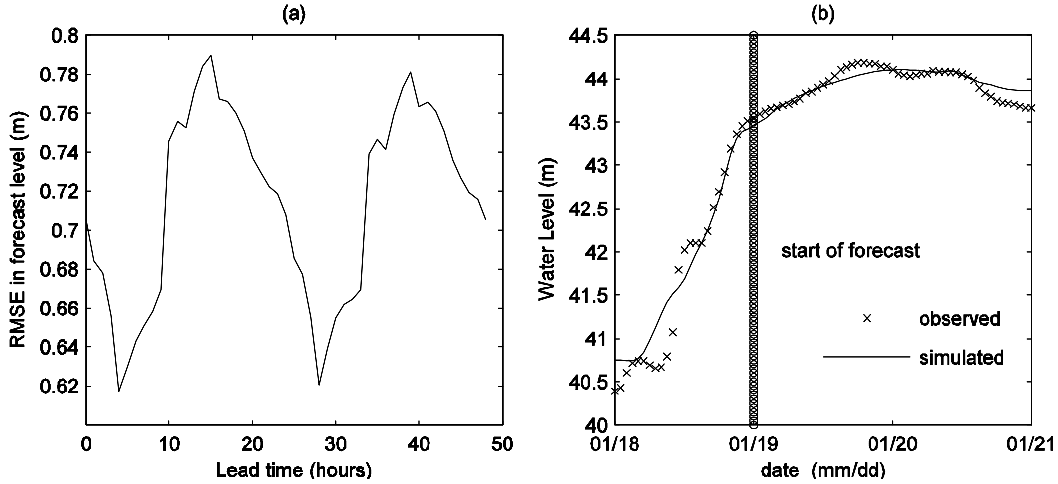

Figure 2.1 *Root mean squared error of the water level forecast at the gauge of Borgharen on the Meuse as a function of lead time determined over a two year hindcast (2006&2007). (b) Observed water level together with the water level forecast for an event in January 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.*

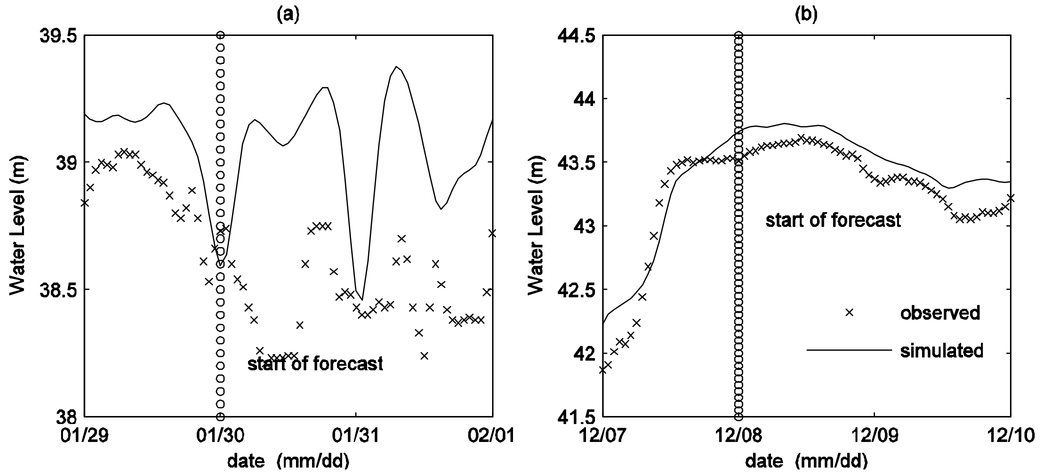

Figure 2.2 *(a) Observed water level together with the water level forecast for an event in January 2006, (b) Observed water level together with the water level forecast for an event in December 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.*

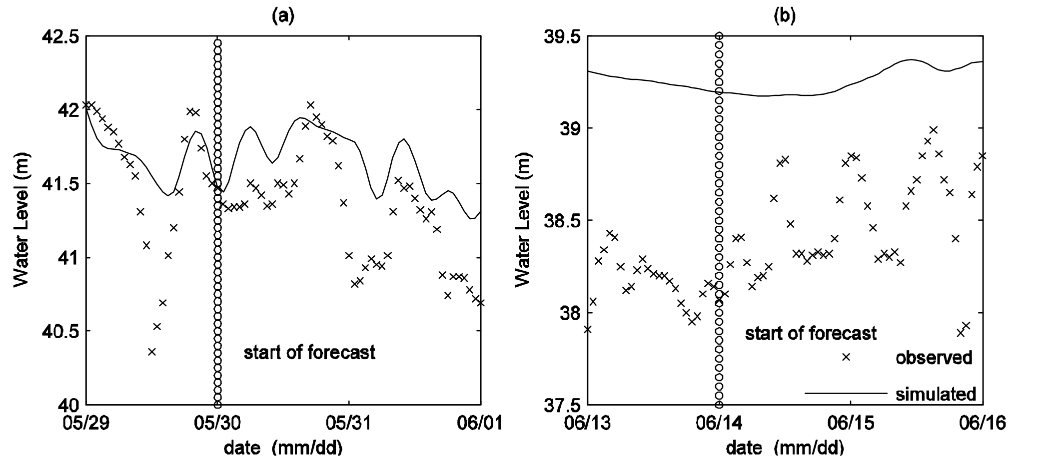

Figure 2.3 *(a) Observed water level together with the water level forecast for an event in May 2006, (b) Observed water level together with the water level forecast for an event in June 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.*

Figure 2.4 shows the RMSE of the forecasted water level at Borgharen for all deterministic numerical weather prediction models available in FewsNL Meuse. This figure shows that the behaviour of the weirs completely dominate the outcome and that almost no difference between the different meteorological forecasts is visible.

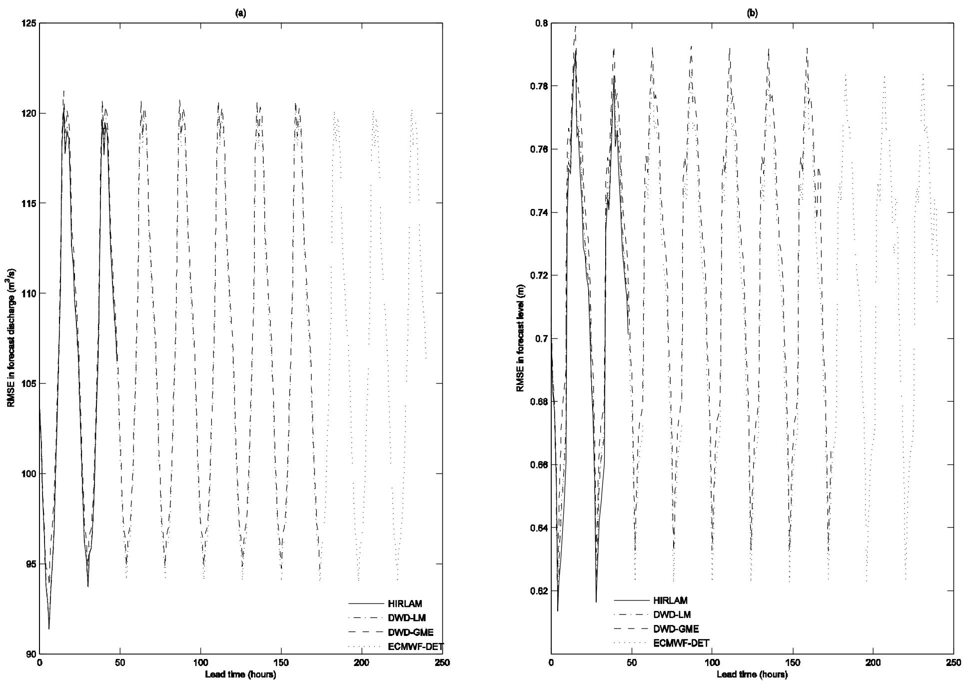

Figure 2.4 Root mean squared error of(a) the water level forecast and (b) the discharge forecast at the gauge of Borgharen on the Meuse determined over a two year hindcast (2006&2007). The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM, DWD-LM, DWD-GME and ECMWF-DET NWP.

2.4 Conclusions

The RMSE as a function of lead time as determined over the two year hindcast (2006&2007) is not a good indicator of the error during a flood peak. The RMSE results as obtained for the hindcast are probably caused by human interference (weirs, controls, etc) and because of the small amounts of flood periods. These problems will be less by taking into account the behaviour of the weirs/controls by implementing week profiles as determined by van der Veen (2007a).

The forecast for two selected flood periods show a smaller error than determined over the complete two year hindcast. To determine the performance during flood period it is probably better to look at the performance during selected flood events and determine the RMSE over these limited number of forecasts. Note that one problem with this suggested approach is that the forecast before approximately 2004 are not available .

3 Hindcast Rhine

3.1 Introduction

The current operational system for the Rhine is the LobithW model which provides 1, 2, 3 & 4 day ahead water level forecasts at Lobith. This data driven (multiple linear regression) model is fed by instantaneous water levels and discharges and daily averaged precipitation measurements and forecasts upstream of Lobith. This model is used operationally since approximately 1980. During flood events the 'hoogwatergroep' uses FloRIJN (Sprokkereef, 2001) which is similar to the model cascade used in FewsNL.

The model cascade in FewsNL Rhine consists of a inter-linked hydrological rainfall runoff model (HBV-96) and a hydrodynamic model (SOBEK-RE). This model chain runs in two principal operational modes; i) a historical mode and ii) a forecast mode. In the first mode the models are forced by hydrological and meteorological observations over a limited time period prior to the onset of the forecast. In the second mode, the models are run over the required forecast lead time, whereby the internal model states at the end of the historic run are taken as initial conditions for the forecast run. The hydrological model is forced using quantitative forecasts of precipitation and temperature. The forecasting lead-time may extend from 96 to 240 hours ahead depending on the forecast used (HIRLAM, DWD-LM, DWD-GME, ECMWF-DET). Available discharge measurements of major tributaries are assimilated using output correction (Broersen and Weerts, 2005) to improve the inputs of the hydraulic model and as a consequence improve the predictions at Lobith.

To improve the forecasts made with FewsNL-Rijn assimilation of water level measurements was recommended by Weerts and Kwadijk (2006). Previous studies (Weerts and Van der Klis, 2003; El Serafy and Mynett, 2004) already showed that assimilation of measurements can improve the forecasts made with FewsNL Rhine at Lobith upto two day lead time.
In FewsNL-Rhine the Ensemble Kalman Filter (EnKF) is implemented and tested in the Hindcast 2006 &2007. The results of the water level forecasts with and without EnKF at Lobith are compared with the measured water levels. Additionally, the water level forecasts with assimilation are compared with the forecasts made using the LobithW model. Thirdly, the effect of the EnKF on the forecast upstream and downstream (Rhine branches) of Lobith is investigated. To investigate the configuration of the EnKF (number of ensemble members and uncertainty specification) on the water level forecast, two additional hindcasts for the period for a limited period (January-June 2006) have been made using more ensembles and a different uncertainty specification.

3.2 Material and Methods

3.2.1 Available data

The meteorological data available for the hindcast of the Rhine are synop data and ttrr data. The water level gauging stations in Germany are available from BC2000 and the water level measurements are available from MSW. For the downstream boundaries, we also use the available astronomical waterlevels and forecasted water levels at Krimpen a/d Lek and Werkendam. The water level measurements at Ketheldiep are used as the downstream boundary condition for the IJssel.

3.2.2 Ensemble Kalman Filtering

In the FewsNL version 1.11, Ensemble Kalman Filter is implemented for improving the forecast for the Rhine basin using the module DATools (Weerts, 2007). As initial estimation of the observational uncertainty and the model uncertainty the values used by Weerts (2007) have been implemented. Table 3.1 shows the measurements used for assimilation and the uncertainty specification for each observation. Table 3.2 shows the uncertainty description of the SOBEK-RE model. The tributaries Neckar, Lahn and Mosel contain structures which are very sensitive to the noise specification. Therefore, it was decided to omit these tributaries in the uncertainty specification.

Table 3.1 Overview of measurement uncertainty specification.

Measurement station	Station Id	River/Branch	Observation uncertainty
Speyer	H-RN-0691	Rhine	N(0,0.05m)
Mannheim	H-RN-0692	Rhine	N(0,0.05m)
Worms	H-RN-0693	Rhine	N(0,0.05m)
Mainz	H-RN-0695	Rhine	N(0,0.05m)
Kaub	H-RN-0943	Rhine	N(0,0.05m)
Andernach	H-RN-0947	Rhine	N(0,0.05m)
Bonn	H-RN-0949	Rhine	N(0,0.05m)
Koln	H-RN-0950	Rhine	N(0,0.05m)
Dusseldorf	H-RN-0951	Rhine	N(0,0.05m)
Ruhrort	H-RN-0952	Rhine	N(0,0.05m)
Wesel	H-RN-0953	Rhine	N(0,0.05m)
Rees	H-RN-0954	Rhine	N(0,0.05m)
Lobith	H-RN-0001	Rhine	N(0,0.05m)
IJsselkop	H-RN-IJSS	Nederrijn/Lek	N(0,0.05m)
Doesburg	H-RN-DOES	IJssel	N(0,0.05m)
Zutphen	H-RN-ZUTP	IJssel	N(0,0.05m)
Olst	H-RN-OLST	IJssel	N(0,0.05m)
Katerveer	H-RN-KATE	IJssel	N(0,0.05m)
Nijmegen	H-RN-NIJM	Waal	N(0,0.05m)
Dodewaard	H-RN-DODE	Waal	N(0,0.05m)
Tiel	H-RN-TIEL	Waal	N(0,0.05m)
Zaltbommel	H-RN-ZALT	Waal	N(0,0.05m)

Table 3.2 Overview model uncertainty specification.

Model branch	Model Uncertainty	Correlation Length Uncertainty	Correlation Model
Max_Lob	N(0,0.05m)	40 km	linear
PanKan	N(0,0.025m)	20 km	linear
Yssel	N(0,0.025m)	20 km	linear
NedRijn	N(0,0.01m)	5 km	linear
Betuwe	N(0,0.01m)	5 km	linear
Neckar	-	-	-
Main	N(0,0.05m)	5 km	linear
Lahn	-	-	-
Mosel	-	-	-

3.3 Results & Discussion Hydraulic SOBEK-RE Model

3.3.1 Results at Lobith

Figure 3.1 (a) shows the Root Mean Squared Error (RMSE) of the forecasted water level at Lobith with and without applying EnKF. It clearly shows that applying assimilation of water level measurements improves the forecasted water level up to 3 days of lead time. It also shows that the RMSE increases from about +/-7 cm at 24 hours, +/-13 cm at +/-48 hours, +/-20 cm at 72 hours and +/-34 cm at 96 hours of leadtime, respectively. Figure 3.1(b) shows a typical example of the observed water level together with the mean of the EnKF water level forecast and the water level forecast without assimilation at Lobith for an event in January 2007. During the forecast no measurements are used to adjust the SOBEK-RE model and the model goes slowly to the behaviour without assimilation. This overestimation of the SOBEK-RE model during peaks is known behaviour of the model also noted during the Water Balance study (Weerts and Mens, 2007). During low flows modelled flows are underestimated (Weerts and Mens, 2007).

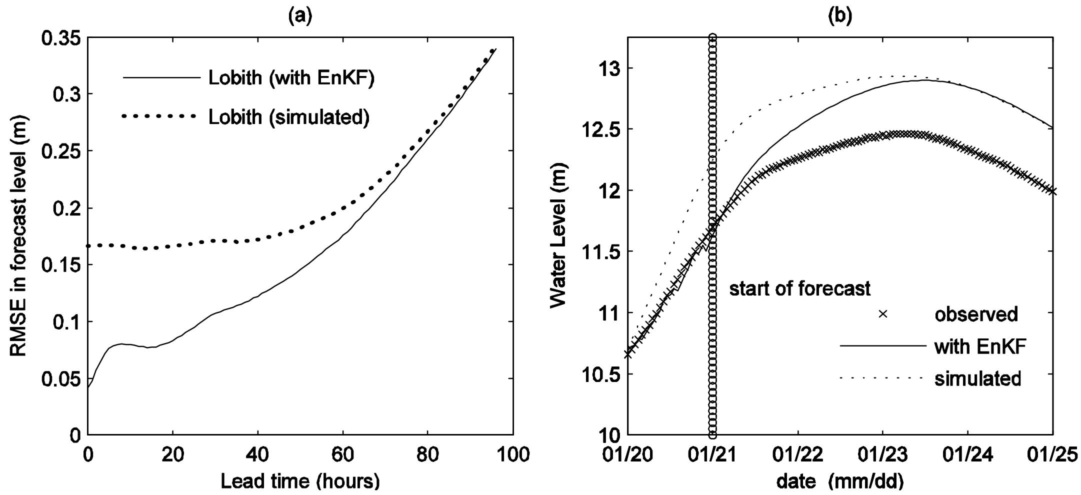

Figure 3.1 Root mean squared error of the water level forecast at the gauge of Lobith on the Rhine with EnKF and without assimilation as a function of lead time determined over a two year hindcast (2006&2007). (b) Observed water level together with the mean of the EnKF water level forecast and the water level forecast without assimilation at Lobith for an event in January 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.

Figure 3.2 shows the RMSE of the forecasted water level at Lobith for all deterministic numerical weather prediction models available in FewsNL Rhine. This figure shows that the different meteorological forecasts start playing a role after 50-60 hours of leadtime. The forecast water level between the start of the forecast and the 50 hours is completely dominated by (1) water already in the system (in HBV-96 and SOBEK-RE) at the start of the forecast, (2) errors in the description of the system (HBV-96 and SOBEK-RE), and (3) errors in the water level measurements. It also shows that RMSE at 72 and 96 hours of leadtime for DWD-LM and ECWMF-DET is lower than for HIRLAM forecast.

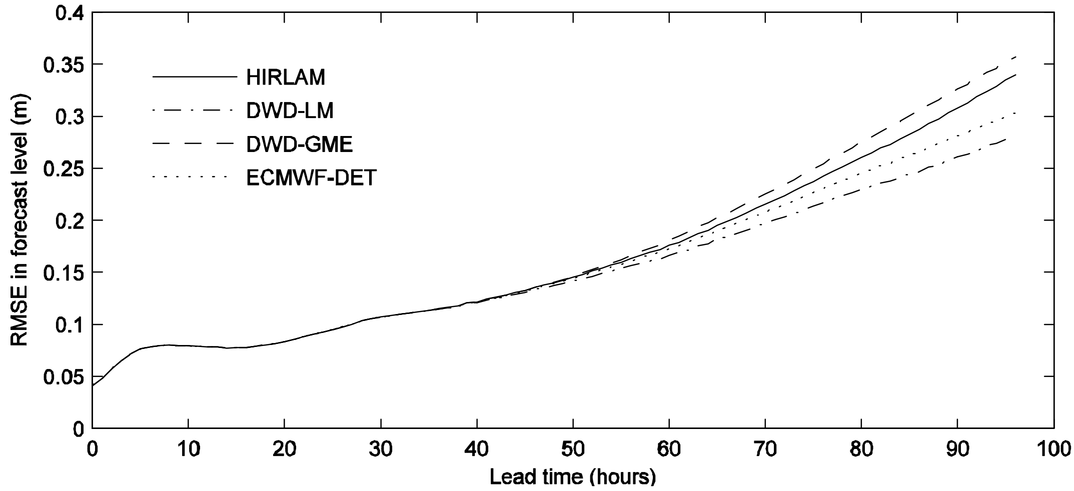

Figure 3.2 Root mean squared error of the water level forecast at the gauge of Lobith on the Rhine determined over a two year hindcast (2006&2007) with EnKF using all NWP forecasts (HIRLAM, DWD-LM, DWD-GME, ECMWF-DET).

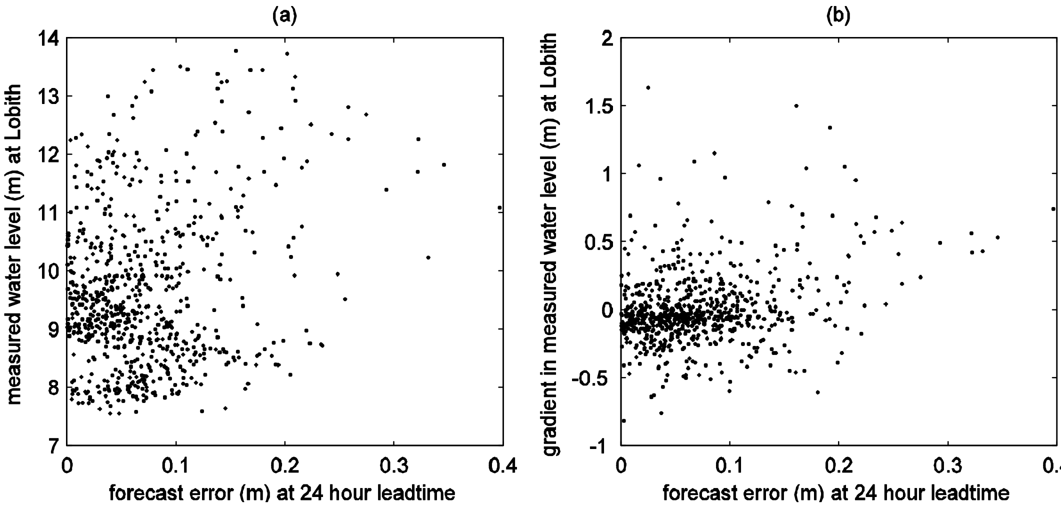

Figure 3.3 (a) Forecast errors at 24 hours leadtime as a function of the measured water level. (b) Forecast errors at 24 hours lead time as a function of the gradient in the measured water level (rising limb (>0), falling limb (<0)).

Figure 3.3(a) shows the forecast error as a function of the measured water level at 24 hours of leadtime. The maximum error is almost 40 centimeters. The maximum error of 40 centimeters is (surprisingly) occurring during an event in August 2007. Most forecast errors for this leadtime are below 10 centimeters. Figure 3.3(b) shows the forecast errors as a function of the gradient in measured water levels (rising or falling). It can be seen that the largest errors are made during a rise (gradient>0) (see for example Figure 3.1b) . As explained previous this is caused by behaviour of the SOBEK-RE model.

3.3.2 Results at the Waal

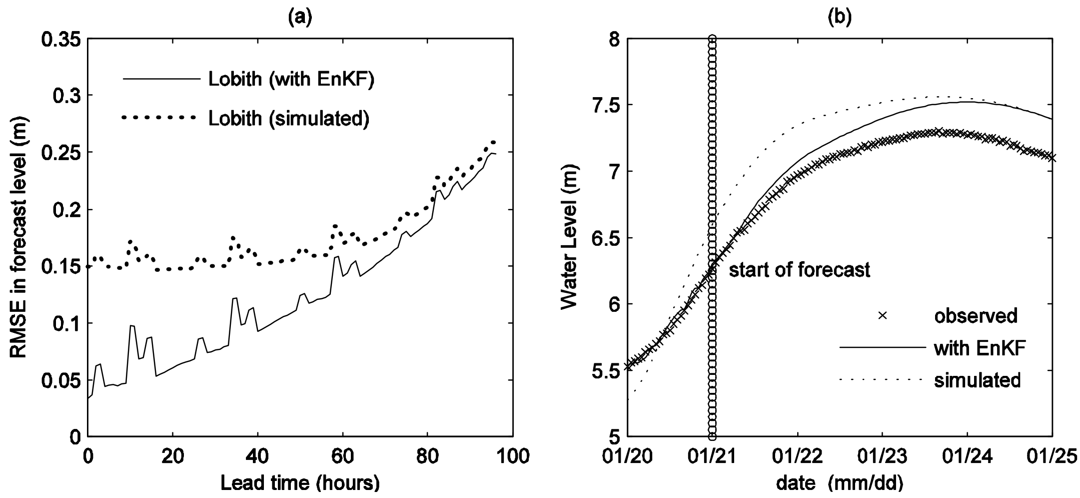

Figure 3.4 Root mean squared error of the water level forecast at the gauge of Tiel on the Rhine with EnKF and without assimilation as a function of lead time determined over a two year hindcast (2006&2007). (b) Observed water level together with the mean of the EnKF water level forecast and the water level forecast without assimilation at Tiel for an event in January 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.

Figure 3.4 shows the RMSE for the water level forecast at Tiel. The assimilation of water levels upstream of and at Tiel results in an improved forecast upto 80 hours of leadtime. The noisy behavior observable in Figure 3.4 is due to errors in the water level measurements. Results for the other stations along the Waal are similar.

3.3.3 Results IJssel

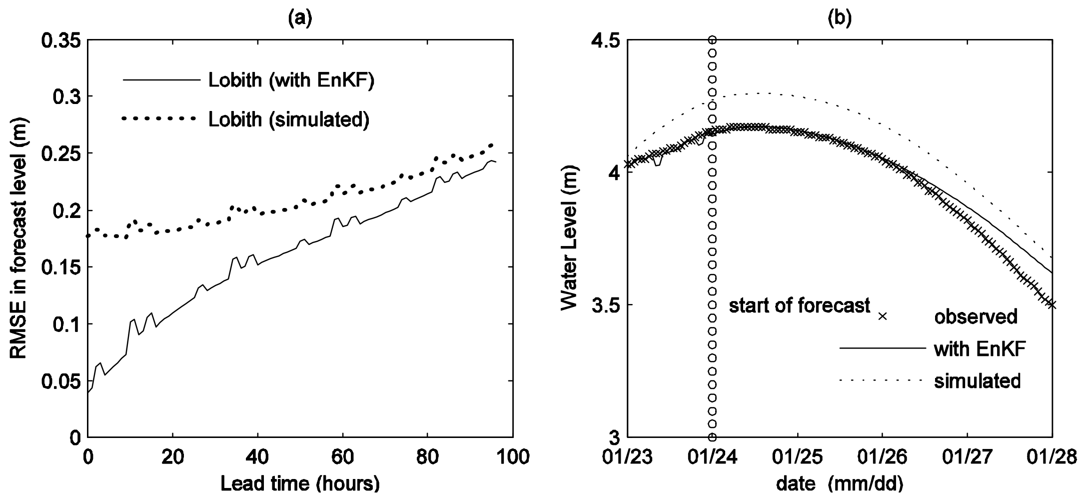

Figure 3.5 Root mean squared error of the water level forecast at the gauge of Olst on the Rhine with EnKF and without assimilation as a function of lead time determined over a two year hindcast (2006&2007). (b) Observed water level together with the mean of the EnKF water level forecast and the water level forecast without assimilation at Olst for an event in January 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.

Figure 3.5 shows the RMSE for the water level forecast at Olst. The assimilation of water levels upstream and at Olst results in an improved forecast upto 96 hours of leadtime. The noise behavior observable in Figure 3.5 is due to errors in the water level measurements. Results for the other stations along the IJssel are similar.
It is clear that the lateral inflow into the IJssel play a big role in the effectiveness of the EnKF. When the lateral inflows are far from reality the EnKF has difficulty to keep the model results close to the measurements because the model is constantly pushed into the wrong direction. Therefore, improving the lateral inflows into the IJssel and the downstream boundary condition (for instance using forecast from WDIJ for Ketheldiep) is expected to further improve the forecast results at the IJssel.

3.3.4 Results Nederrijn

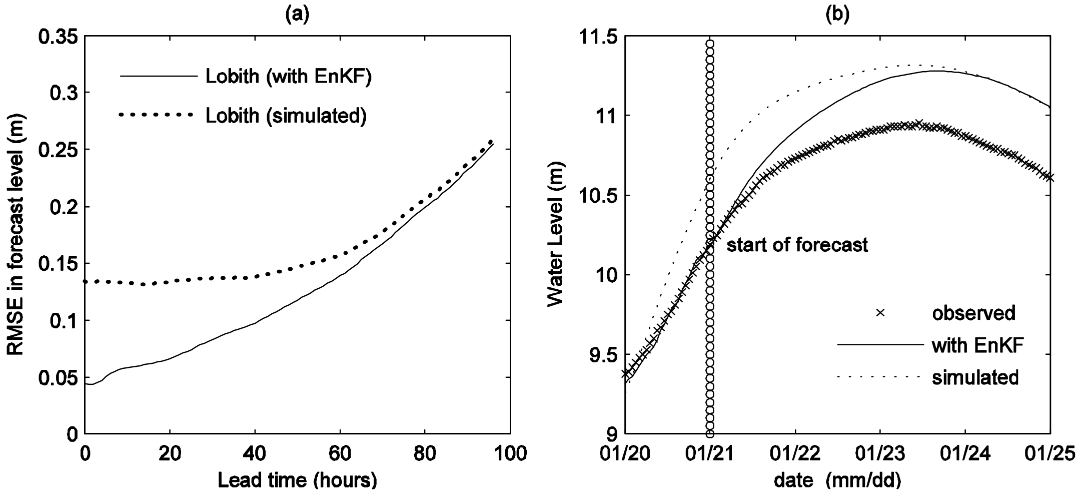

Figure 3.6 Root mean squared error of the water level forecast at the gauge of IJsselkop on the Rhine with EnKF and without assimilation as a function of lead time determined over a two year hindcast (2006&2007). (b) Observed water level together with the mean of the EnKF water level forecast and the water level forecast without assimilation at IJsselkop for an event in January 2007. The HBV-96 - SOBEK-RE model cascade is forced using HIRLAM NWP.

Figure 3.6 shows the RMSE for the water level forecast at IJselkop. The assimilation of water levels upstream and at IJsselkop results in an improved forecast upto 60 hours of leadtime. The IJsselkop is the only measurement that is used on the Nederrijn/Lek for assimilation. This is due to the fact that there are a lot of weirs in the Nederrijn/Lek. The simulation of the weirs and their effect on the water level and discharge are often far from reality and influences the results of the model upstream (Emmerich-Lobith) and in the IJssel. Improvements in the model behavior of the weirs in the Nederrijn/Lek is expected to improve the results at Lobith and along the IJssel and at the upstream part of the Waal. This is of course important during mean and low flows. During high flows the weirs are open and the model behaves more smoothly.

3.4 Comparison Model Cascade HBV-96 / SOBEK-RE and LobithW

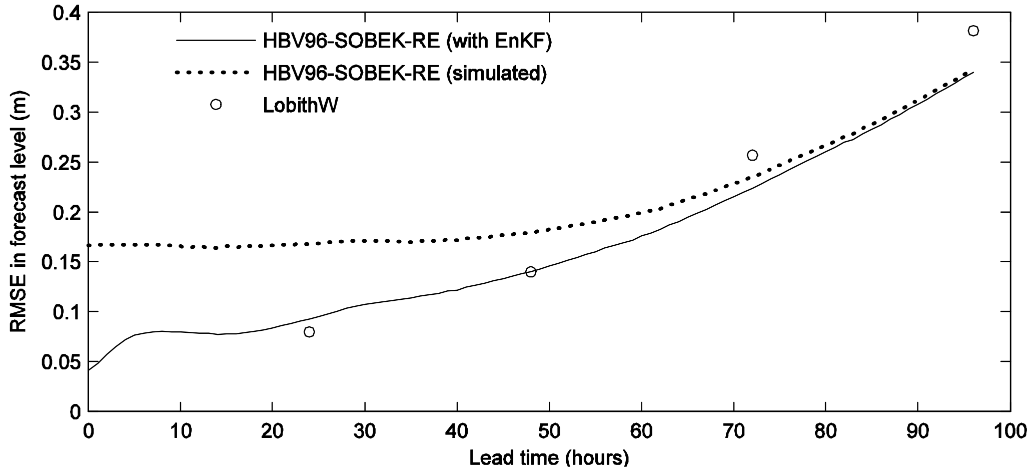

Figure 3.7 Root mean squared error of the water level forecast at the gauge of Lobith on the Rhine over a two year hindcast (2006&2007) at Lobith using HBV-96/Sobek-Re with and without EnkF and using the multiple linear regression model LobithW.

Figure 3.7 shows the comparison of the results obtained with the hydrological-hydraulic model cascade used in FewsNL and the operational forecasts (adjusted by forecasters) issued by the operational service operational service WMCN of the Centre for Water Management using the LobithW model. The LobithW model (including forecaster adjustments) outperforms the hydrological-hydraulic model cascade with EnKF at 24 hours of leadtime, although the difference is small. At 48 hours of leadtime the performance of the two forecasts is almost equal. After 48 hours of leadtime the hydrological-hydraulic model cascade is outperforming the LobithW model. Especially, if we take into account that in this example the model cascade is forced using the HIRLAM NWP. Figure 3.2 shows that the difference would even be larger if the DWD-LM or the ECMWF-DET forecast had been used in the comparison.

3.5 Effect Ensemble Size & Error Specification

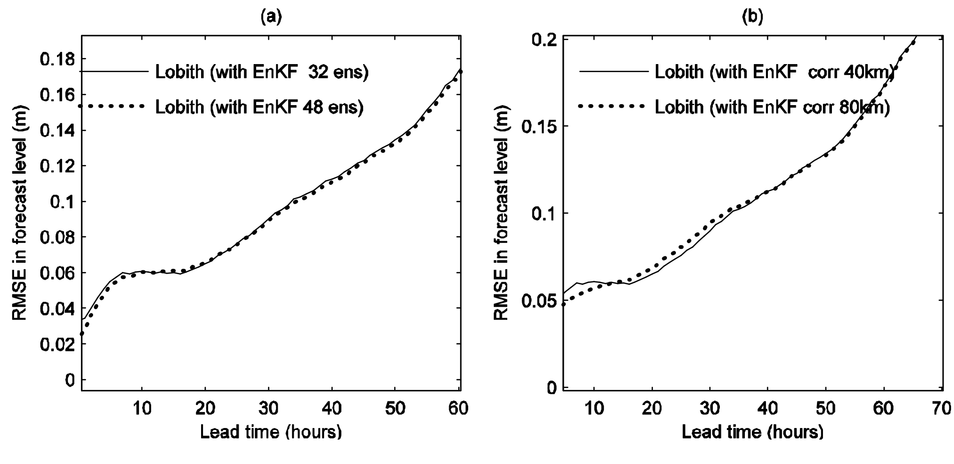

Figure 3.8 (a) Root mean squared error of the water level forecast at the gauge of Lobith on the Rhine over a two year hindcast (2006&2007) at Lobith using HBV-96/Sobek-Re using 32 and 48 ensemble members and a correlation length of 40 km, (b) Root mean squared error of the water level forecast at the gauge of Lobith on the Rhine over a two year hindcast (2006&2007) at Lobith using HBV-96/Sobek-Re using 32 members and a correlation length of 40 and 80 km.

During the forecast the mean state of the ensemble is being used. The error in the estimated mean is smaller when more ensembles are being used. Figure 3.8a shows the effect of running the model with 32 and 48 ensemble members. It can be seen that the result slightly improves with 48 ensemble members.

The correlation length determines the length scale over which an measurement has influence on the state. The measurement stations are approximately 40 km apart from each other. A correlation length of 40 km with a linear correlation function as used here means that the measurement looses its influence over the state linearly over 40 km (upstream and downstream). Figure 3.8b shows the effect of using a 80 km correlation length versus a 40 km correlation length. It can be seen that using the 80 km correlation length yields somewhat better results at small leadtimes.

The somewhat strange behaviour at small leadtimes may be caused by the fact that the mean state is used during the forecast instead of the full ensemble. Another cause may be the chosen correlation length (see also Figure 3.8b).

3.6 Conclusions

EnKF results in improved forecast at Lobith and along the Rhine branches. The RMSE at Lobith is lower upto 60 hours of leadtime at Lobith. For locations downstream of Lobith the improvements are up to 60-96 hours of leadtime depending on the branch of the Rhine.

The performance of the LobithW model (with forecaster adjustments) is better than the model cascade implemented in FewsNL upto 24 hours of leadtime. After 48 hours the performance of the LobithW model and the model cascade implemented in FEWS-NL is similar. After 48 hours of lead time the performance of the model cascade is better than the LobithW model. These conclusions are valid for all weather prediction models used in FEWS-NL.

4 Conclusions and Recommendations

4.1 Meuse

- The results for the Meuse are difficult to interpret. The determined RMSE over the two year hindcast 2006&2007 is quite large. However, during flood events the results obtained with the model cascade implemented in FEWS-NL is probably more accurate than the RMSE determined over 2 years of hindcast. It is recommended to study the performance of the system during flood events instead of a fixed two year period.

- Implementing week profiles for the lateral inflows is highly recommended and should be implemented in the next release. This has already been done in the FewsNL version 1.12. The hindcast must be repeated to see if the results really have improved and how much.

4.2 Rhine

- The use of EnKF improves the forecasts made for Lobith and downstream of Lobith considerably. The improvements are visible upto 60-96 hours of leadtime depending on the location.

- It is advised to use as much ensemble members as possible. Current configuration makes use of 48 ensemble members and a correlation length of 80 km. Although not discussed in the previous part improvements in the noise specification (time-correlated model noise) could further improve the results.

- During the forecast use is made of the mean state of the ensemble determined during the historical period after assimilation of the measurements. This causes some strange behaviour at smaller lead times especially during lower flows.

- The EnKF is only used during the update run which is run once a day. This implies that measurements that become available after the update are not used to update the model when forecasting. This may be solved by either running the full ensemble when running in forecast mode. This makes it possible to assimilate the measurements that are available and it might improve the results at smaller lead times. However, this requires a major investment in computing power. Or either run the update run more often (twice a day).

- Use of EnKF makes it also important that forecasters take a very close look at the measurements that enter the system and correct these if necessary. During training this issue should be addressed.

- The LobithW model (with forecaster adjustments) shows the best performance at 24 hours of leadtime. At 48 hours of leadtime the performance of both models (LobithW vs model cascade) are comparable. After 48 hours of leadtime the model cascade outperforms the LobithW model. Given these results it makes sense to optimize the implementation of the LobithW model as available within FEWS-NL for 24 and 48 hours or leadtime.

- The EnKF is now being used to remove errors in the SOBEK-RE model. It is unclear why these errors are present. As known from past studies the SOBEK-RE model shows systematic biases during high flows (simulations always to high) and during low flows (simulations always to low). It is highly recommended to improve the calibration of the model. This will further improve the forecast results.

- The results at Lobith but also Nijmegen and Doesburg are affected by the behaviour of the weirs and their modelled control in the Neder-Rijn (especially during mean and low flows). This needs improvements. It may also be worth investigating to use two different SOBEK-RE models one for flood periods and one for low flow conditions.

- The lateral inflows of the IJssel sometimes deteriorate the forecast results at the IJssel considerably. This is caused by the fact that the inflows of the Oude IJssel and Twenthekanaal are modelled using simple statistical relationships. Additionally, for these two locations measurements of the discharge are not available for error correction. Inclusion of measurements and improved modelling of the lateral inflow is expected to further improve the forecasts along the IJssel.

- The lower boundary of the IJssel Ketheldiep is still being modelled using a ‘streefpeil’. Using forecasts for this point (from WDIJ) as is done for the other lower boundaries is expected to improve the forecast results at the IJssel.

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