Validation HBV for FewsNL Meuse

Report

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Validation HBV for FewsNL Meuse

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TITLE: Validation HBV for FewsNL Meuse

ABSTRACT:

To validate the hourly HBV model used in FewsNL Meuse the performance of the hourly HBV model is tested against the daily model and against measurements. Effect of error correction on the outcome of the SOBEK model at Borgharen and Ampsin/Amay is also investigated. The hourly HBV model had to be recalibrated by adjusting values of the HQ and MAXBAS parameter. The daily and hourly HBV model compare well. Differences can be explained given the different rainfall data used for both models. Timing of the flood peaks is good and this gives confidence in the current parameter settings of the hourly HBV model. When comparing the hourly model with the measurements it appears that the results for most selected flood periods are good. The flood of 1995 is somewhat overestimated by the model. The comparison of the model with the measurements for the tributaries is good with the exception of Tregnas, Membre pont and Salzinne. Error correction of the lateral inflows improves the performance of the SOBEK model. For all flood periods the results are improved. It is clear that error correction in operational forecasting will result in better forecasts. It is recommended that more effort should be direct to obtain better/more rainfall data. Assimilation of the measurements in the HBV model (by direct insertion) will improve the performance of the HBV model.

REFERENCES:

<table>
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<tr>
<th>VER</th>
<th>AUTHOR</th>
<th>DATE</th>
<th>REMARKS</th>
<th>REVIEW</th>
<th>APPROVED BY</th>
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<tr>
<td></td>
<td>A.H. Weerts</td>
<td>8 mei 2007</td>
<td>J. Kwadijk</td>
<td>C.A. Bons</td>
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I Introduction

1.1 Background and Objectives

The hourly HBV model for the Meuse is used by Rijkswaterstaat RIZA within the operational system FewsNL. This hourly model is obtained from the daily HBV model of the Meuse which was calibrated by van Deursen (2004). van Deursen (2004) fine tuned a version of the HBV model developed by Booij (2002). The daily model as derived by van Deursen (2004) is also used within the framework of Generator of Rainfall and Discharge Extremes (GRADE) for the Meuse (Leander et al., 2005), and hydrological analyses on climate change (Booij, 2005), land use change (Ashagrie et al, 2006) and low flows (de Wit et al, 2007).

The hourly HBV model for the Meuse as used in the operational system FewsNL has never been validated or tested against measurements. The daily model was calibrated using high quality precipitation, temperature and evaporation data. In the operational system the data that are available are different and of a lesser quality. Therefore several questions remain:

1. What is the performance of the HBV hourly model using the operational available data as compared to the daily model?
2. What is the performance of the HBV hourly model during floods?
3. What is the effect of error correction on the discharge predictions at Borgharen-dorp?

To answer these questions the following analyses have been carried out. Chapter 2 provides an overview of the available input data of the HBV model and results of a first test of the hourly model. In chapter 3, the daily HBV model is compared with the hourly model. In this chapter, the measured data are not included in the comparison. This has been done on purpose because in this study we are only interested in performance of the hourly model. The comparison of the daily model and the measurements has been carried out by van Deursen (2004). In chapter 4, the hourly HBV model is compared with measured discharge data. In the operational system the HBV results provide lateral inflows into the SOBEK model of the Meuse. Chapter 5 shows what the effect is of using either measured data or HBV simulations as lateral inflows on the simulated discharge by the SOBEK model at Borgharen and Amay/Ampsin.

This study has been directed from Rijkswaterstaat RIZA. FEWSNL Maas will be used by Rijkswaterstaat for flood forecasting along the Dutch part of the Meuse. However, discharge and precipitation data from upstream countries are essential for the forecast. MET-Sethy kindly provided the historical precipitation and discharge data for the Walloon part of the Meuse basin. Meteorological data has also been provided and/or collected by KNMI and the Deutscher Wetter Dienst.
2 HBV-Meuse: first test of the hourly model used in FewsNL 1.60/1.70

As start HBV-Meuse hourly model as used in the FewsNL configuration 1.60 and 1.70 was tested using available meteorological data for the period 2001-2005. Table 2-1 shows an overview of the available meteorological data for the Meuse. Table 2-2 shows an overview of the available discharge data.

Table 2-1. Overview available meteorological data.

<table>
<thead>
<tr>
<th>source</th>
<th>availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTRR</td>
<td>Mar1996-2005</td>
</tr>
<tr>
<td>DWD-synop</td>
<td>Mar1996-2005</td>
</tr>
<tr>
<td>Met-Sethy</td>
<td>Jan93, Dec93, Dec94Feb95, Oct98Nov98, Feb99Mar99, Dec99, Mar00, Jan01Mar01, Jan02Mar02, Nov02Jan03, Jan04</td>
</tr>
<tr>
<td>KNMI-synoptic</td>
<td>Jan95Feb95, 2001-2005</td>
</tr>
</tbody>
</table>

1 2 The number of TTRR and DWD-synop station stations increases from 1990-2000.

Table 2-2. Overview available hourly discharge data.

<table>
<thead>
<tr>
<th>Source</th>
<th>station</th>
<th>availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rijkswaterstaat</td>
<td>Borgharen-dorp (H-MS-BORD)</td>
<td>Dec93, Jan95Feb95, Oct98Dec05</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Ampsin/Amay (H-MS-0008)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Chaudfontaine (H-MS-0010)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Chooz (H-MS-0011)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Gendron (H-MS-0013)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Martinrive (H-MS-0017)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Membre pont (H-MS-0018)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Salzinnes (H-MS-0019)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Tabreux (H-MS-0020)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
<tr>
<td>MET-Sethy</td>
<td>Treignes (H-MS-0021)</td>
<td>Dec93, Jan95Feb95, Dec01Mar02, Dec02Jan03</td>
</tr>
</tbody>
</table>
First, a run was made for the period 2001-2005 and the results of the hourly HBV model were compared with the available measurements. It was clear that the results were not correct (not shown here). After a comparison with the daily model, it was found that in the hourly HBV configuration the values of HQ were divided by 24 and this led to erroneous results. After these values were corrected the run for the same period was repeated and it appeared that the timing of the peaks was incorrect. Therefore, an adjustment of the MAXBAS parameter in the HBV model was necessary. Table 2-3 shows the adjusted values, found by trial and error, of the MAXBAS parameter for the hourly model together with the values used in the daily model. Other parameters were not altered. The parameter mentioned in Table 2-3 and Table 2-4 are used in the remainder of this report and are also implemented in the hourly HBV model used in FewsNL 1.80 and 1.90.

Table 2-3. HBV-96 calibration values for MAXBAS (day) for the daily and hourly model.

<table>
<thead>
<tr>
<th>model</th>
<th>basin</th>
<th>4</th>
<th>5</th>
<th>8</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>rest*</th>
</tr>
</thead>
<tbody>
<tr>
<td>daily-</td>
<td></td>
<td>1.2</td>
<td>2.5</td>
<td>2</td>
<td>2.2</td>
<td>1.4</td>
<td>1.1</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>MAXBAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>hourly-</td>
<td></td>
<td>0.2</td>
<td>1.5</td>
<td>1</td>
<td>1.2</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>MAXBAS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*as defined in rmod.par

Table 2-4. HBV-96 calibration values for HQ (mm/day) for the daily and hourly model.

<table>
<thead>
<tr>
<th>basin</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>15</th>
<th>rest*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HQ</td>
<td>2.54</td>
<td>1.69</td>
<td>2.54</td>
<td>3.5</td>
<td>4.3</td>
<td>3.66</td>
<td>3.23</td>
<td>3.02</td>
<td>2.56</td>
<td>3.27</td>
<td>4.3</td>
<td>3.5</td>
<td>2.56</td>
<td>2.56</td>
<td>3.4</td>
</tr>
</tbody>
</table>

*as defined in rmod.par
3 HBV-Meuse: comparison HBV hourly vs daily model for several historical events

Data availability allows for producing results for the period 1967-1998 with the daily model. Therefore, the results of the daily model and the hourly model are compared for four events (Jan93, Dec93, FebMar95, OctNov98). The HBV daily model is been used in combination with the high quality meteorological data (see Leander et al, 2005). The hourly model is being used in combination with the available meteorological data (see Table 2-1). Consequently, the amount of input data for the four events is not the same and may therefore influence the results (see Table 2-1). However, this situation of missing input data can also occur during operational forecasting. The results for Borgharen are given below. The results for the tributaries are given in Appendix A. Note that the warm states for the hourly model runs were extracted from model runs with the daily model. The use of the state files of the daily model and use them for the hourly model causes the strange behaviour at the beginning of the x-axis of each figure.

3.1 Results for Borgharen-dorp

January 1993 & December 1993

Figure 3-1. Discharge simulated with HBV day model (magenta) and HBV hourly model (red) for top figure: January 1993 and bottom figure: December 1993 – February 1994.
January/February 1995 & October/November 1998

The results for January 1993 show that HBV hourly model produces similar results as the daily model, although there are some differences. The rise of the peak is a little bit later. The peak produced by the hourly model is almost as high as the peak of the daily model. The agreement for December 1993 is better and almost no difference between the hourly and daily HBV model can be noted. The comparison for January 1995 is also good although the peak values of the hourly model are higher. The peak discharge of October-November 1998 of the hourly model is somewhat underestimated compared to the daily model. The differences can be explained from the different rainfall amounts for the daily and hourly model as shown in Table 3-1.

Table 3-1. Cumulative rainfall (mm) per event per sub basin for the daily and hourly model.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
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<tr>
<td>SB1 Lorraine Sud</td>
<td>103.6</td>
<td>189.4</td>
<td>241.9</td>
<td>326.3</td>
</tr>
<tr>
<td>SB2 Chiers</td>
<td>153.9</td>
<td>173.3</td>
<td>290.3</td>
<td>316.9</td>
</tr>
<tr>
<td>SB3 Lorraine Nord</td>
<td>136.8</td>
<td>177.6</td>
<td>293.5</td>
<td>309.1</td>
</tr>
<tr>
<td>SB4 Bar etc</td>
<td>142.2</td>
<td>156.2</td>
<td>290.0</td>
<td>277.0</td>
</tr>
<tr>
<td>SB5 Semois</td>
<td>213.2</td>
<td>165.2</td>
<td>411.8</td>
<td>304.3</td>
</tr>
<tr>
<td>SB6 Viroin</td>
<td>146.7</td>
<td>137.1</td>
<td>287.2</td>
<td>227.0</td>
</tr>
<tr>
<td>SB7 Chooz-Namur</td>
<td>132.7</td>
<td>130.1</td>
<td>262.3</td>
<td>222.5</td>
</tr>
<tr>
<td>SB8 Lesse</td>
<td>144.6</td>
<td>147.4</td>
<td>276.9</td>
<td>264.3</td>
</tr>
<tr>
<td>SB9 Sambre</td>
<td>116.8</td>
<td>122.5</td>
<td>231.3</td>
<td>184.6</td>
</tr>
<tr>
<td>SB10 Ourthe</td>
<td>133.5</td>
<td>122.3</td>
<td>267.4</td>
<td>235.7</td>
</tr>
<tr>
<td>SB11 Ambleve</td>
<td>156.9</td>
<td>122.9</td>
<td>288.8</td>
<td>266.4</td>
</tr>
<tr>
<td>SB12 Vesdre</td>
<td>158.2</td>
<td>51.4</td>
<td>252.1</td>
<td>209.8</td>
</tr>
<tr>
<td>SB13 Mehaigne</td>
<td>101.5</td>
<td>86.6</td>
<td>177.0</td>
<td>171.9</td>
</tr>
<tr>
<td>SB14 Namur-Monsin</td>
<td>95.5</td>
<td>58.1</td>
<td>196.6</td>
<td>172.7</td>
</tr>
<tr>
<td>SB15 Jeker</td>
<td>91.2</td>
<td>66.4</td>
<td>163.9</td>
<td>176.5</td>
</tr>
</tbody>
</table>

### 3.2 Conclusions

The comparison of the daily model results with the hourly model is satisfactory. Results of the hourly and daily model both for the main river and its tributaries are comparable for all four peaks, although small differences are found. Timing of the flood peaks is good and this result gives confidence in the changes made in the MAXBAS parameter as mentioned in the previous chapter. Difference between the daily and hourly model can be explained given the difference in rainfall used for the daily and hourly model as shown in Table 3-1.
4 Evaluation of HBV-Meuse hourly model for several historical events

4.1 Results for Borgharen-dorp

The hourly HBV model is evaluated for the periods were discharge data is available. From Table 2-1 it is clear that for tributaries only data is available for several floods and for Borgharen also discharge data for the complete period October 1998 – June 2005 is available.

First, the results for the complete period are shown followed by closer look to the flood peaks (November 1998, 1999, March 2000, 2001, 2002, January 2003, January 2004). The hourly model is started in 01-10-1998 using the state of that same day obtained using the daily model. The results for the tributaries are given in Appendix B.

Note that the weirs at Liege are not included in the HBV model. These weirs cause strong fluctuation of the discharge at Borgharen. There are also some canals between Liege and Borgharen these canals extract water from the Meuse. These extractions are also not included in the HBV model resulting in overestimation of the discharge during low flow periods.

Figure 4-1. HBV results (red line) versus the measured discharge (black line) for the period October 1998 – June 2001
Figure 4-2. HBV results (red line) versus the measured discharge (black line) for the period July 2001 – June 2004.

Figure 4-3. HBV results (red line) versus the measured discharge (black line) for the period July 2004 – June 2005.
Overall the results of the HBV model are in good agreement with the measurements. Although the hourly HBV model underestimates the measured discharges during flood peaks for the period October 1998 - July 2005. For the peak in January 1995 there is some overestimation of the discharge (Figure 4-4).

This results are shown in more detail for the flood peaks of December 1993, January/February 1995, October 1998, February 1999, December 1999, March 2000, January 2001, February 2002, January 2003, January 2004 in more detail in Figure 4-5 - Figure 4-9. The Nash-Sutcliffe efficiencies for these peaks are given in Table 4-1.

Figure 4-4. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) Flood peak of January 1999: measured discharge (black dots) together with HBV simulation (red line).
Figure 4-5. Flood peak of October-November 1998: measured discharge (black dots) together with HBV simulation (red line).
Figure 4-6. (a) Flood peak of March 1999: measured discharge (black dots) together with HBV simulation (red line), (b) Flood peak of December 1999: measured discharge (black dots) together with HBV simulation (red line).
Figure 4-7. (a) Flood peak of March 2000: measured discharge (black dots) together with HBV simulation (red line), (b) Flood peak of January 2001: measured discharge (black dots) together with HBV simulation (red line).
Figure 4-8. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line).
Figure 4-9. Flood peak of January 2004: measured discharge (black dots) together with HBV simulation (red line).

Table 4-1. Nash-Sutcliffe coefficient for several discharge peaks at Borgharen.

<table>
<thead>
<tr>
<th>Period</th>
<th>Borgharen</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 1993</td>
<td>0.89</td>
</tr>
<tr>
<td>January 1995</td>
<td>-0.46</td>
</tr>
<tr>
<td>January-March 2002</td>
<td>0.88</td>
</tr>
<tr>
<td>January 2003</td>
<td>0.71</td>
</tr>
</tbody>
</table>

4.2 Conclusions

Given the limited input data set for 1993 and 1995 the results are good for these two events, although the event of 1995 is somewhat overestimated by the model. The discharge at Borgharen is simulated well for the 1993 and also for the other two events in January-March 2002 and January 2003 and the whole period October 1998- June 2005. This is further illustrated by Table 4-1. Generally, the HBV model is somewhat underestimating the discharge at Borgharen during peak flows.
The results for the tributaries are generally good with exceptions for Treignes, Membre pont and also Salzinnes which are clearly underestimated during all events. This is further illustrated by the Nash Sutcliffe coefficients in Table 4-2 which gives the Nash-Sutcliffe efficiencies for all Tributaries for the different peak periods. Note, that during operational forecasting the rainfall data of Met-Sethy is available which is only available for some flood periods for the simulations performed in this chapter (see Table 2-1). Note also that the period over which the coefficients are determined is short. The simulation at Chooz during the flood in 1995 is affected by the limited rainfall data. A Nash Sutcliffe value of 0 means that a straight line around the mean of the measurements is as good as the simulation. However, in Appendix B it is clear that the simulation is constantly underestimating the discharge but describes the behaviour of the measured discharge better than a straight line.

Table 4-2. Nash-Sutcliffe coefficient for several discharge peaks for all tributaries of the Meuse.

<table>
<thead>
<tr>
<th>Period</th>
<th>Chaudfontaine</th>
<th>Chooz</th>
<th>Gendron</th>
<th>Martinrive</th>
<th>Membre pont</th>
<th>Salzinnes</th>
<th>Tabreux</th>
<th>Treignes</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 1993</td>
<td>0.77</td>
<td>0.83</td>
<td>0.63</td>
<td>0.78</td>
<td>-0.69</td>
<td>-1.18</td>
<td>0.91</td>
<td>-0.25</td>
</tr>
<tr>
<td>January 1995</td>
<td>0.58</td>
<td>-0.13</td>
<td>0.84</td>
<td>0.88</td>
<td>-1.68</td>
<td>-0.93</td>
<td>0.81</td>
<td>-0.34</td>
</tr>
<tr>
<td>January – March 2002</td>
<td>0.87</td>
<td>0.78</td>
<td>0.76</td>
<td>0.75</td>
<td>0.39</td>
<td>0.65</td>
<td>0.77</td>
<td>0.70</td>
</tr>
<tr>
<td>January 2003</td>
<td>0.71</td>
<td>0.45</td>
<td>0.86</td>
<td>-0.03</td>
<td>-0.39</td>
<td>-1.24</td>
<td>0.87</td>
<td>-0.01</td>
</tr>
</tbody>
</table>
5 Effect error correction on SOBEK-RE simulations for several historical events

In the operational system the lateral inflows of the SOBEK model are error corrected. In practise this means that during a state or update run the measured values of the tributaries are used instead of the HBV model results. During the forecast the error (between the HBV model and measurement) is being predicted. This error is than added to the HBV simulation and serves as an error corrected forecast. The discharge gauging stations that are being used for error correction are given in Table 5-1 together with corresponding tributary or HBV basin. Paragraph 5.1 and 5.2 shows what the effect of error correction is on the SOBEK simulations at Borgharen and Amay/Ampsin.

Table 5-1. List with stations that are being used for input correction

<table>
<thead>
<tr>
<th>HBV</th>
<th>Gauging station</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar etc</td>
<td>Chooz</td>
</tr>
<tr>
<td>Lesse</td>
<td>Gendron</td>
</tr>
<tr>
<td>Sambre</td>
<td>Salzinnes</td>
</tr>
<tr>
<td>Ourthe</td>
<td>Tabreux</td>
</tr>
<tr>
<td>Ambleve</td>
<td>Martinrive</td>
</tr>
<tr>
<td>Vesdre</td>
<td>Chaudfontaine</td>
</tr>
</tbody>
</table>

5.1 Results for Borharen-dorp

Error correction applied to the lateral inflows and upper model boundary (Chooz) of the SOBEK-RE model results in better simulations during the 1993 event. The results for the other three events also improve by applying error correction on the HBV results, especially for January/February 2002 and January 2003. For 1995 the improvement is less because most HBV simulations of the tributaries are close to the measurements. In case no error correction is applied the SOBEK simulations are very close to the HBV simulations (results are not shown).
Figure 5-1. (a) Simulated discharges with SOBEK-RE at Borgharen-dorp with (blue line) and without (green line) together with the measurements (black line) for December 1993; (b) Same as for (a) for January/February 1995.
5.2 Results for Ampsin/Amay

The effect of error correction for Ampsin is identical to the results at Borharen-dorp. The SOBEK-RE model with error correction are worse for 1993 and the results for the three other events improve by applying error correction on the HBV results, especially for January/February 2002 and January 2003. In case no error correction is applied, the SOBEK simulations are very close to the HBV simulations (results are not shown).
Figure 5-3. (a) Simulated discharges with SOBEK-RE at Ampsin/Amay with (blue line) and without (green line) together with the measurements (black line) for December 1993; (b) Same as for (a) for January/February 1995.
5.3 Conclusions

Error corrections for the lateral inflows of the SOBEK model improve the model results during the simulation. Error correction implies that the measured discharges are being used as input for the SOBEK-RE model of the Meuse. For the extreme event in 1993 the use of the measured discharges as input for the SOBEK-RE model results in better simulations when compared with the measurements. The result of the other extreme event in 1995 is also improved. For the events in 2002 and 2003, the error correction also results in much better simulations. It is clear that error correction will result in improved forecasts during operational forecasting because as a result the initial state of the SOBEK model is closer to the “true” state of the system.
6 Conclusions and Recommendations

- The values of the HQ parameter and the MAXBAS parameter of the hourly HBV model have been adapted. The results produced by the hourly model are now much more consistent;
- The daily model and the hourly HBV model give comparable results at Borgharen for all periods. For most tributaries the results are also comparable, with the exception at Membre pont and Treignes; These results give confidence in the hourly model and in the changes made to the HQ and MAXBAS parameter;
- When comparing the hourly model results with the measurements good results are obtained at Borgharen (Table 4-1). However, for most flood periods discharges are underestimated at Borgharen. This underestimation may partly be explained by the underestimation of precipitation depths (e.g. Table 3.1). For most of the tributaries, the results are satisfactory, with the exception at Membre pont, Salzinnes and Treignes (Table 4-2);
- Error correction applied to the SOBEK upper boundary and some of the SOBEK laterals improve the SOBEK simulations at Borgharen and Amay/Ampsin. When applying no error correction the SOBEK simulations are very close to the HBV simulations. In operational forecasting, error correction will lead to better flood forecasts with the SOBEK model.
- It is recommended that more effort should be direct to obtain more rainfall data (gauging stations/radar etc) in the operational system to obtain a better estimate of area averaged rainfall in the Meuse basin;
- Direct insertion of the measured discharges in the HBV model (by splitting up the HBV model into several HBV models will improve the performance of the HBV model. For instance the measured discharge of Chooz will than be used as upper boundary of one of the HBV models. In this way the measured discharge is directly used to improve the HBV model result;
- In the previous studies with the HBV daily model the sub-basins of the Semois, Viroin and Sambre have been calibrated with data from Meuse-Chooz and Meuse-Borgharen. The results of this study suggest that the schematisation of these sub-basins can be improved using discharge and precipitation data for these tributaries.
7 References


A Hourly vs Daily HBV model results for the Tributaries

A.1 Chaudfontaine

January 1993 & December 1993

Figure A.1. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.2. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

For the flood peak of January 1993 the discharge of the hourly model is less than the modelled with the daily model. For the peaks of December 1993, December 1994-February 1995, and November 1998 the results of the two models are comparable.

A.2 Chooz

January 1993 & December 1993
Figure A.3. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.4. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

For the flood peak of January 1993 the timing of the flood peak of the hourly model is different than the modelled with the daily model. For the peak of December 1993 the hourly model produces almost the same results as the daily model. For the peak of 1995 the hourly model produces more discharge than the daily model. For November 1998 the hourly model produces less discharge than the daily model.

A.3 Gendron

January 1993 & December 1993
Figure A.5. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
For Gendron the results of the hourly and daily model are comparable for December 1993 events and 1995 event. The timing of the January 1993 event is somewhat different between the two models and for the flood peak of 1998 the hourly model is producing less discharge than the daily model.

A.4 Martinrive

January 1993 & December 1993
Figure A.7. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.8. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

For Martinrive the height of the peak discharge of the January 1993 event is different when comparing the hourly and daily model. For the other three events the results are comparable.

A.5 Membre pont

January 1993 & December 1993
Figure A.9. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.10. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

For all four events the daily model produces more discharge than the hourly model at Membre pont.

A.6 Salzinne

January 1993 & December 1993
Figure A.11. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.12. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

For Salzinne the peak of the January 1993 the daily and hourly model are almost identical. The simulated discharge with the hourly and daily model is for peaks of 1995 and 1998 are comparable.

### A.7 Tabreux

January 1993 & December 1993
Figure A.13. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.14. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

The results for the Ourthe of the daily and hourly model are comparable for all four events.

A.8 Treignes

January 1993 & December 1993
Figure A.15. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

January/February 1995 & October/November 1998
Figure A.16. Comparison daily (pink) and hourly (red) HBV model for two specific flood events.

For Treignes the discharges obtained with the daily model are higher for December 1993 and for November 1998. The results of the daily and hourly model for the January 1993 and 1995 events are comparable.
B Hourly HBV model versus the measurements results for the tributaries

B.1 Chaudfontaine

For Chaudfontaine (Sambre) the model underestimates the data (<60 m$^3$/s) but in general the result is good. The simulated discharge at Chaudfontaine is a lateral inflow of the SOBEK-RE model.

Figure B.1. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.2. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.3. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.4. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.2 Chooz

At Chooz the model underestimates the measured data during peaks (+/- 300 m$^3$/s). Only for January 1995 the model overestimates the discharge. This overestimation during 1995 explains for a large part the overestimation at Borgharen. Chooz is a model boundary of the SOBEK-RE model.

Figure B.5. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.6. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.7. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.8. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.3 Gendron

The flood peaks at Gendron (Lesse) are underestimated by the model ranging from $200\text{m}^3/\text{s}$ – $50\text{ m}^3/\text{s}$. The simulated discharge at Gendron is a lateral inflow of the SOBEK-RE model.

Figure B.9. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.10. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.11. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.12. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.4 Martinrive

The discharges at Martinrive are underestimates (+/- 50 m$^3$/s) during the flood peaks of 1993, 1995 and 1998 and overestimated for the peak of 2003 (70 m$^3$/s). The simulated discharge at Martinrive is a lateral inflow of the SOBEK-RE model.

Figure B.13. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.14. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.15. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.16. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.5 Membre pont

The simulated discharge at Membre pont is not a lateral inflow of the SOBEK-RE model, but adds to the discharge simulated with the HBV model at Chooz. The simulations are clearly underestimated (150-400 m³/s).

![Graph showing discharge comparison](image)

Figure B.17. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.18. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.19. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.20. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.6 Salzinnes

The simulated discharge at Salzinnes (Sambre) is a lateral inflow of the SOBEK-RE model. The model underestimates the discharge in December 1993 (250 m$^3$/s), is better for January 1995, and underestimates the discharge for the peaks in February 2002 and January 2003 (both +/- 100-200 m$^3$/s).

Figure B.21. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.22. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.23. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.24. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.7 Tabreux

The simulated discharge for the Ourthe (Tabreux) is a lateral inflow of the SOBEK-RE model. The simulations for Tabreux are good.

Figure B.25. (a) Flood peak of January 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.26. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.27. (a) Flood peak of February 2002: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.28. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
B.8 Treignes

Like Membre pont, the simulated discharge at Treignes is not a lateral inflow of the SOBEK-RE model, but adds to the discharge simulated with the HBV model at Chooz. The simulations are clearly underestimated (60-200 m$^3$/s).

Figure B.29. (a) Flood peak of December 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.30. (a) Flood peak of January 1995: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.31. (a) Flood peak of February 1993: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
Figure B.32. (a) Flood peak of January 2003: measured discharge (black dots) together with HBV simulation (red line), (b) difference between measured and simulated discharge (blue line).
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