Prepared for:

RIZA and BfG

Water balance Maxau-Rhine branches

Phase 2: Water balance analyses between the main hydrometric stations

Report

July, 2007

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WL | delft hydraulics

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Contents

1 Introduction

1.1 General

On 25 July 2006 Contract RI-4598/4500045718 was signed by Rijkswaterstaat RIZA and WL | Delft Hydraulics, which commissioned the latter to carry out the study “Waterbalans Maxau-Rijntakken”. The study concerns analyses of water balances between 14 main hydrometric stations of the Rhine from Maxau to Lobith for low, medium and high flows in the period July 1993 and July 2004. The Terms of Reference of the Project as specified in the RIZA document BIO/1994, dated 1 May 2006 and the proposal of WL | Delft Hydraulics of 22 May with reference ZWS-18383/Q4231/tk and its supplement with reference ZWS-18688/Q4231/lj, dated 2 June 2006 form an integral part of the above agreement.

The execution of the Project takes place in three phases:

- Phase 1: Data collection and description of methods (see Mens et al., 2006);
- Phase 2: Water balance analyses between the main hydrometric stations;
- Phase 3: Sensitivity analysis of possible sources of errors in the water balances.

This document describes the activities carried out in Phase 2 of the Project. The Project background, and the objectives of Phase 2 are described in the following paragraph. In Chapter 3, the method of analysis is described, followed in Chapter 4 by a presentation of the results of the water balances analyses for each river section. Chapter 5 gives an overview of the effect of the SOBEK ground water module on the water balance. In Chapter 6 conclusions are drawn and the sensitivity analyses to be performed in Phase 3 are described.

The first step of Phase 2, the third meeting of the Project, took place on January 25th, 2007 at RIZA Arnhem and was attended by representatives of RIZA, BfG and WL | Delft Hydraulics. In this meeting the goals of Phase 2 were reviewed and the first results were discussed, and actions agreed upon for the execution of Phase 2.

1.2 Background and objectives

For operational information on water levels and discharges of the Rhine use is made of coupled SOBEK-Rhine-section models downstream of Maxau (SOBEK-model FewsNL-Rijn version 2.05 as described in Memo WRR 2005-024, 2005) fed with lateral inflows derived from transformed stage observations and lateral inflows derived with the HBV-96 hydrological model of the Rhine basin. For forecasting all inflows are generated by the HBV-96 hydrological model.

The SOBEK models of various Rhine sections were calibrated separately. These section models were later on extended with models of the main tributaries, but were never recalibrated thereafter, nor has the coupled model downstream of Maxau been calibrated in its entirety. The question remains if errors in the section models are additive in downstream direction.

During calibration of the model Andernach-Lobith unacceptable differences were observed which led to the addition of a ground water component on this reach. However, unacceptable differences were observed mainly under low flow condition and under flood conditions with the tendency of having too much water flowing in the system.

The analysis of the possible error sources is not an objective of the Project, such analyses will be taken up in subsequent studies. The sole objective of the Project and especially Phase 2 is to visualise the discrepancies in the water balance between the 14 key stations between Maxau and Lobith using SOBEK, where the hydraulic model boundaries are either measured values (calibration set) or are operationally available measured values in combination with discharges derived with the HBV model. This mixture of measured and modelled discharges, as used in the operational FewsNL system, is called the HBV set in the remainder of the report.

2 Background SOBEK-HBV modelling chain

2.1 Introduction

The goal of the water balance analysis is to identify and detect errors in the input data of the modelling chain (water level measurements-derived discharges-HBV-SOBEK) that is also being used in FewsNL-Rijn. In FewsNL-Rijn, HBV calculated discharges (small tributaries and areas close to the main river) and discharges of the larger tributaries derived from water level measurements (using a stage-discharge relationship) provide input for the SOBEK models. In this study the SOBEK model refers to the coupled SOBEK-model Maxau-Rhine delta, called FewsNL-Rijn version 2.05. Analyses have been carried out between subsequent measurement points in downstream direction (14 in total) in the Rhine corresponding to 13 river sections.

In this chapter first an overview of the components of the SOBEK-HBV modelling chain is given starting with a description of the SOBEK model FewsNL-Rijn version 2.05 and followed by the layout of the HBV-model. Finally, the calibration set and HBV set are presented per river section.

2.2 SOBEK model FewsNL-Rijn version 2.05

The SOBEK-model FewsNL-Rijn version 2.05 is a coupled version of the following SOBEK models:

1. Rhein Maxau-Mainz (with prefix MM1),
2. Rhein Mainz-Andernach (with prefix RM1),
3. Rhein Andernach-Lobith (with prefix AL1),
4. Rijntakken 2004.2 stuwen HYD control (with prefix RT2),
5. Neckar Rockenau-Muendung stuwen HYD control (with prefix NE1),
6. Main Raunheim-Muendung stuwen HYD control (with prefix MA3),
7. Lahn Kalkofen-Muendung stuwen HYD control (with prefix LA1), and
8. Mosel Cochem-Muendung (with prefix MO1).

The set up of the model is described in van der Veen (2005) and Lammersen (2006). A summary is given below.

Re. 1 Rhein Maxau-Mainz

The SOBEK model Rhein Maxau-Mainz was developed in 2001 in the frame of the LAHoR-project (Ritter et al., 2002) by M. Weiand under the guidance of the BfG (Weiand, 2001). The SOBEK cross-sections were generated with BASELINE in 2000-2001 (Weidema, 2000;Immerzeel, 2000ab). The model has been adapted for FewsNL-Rijn to allow coupling with models for the Neckar and Main and the schematisation has been updated for the 2002 conditions in the frame of the Niederrheinstudie (van der Veen, 2004).

Re. 2 Rhein Mainz-Andernach

The SOBEK model Rhein Mainz-Andernach was developed in 2001 in the frame of the LAHoR-project by the BfG. The SOBEK cross-sections were generated with BASELINE in 2000-2001 (Weidema, 2000). The model has been adapted for FewsNL-Rijn to allow coupling with models for the Lahn and Mosel and the schematisation has been updated for the 2002 conditions in the frame of the Niederrheinstudie (van der Veen, 2004). The external groundwater interaction has been replaced by the SOBEK groundwater module.

Re. 3 Rhein Andernach-Lobith

The SOBEK model Rhein Andernach-Lobith was developed in 1997 by $HKV_{\text{lijn in water}}$, commissioned by RWS RIZA and guided by the BfG (Barneveld and Meijer, 1997). The SOBEK cross-sections were generated with an older version of the GIS application for SOBEK-cross sections. This model was recalibrated by Schieder (2001). The model has been adapted for FewsNL-Rijn and the schematisation has been updated for the 2002 conditions in the frame of the Niederrheinstudie (van der Veen, 2004). The external groundwater interaction has been replaced by the SOBEK groundwater module (Hammer, 2003; Kroekestoel, 2003).

Re. 4 Rijntakken 2004.2 stuwen HYD control

The SOBEK-model for the Rhine branches was developed in 2004 by RIZA. In the model the river-bed is based on 2002/2003 conditions, whereas the flood plain describes the situation of 1995. The SOBEK cross-sections have been generated with BASELINE. For FewsNL-Rijn the control of the barrages has been adapted to reduce instabilities (van der Veen, 2004).

Re. 5 Neckar Rockenau-Muendung stuwen HYD control

The SOBEK-model Neckar Plochingen-Mündung was developed in 2003 by WL | Delft Hydraulics and Björnsen BI, commissioned by the BfG (Schwanenberg and Stuchly, 2003). The SOBEK cross-sections have been generated with BASELINE. For FewsNL-Rijn the model reach has been reduced to the section Rockenau-Mündung and the control of the barrages has been adapted to reduce instabilities (van der Veen, 2004).

Re. 6 Main Raunheim-Mündung stuwen HYD control

The SOBEK-model Main Würzburg-Mündung was developed in 2001 by Meander (Meijer et al., 2001) in the frame of the LAHoR Project, commissioned by RIZA. The SOBEK cross-sections have been generated with BASELINE (Immerzeel, 2000ab). For FewsNL-Rijn the model reach has been reduced to the section Raunheim-Mündung and the control of the barrages has been adapted to reduce instabilities (van der Veen, 2004).

Re. 7 Lahn Kalkofen-Mündung stuwen HYD control

The SOBEK-model Lahn Giessen-Mündung was developed in 2004 by WL | Delft Hydraulics and Björnsen BI, commissioned by the BfG (Schwanenberg et al., 2004). The SOBEK cross-sections have been generated with BASELINE. For FewsNL-Rijn the model reach has been reduced to the section Kalkofen-Mündung and the control of the barrages has been adapted to reduce instabilities (van der Veen, 2004).

Re. 8 Mosel Cochem-Mündung

The SOBEK-model of the Mosel between Cochem and the river mouth was developed in 2001 by Meander in the frame of the IRMA-Sponge/DEFLOOD Project (Bemmel and Meijer, 2001). The SOBEK cross-sections have been generated with BASELINE. For FewsNL-Rijn the control of the barrages has been adapted to reduce instabilities (van der Veen , 2004).

Above partial models are coupled by running program COMBINE. For simulations use is made of boundary conditions consisting of a mixture of measurements (point inflows) and HBV generated lateral inflows (point or diffuse), whereas for forecasts the boundary conditions are fully based on HBV data. The measurements and HBV data are multiplied with a factor to correct for basin area and/or bias in the flows and where applicable a time shift is introduced to correct for travel time from the measuring station/HBV sub-basin outflow location to the river model. The time step used in FewsNL-Rijn is 1 hour.

2.3 HBV-model

The HBV model of the Rhine between Basel and Lobith, used by FewsNL-Rijn, has been described in detail in Sprokkereef et. al. (2001). The HBV model is a conceptual semi-distributed precipitation-runoff model and covers 101 sub-basins ranging in size between 500 and 2,000 km^2. Elevation zones in the sub-basins are based on the digital elevation model of the US Geological Survey, whereas the land use data have been derived from grid based GIS Landsat-TM satellite data.

Input are hourly and daily precipitation values, air temperature and mean monthly potential evaporation values. Hourly discharge data have been used for the calibration of the model. Ungauged sub-basins along the Rhine were calibrated by comparison with discharges of smaller representative tributaries. Calibration/verification was done for the period 1990 to 1999, whereas the calibration period for the Mosel covered the period 1990 to 1998. Best calibration results were obtained for the Ruhr, Mosel and Lahn. Figure 2.1- Figure 2.12 show the division of the subbasins that provide lateral inflows into the SOBEK model.

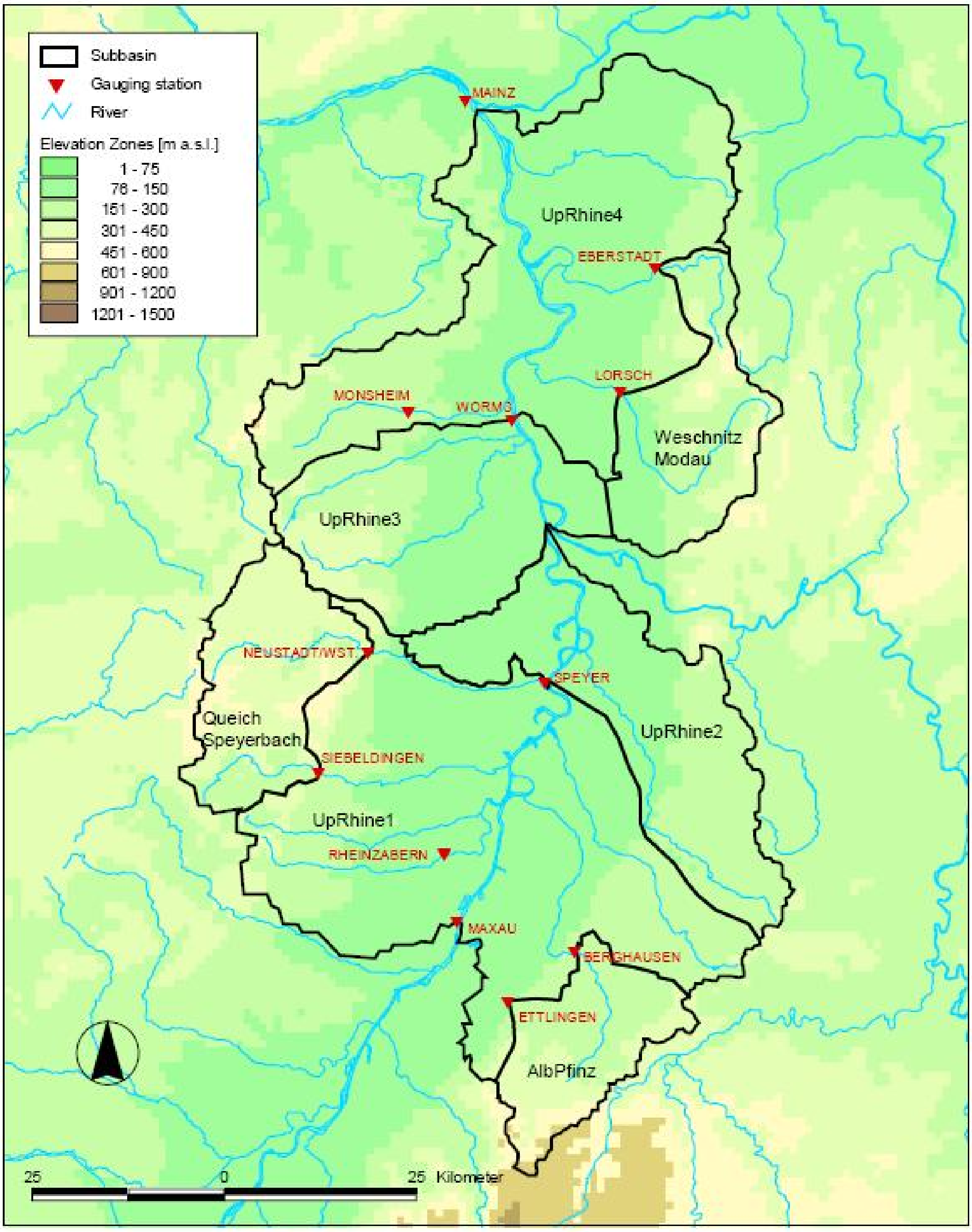

Figure 2.1. Map of sub-basins that are input into the SOBEK model between Maxau and Mainz.

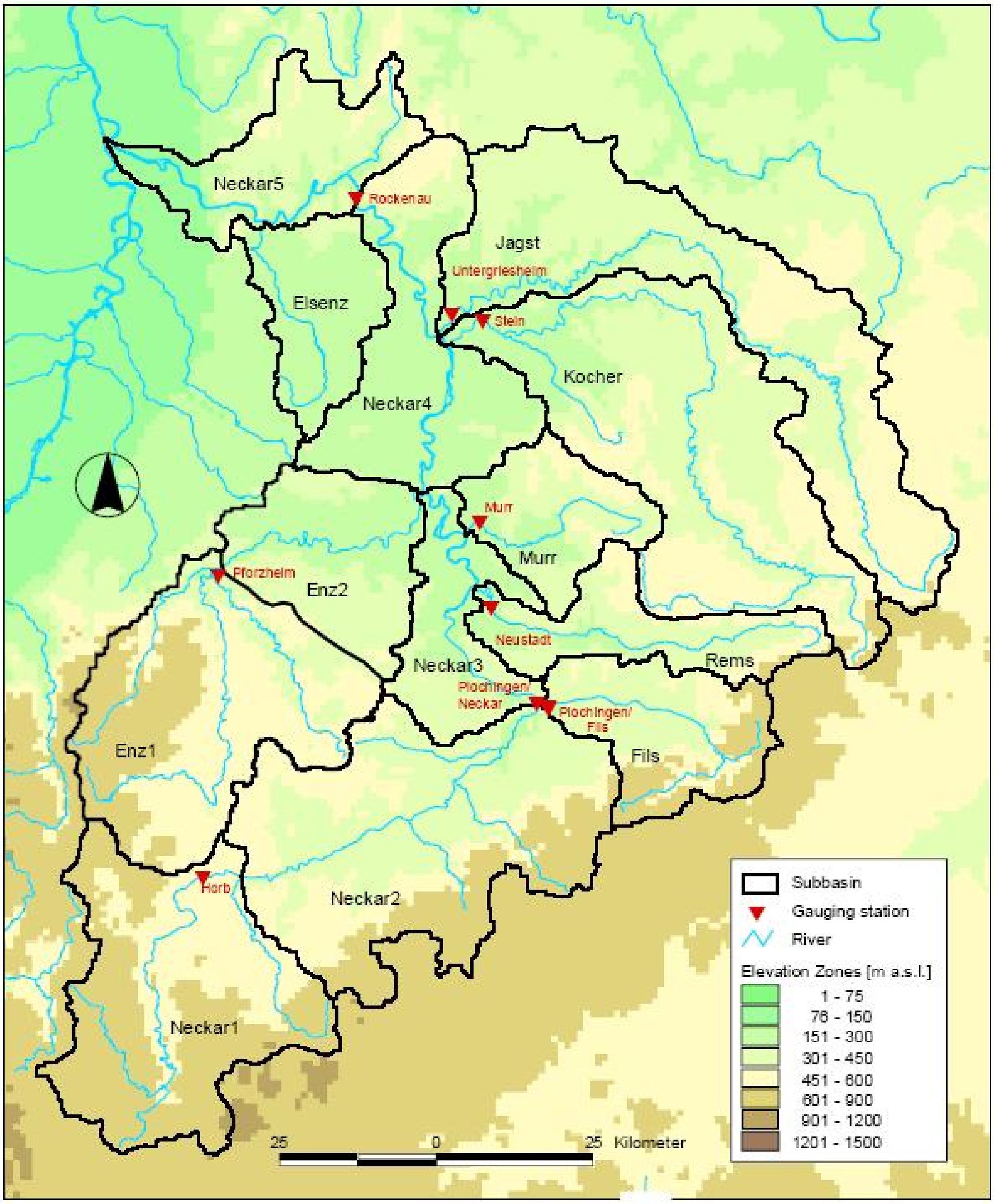

Figure 2.2. Map of sub-basins of the Neckar that are input into the SOBEK model between Speyer and Worms.

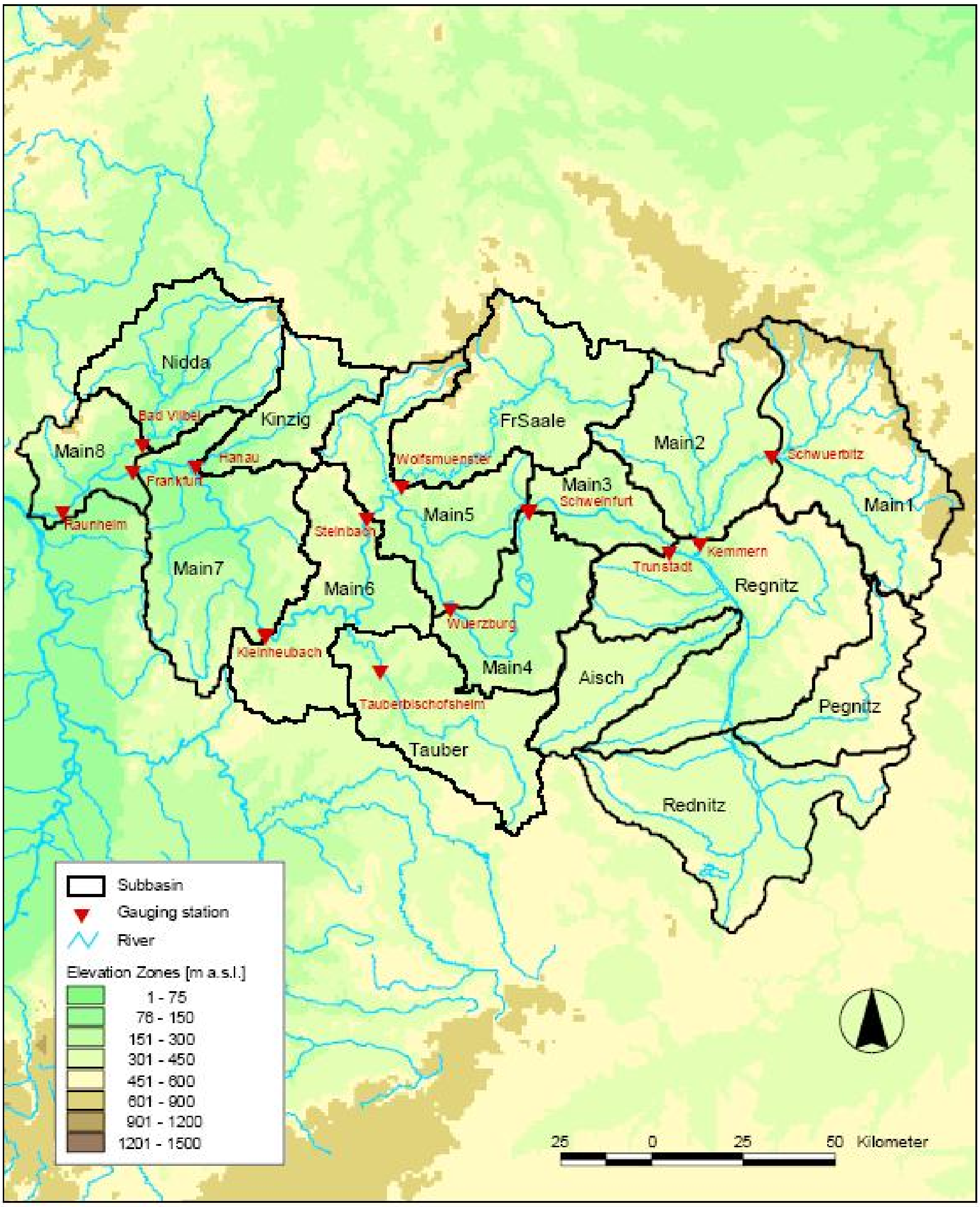

Figure 2.3. Map of sub-basins of the Main that are input into the SOBEK model between Worms and Mainz.

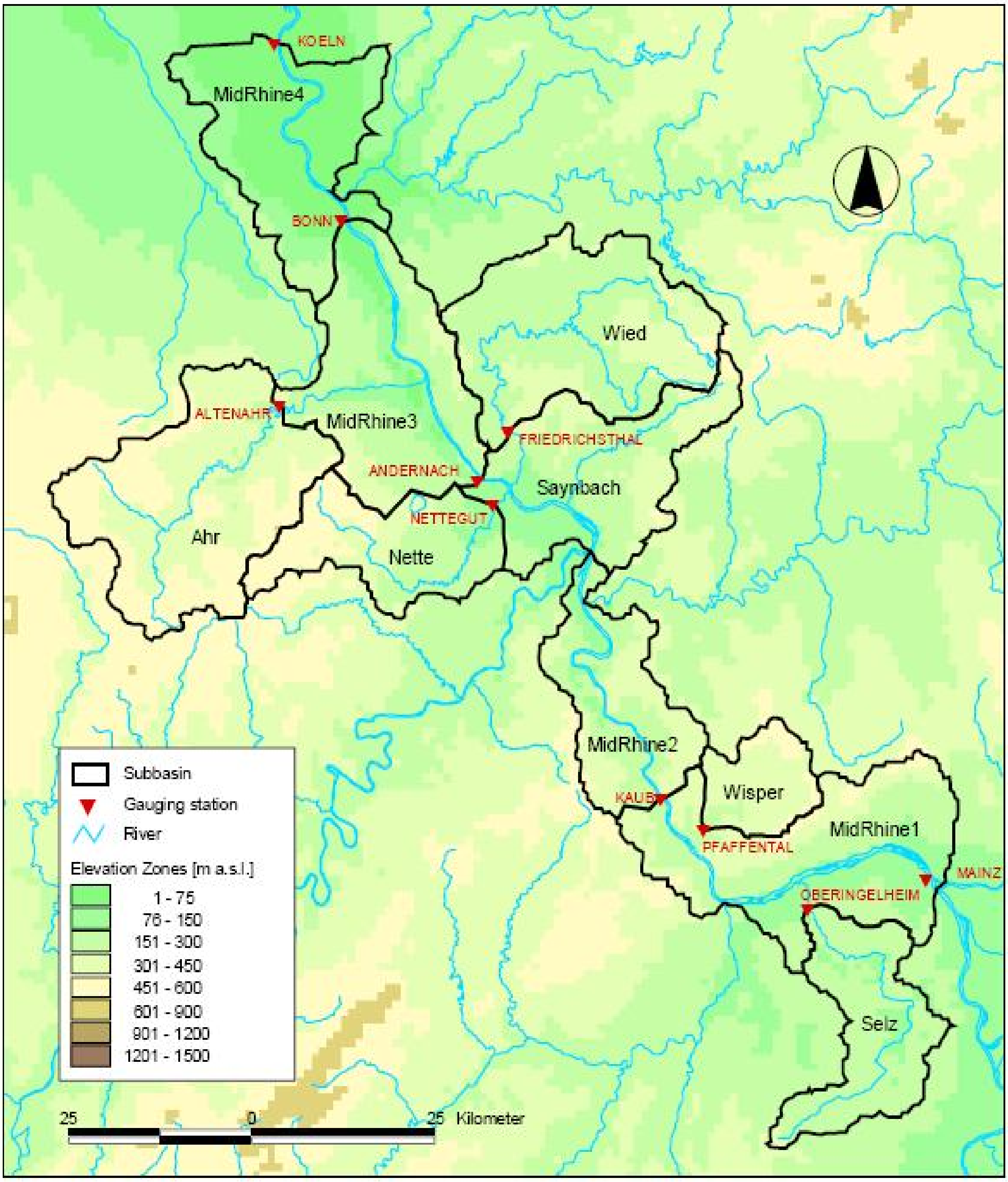

Figure 2.4. Map of sub-basins that are input into the SOBEK model between Mainz and Köln.

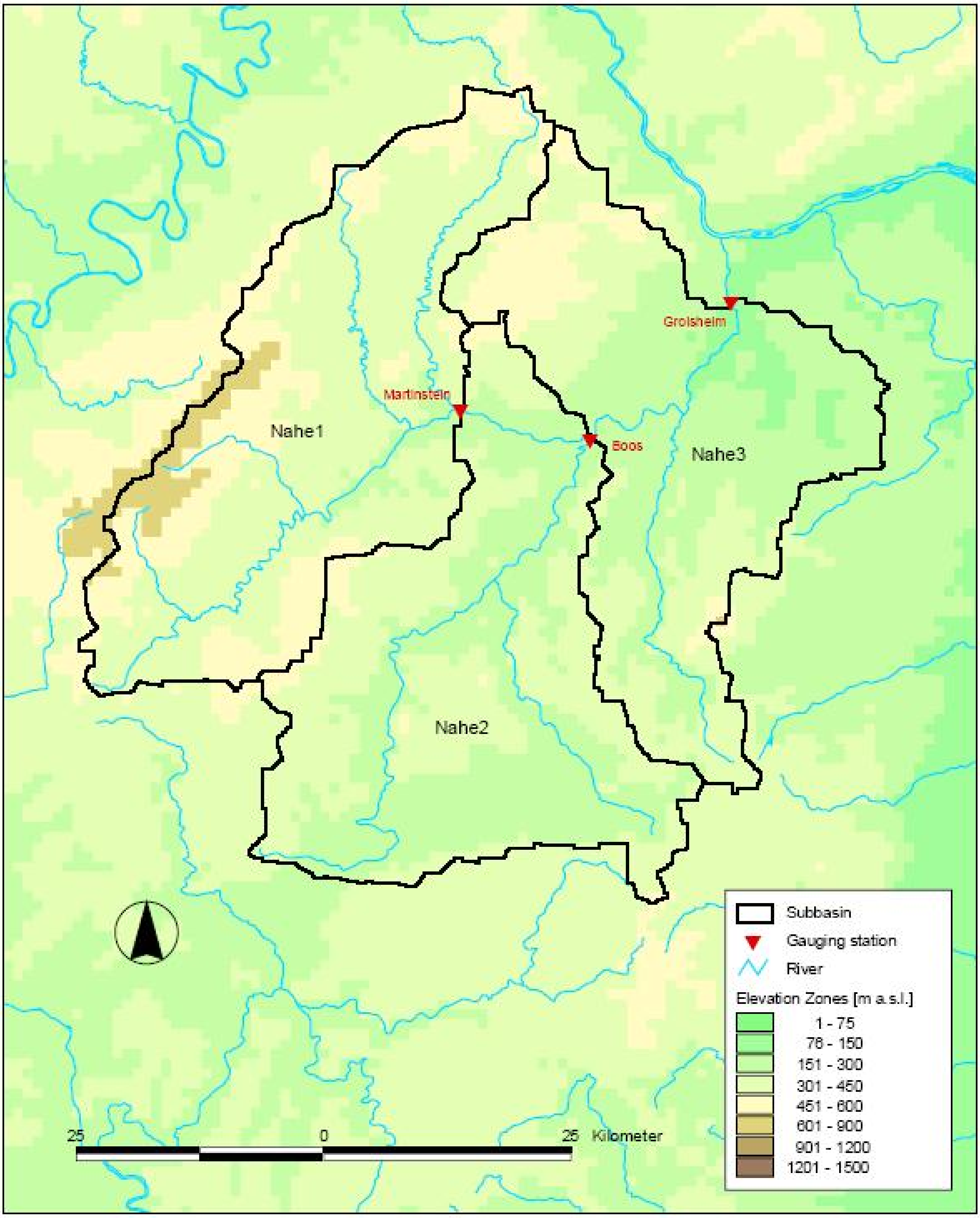

Figure 2.5. Map of sub-basins of the Nahe that are input into the SOBEK model between Mainz and Kaub.

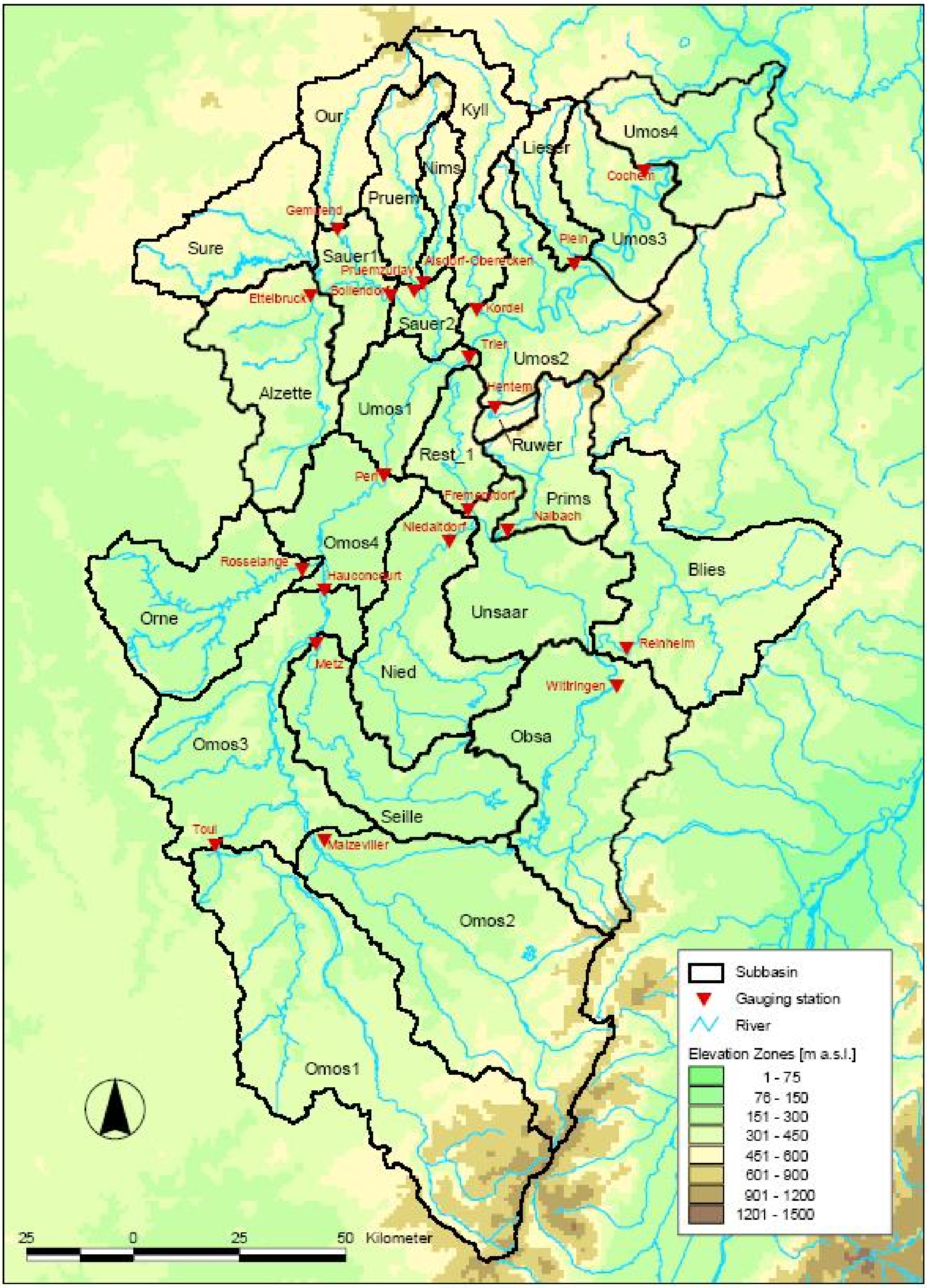

Figure 2.6. Map of sub-basins of the Mosel that are input into the SOBEK model between Koblenz and Andernach.

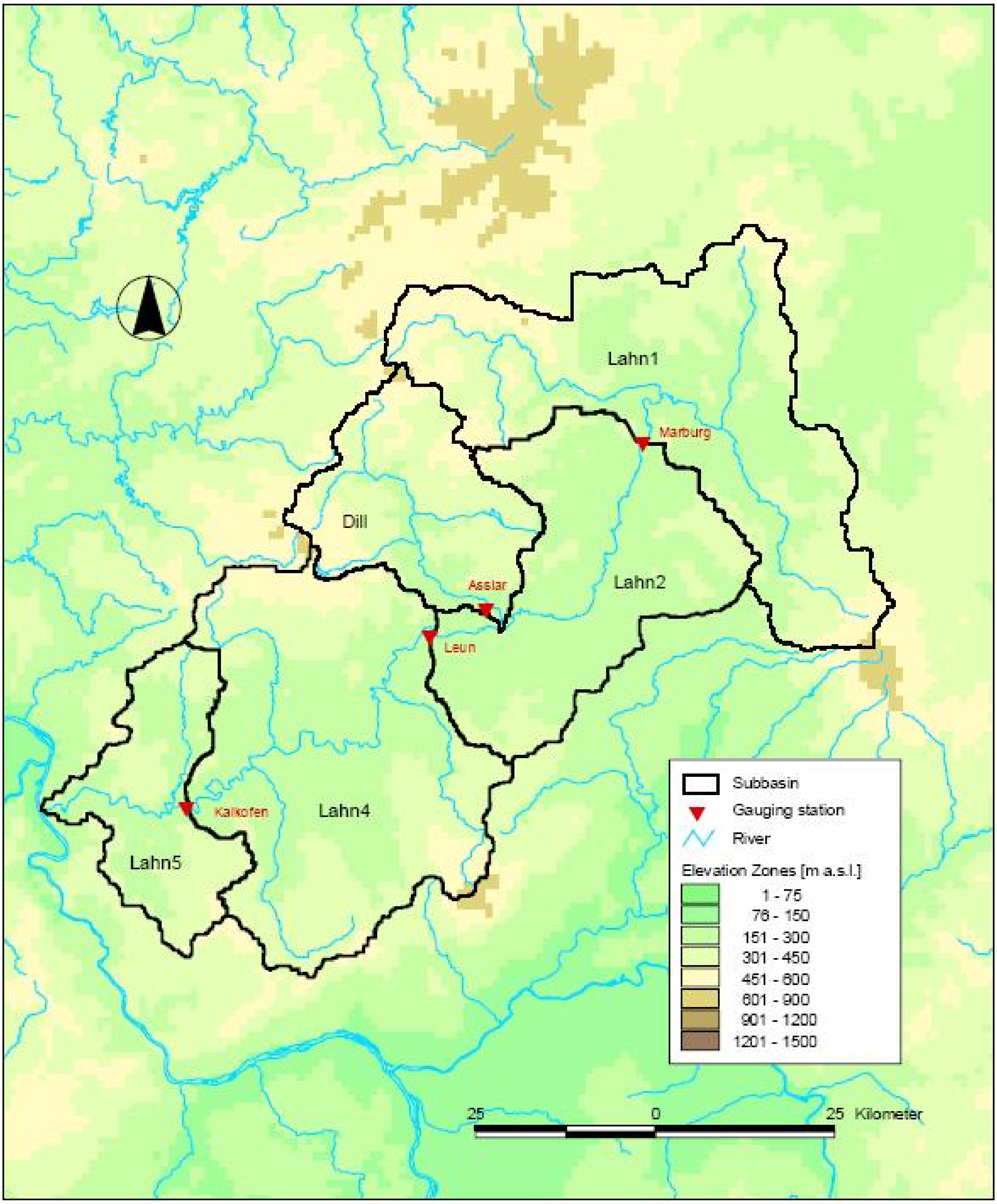

Figure 2.7. Map of sub-basins of the Lahn that are input into the SOBEK model between Kaub and Koblenz.

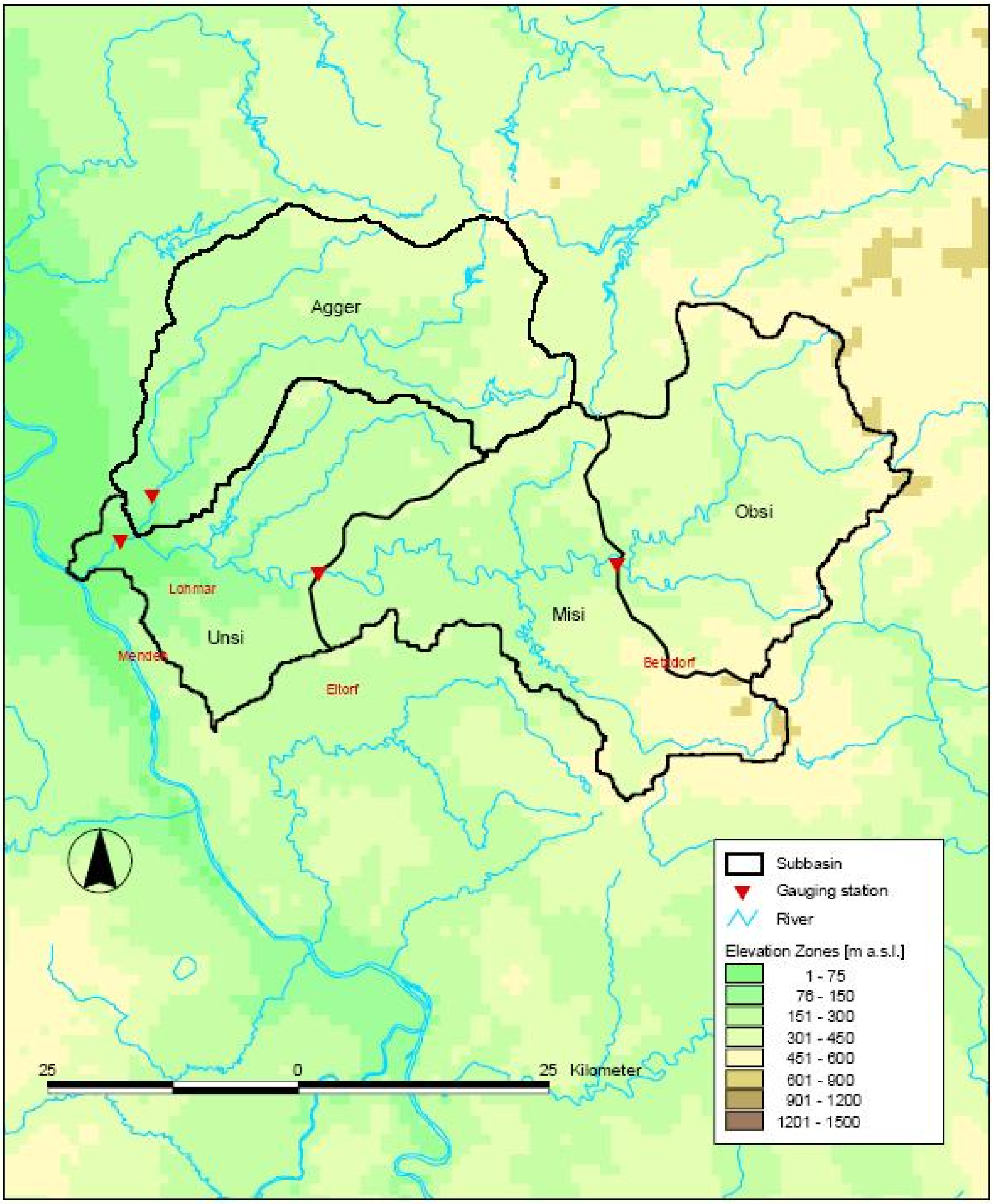

Figure 2.8. Map of sub-basins of the Sieg that are input into the SOBEK model between Bonn and Köln.

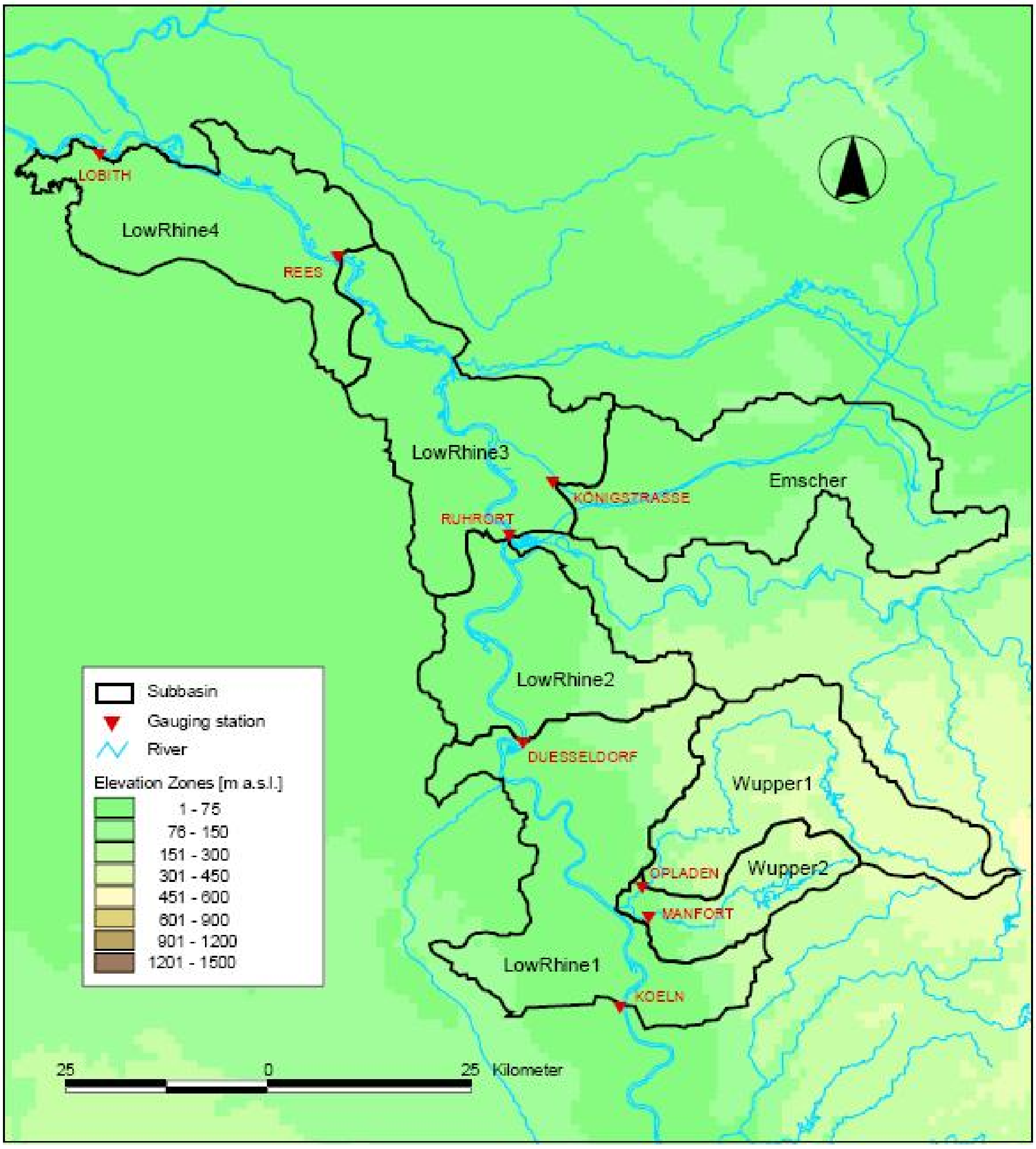

Figure 2.9. Map of sub-basins that are input into the SOBEK model between Köln and Lobith.

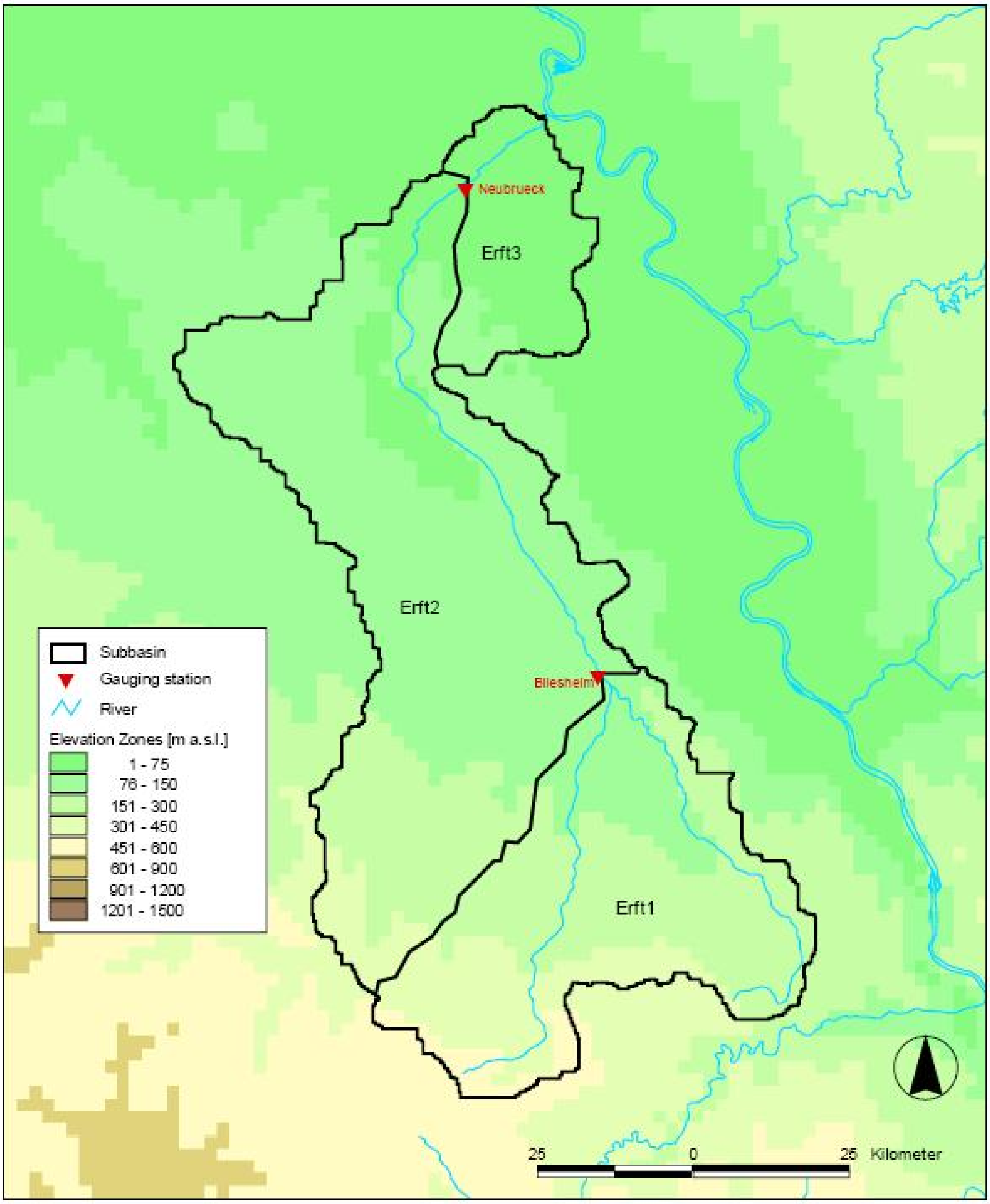

Figure 2.10. Map of sub-basins of the Erft, that are input into the SOBEK model between Köln and Düsseldorf.

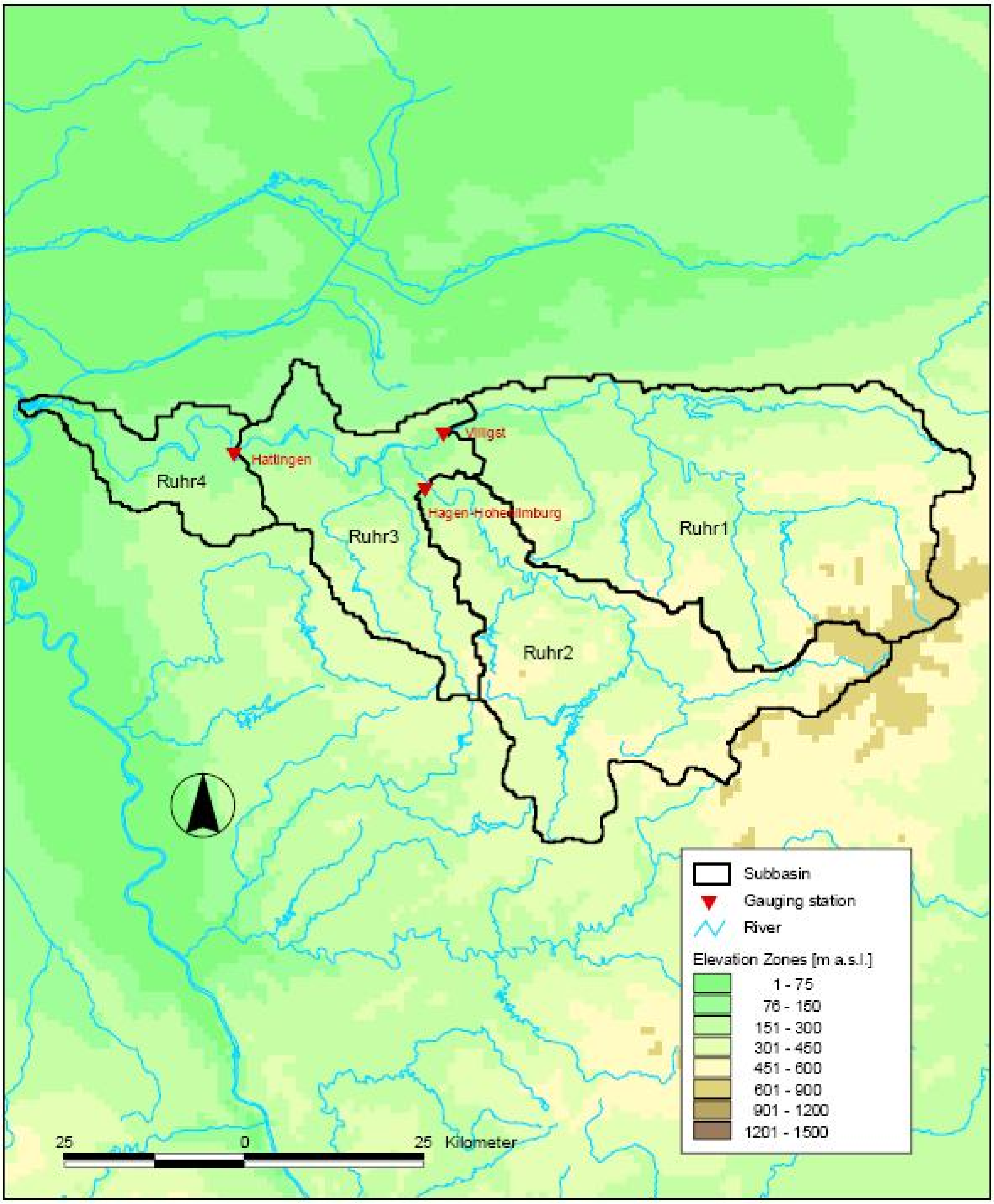

Figure 2.11. Map of sub-basins of the Ruhr that are input into the SOBEK model between Düsseldorf and Ruhrort.

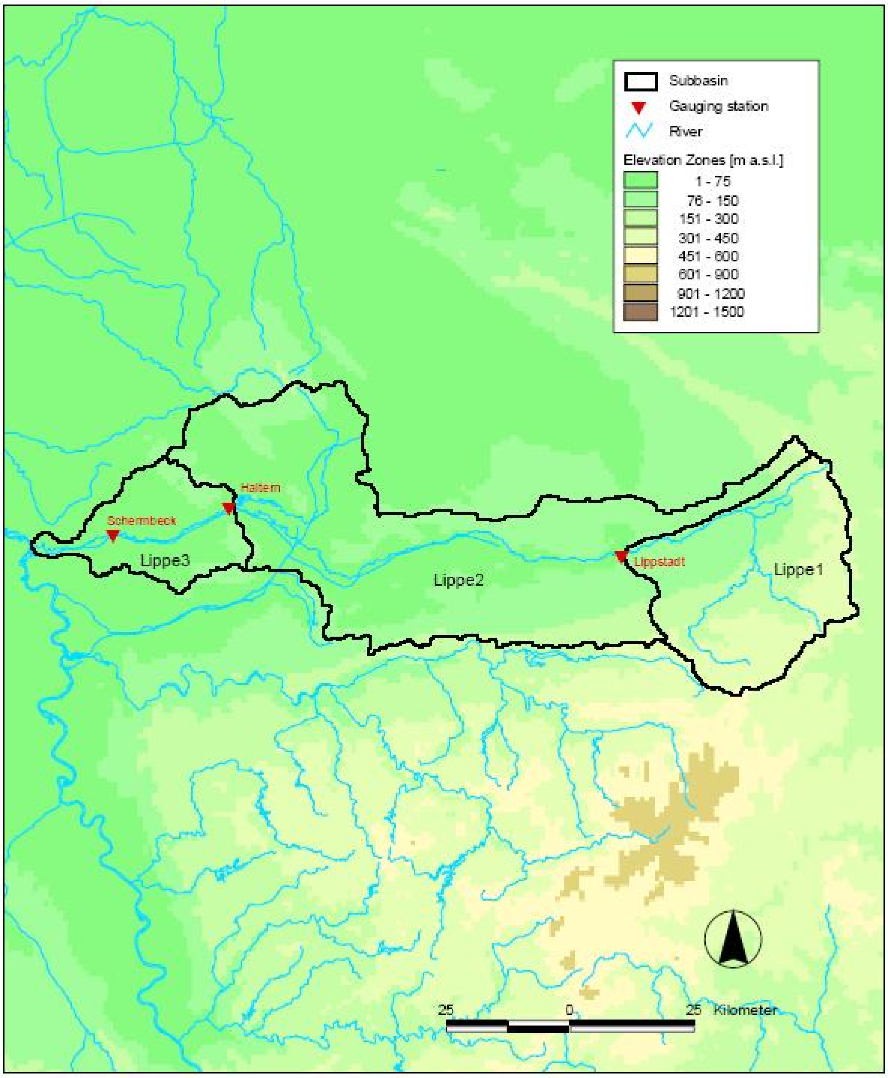

Figure 2.12. Map of sub-basins of the Lippe that are input into the SOBEK model between Wesel and Rees.

2.4 Boundary conditions SOBEK model FewsNL-Rijn version 2.05

Water balances have been established for the 13 river sections listed in Table 2.1. The boundary conditions are either solely measured discharge (derived from water levels and a stage-discharge relation) as is the case for the calibration set. Or as in the case of the HBV set, the lateral inflows consist of a mixture of measured discharges (derived from water levels and a stage-discharge relation) and HBV simulated discharges. In FewsNL-Rijn, for almost all small tributaries use is made of the HBV simulated discharges as measured discharges for these tributaries are not operationally available at the moment. In Table 2.1, **bold** font indicates what is being used in FewsNL-Rijn. The detention areas follow the convention as described below:

- _VolXX: modelled area's dike overflow Oberrhein
- _name: detention measures Oberrhein
- _O_XXX: modelled area's dike overflow Andernach-Lobith
- _D_XXX: modelled area's dike breach Andernach-Lobith
- _Y_XXX_dX: modelling of flow inside the dikes Andernach Lobith

The measurements and HBV data are multiplied with a factor to correct for basin area and where applicable a time shift is introduced to correct for travel time from the measuring station/HBV sub-basin outflow location to the river model. Both the time shift and hydrological factor are indicated in Table 2.1. When comparing HBV-data and data from the calibration set the following has to be taken into account:

- HBV subcatchments often are not identical with the catchments of the calibration set;
- The HBV-model and the SOBEK-model partly were developed parallel. Plans to couple these models were made later, when half of the HBV-model already was finished. Therefore in some cases (mainly in the upper part of the model) some of the subcatchments in HBV had to be fit to the necessities of SOBEK. This has been done using factors (e.g. QueichSp);
- In the case of the calibration set, the link between data and SOBEK-model is done using factors for parts of the (sub)catchment which is downstream the gauge. Using this factor might be wrong because the characteristics of this part of the catchment are different from the other part;
- The HBV-subcatchments along the Rhine such as UpRhine1 and UpRhine2 are catchments, which in fact are representing smaller tributaries along the Rhine, where operational no data available or gauging stations exist at all. When calibrating these subcatchments in HBV measurements from other catchments near by of part of these subcatchments were used, again using factors (BfG, 2000, Table 2.4). In some cases such as UpRhine2, the HBV catchment is matched to a calibration set, which is not identical with that used for calibration. In other cases such as UpRhine1 other factors are used for calibrating the HBV-subcatchment using the neighbouring river gauge Rheinzabern, than it is used in the coupling of the measured data of Rheinzabern with the SOBEK-model.

Table 2.1. Overview river sections and their inflows from measurements (calibration set) or from HBV. **Bold** printed names indicate what is being used operational in FewsNL-Rijn. Addition of + = + all upstream subbasins and n.a. means not available.

River Section	ID	River/ Tributary	Discharge gauging station	Factor hydro.	Shift (hr)	FewsNL-Rijn	Factor hydro.	Shift (hr)	Detention areas
1	MM1_3037	Rhine	**Maxau**	1.00	0.00	UpRh2_3+	1.000	0.00	MM1_Vol1, MM1_Vol2, MM1_Vol3, MM1_Vol4, MM1_Flotzgruen
Maxau	MM1_3039	Alb	Ettlingen	1.00	4.35	**AlbPfinz**	0.390	4.35	
Speyer	MM1_3040	Pfinz	Berghausen	1.00	7.04	**AlbPfinz**	0.610	7.04	
	MM1_3042	Queich	Siebeldingen	1.00	5.35	**QuiechSp**	0.390	5.35	
	MM1_3043	Speyerbach	Neustadt/Wst.	1.00	4.74	**QuiechSp**	0.610	4.74	
	MM1_3044	Erlenbach	Rheinzabern	11.02	0.00	**UpRhine1**	1.000	0.00	
	-	Rhine	Speyer	-	-	-	-	-	
2	-	Rhine	Speyer	-	-	-	-	-	MM1_Vol5, MM1_Vol6, MM1_Vol7, MM1_Vol8, MM1_Kollerinsel
Speyer	MM1_3045	Kraichbach	Ubstadt	2.48	0.00	**UpRhine2**	0.341	0.00	
Worms	NE1_5615460	Neckar	**Rockenau**	1.00	0.00	Neckar4+	1.000	0.00	
	NE1_24114	Elsenz	Meckesheim	2.10	2.96	**Elsenz**	1.000	0.00	
	NE1_24115	Itter	Eberbach	1.66	1.39	**Neckar5**	0.227	0.00	
	NE1_24116-24121	Neckar-lat	Eberbach	3.72	0.00	**Neckar5**	0.773	0.00	
	MM2_3046	Leinbach	Wiesloch	2.03	0.00	**UpRhine2**	0.659	0.00	
	MM1_3049	Pfrimm	Monsheim	4.24	0.00	**UpRhine3**	1.000	0.00	
	-	Rhine	Worms	-	-	-	-	-	

River Section	ID	River/ Tributary	Discharge gauging station	Factor hydro.	Shift (hr)	FewsNL-Rijn	Factor hydro.	Shift (hr)	Detention areas
3	-	Rhine	Worms	-	-	-	-	-	MM1_Vol9, MM1_Vol10, MM1_Vol11, MM1_Vol12, MM1_Vol13
Worms	MM1_3053	Rhine-lat	Monsheim	2.09	0.00	**UpRhine4**	0.370	0.00	
Mainz	MM1_3051	Weschnitz	Lorch	1.00	2.50	**WeschMod**	0.810	2.50	
	MM1_3052	Modau	Eberstadt	1.00	2.78	**WeschMod**	0.190	2.78	
	MM1_3054	Schwarzbach	Naunheim	5.98	0.00	**UpRhine4**	0.630	0.00	
	MA3_15910		Epstein	0.624	2.60	**Main8**	0.082	-	
	MA3_58596	Main	**Raunheim**	1.00	0.00	Main8+	1.000	0.00	
	-	Rhine	Mainz	-	-	-	-	-	
4	-	Rhine	Mainz	-	-	-	-	-	MM1_Vol14, RM1_Vol15, RM1_Vol16, RM1_Vol17, RM1_Vol18
Mainz	RM1_2148	Selz	Oberingelheim	1.03	0.00	**Selz**	1.000	0.00	
Kaub	RM1_2149	Rhine-lat	Pfaffental	1.79	0.00	**MidRhine1**	0.710	0.00	
	RM1_2150	Nahe	**Grolsheim**	1.01	0.00	Nahe3+	1.01	0.00	
	RM1_2151	Wisper	Pfaffental	1.23	0.00	**Wisper**	1.000	0.00	
	RM1_2153	Rhine-lat	Pfaffental	0.77	0.00	**MidRhine1**	0.290	0.00	
	-	Rhine	Kaub	-	-	-	-	-	
5/6	-	Rhine	Kaub	-	-	-	-	-	RM1_Vol19, RM1_Vol20, RM1_Vol21, RM1_Vol22, RM1_Vol23
Kaub	RM1_2154	Rhine-lat	Pfaffenthal	2.16	0.00	**MidRhine2**	1.000	0.00	
Koblenz	LA1_5365	Lahn	**Kalkofen**	1.00	0.00	Lahn4+	1.000	0.00	
	LA1_1489	Gelbach	Weinähr	1.03	0.49	**Lahn5**	0.348	0.00	
	LA1_3563		Weinähr	1.12	0.00	**Lahn5**	0.381	0.00	
	LA1_1490	Mühlbach	Schulmühle	1.18	1.25	**Lahn5**	0.271	0.00	
	-	Rhine	Koblenz	-	-	-	-	-	

River Section	ID	River/ Tributary	Discharge gauging station	Factor hydro.	Shift (hr)	FewsNL-Rijn	Factor hydro.	Shift (hr)	Detention areas
Koblenz	-	Rhine	Koblenz	-	-	-	-	-	RM1_Vol24, RM1_Vol25, RM1_Vol26 AL1_W_101_103, Al1_O_001
Andernach	MO1_409	Mosel	**Cochem**	1.00	0.00	Umos3+	1.00	0.00	
	MO1_1815	Mosel-lat	n.a.	1.00	0.00	**Umos4**	1.00	0.00	
	RM1_2158	Nette	Nettegut	1.01	0.00	**Nette**	1.010	0.00	
	RM1_2157-59	Wied	**Friedrichsthal**	1.35	0.00	Saynbach	1.35	0.00	
	RM1-2160	Rhine-lat	Friedrichsthal	0.18	0.00	**Saynbach**	0.570	0.00	
	-	Rhine	Andernach	-	-	-	-	-	
7	-	Rhine	Andernach	-	-	-	-	-	Al1_103, Al1_1031, Al1_1032, Al1_O_002, Al1_O_003, Al1_O_004, Al1_O_005, Al1_O_005_d1, Al1_O_005_d2 Al1_O_006, Al1_O_006_d1 Al1_O_006_d2, Al1_O_006_d3, Al1_O_006_d4, Al1_O_008, Al1_O_008_d1, Al1_O_008_d2 Al1_O_009, Al1_O_010, Al1_O_011, Al1_O_012
Andernach	AL1_6	Ahr	**Altenahr/R'hoven**	1.20	5.00	Ahr	1.00	5.00	
Bonn	AL1_1402	Rhine-lat	n.a	1.00	0.00	**MidRhine3**	1.00	0.00	
	-	Rhine	Bonn	-	-	-	-	-	

River Section	ID	River/ Tributary	Discharge gauging station	Factor hydro.	Shift (hr)	FewsNL-Rijn	Factor hydro.	Shift (hr)	Detention areas
8	-	Rhine	Bonn	-	-	-	-	-	Al1_103, Al1_1031, Al1_1032, Al1_O_002, Al1_O_003, Al1_O_004, Al1_O_005, Al1_O_005_d1, Al1_O_005_d2, Al1_O_006, Al1_O_006_d1, Al1_O_006_d2, Al1_O_006_d3, Al1_O_006_d4, Al1_O_008, Al1_O_008_d1, Al1_O_008_d2, Al1_O_009, Al1_O_010, Al1_O_011, Al1_O_012,
Bonn	AL1_8	Sieg	**Menden**	1.00	1.50	Unsi+	1.00	1.50	
Köln	AL1_1403	Rhine-lat	n.a	1.00	0.00	**MidRhine4**	1.000	0.00	
	-	Rhine	Köln	-	-	-	-	-	

River Section	ID	River/ Tributary	Discharge gauging station	Factor hydro.	Shift (hr)	FewsNL-Rijn	Factor hydro.	Shift (hr)	Detention areas
9	-	Rhine	Köln	-	-	-	-	-	Al1_Mohne_d1, Al1_Mohne_d2, Al1_O_013, Al1_O_014, Al1_O_014_d1, Al1_O_014_d2, Al1_O_015, Al1_O_016, Al1_O_016_d1, Al1_O_016_d2, Al1_O_017, Al1_O_018, Al1_O_021, Al1_O_021_d1, Al1_O_021_d2, Al1_O_021_d3, Al1_O_021_d4, Al1_O_022, Al1_O_024, Al1_O_025, Al1_D_019, Al1_D_019_d1, Al1_D_019_d2, Al1_D_023, Al1_D_023_d1, Al1_D_023_d2, Al1_D_023_d3, Al1_D_023_d4, Al1_O_026, Al1_O_027, Al1_O_027_b, AL1_O_027_d1 Al1_O_027_d2
Köln	AL1_10	Wupper	**Opladen**	1.36	1.00	Wupper1+	1.36	1.00	
Düsseldorf	AL1_11	Erft	**Neubrück**	1.15	2.00	Erft2+	1.15	2.00	
	AL1_1404	Rhine-lat	n.a	1.00	0.00	**LowRhine1**	1.000	0.00	
	-	Rhine	Düsseldorf	-	-	-	-	-	

River Section	ID	River/ Tributary	Discharge gauging station	Factor hydro.	Shift (hr)	FewsNL-Rijn	Factor hydro.	Shift (hr)	Detention areas
10 Düsseldorf Ruhrort	- AL1_13 AL1_1405 -	Rhine Ruhr Rhine-lat Rhine	Düsseldorf **Hattingen** n.a Ruhrort	- 1.09 1.00 -	- 10.00 0.00 -	- Ruhr3+ **LowRhine2** -	- 1.09 1.000 -	- 10.00 0.00 -	AL1_O_030, AL1_D_031, AL1_D_031_d1, AL1_D_031_d2, AL1_D_033, AL1_D_033_d1, AL1_D_033_d2, AL1_D_034, AL1_D_035
11 Ruhrort Wesel	- AL1_4 AL1_1406 -	Rhine Emscher Rhine	Ruhrort **Königstrasse** n.a Wesel	- 1.11 0.210 -	- 2.00 0.00 -	- Emscher **LowRhine3** -	- 1.11 0.210 -	- 2.00 0.00 -	AL1_O_037
12 Wesel Rees	- AL1_1 AL1_1407 -	Rhine Lippe Rhine-lat Rhine	Wesel **Schermbeck** n.a Rees	- 1.02 - -	- 4.10 - -	- Lippe3+ **LowRhine3** -	- 1.02 0.79 -	- 4.10 0.00 -	AL1_107
13 Rees Emmerich	- AL1_1408 -	Rhine Rhine-lat Rhine	Rees n.a Emmerich	- - -	- - -	- **LowRhine4** -	- a -	- 0.00 -	AL1_O_39, AL1_O_40, AL1_O_41
14 Emmerich Lobith	- AL1_1408 -	Rhine Rhine-lat Rhine	Emmerich n.a Lobith	- - -	- - -	- **LowRhine4** -	- 1-a -	- 0.00 -	

3 Method of analysis

3.1 General

The goal of the analysis in Phase 2 is to identify and detect errors in the input data (calibration set vs HBV set) of the SOBEK model that is also being used in FewsNL-Rijn. This means that in this Phase 2 report no solutions are being provided but only errors are detected. Possible sources of error are:

- stage-discharge relationship at the upstream and downstream measurement point;
- discharge model boundaries;
- hysteresis effects in the stage-discharge relationship;
- errors in the lateral inflows between measurement points in the main river;
- detention-effects;
- interaction with groundwater (between Kaub and Lobith);

In FewsNL-Rijn, HBV calculated discharges (small tributaries and areas close to the main river) and discharges of the larger tributaries derived from water level measurements (using a stage-discharge relationship) provide input for the SOBEK models. Most notable differences between the SOBEK model and measured water levels occur during low flow periods and during flood periods.

Water balance analyses have been carried out between 14 subsequent measurement points in the river Rhine leading to the 13 river sections as presented in Table 2-1 with special attention to low flow and flood periods.

3.2 Analysis and Simulations

The idea of the analysis is to investigate periods where anomalies in the water balance occur for each of the 13 river sections (Mens et al., 2006). The water balance has been calculated using two scenarios for determining the lateral inflows into the Rhine in combination with the derived discharge of the gauging stations in the river Rhine:

1. SOBEK lateral inflows used during calibration (i.e. only measured data and data derived from measured data)
2. SOBEK lateral inflows used in the operational FewsNL-Rijn system during the update period (i.e. data partly directly measured and partly resulting from HBV simulations)

These SOBEK simulations have been carried out for each section for the period 1/1/1993 – 31/12/2-2004 for the calibration set and 1/1/1997 – 31/12/2004 for the HBV set. For the period 1989 until March 1996 no meaningful HBV simulations can be carried out with FewsNL because of a lack of synoptic data for this period.

In the water balance analysis the main focus has been on the period 1/11/1997 -31/10/2004. This choice is based on the fact that most of the analysis is done for German territory and it seems therefore logical to use German hydrological years. Note however, that the simulations for the floods of 1993 and 1995 using the calibration set have been carried out. For the upstream boundary of all the SOBEK models a discharge boundary, where the discharge series is derived from water levels using a single stage-discharge relation, is used. Besides these simulations, SOBEK simulations between Kaub and Lobith with groundwater model switched (section 5/6 – section 14) off have also been carried out with an observed discharge as upper boundary and calibration and HBV set used for the laterals. Table 3.1 provides an overview of all the models used in this study.

The analysis of the water balance for interesting periods will be carried out for

- each river section using by Client specified periods
  low flow: 2003;
  flood: 1993, 1995,1998, 1999 (only for the Upper Rhine), 2002 and 2003;
- for selected other periods. This selection is done on the basis of the analysis described in Phase 1 (Mens et al., 2006). The anomalies are directly spotted from the comparison of the measured series and the SOBEK simulations as shown in Figure 3.1 and not from an analysis within HYMOS as described in the Phase 1 report. From Figure 3.1, it can be observed that largest deviation occurs near the peak of October/November 1998 and this is therefore an interesting period to look upon.

Table 3.1. Overview of SOBEK models used in this study. Note that all models have the same downstream model boundary conditions that consists of a water level at Werkendam, Krimpen a/d Lek and Ramspolbrug (all at the downstream end of the Rhine branches).

Model	**Upstream model boundary**	**Calibration and HBV lateral inflow set**	**with and without ground water**
section 1	Maxau	both	with
section 2	Speyer	both	with
section 3	Worms	both	with
section 4	Mainz	both	with
section 5/6	Kaub	both	both
section 7	Andernach	both	both
section 8	Bonn	both	both
section 9	Koln	both	both
section 10	Dusseldorf	both	both
section 11	Ruhrort	both	both
section 12	Wesel	both	both
section 13	Rees	both	both
section 14	Emmerich	both	both

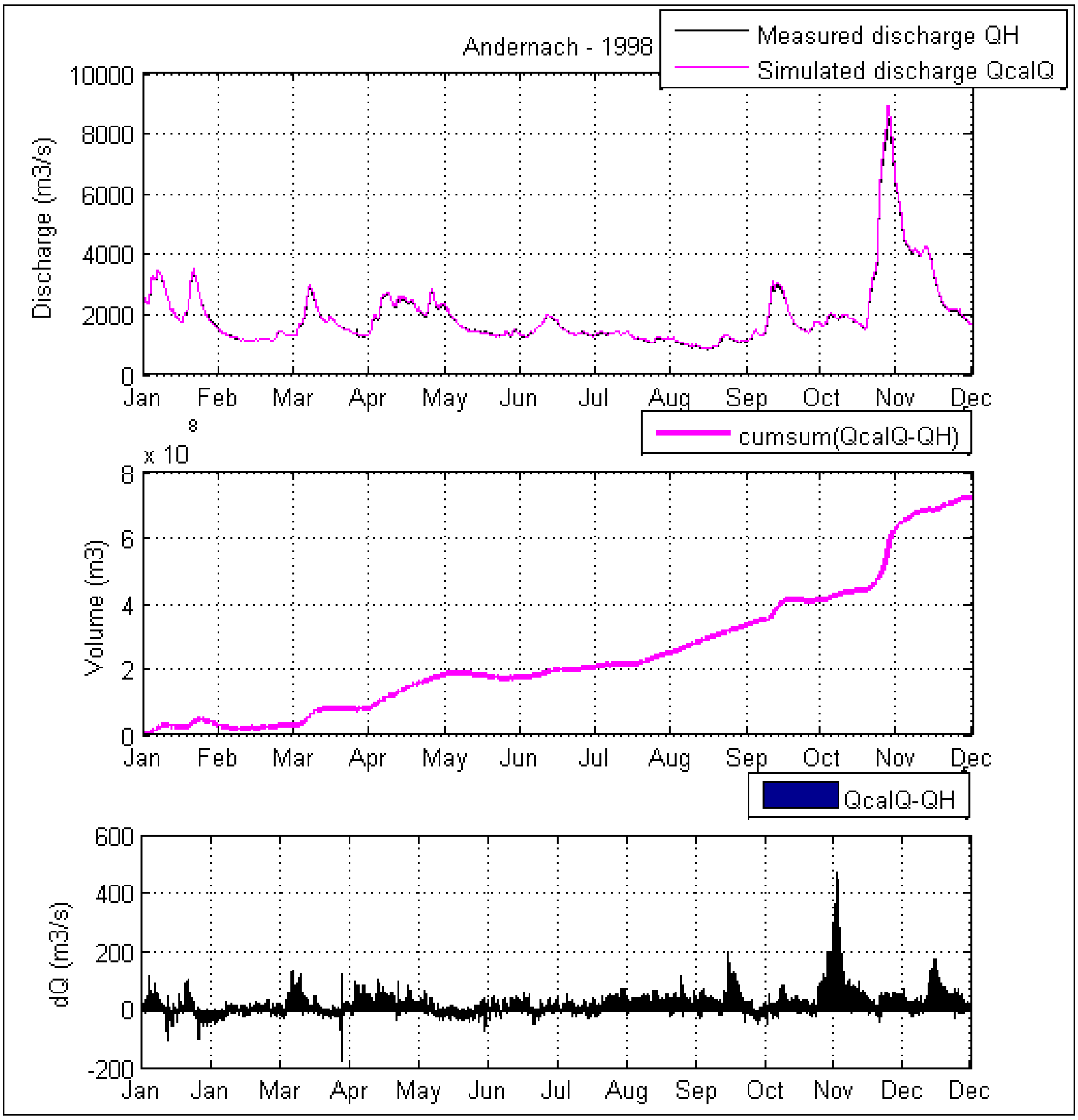

Figure 3.1. Overview water balance section 5/6: Kaub-Andernach for 1998.

4 Results per section

4.1 General

The following table shows the available series that can be compared. Each series has an unique colour and a series name (abbreviation) which are used in the figures.

Table 4.1 Overview of available series with colour coding

Data	Source	Series name	Color
Measured discharge Rhine as derived from discharge rating curve	HYMOS	QH	
Measured lateral discharge as derived from discharge rating curves, including hydrological factor and factor for time lag	HYMOS	QcalL	
Lateral discharge derived with HBV, including hydrological factor and factor for time lag	HYMOS	QhbvL	
Simulated discharge Rhine, calibration set, upstream Q	SOBEK	QcalQ	
Simulated discharge Rhine, calibration set, upstream H	SOBEK	QcalH	
Simulated discharge Rhine, HBV set, upstream Q	SOBEK	QhbvQ	

Each section starts with an overview of the overall water balance for 7 hydrological years (1/11/1997 - 31/10/2004). In this overview section a water balance table is given for the whole period. After this overview section, the periods of interest are shown using a similar format of the water balance table followed by an analysis of the laterals. A short explanation of what can be found in the figures and tables is given for each section. In the following, the name of discharge gauging station as mentioned in the figures is also used for the HBV-catchments. However, they are not really corresponding, see also Table 2.1 (column 4 and 7).

4.2 Section 1: Maxau – Speyer

4.2.1 Overview

Figure 4.1 shows a schematic overview of the first river section. Maxau is the upper boundary in SOBEK. Five laterals are contributing to the Rhine flow in this section (see also Table 2.1). Also one detention area (Flotzgrün) is present in the section Maxau-Speyer. Until now the detention area at Flotzgrün has not been used in reality (Meissner, pers. comm. after consulting the Landesamt für Umwelt, Wasserwirtschaft und Gewerbeaufsicht of the Federal state Rhineland-Palatinate). It is assumed that the detention area has no influence on the overall water balance. However, it can influence the shape of hydrograph and therefore the water balance for short periods of time.

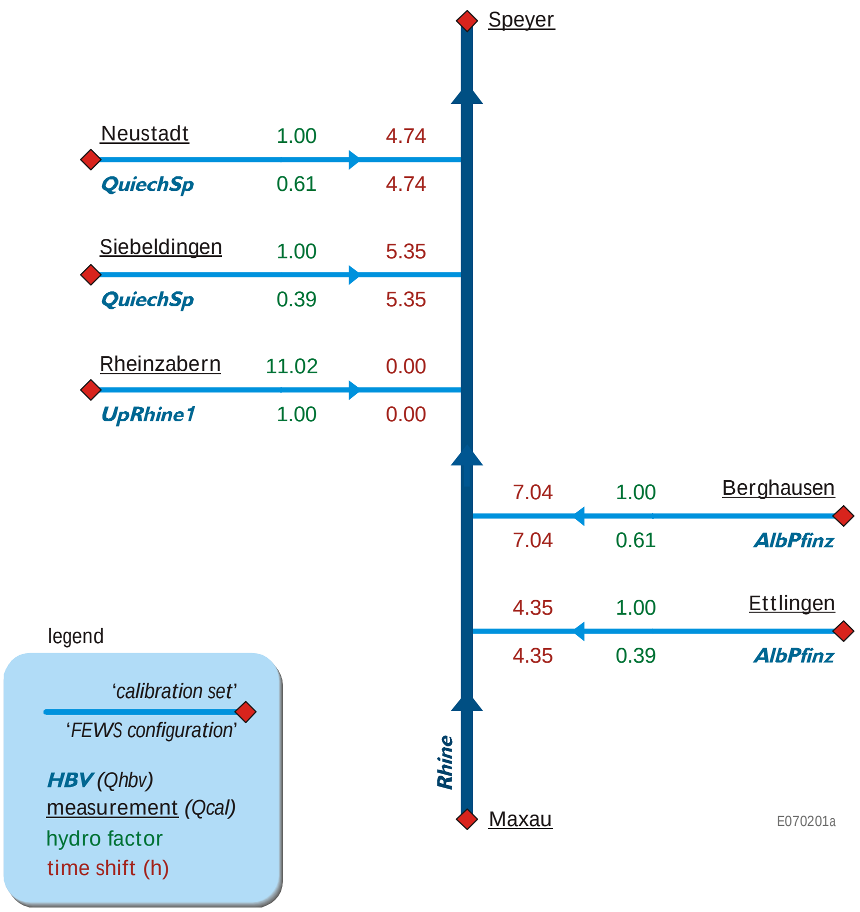

Figure 4.1 Schematic overview of section 1

Table 4.2 shows the water balance of the section Maxau-Speyer. Detention does not occur in the section Maxau-Speyer during the whole simulation period. From Table 4.2, the following is observed:

- according to the derived discharges (QH) the volume of water at Maxau is larger than at Speyer (0.27%);
- the water balance is positive (0.64 Bm^3/year), note that the behaviour of the water balance in time is not constant (see Appendix D) probably due to rating curve changes.
- on average the laterals are of minor importance in their contribution to the discharge at Speyer (calibration: 1.24% and HBV 1.39%);
- both SOBEK models show an increase of flow volume between Maxau and Speyer with the size of the laterals (calibration: 1.26% or HBV: 1.51%) ;
- Rheinzabern contributes to the sum of laterals with about 46% (cal) and 73% (HBV);
- the greatest difference between the laterals from the calibration and HBV set is found for Rheinzabern (27%);
- the differences between the HBV set and the calibration set show an increase of about 57% for Rheinzabern and a decrease for Ettlingen and Neustadt with 44 and 46%, respectively.

Table 4.2. Overview water balance section 1: Maxau-Speyer (in $Bm^3/y=10^9m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 1: Maxau-Speyer period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Speyer (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Maxau	42.56			100.27			4542	1349	394
Speyer	42.45			100.00			4446	1345	408
Sum of Laterals	0.53			1.24					
I+SoL-O[1]	0.64			1.51					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Speyer (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH vs QcalQ**		
Maxau	42.56	42.56	0	100.27	100.27	0	±100		
Speyer	43.09	43.15	0.06	101.50	101.65	0.15	±150		
Sum of Laterals	0.53	0.59	0.06	1.24	1.39	0.15			
I+SoL-O[1]	0.00	0.00	0.00	0.01	0.01	0.00			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
Berghausen	0.07	0.07	0.01	12.51	13.85	1.34	87.84	2.10	0.23
Ettlingen	0.08	0.05	-0.04	16.00	8.86	-7.14	96.49	2.57	0.18
Siebeldingen	0.04	0.03	0.00	7.09	6.47	-0.62	27.40	1.22	0.13
Neustadt	0.10	0.05	-0.04	18.58	10.11	-8.47	12.50	2.73	0.88
Rheinzabern	0.24	0.38	0.14	45.82	72.61	26.79	88.81	7.26	0.65
Sum of Laterals	0.53	0.59	0.06	100.00	111.90	11.90			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

The rating curves of the up- and downstream station and the simulated hysteresis are given in Appendix A. The rating curve at Maxau has been changed frequently. The changes in rating curves reflect the morphodynamics of the channel geometry. The changing channel geometry is not taken into account in the SOBEK model. The effect of the hysteresis can be in the order of 150 m^3/s for Speyer (see for instance peak of 1999, Appendix A). At Maxau the hysteresis is smaller (about 100 m^3/s) when compared to the hysteresis at Speyer.

4.2.2 Periods of Interest

Figure 4.2 shows the flood period of May 1999. Table 4.3 shows the results of water balance for the flood period of May 1999. For this flood period more flow volume is being measured at Speyer than can be explained on the basis of the simulations. The difference between the sum of the laterals from the calibration and HBV set is minimal for this period. For the flood period of 2003 also more water is being measured at Speyer than can be explained on the basis of the simulations. The sum of laterals of the HBV set is much larger than of the calibration set for this flood period. The contribution of sum of laterals of the HBV set is almost 70% larger compared to the calibration set. The table and figure of the flood period of 2003 are given in Appendix B.
Figure 4.3 and Table 4.4 shows the results for the low flow period in 2003. For this low flow period the same volume of water is being measured at Maxau and Speyer. Compared to the simulations the volume measured at Speyer is too low. The sum of laterals of the HBV set is about 40% larger than of the calibration set.

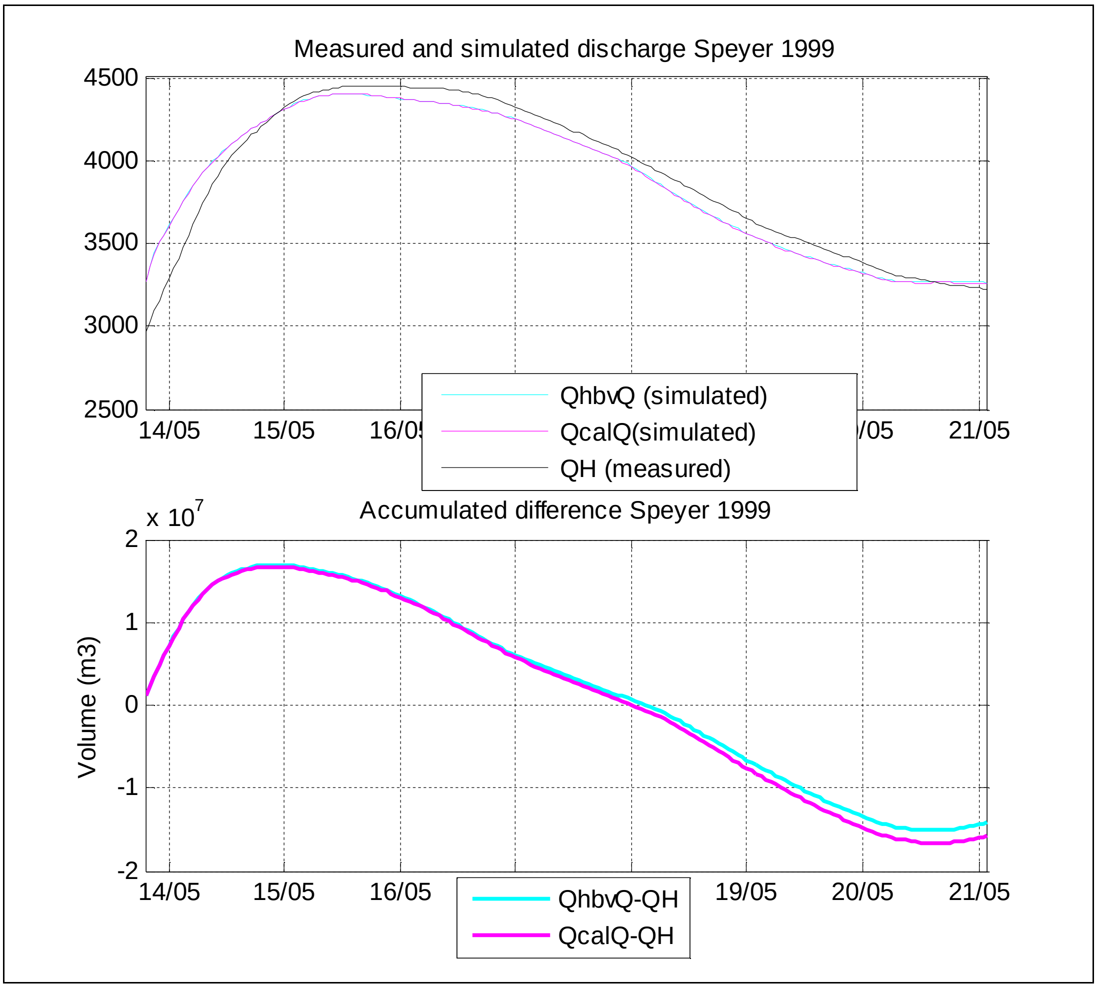

Figure 4.2. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Speyer, (b) accumulated difference at Speyer for both the calibration set and the HBV set.

Table 4.3. Overview waterbalance section 1: Maxau-Speyer for flood period of May 1999 (in Bm^3=$10^9 m^3$) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 1: Maxau-Speyer Flood period: 13/05/1999 13:00 – 21/05/1999 09:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Speyer (%)**		
Maxau	2.52			98.67		
Speyer	2.55			100.00		
Sum of Laterals	0.01			0.51		
I+SoL-O[1]	-0.02			-0.82		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Speyer (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Maxau	2.52	2.52	0	98.67	98.67	0
Speyer	2.54	2.54	0.00	99.51	99.53	0.02
Sum of Laterals	0.01	0.01	0.00	0.51	0.54	0.03
I+SoL-O[1]	-0.01	-0.01	0.00	-0.33	-0.33	0.01
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Berghausen	1.87	1.72	-0.14	14.30	13.20	-1.10
Ettlingen	2.11	1.10	-1.01	16.18	8.44	-7.75
Siebeldingen	0.91	0.71	-0.20	6.98	5.45	-1.52
Neustadt	2.28	1.11	-1.16	17.42	8.53	-8.89
Rheinzabern	5.90	9.12	3.23	45.12	69.82	24.70
Sum of Laterals	13.07	13.78	0.71	100.00	105.44	5.44

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

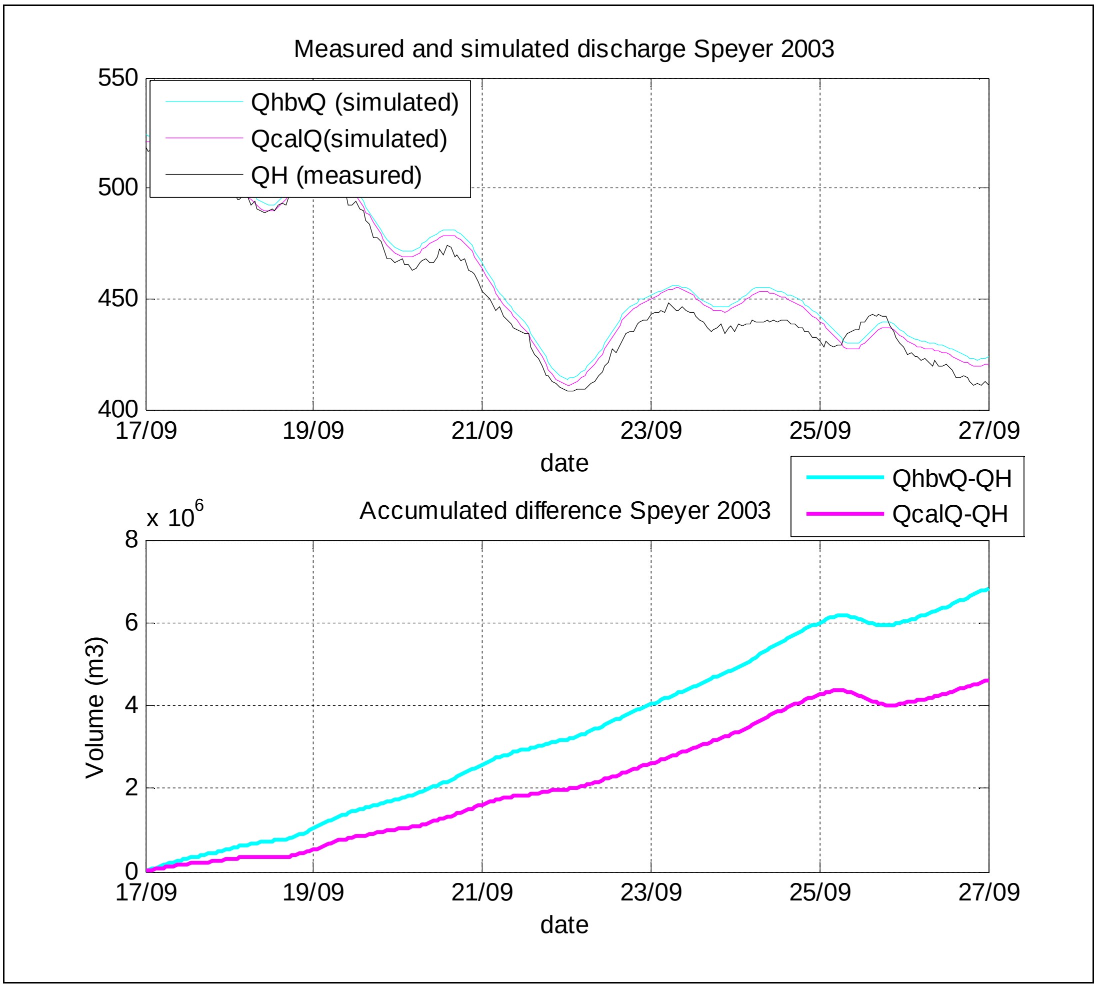

Figure 4.3. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Speyer, (b) accumulated difference at Speyer for both the calibration set and the HBV set.

Table 4.4. Overview waterbalance section 1: Maxau-Speyer for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 1: Maxau-Speyer Low flow period: 17/09/2003 – 27/09/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Speyer (%)**		
Maxau	0.39			98.59		
Speyer	0.39			100.00		
Sum of Laterals	0.01			1.42		
I+SoL-O[1]	0.00			0.01		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Speyer (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Maxau	0.39	0.39	0	98.59	98.59	0
Speyer	0.40	0.40	0.00	101.17	101.73	0.56
Sum of Laterals	0.01	0.01	0.00	1.42	2.00	0.58
I+SoL-O[1]	0.00	0.00	0.00	-1.16	-1.14	0.01
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Berghausen	0.64	0.93	0.29	11.40	16.64	5.23
Ettlingen	0.70	0.60	-0.10	12.48	10.63	-1.85
Siebeldingen	0.20	0.55	0.34	3.63	9.73	6.09
Neustadt	2.06	0.85	-1.20	36.71	15.21	-21.50
Rheinzabern	2.01	4.95	2.95	35.78	88.37	52.59
Sum of Laterals	5.60	7.88	2.27	100.00	140.57	40.57

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.2.3 Lateral inflows

As shown in section 4.2.1 the lateral inflows in this river section are of minor importance for the overall water balance at Speyer. Rheinzabern is the most important one. The figures for the remaining laterals can be found in Appendix C. Figure 4.4 shows that during peaks the HBV results for Rheinzabern are much higher than those derived from calibration set. This behaviour is consistent and indicates that the factor chosen for this lateral is too large. For the laterals Ettlingen and Neustadt the opposite is the case (the factor is too small). Table 4.5 gives statistical information regarding the comparison of the laterals from the calibration and HBV set. This table confirms earlier findings. It also shows that the Nash-Sutcliffe Efficiency (NSE) values are low.

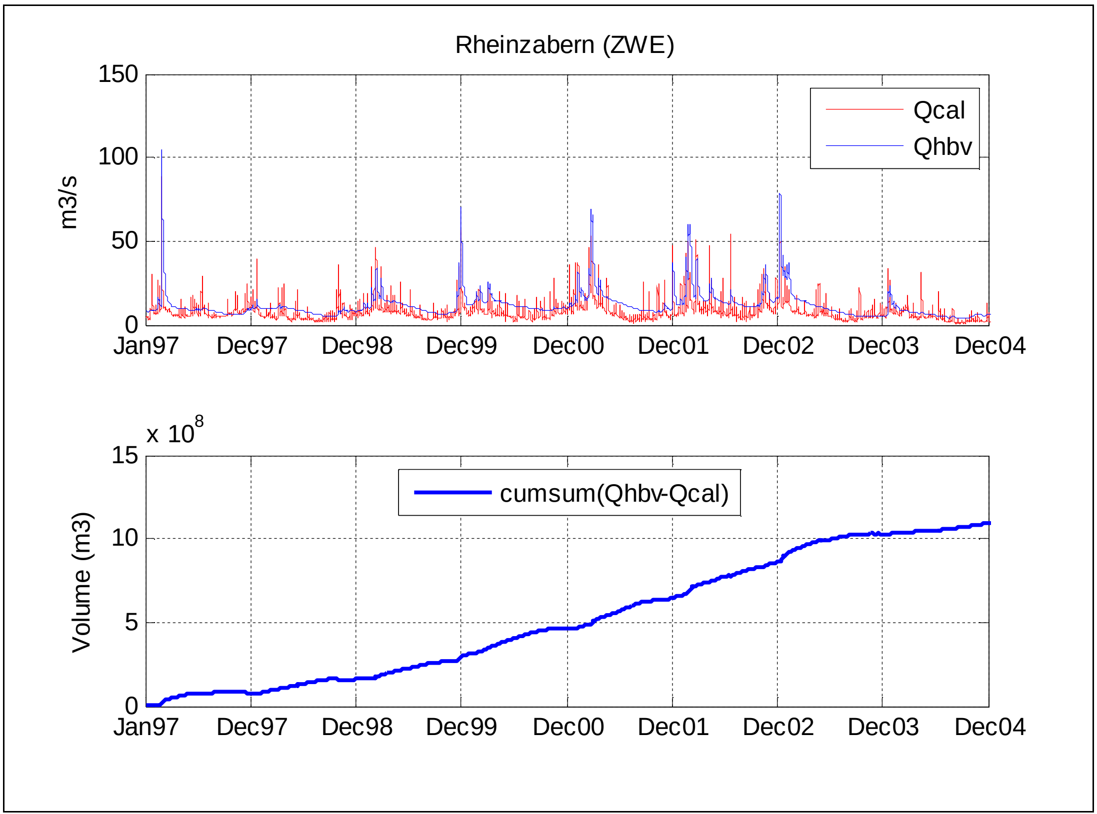

Figure 4.4. (a) Calibration set lateral versus HBV set lateral for Rheinzabern, (b) accumulated difference between simulation and measurement

Table 4.5. Overview statistical information regarding the laterals in Section 1: Maxau-Speyer for the period 01-11-1997-31-10-2004. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Berghausen	0.15	10.32	73.13	0.83
Ettlingen	0.26	-44.00	94.29	1.20
Siebeldingen	0.37	-11.53	19.00	0.48
Neustadt	-0.38	-46.08	6.28	1.36
Rheinzabern	-0.30	57.30	47.29	5.35

4.3 Section 2: Speyer - Worms

4.3.1 Overview

Figure 4.5 shows a schematic overview of the second river section Speyer-Worms. Eleven laterals are contributing to the Rhine flow in this section (see also Table 2.1). One of these laterals is the discharge measured at Rockenau (Neckar) which is the upper boundary of the Neckar branch of the SOBEK model. The lateral Eberbach in Figure 4.5 consist of 1 point inflow and 5 diffuse inflows. Table 4.6 shows the subdivision of the lateral Eberbach into 6 lateral inflows. Therefore in SOBEK, there are in total eleven laterals. Also one detention area (Kollerinsel) is present in the section Speyer-Worms. Until now this detention area has not been active or used (Meissner, pers. comm. after consulting the Landesamt für Umwelt, Wasserwirtschaft und Gewerbeaufsicht of the Federal state Rhineland-Palatinate).

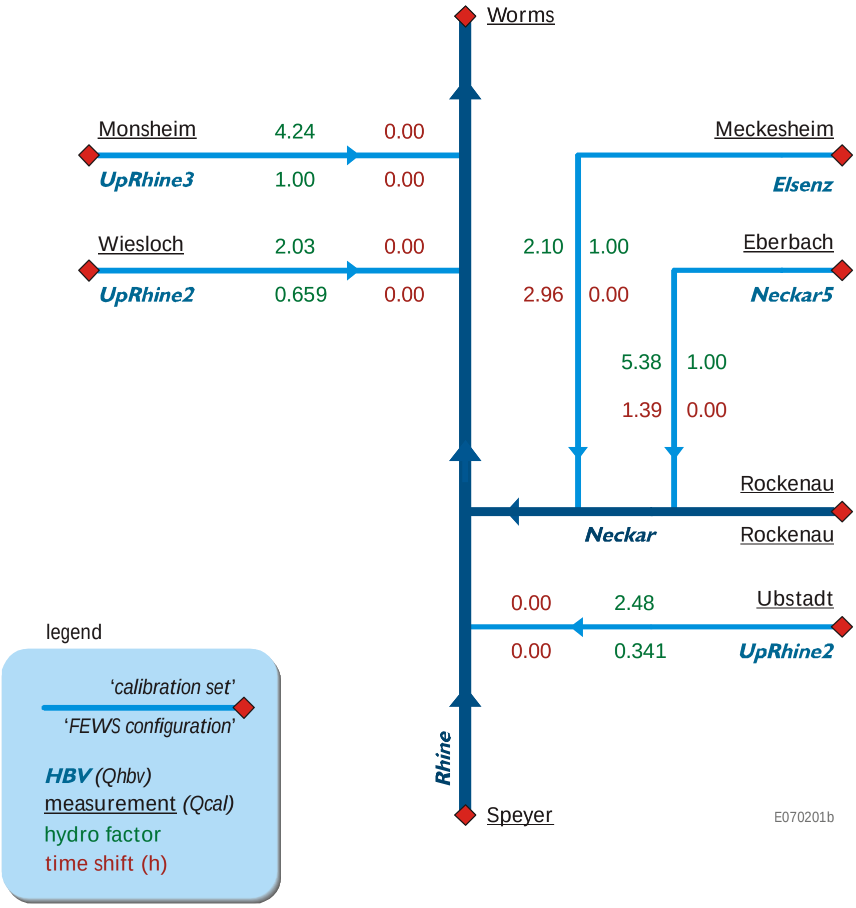

Figure 4.5. Schematic overview of section 2.

Table 4.6. Division of laterals inflow Eberbach as shown in Figure 4.5.

Name FewsNL version 2.05	Calibration set HBV set	hydro factor	time shift (h)
NE1_Itter	Eberbach	1.66	1.39
	Neckar5	0.227	0
NE1_ZWE5/I	Eberbach	1.18	0
	Neckar5	0.270	0
NE1_ZWE5/II	Eberbach	1.13	0
	Neckar5	0.257	0
NE1_ZWE5/III	Eberbach	0.07	0
	Neckar5	0.012	0
NE1_ZWE5/ IV	Eberbach	0.69	0
	Neckar5	0.120	0
NE1_ZWE5/ V	Eberbach	0.65	0
	Neckar5	0.114	0
Total	Eberbach	5.38	1.39
	Neckar5	1	0

Table 4.7 shows the water balance of the section 2: Speyer-Worms. Detention does not occur in the section Speyer-Worms during the whole simulation period. From Table 4.7, the following is observed

- The inflow from the tributaries account for 12% of the flow volume at Worms;
- Rockenau (Neckar) is the largest tributary in this section accounting for 89% of the inflow of the tributaries;
- the water balance is negative (-0.31 Bm^3/year), note that the behaviour of the water balance in time is not constant (see Appendix D) probably due to rating curve changes.
- the maximum hysteresis at Speyer and Worms is comparable;
- the sum of lateral inflows of the HBV set is ±6% higher than the sum of laterals from the calibration set.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The hysteresis effect can be in the order of 150 m^3/s for Speyer and Worms. Note that the rating curve of Speyer changed in 1999. This change has quite an effect on the calculated water balance for the whole period. Until 1999 the derived QH at Worms was on the average lower than the simulated QcalQ. After the rating curve change at Speyer, this changed and QH at Worms was on average large than QcalQ (see also Appendix 7D).

Figure 4.6 shows that there is a great difference between the measured rating curve at Worms and the simulated rating curve by the SOBEK model. Figure 4.6 also shows a distinct break at a stage of 90 meter in the simulated rating curve. This break indicates when in the SOBEK model the winter bed is activated. Note that this break is not present in the measured rating curve at Worms.

Table 4.7. Overview water balance section 2: Speyer-Worms (in B$m^3/y=10^9$ m^3/y) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 2: Speyer-Worms
period: 1/11/1997 – 31/10/2004

Water balance from derived discharges

	Average volume (Bm^3/y)	Average volume relative to QH Worms (%)	QH (m^3/s)		
			max	min	mean
Speyer	42.45	87.84	4446	1345	408
Worms	48.32	100.00	4765	1532	465
Sum of Laterals	5.56	11.51			
I+SoL-O[1]	-0.31	-0.65			

Water balance from SOBEK calculations

	Average volume (Bm^3/y)			Average volume relative to QH Worms (%)			Maximal hysteresis (m^3/s)
	QcalQ	QhbvQ	Δ	QcalQ	QhbvQ	Δ	QcalH - QcalQ
Speyer	42.45	42.45	0	87.84	87.84	0	±150
Worms	48.00	48.31	0.31	99.33	99.98	0.65	±150
Sum of Laterals	5.56	5.87	0.31	11.51	12.15	0.65	
I+SoL-O[1]	0.01	0.01	0.00	0.01	0.01	0.00	

Overview laterals

	Average volume (Bm^3/y)			Average volume relative to Sum of Laterals QcalL (%)			QcalL (m^3/s)		
	QcalL	QhbvL	Δ	QcalL	QhbvL	Δ	max	mean	min
Ubstadt	0.09	0.04	-0.06	1.70	0.65	-1.05	66.10	2.85	0.00
Meckesheim	0.14	0.20	0.07	2.46	3.66	1.20	72.23	3.99	0.96
NE1_Itter	0.07	0.11	0.04	1.19	2.00	0.81	60.36	2.07	0.49
NE1_ZWE5/I	0.05	0.13	0.08	0.85	2.35	1.50	42.91	1.47	0.35
NE1ZWE5/II	0.05	0.12	0.08	0.81	2.23	1.42	41.09	1.41	0.34
NE1_ZWE5/III	0.00	0.01	0.00	0.05	0.10	0.05	2.55	0.09	0.02
NE1_ZWE5/IV	0.03	0.06	0.03	0.49	1.04	0.55	25.09	0.86	0.21
NE1_ZWE5/V	0.03	0.06	0.03	0.47	0.99	0.52	23.64	0.81	0.19
Wiesloch	0.05	0.07	0.02	0.96	1.26	0.30	27.89	1.55	0.15
Monsheim	0.13	0.15	0.02	2.33	2.65	0.32	238.5	3.76	0.16
Rockenau	4.93	4.93	0.00	88.70	88.70	0.00	2682	150.7	0.00
Sum of Laterals	5.56	5.87	0.31	100.00	105.63	5.63			

[1] I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

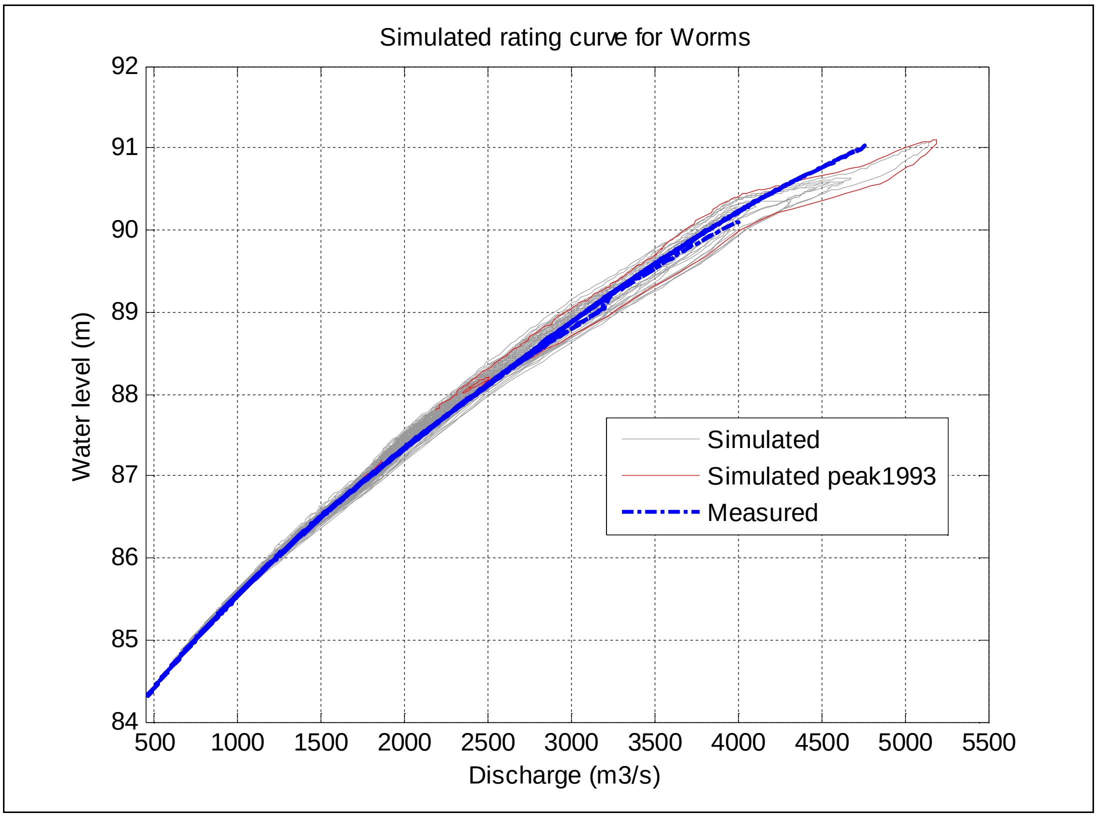

Figure 4.6. Measured rating curve (blue lines) at Worms versus the simulated rating curve by SOBEK.

4.3.2 Periods of Interest

Figure 4.7 and Table 4.8 show results for a typical flood period for section 2. From the table, it is clear that more water is being simulated than is being measured at Worms. This is also clearly visible in Figure 4.7 (0.04 Bm^3 in 47 hours is ±236 m^3/s if storage effects are ignored). The difference between the SOBEK simulations using the calibration set and HBV set is smaller than between the SOBEK simulations and measurement at Worms. The sum of laterals of HBV set is larger than the calibration set (±80 m^3/s).
Figure 4.8 and Table 4.9 show a results for the low flow period of 2003. The results for the two simulations are almost identical, because the sum of laterals is almost identical for this low flow period. The difference between the simulations and the measurements (0.04 Bm^3 over 10 days =± 46m^3/s) is also clearly visible in this figure.

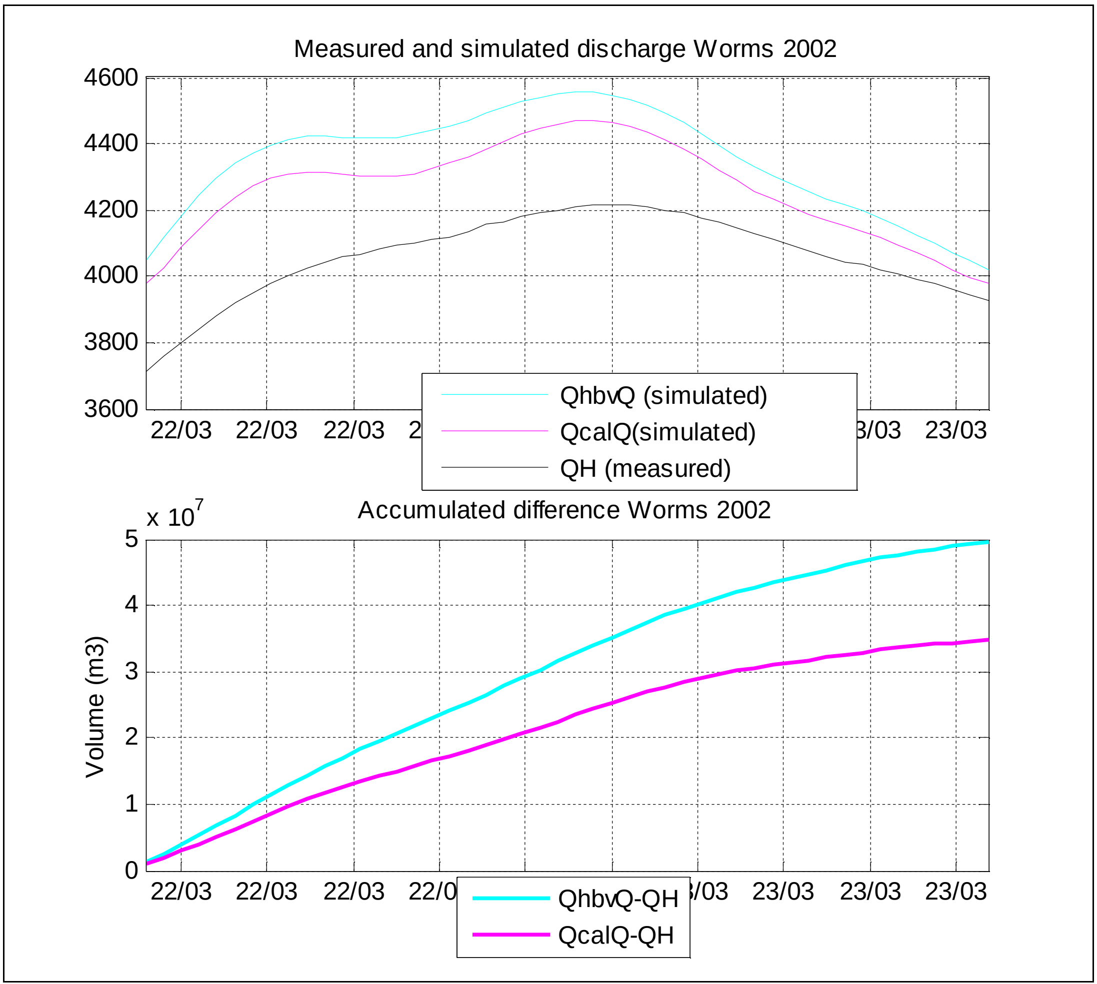

Figure 4.7. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Worms, (b) accumulated difference at Worms for both the calibration set and the HBV set.

Table 4.8. Overview waterbalance section 2: Speyer-Worms for the flood period of 2002 (in B$m^3 = 10^9 m^3$) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3 = 10^6$ m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 2: Speyer-Worms Flood period: 21/03/2002 22:00 – 23/03/2002 21:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Worms (%)**		
Speyer	0.46			64.94		
Worms	0.70			100.00		
Sum of Laterals	0.27			39.14		
I+SoL-O[1]	0.03			4.08		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Worms (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Speyer	0.46	0.46	0	64.94	64.94	0
Worms	0.74	0.75	0.02	104.80	106.97	2.16
Sum of Laterals	0.27	0.29	0.01	39.14	40.99	1.85
I+SoL-O[1]	-0.01	-0.01	0.00	-0.73	-1.04	-0.32
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Ubstadt	3.13	0.68	-2.45	1.14	0.25	-0.89
Meckesheim	4.32	10.09	5.76	1.57	3.67	2.10
NE1_Itter	2.61	3.87	1.26	0.95	1.41	0.46
NE1_ZWE5/I	1.85	4.54	2.69	0.67	1.65	0.98
NE1_ZWE5/II	1.77	4.32	2.55	0.65	1.57	0.93
NE1_ZWE5/III	0.11	0.20	0.09	0.04	0.07	0.03
NE1_ZWE5/IV	1.08	2.02	0.94	0.39	0.74	0.34
NE1_ZWE5/V	1.02	1.92	0.90	0.37	0.70	0.33
Wiesloch	1.34	1.33	-0.02	0.49	0.48	-0.01
Monsheim	3.52	4.77	1.24	1.28	1.74	0.45
Rockenau	253.85	253.85	0.00	92.44	92.44	0.00
Sum of Laterals	274.61	287.59	12.97	100.00	104.72	4.72

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

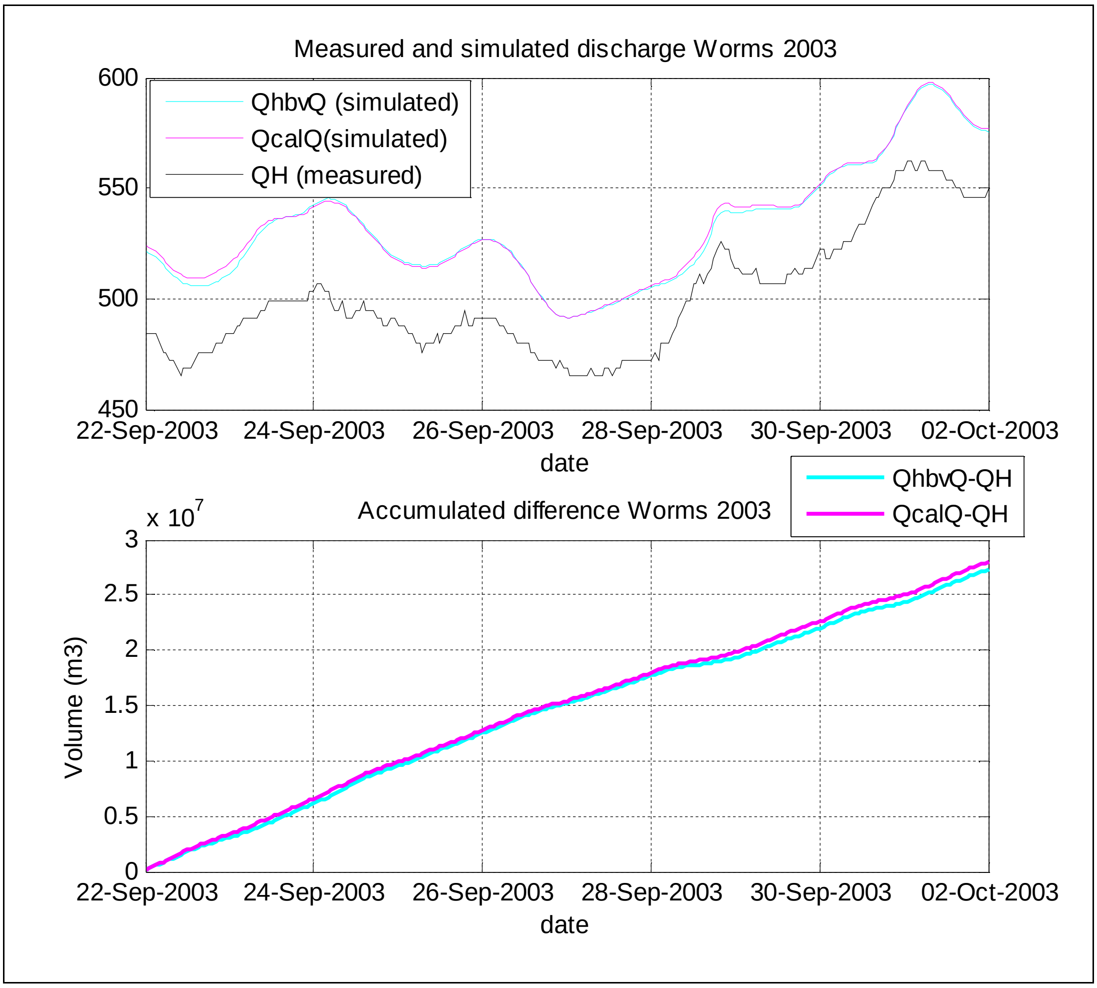

Figure 4.8. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Worms, (b) accumulated difference at Worms for both the calibration set and the HBV set.

Table 4.9. Overview waterbalance section 2: Speyer-Worms for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 2: Speyer- Worms Low flow period: 22/09/2003 – 02/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Worms (%)**		
Speyer	0.39			89.77		
Worms	0.43			100.00		
Sum of Laterals	0.07			17.02		
I+SoL-O[1]	0.03			6.79		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Worms (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Speyer	0.39	0.39	0	89.77	89.77	0
Worms	0.46	0.46	0.00	106.45	106.28	-0.17
Sum of Laterals	0.07	0.07	0.00	17.02	17.17	0.15
I+SoL-O[1]	0.00	0.00	0.00	0.02	0.33	0.31
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Ubstadt	1.85	0.56	-1.28	2.50	0.76	-1.73
Meckesheim	1.67	0.80	-0.87	2.26	1.08	-1.18
NE1_Itter	0.58	0.98	0.41	0.78	1.33	0.55
NE1_ZWE5/I	0.41	1.16	0.75	0.56	1.56	1.01
NE1_ZWE5/II	0.39	1.10	0.71	0.53	1.49	0.96
NE1_ZWE5/III	0.02	0.05	0.03	0.03	0.07	0.04
NE1_ZWE5/IV	0.24	0.51	0.28	0.32	0.70	0.37
NE1_ZWE5/V	0.23	0.49	0.26	0.31	0.66	0.35
Wiesloch	0.75	1.09	0.34	1.02	1.48	0.46
Monsheim	0.85	0.88	0.03	1.15	1.20	0.04
Rockenau	66.89	66.89	0.00	90.54	90.54	0.00
Sum of Laterals	73.87	74.52	0.65	100.00	100.88	0.88

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.3.3 Lateral Inflows

Table 4.10 shows the results per lateral. From this table it is clear that large differences exist between the HBV and calibration set. The laterals depending on Neckar5 calculations of the HBV model are about 67-180% larger than the laterals form the calibration set. This is probably caused by the fact that soil moisture storages of the HBV model of subbasin Neckar5 stays to wet during the whole simulation period. The contribution of Meckesheim is also ±50% larger when compared to the calibration set. This behaviour is compensated by Ubstadt that shows an underestimation of the volume when compared to the calibration set.

Table 4.10. Overview statistical information regarding the laterals in Section 2: Speyer-Worms for the period 01-03-1996-31-12-2004. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Ubstadt	-0.60	-61.88	62.54	1.86
Meckesheim	-6.69	49.23	191.72	3.77
NE1_Itter	-1.61	66.73	51.87	2.13
NE1_ZWE5/I	-7.42	175.39	62.08	2.77
NE1_ZWE5/II	-7.30	173.59	59.08	2.63
NE1_ZWE5/III	-3.24	106.28	2.73	0.11
NE1_ZWE5/IV	-3.39	109.34	27.34	1.15
NE1_ZWE5/V	-3.48	111.19	25.97	1.09
Wiesloch	-0.27	33.79	24.85	0.82
Monsheim	0.35	12.81	81.70	1.68
Rockenau	-	-	-	-

4.4 Section 3: Worms - Mainz

4.4.1 Overview

Figure 4.9 shows a schematic overview of the third river section Worms-Mainz. Six laterals are contributing to the Rhine flow in this river section (see also Table 2.1). The lateral Raunheim is the upper boundary of the Main branch of the SOBEK model.

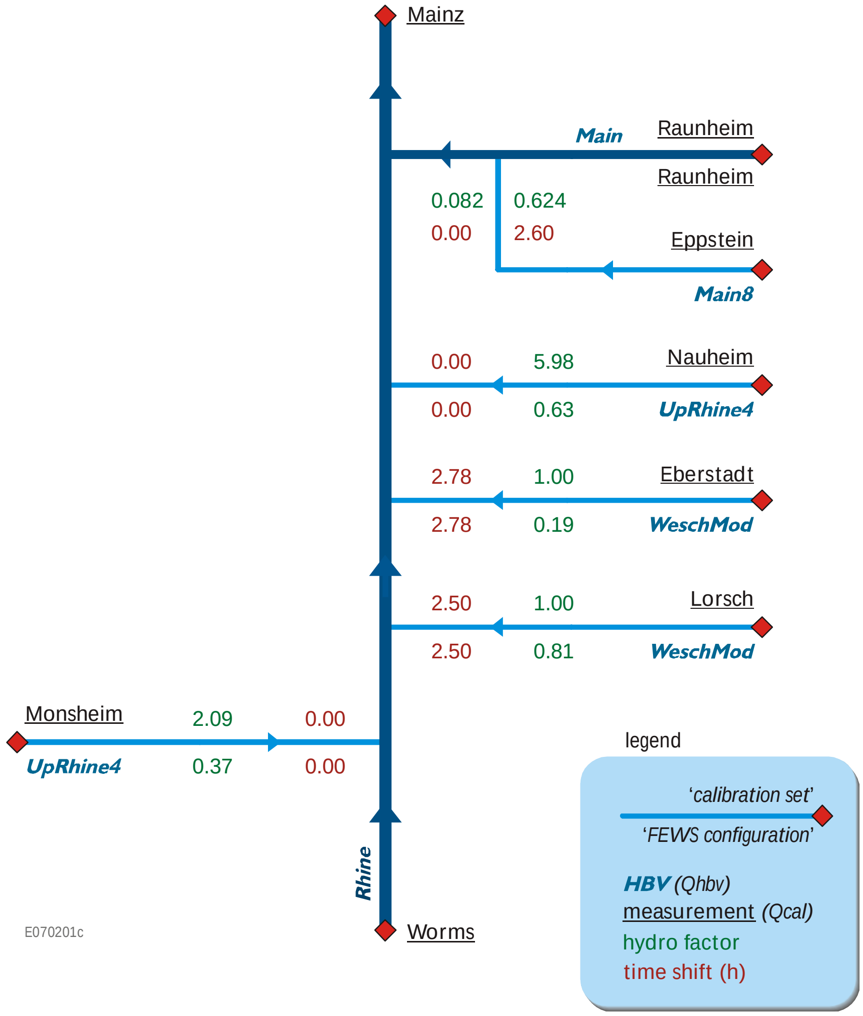

Figure 4.9. Overview Section 3: Worms-Mainz.

Table 4.11 shows the water balance of the section 3: Worms-Mainz. Detention or dike overtopping does not occur in the section Worms-Mainz during the whole simulation period. From Table 4.11, the following is observed

- The inflow from the tributaries account for 12% of the flow volume at Mainz;
- Raunheim (Main) is the largest tributary in this section accounting for 95% of the inflow of the tributaries;

- the waterbalance is positive (0.31 Bm^3/year), note however that the behaviour of the water balance in time is not constant (see Appendix D) probably due to rating curve changes;
- the volume of water measured at Mainz is less than what has been simulated using the SOBEK models;
- the sum of lateral inflows of the HBV set is almost equal to the sum of laterals from the calibration set.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis is estimated at 150 m^3/s for Worms and 100 m^3/s for Mainz.

Table 4.11. Overview water balance section 3: Worms-Mainz (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 3: Worms - Mainz period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Mainz (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Worms	48.32			88.18			4765	1532	465
Mainz	54.80			100.00			5497	1737	543
Sum of Laterals	6.79			12.39					
I+SoL-O[1]	0.31			0.57					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Mainz (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH – QcalQ**		
Worms	48.32	48.32	0	88.18	88.18	0	±150		
Mainz	55.11	55.17	0.06	100.56	100.67	0.11	±100		
Sum of Laterals	6.79	6.85	0.06	12.39	12.50	0.11			
I+SoL-O[1]	0.01	0.01	0.00	0.01	0.01	0.00			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
Monsheim	0.06	0.13	0.06	0.94	1.85	0.91	117.58	1.85	0.11
Lorsch	0.11	0.03	-0.08	1.67	0.51	-1.15	38.36	3.26	0.11
Eberstadt	0.03	0.01	-0.02	0.40	0.12	-0.28	13.43	0.79	0.13
Naunheim	0.12	0.21	0.10	1.74	3.15	1.41	27.46	3.58	0.00
Eppstein	0.02	0.01	0.00	0.22	0.21	-0.01	22.18	0.47	0.00
Raunheim	6.45	6.45	0.00	95.02	95.02	0.00	2040	191.78	0.00
Sum of Laterals	6.79	6.85	0.06	100.00	100.87	0.87			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.4.2 Periods of Interest

Figure 4.10 and Table 4.12 show results for a typical flood period for section 3. From the table, it is clear that more water is being simulated than is being measured at Mainz. This is also clearly visible in the Figure 4.10. The difference between the SOBEK simulations using the calibration set and HBV set is much smaller than between the SOBEK simulations and measurement at Mainz. The sum of laterals of HBV set is almost equal to the calibration set.

Figure 4.11 and Table 4.13 show the results for the low flow period of 2003. The results for the two simulations are almost identical, because the sum of laterals is almost identical for this low flow period. The difference between the simulations and the measurements is also very small and this is clearly visible in Table 4.13.

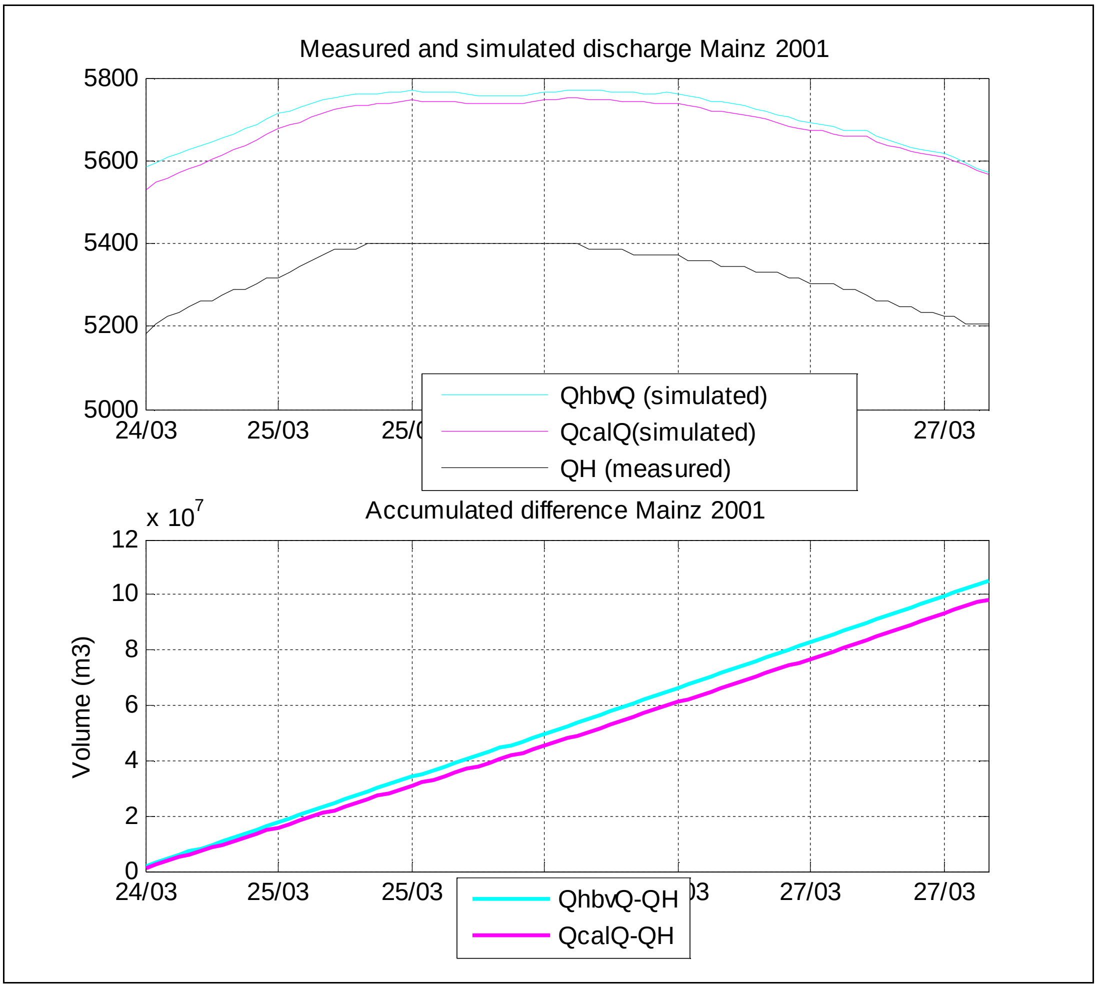

Figure 4.10. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Mainz, (b) accumulated difference at Mainz for both the calibration set and the HBV set.

Table 4.12. Overview waterbalance section 3: Worms-Mainz for the flood period of 2001 (in B$m^3=10^9$ m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6$ m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 3: Worms-Mainz Flood period: 24/03/2001 12:00 – 27/03/2001 16:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Mainz (%)**		
Worms	1.16			78.41		
Mainz	1.48			100.00		
Sum of Laterals	0.41			27.87		
I+SoL-O[1]	0.09			6.28		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Mainz (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Worms	1.16	1.17	0	78.41	78.41	0
Mainz	1.58	1.58	0.01	106.66	107.11	0.45
Sum of Laterals	0.41	0.42	0.00	27.87	28.11	0.24
I+SoL-O[1]	-0.01	-0.01	0.00	-0.39	-0.60	-0.21
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Monsheim	3.44	6.02	2.59	0.83	1.46	0.63
Lorsch	3.91	0.58	-3.32	0.95	0.14	-0.81
Eberstadt	0.92	0.14	-0.78	0.22	0.03	-0.19
Naunheim	5.22	10.26	5.03	1.27	2.49	1.22
Eppstein	0.86	0.88	0.02	0.21	0.21	0.00
Raunheim	397.42	397.42	0	96.52	96.52	0
Sum of Laterals	411.76	415.30	3.54	100.00	100.86	0.86

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals;

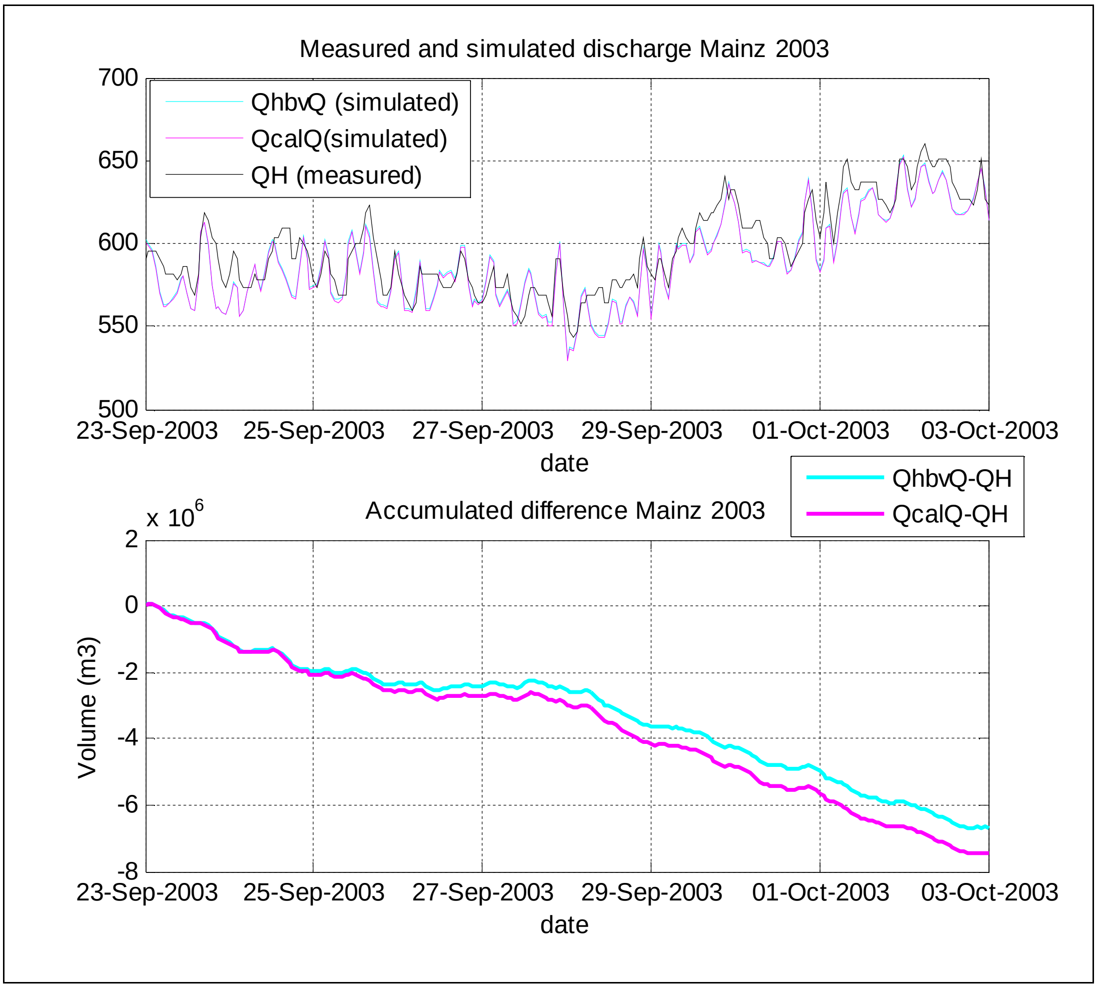

Figure 4.11. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Mainz, (b) accumulated difference at Mainz for both the calibration set and the HBV set.

Table 4.13. Overview waterbalance section 3: Worms-Mainz for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 3: Worms-Mainz Low flow period: 23/09/2003 – 03/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Mainz (%)**		
Worms	0.44			84.53		
Mainz	0.52			100.00		
Sum of Laterals	0.08			14.69		
I+SoL-O[1]	0.00			-0.78		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Mainz (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Worms	0.44	0.44	0	84.53	84.53	0
Mainz	0.51	0.51	0.00	98.56	98.71	0.15
Sum of Laterals	0.08	0.08	0.00	14.69	14.96	0.27
I+SoL-O[1]	0.00	0.00	0.00	0.66	0.78	0.12
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Monsheim	0.44	0.66	0.22	0.58	0.87	0.29
Lorsch	0.90	0.72	-0.18	1.18	0.95	-0.23
Eberstadt	0.33	0.17	-0.17	0.44	0.22	-0.22
Naunheim	0.30	1.12	0.83	0.39	1.48	1.09
Eppstein	0.00	0.70	0.70	0.00	0.92	0.92
Raunheim	74.11	74.11	0.00	97.41	97.41	0.00
Sum of Laterals	76.07	77.49	1.41	100.00	101.86	1.86

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.4.3 Lateral Inflows

Table 4.14 shows the results per lateral for section 3. Again, large differences exist between the HBV and calibration set. Especially the lateral Monsheim (97%) and Nauheim (76%) are overestimated when compared to the calibration set. This behaviour is compensated by the laterals Lorsch and Eberstadt. As a consequence the Nash-Sutcliffe values for these four laterals are very low.

Table 4.14. Overview statistical information regarding the laterals in Section 3:Worms-Mainz for the period 01-03-1996-31-12-2004. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Monsheim	-2.27	97.00	88.68	1.97
Lorsch	-0.54	-67.45	36.32	2.34
Eberstadt	-0.54	-68.43	13.27	0.57
Naunheim	-8.95	75.75	199.14	3.09
Eppstein	0.45	-6.26	19.79	0.22
Raunheim	-	-	-	-

4.5 Section 4: Mainz-Kaub

4.5.1 Overview

Figure 4.12 shows a schematic overview of the fourth river section Mainz-Kaub. Five laterals are contributing to the Rhine flow in this river section (see also Table 2.1).

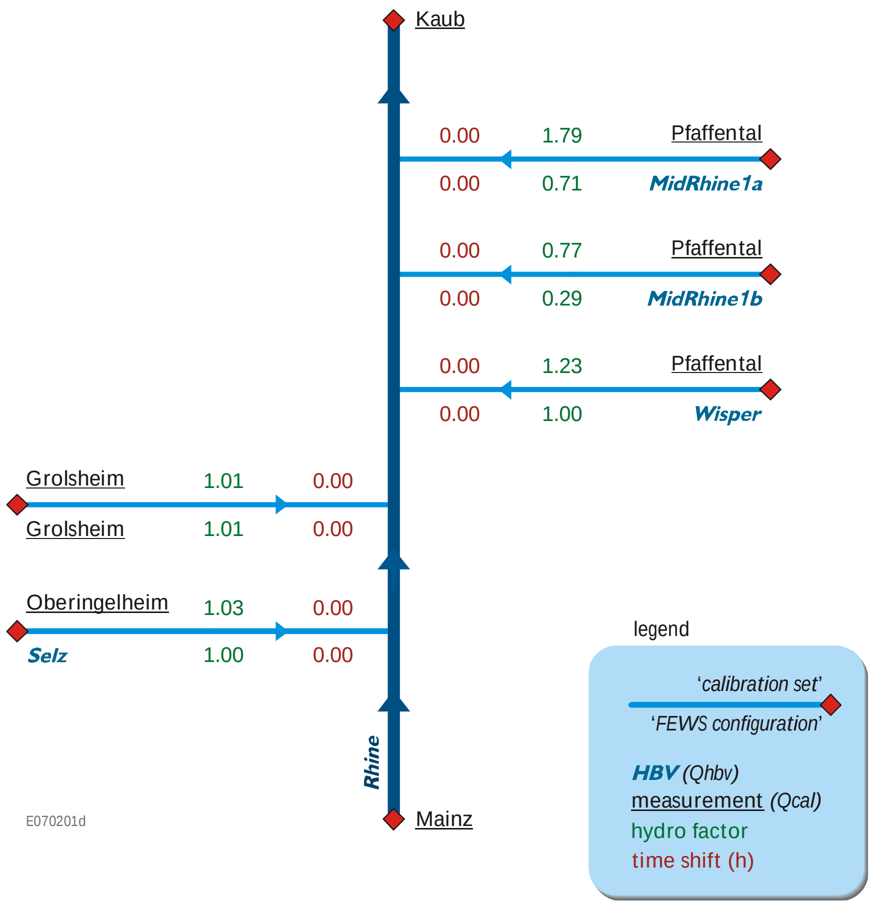

Figure 4.12. Overview Section 4: Mainz-Kaub

Table 4.15 shows the water balance of the section 4: Mainz-Kaub. Detention/dike over topping does not occur in this section during the whole simulation period. From Table 4.15, the following is observed

- the water balance is negative (-1.71 Bm^3/year), note that the behaviour of the water balance in time is fairly constant (see Appendix D);
- more water is being measured at Kaub than is being simulated (±97%) by the two SOBEK models;
- the simulated hysteresis is much smaller at Kaub than at Mainz;
- The inflow from the tributaries account for 2.28% of the flow volume at Kaub;
- Grolsheim (Nahe) is the largest tributary in this section accounting for 88% of the inflow of the tributaries;
- the sum of lateral inflows of the HBV set is 12% larger than the sum of laterals of the calibration set;

The rating curves of the up- and downstream point together with the simulated hysteresis with the SOBEK model are given in Appendix A. The effect of the hysteresis can be in the order of 100 m^3/s for Mainz and 40 m^3/s for Kaub.

Table 4.15. Overview water balance section 4: Mainz-Kaub (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 4: Mainz - Kaub
period: 1/11/1997 – 31/10/2004

Water balance from derived discharges

	Average volume (Bm^3/y)	Average volume relative to QH Kaub (%)	QH (m^3/s)		
			max	mean	min
Mainz	54.80	94.77	5497	1737	543
Kaub	57.83	100.00	5922	1833	532
Sum of Laterals	1.32	2.28			
I+SoL-O[1]	-1.71	-2.95			

Water balance from SOBEK calculations

	Average volume (Bm^3/y)			Average volume relative to QH Kaub (%)			Maximal hysteresis (m^3/s)
	QcalQ	QhbvQ	Δ	QcalQ	QhbvQ	Δ	QcalH - QcalQ
Mainz	54.80	54.80	0	94.77	94.77	0	±100
Kaub	56.11	56.28	0.17	97.04	97.33	0.29	±40
Sum of Laterals	1.32	1.49	0.17	2.28	2.57	0.29	
I+SoL-O[1]	0.00	0.00	0.00	0.01	0.01	0.00	

Overview laterals

	Average volume (Bm^3/y)			Average volume relative to Sum of Laterals QcalL (%)			QcalL (m^3/s)		
	QcalL	QhbvL	Δ	QcalL	QhbvL	Δ	max	mean	min
Oberingelheim	0.02	0.07	0.05	1.76	5.56	3.79	8.26	0.64	0.07
MidRhine1a (ZWE)	0.06	0.13	0.07	4.68	10.14	5.46	62.73	1.78	-0.03
MidRhine1b (ZWE)	0.03	0.05	0.03	2.02	4.14	2.13	26.99	0.77	-0.02
Pfaffenthal	0.04	0.06	0.02	3.22	4.72	1.50	43.11	1.22	-0.03
Grolsheim	1.16	1.16	0.00	88.32	88.32	0.00	1010	34.32	1.32
Sum of Laterals	1.32	1.49	0.17	100.00	112.88	12.88			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.5.2 Periods of Interest

Figure 4.13 and Table 4.16 show results for a typical flood period for section 4. From the table, it is clear that more water is being measured than is being simulated at Kaub. This is also clearly visible in Figure 4.13. The difference between the SOBEK simulations using the calibration set and HBV set is much smaller than between the SOBEK simulations and measurement at Kaub. The sum of laterals of HBV set is about 10% larger than the sum of laterals of the calibration set.

Figure 4.14 and Table 4.17 show the results for the low flow period of 2003. The results for the two simulations are almost identical, despite the fact that the sum of laterals of the HBV set is 22% larger than the sum of laterals of the calibration set. This can be explained by the fact that the sum of laterals during this low flow period is very small. The difference between the simulations and the measurements is also clearly visible in the figure. During the low flow period more water is being measured at Mainz than at Kaub. And during low flow periods the simulations tend to be higher than the measurement at Kaub, but for most of the time the measurement at Kaub is higher than the simulation.

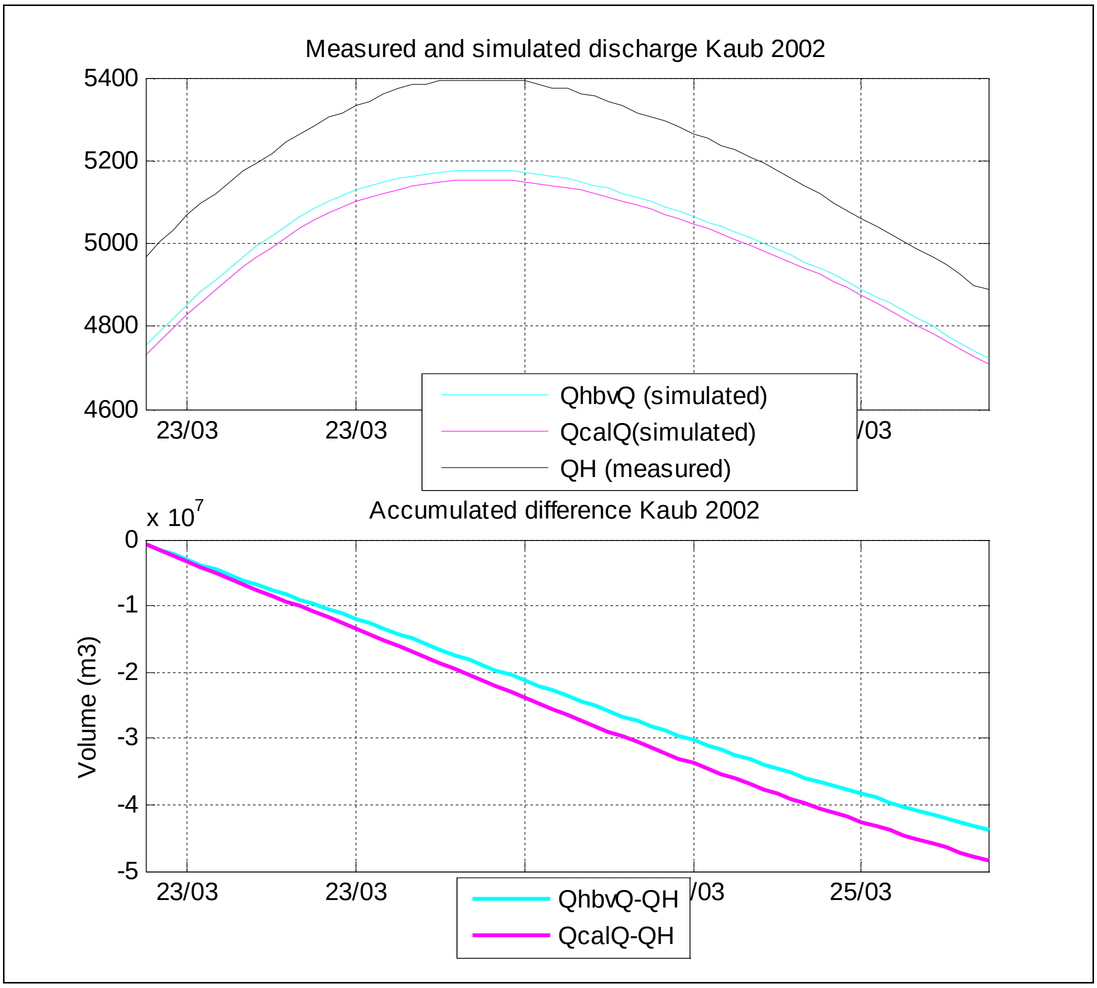

Figure 4.13. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Kaub, (b) accumulated difference at Kaub for both the calibration set and the HBV set.

Table 4.16. Overview waterbalance section 4: Mainz-Kaub for the flood period of 2002 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 4: Mainz-Kaub Flood period: 22/03/2002 21:00 – 25/03/2002 09:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Kaub (%)**		
Mainz	1.05			91.65		
Kaub	1.15			100.00		
Sum of Laterals	0.05			3.91		
I+SoL-O[1]	-0.05			-4.44		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Kaub (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Mainz	1.05	1.05	0	91.65	91.65	0
Kaub	1.10	1.10	0.00	95.77	96.17	0.40
Sum of Laterals	0.04	0.05	0.00	3.91	4.31	0.39
I+SoL-O[1]	0.00	0.00	0.00	-0.21	-0.21	-0.01
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Oberingelheim	0.52	1.51	0.99	1.15	3.36	2.21
MidRhine1a (ZWE)	1.98	4.02	2.04	4.43	8.97	4.54
MidRhine1b (ZWE)	0.85	1.64	0.79	1.90	3.66	1.76
Pfaffenthal	1.36	2.07	0.71	3.04	4.61	1.57
Grolsheim	40.10	40.10	0.00	89.48	89.48	0.00
Sum of Laterals	44.82	49.34	4.52	100.00	110.09	10.09

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

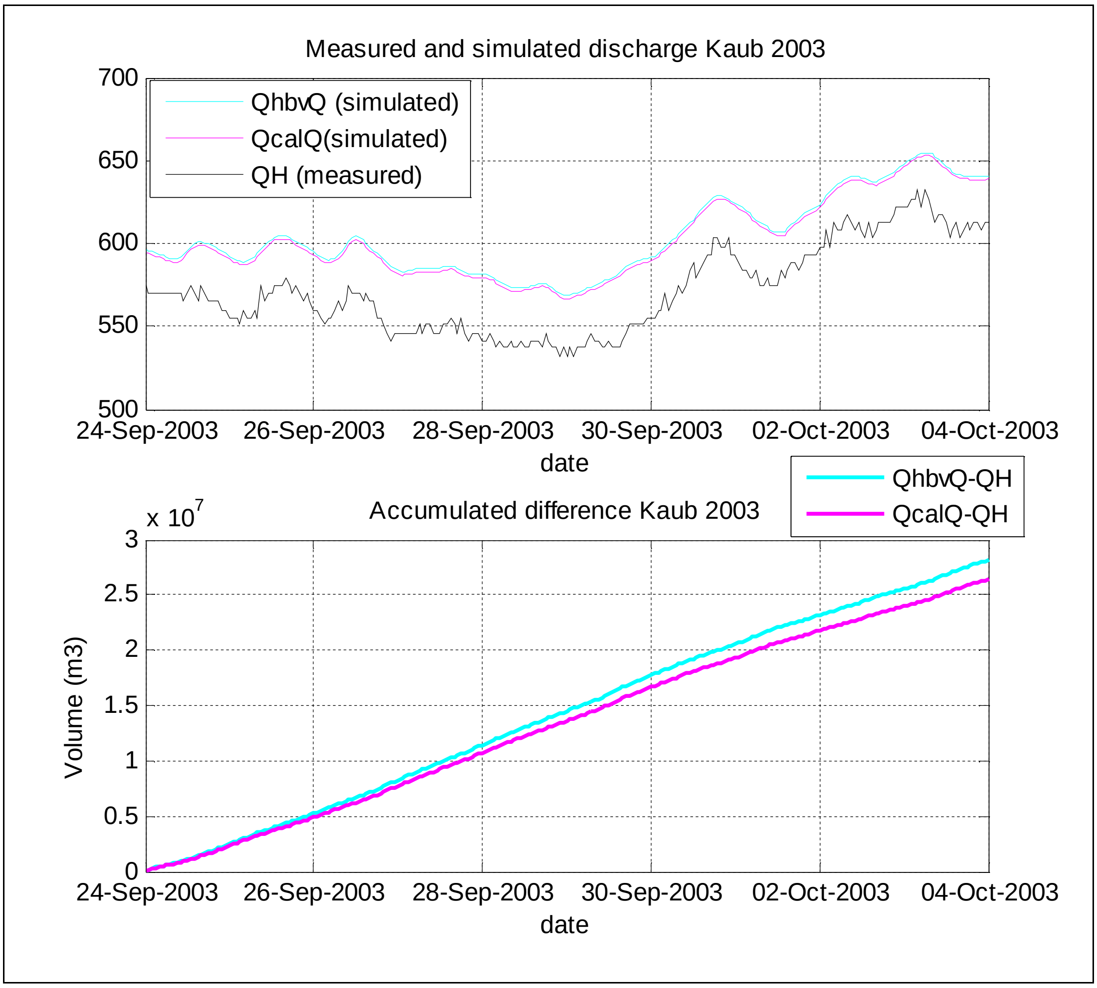

Figure 4.14. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Kaub, (b) accumulated difference at Kaub for both the calibration set and the HBV set.

Table 4.17. Overview waterbalance section 4: Mainz-Kaub for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 4: Mainz-Kaub Low flow period: 24/09/2003 – 04/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Kaub (%)**		
Mainz	0.52			104.93		
Kaub	0.50			100.00		
Sum of Laterals	0.00			0.88		
I+SoL-O[1]	0.02			5.81		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Kaub (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Mainz	0.52	0.52	0	104.93	104.93	0
Kaub	0.52	0.52	0.00	105.33	105.69	0.35
Sum of Laterals	0.00	0.01	0.00	0.88	1.23	0.35
I+SoL-O[1]	0.00	0.00	0.00	0.48	0.48	0.00
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Oberingelheim	0.30	0.96	0.67	6.76	22.00	15.24
MidRhine1a (ZWE)	0.15	0.83	0.67	3.51	18.84	15.34
MidRhine1b (ZWE)	0.07	0.34	0.27	1.52	7.69	6.17
Pfaffenthal	0.11	0.23	0.12	2.48	5.32	2.84
Grolsheim	3.75	3.75	0.00	85.73	85.73	0.00
Sum of Laterals	4.38	6.11	1.73	100.00	139.58	39.58

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.5.3 Lateral Inflows

Table 4.18 shows the results per lateral for section 4. Large differences exist between the HBV and calibration set. All laterals are grossly overestimated (46-217%) when compared to the calibration set. As consequence the Nash-Sutcliffe values for these four laterals are very low.

Table 4.18. Overview statistical information regarding the laterals in Section 4: Mainz-Kaub for the period 01-03-1996-31-12-2004. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	**NSE**	**relative volume difference %**	**maximum absolute difference (m^3/s)**	**mean absolute difference (m^3/s)**
Oberingelheim	-9.88	216.70	24.35	1.52
MidRhine1a (ZWE)	-1.09	116.40	72.57	2.27
MidRhine1b (ZWE)	-0.78	105.45	29.30	0.89
Pfaffenthal	0.11	46.80	29.32	0.97
Grolsheim	-	-	-	-

4.6 Section 5/6: Kaub-Andernach

4.6.1 Overview

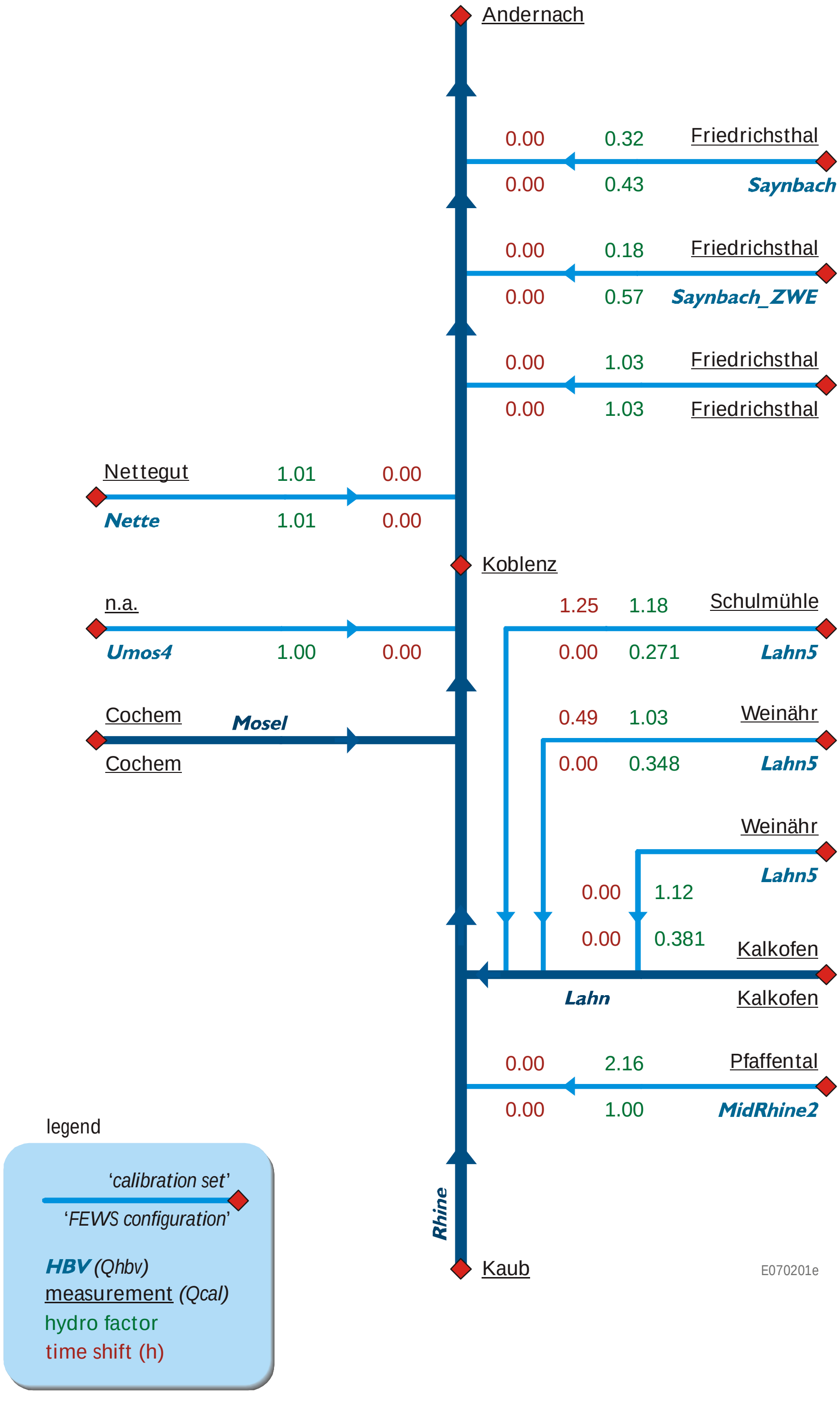

Figure 4.15. Overview Section 5/6: Kaub-Andernach.

Figure 4.15 shows a schematic overview of the combined river section 5/6: Kaub-Andernach. Eleven laterals are contributing to the Rhine flow in this river section (see also Table 2.1). Kalkofen is the upper boundary of the Lahn branch and Cochem is the upper boundary of the Mosel branch of the SOBEK model. Exchange of water between the river and the ground water aquifer is also included in the SOBEK model.

Table 4.19 shows the water balance of the section 5/6: Kaub-Andernach. Dike overtopping does not occur in this section during the whole simulation period. From Table 4.19, the following is observed

- the water balance at Andernach is positive (1.71 Bm^3/year), note that the behaviour of the water balance in time is fairly constant (see Appendix D);
- the inflow from the tributaries account for 20% of the flow volume at Andernach;
- Cochem (Mosel) is the largest tributary in this section accounting for 83.5% of the inflow of the tributaries, Kalkofen (Lahn) is the second largest accounting for 11% of the inflow of the tributaries;
- the maximum hysteresis at Kaub and Andernach is comparable;
- in the SOBEK simulations water is being lost, 0.18% (calibration set) and 0.19% (HBV set), probably to the groundwater;
- the lateral inflows from the calibration set and HBV set are almost equal.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis can be in the order of 40 m^3/s for both Kaub and Andernach.

Table 4.19. Overview water balance section 5/6: Kaub-Andernach (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 5/6: Kaub - Andernach period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Andernach (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Kaub	57.83			82.53			5922	1833	532
Andernach	70.07			100.00			8722	2221	621
Sum of Laterals	13.95			19.90					
I+SoL-O[1]	1.71			2.44					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Andernach (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH - QcalQ**		
Kaub	57.83	57.83	0	82.53	82.53	0	±40		
Andernach	71.65	72.08	0.43	102.26	102.87	0.62	±40		
Sum of Laterals	13.95	14.39	0.44	19.90	20.53	0.63			
I+SoL-O[1]	0.13	0.14	0.01	0.18	0.19	0.01			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
Umos4	0	0.41	0.41	0.00	0.00	0.00	0.00	0.00	0.00
Schulmuehle	0.04	0.04	0.00	0.26	0.27	0.01	38.00	1.02	0.12
Weinaehr	0.08	0.05	-0.03	0.58	0.34	-0.23	54.44	2.42	0.22
Kalkofen	1.54	1.54	0.00	11.02	11.02	0.00	597	47.33	0.00
Pfaffenthal (ZWE)	0.07	0.14	0.07	0.53	1.00	0.47	75.71	2.14	-0.04
Saynbach	0.09	0.05	-0.04	0.62	0.33	-0.29	40.64	2.57	0.19
Friedrichsthal	0.28	0.28	0.00	2.00	2.00	0.00	130.8	8.26	0.62
Nettegut	0.07	0.14	0.07	0.53	1.00	0.47	34.90	2.20	0.42
Weinaehr (ZWE)	0.09	0.05	-0.03	0.63	0.38	-0.25	59.20	2.63	0.24
Saynbach (ZWE)	0.05	0.06	0.01	0.35	0.44	0.09	22.85	1.44	0.11
Cochem	11.64	11.64	0.00	83.48	83.48	0.00	4165	353	37.5
Sum of Laterals	13.95	14.39	0.44	100.00	100.26	0.26			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.6.2 Periods of Interest

Figure 4.16 and Table 4.20 show the results for a typical flood period for section 5/6. Less water is being measured (4.4%) than is being provided by the upper boundary and the lateral inflows. During the flood period exchange of water with the ground water is not important. Slightly more water is provided as input for the SOBEK model by the HBV set (2.78%). More or less the same applies to the low flow period as shown in Table 4.21 and Figure 4.17.

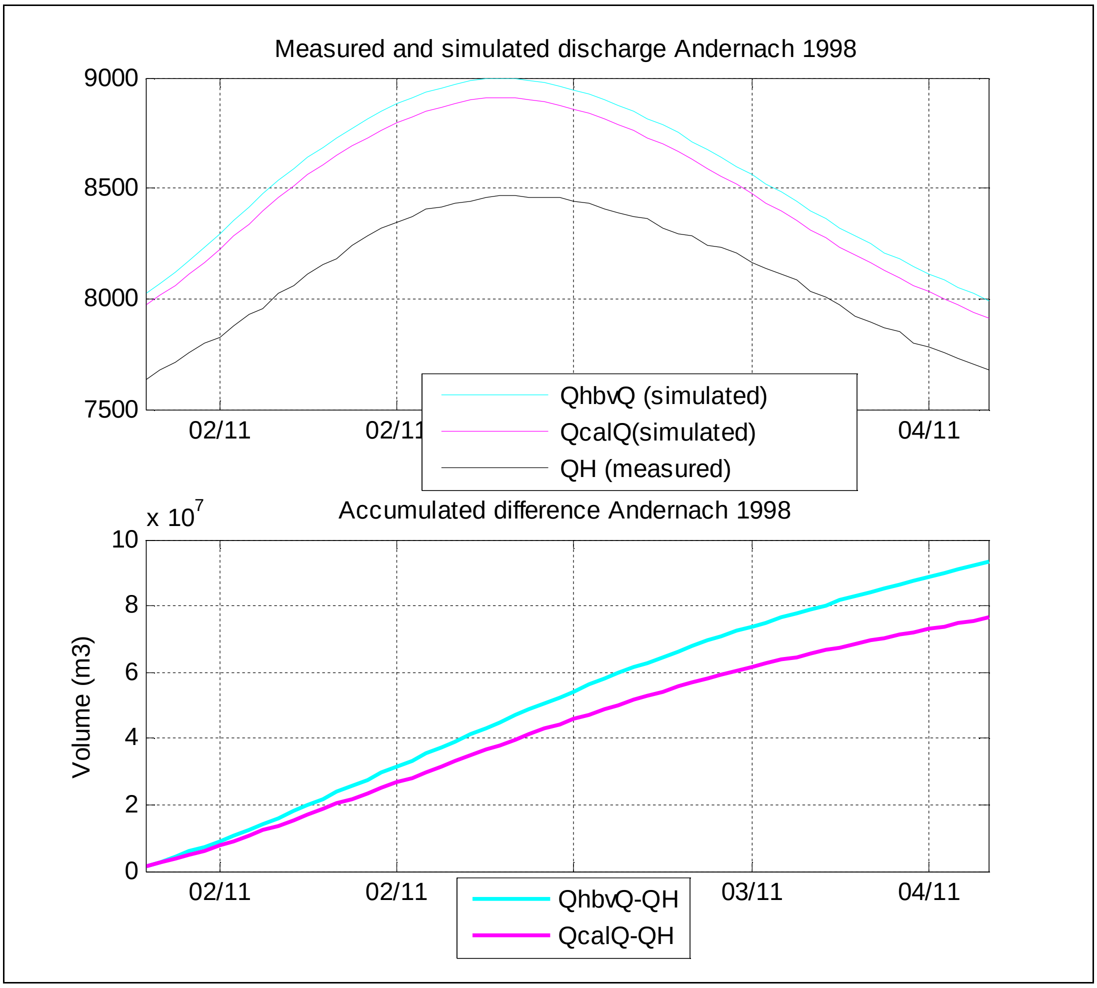

Figure 4.16. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Andernach, (b) accumulated difference at Andernach for both the calibration set and the HBV set.

Table 4.20. Overview waterbalance section 5/6: Kaub-Andernach. The waterbalance is calculated for the flood period of 1998 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 5/6: Kaub – Andernach Flood period:01/11/1998 19:00 – 04/11/1998 04:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Andernach (%)**		
Kaub	1.12			65.92		
Andernach	1.70			100.00		
Sum of Laterals	0.65			38.47		
I+SoL-O[1]	0.07			4.39		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Andernach (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Kaub	1.12	1.12	0	65.92	65.92	0
Andernach	1.77	1.79	0.02	104.51	105.52	1.01
Sum of Laterals	0.65	0.67	0.02	38.47	39.53	1.07
I+SoL-O[1]	0.00	0.00	0.00	-0.12	-0.06	0.06
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Umos4	0.00	15.33	15.33	0.00	2.35	2.35
Schulmuehle	0.81	1.74	0.93	0.12	0.27	0.14
Weinaehr	3.13	2.24	-0.90	0.48	0.34	-0.14
Kalkofen	99.72	99.72	0.00	15.28	15.28	0.00
Pfaffenthal (ZWE)	2.71	5.76	3.05	0.42	0.88	0.47
Saynbach	3.84	1.76	-2.08	0.59	0.27	-0.32
Friedrichsthal	12.36	12.36	0.00	1.89	1.89	0.00
Nettegut	2.11	4.68	2.56	0.32	0.72	0.39
Weinaehr (ZWE)	3.41	2.45	-0.96	0.52	0.38	-0.15
Saynbach (ZWE)	2.16	2.33	0.17	0.33	0.36	0.03
Cochem	522.24	522.24	0.00	80.04	80.04	0.00
Sum of Laterals	652.50	670.61	18.11	100.00	102.78	2.78

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

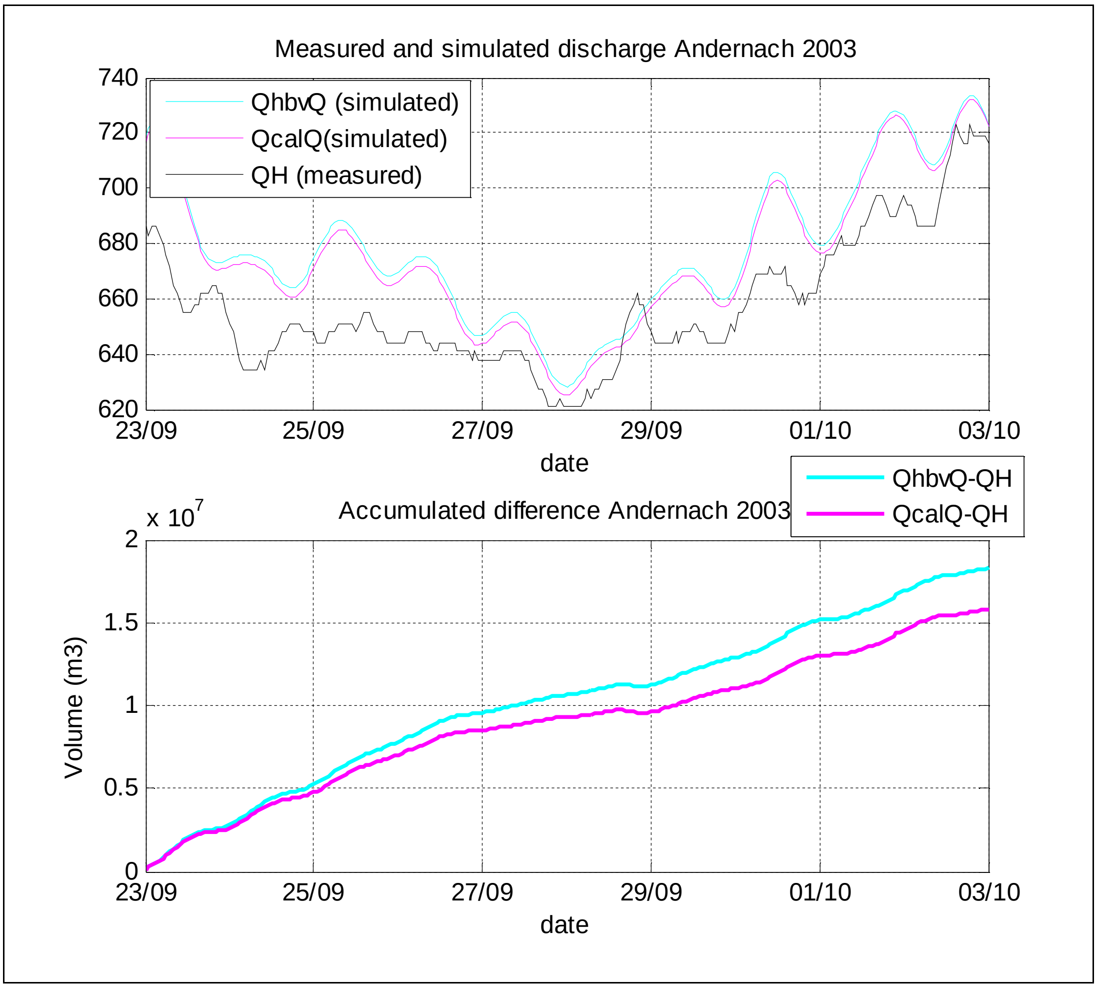

Figure 4.17. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Andernach, (b) accumulated difference at Andernach for both the calibration set and the HBV set.

Table 4.21. Overview waterbalance section 5/6: Kaub-Andernach. The waterbalance is calculated for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 5/6: Kaub – Andernach Low flow period: 23/09/2003 – 03/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Andernach (%)**		
Kaub	0.50			86.84		
Andernach	0.57			100.00		
Sum of Laterals	0.09			15.39		
I+SoL-O[1]	0.01			2.23		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Andernach (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Kaub	0.50	0.50	0	86.84	86.84	0
Andernach	0.59	0.59	0.00	102.77	103.20	0.43
Sum of Laterals	0.09	0.09	0.00	15.39	15.83	0.44
I+SoL-O[1]	0.00	0.00	0.00	-0.54	-0.54	0.00
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Umos4	0.00	2.94	2.94	0.00	3.35	3.35
Schulmuehle	0.25	0.12	-0.13	0.29	0.14	-0.15
Weinaehr	0.58	0.15	-0.42	0.66	0.18	-0.48
Kalkofen	10.29	10.29	0.00	11.73	11.73	0.00
Pfaffenthal (ZWE)	0.19	0.77	0.58	0.22	0.88	0.66
Saynbach	0.79	0.33	-0.46	0.90	0.37	-0.53
Friedrichsthal	2.54	2.54	0.00	2.89	2.89	0.00
Nettegut	0.84	1.31	0.46	0.96	1.49	0.53
Weinaehr (ZWE)	0.63	0.17	-0.46	0.72	0.19	-0.53
Saynbach (ZWE)	0.44	0.43	-0.01	0.51	0.49	-0.01
Cochem	71.19	71.19	0.00	81.13	81.13	0.00
Sum of Laterals	87.75	90.25	2.49	100.00	102.84	2.84

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.6.3 Lateral inflows

Table 4.22 show the results per lateral for section 5/6. Large differences exist between the HBV set and the calibration set varying form -47% to 88%. However, errors seem to compensate each other resulting in small differences in the sum of laterals for the HBV and calibration set (<3%).

Table 4.22. Overview statistical information regarding the laterals in Section 5/6: Kaub-Andernach for the period 01-03-1996-31-12-2004. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Umos4	na	na	na	na
Schulmuehle	0.63	2.12	22.08	0.43
Weinaehr	0.51	-42.13	30.53	1.13
Kalkofen	-	-	-	-
Pfaffenthal (ZWE)	-0.42	88.29	69.19	2.22
Saynbach	0.37	-47.39	28.32	1.36
Friedrichsthal	-	-	-	-
Nettegut	-2.51	86.64	53.90	2.04
Weinaehr (ZWE)	0.51	-41.69	33.05	1.22
Saynbach (ZWE)	0.48	24.04	13.79	0.79
Cochem	-	-	-	-

[1] measured data (calibration set) not available (na) for Umos4.

4.7 Section 7: Andernach-Bonn

4.7.1 Overview

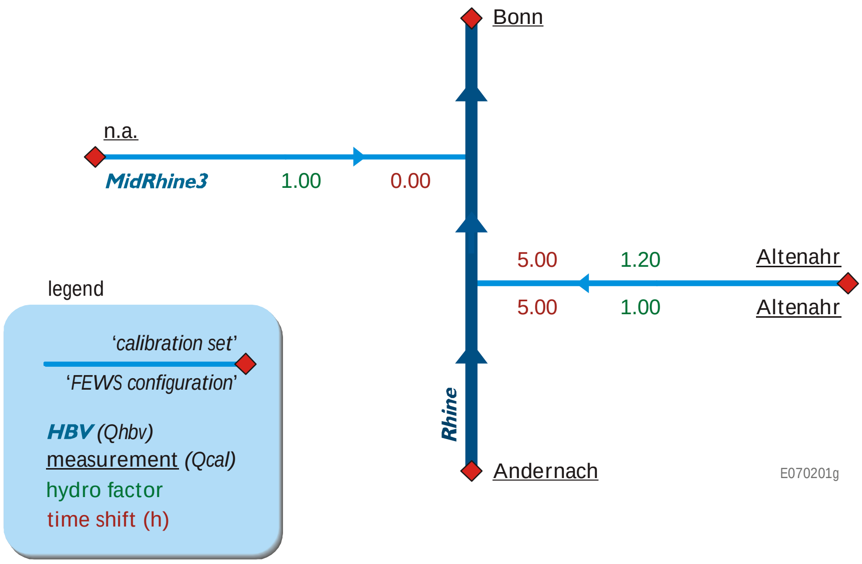

Figure 4.18. Overview Section 7: Andernach-Bonn.

Figure 4.18 shows a schematic overview of the river section 7: Andernach-Bonn. Two laterals are contributing to the Rhine flow in this section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled. Note that the measured discharge at Ahr is being used both in the calibration and HBV set, but that the hydrological factors differ. The hydrofactor differ because the hydrological factor of the calibration set accounts for the area between the gauging station Altenahr and the inflow of the Ahr into the Rhine. In the HBV configuration this is taken into account via MidRhine3 (see also Figure 2.4).

Table 4.23 shows the water balance of the section 7: Andernach-Bonn. Dike overtopping does not occur in this section during the whole simulation period. From Table 4.23 the following is observed

- the water balance at Bonn is negative (-0.16 Bm^3/year), note that the behaviour of the water balance in time is changing (see Appendix D);
- the maximal hysteresis at Andernach and Bonn is comparable;
- the lateral inflows from the calibration set and HBV set are different (68%) because the lateral MidRhine3a is not available in the calibration set and is therefore replaced by zero;
- there is a small loss of water to the groundwater (0.03%);
- the difference between the measurement and the two simulations is larger than the difference between the two SOBEK simulations.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis can be in the order of 40 m^3/s for both Andernach and Bonn. The rating curve at Bonn is influenced by the inflow of the Sieg in the Rhine just downstream of Bonn (see Appendix A). The SOBEK simulations take this into account. The measured rating curve does not.

Table 4.23. Overview water balance section 7: Andernach-Bonn (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 7: Andernach - Bonn period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Bonn (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Andernach	70.07			99.42			8722	2221	621
Bonn	70.48			100.00			9048	2234	628
Sum of Laterals	0.25			0.35					
I+SoL-O[1]	-0.16			-0.23					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Bonn (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH - QcalQ**		
Andernach	70.07	70.07	0	99.42	99.42	0	±40		
Bonn	70.29	70.46	0.17	99.73	99.97	0.24	±40		
Sum of Laterals	0.25	0.41	0.17	0.35	0.59	0.24			
I+SoL-O[1]	0.02	0.02	0.00	0.03	0.03	0.00			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
Ahr	0.25	0.20	-0.04	100.00	83.33	-16.67	245.89	7.62	0.33
MidRhine3	0	0.21	0.21	0	84.72	84.72	0	0	0
Sum of Laterals	0.25	0.41	0.17	100.00	168.05	68.05			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.7.2 Periods of Interest

Figure 4.19 and Table 4.23 show results for a typical flood period for section 7. During a flood period more water is being measured than is provided by the upper boundary and the lateral inflows. Differences between the two SOBEK simulations are small. For the low flow period the results of the measurements and simulations compare well. Groundwater is not important during the flood and low flow period in this section.

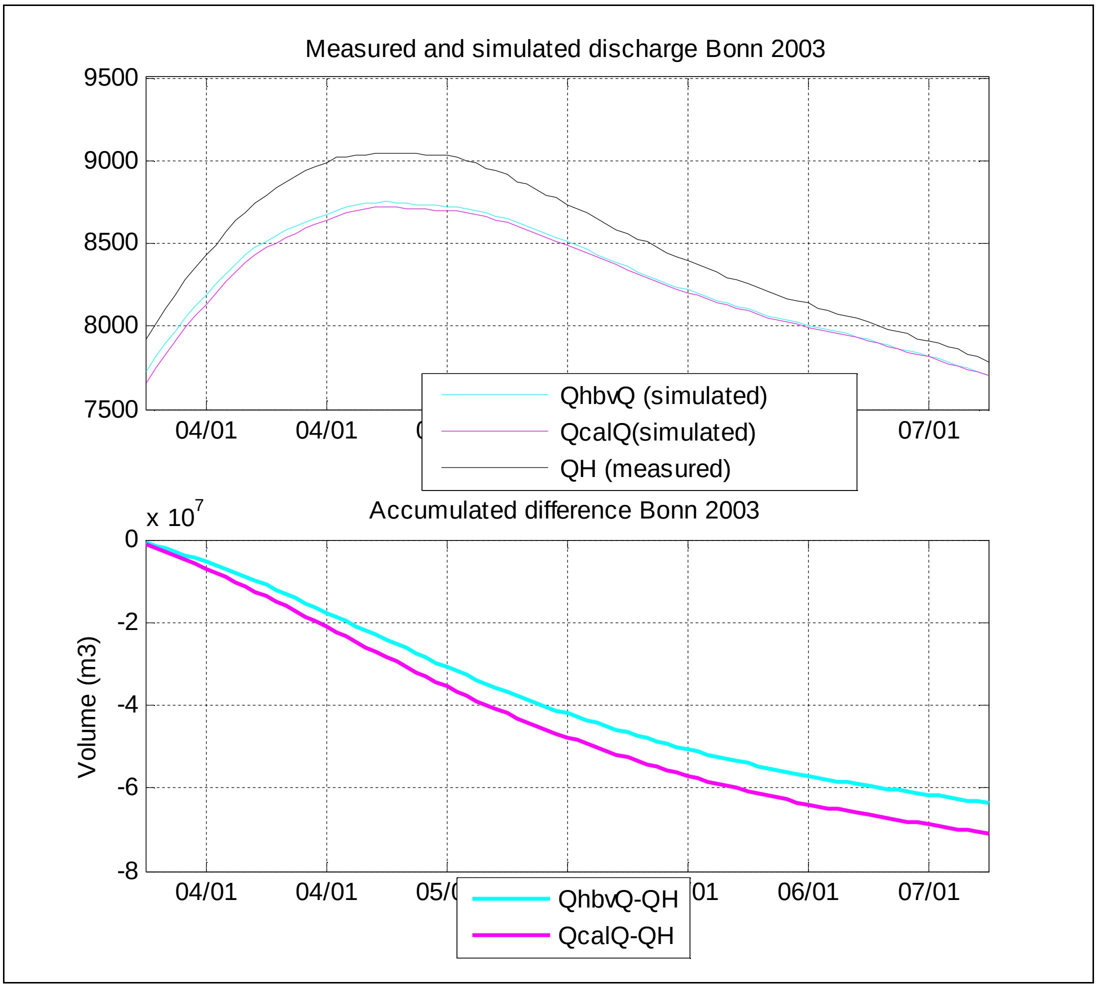

Figure 4.19. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Bonn, (b) accumulated difference at Bonn for both the calibration set and the HBV set.

Table 4.24. Overview waterbalance section 7: Andernach-Bonn for the flood period of 2003 (in B$m^3=10^9\ m^3$) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6\ m^3$) are the laterals from the calibration set and the HBV set, respectively.

Section 7: Andernach – Bonn Flood period: 03/01/2003 18:00 - 07/03/2003 06:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Bonn (%)**		
Andernach	2.53			97.12		
Bonn	2.60			100.00		
Sum of Laterals	0.01			0.49		
I+SoL-O[1]	-0.06			-2.39		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Bonn (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Andernach	2.53	2.53	0	97.12	97.12	0
Bonn	2.53	2.54	0.01	97.28	97.56	0.28
Sum of Laterals	0.01	0.02	0.01	0.49	0.75	0.25
I+SoL-O[1]	0.01	0.01	0.00	0.34	0.31	-0.03
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Ahr	12.83	10.69	-2.14	100.00	83.33	-16.67
MidRhine3	0	8.71	8.71	0	67.88	67.88
Sum of Laterals	12.83	19.40	6.57	100.00	151.22	51.22

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

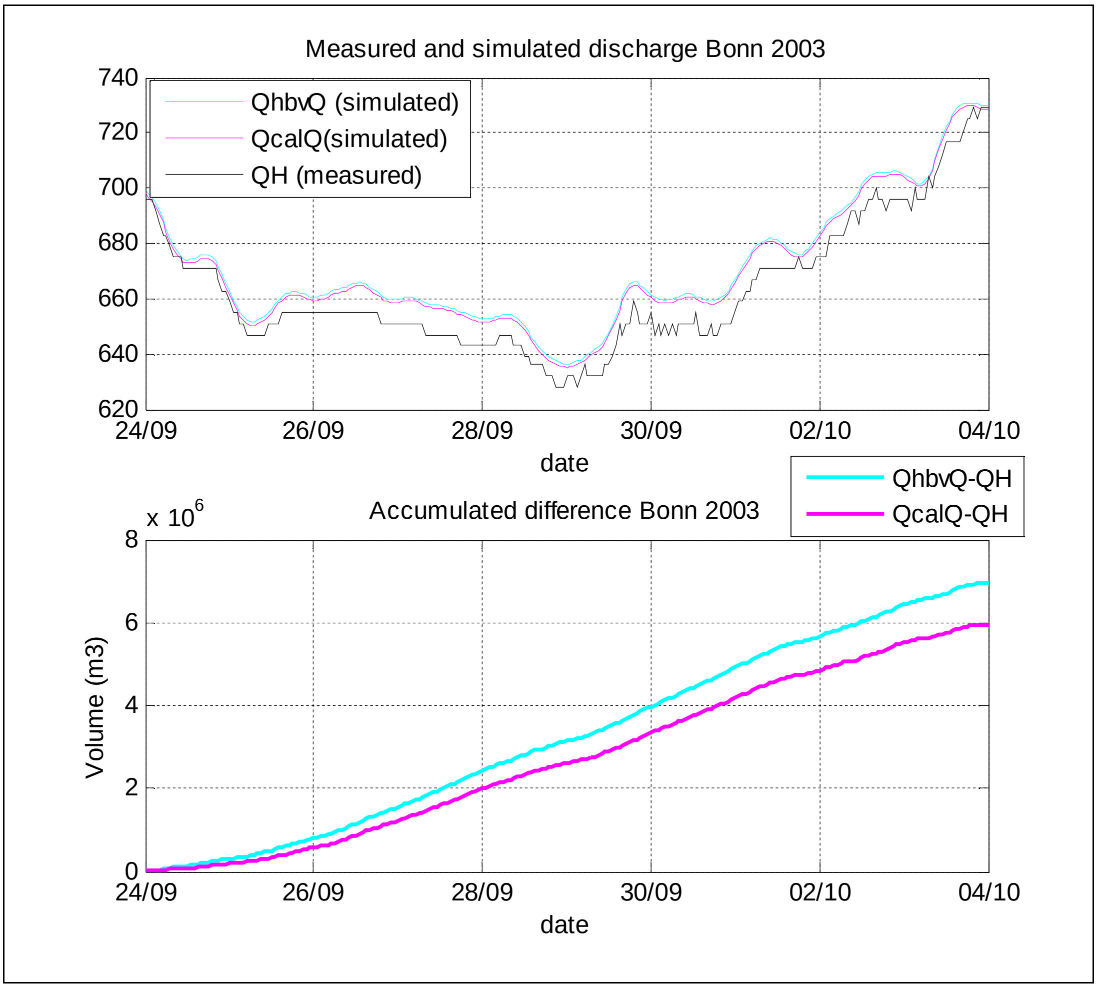

Figure 4.20. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Bonn, (b) accumulated difference at Bonn for both the calibration set and the HBV set.

Table 4.25. Overview waterbalance section 7: Andernach-Bonn for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 7: Andernach – Bonn Low flow period: 24/09/2003 - 04/10/2003		
Water balance from derived discharges		
	Average volume (Bm^3)	**Average volume relative to QH Bonn (%)**
Andernach	0.57	99.31
Bonn	0.58	100.00
Sum of Laterals	0.00	0.16
I+SoL-O[1]	0.00	-0.53

Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Bonn (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Andernach	0.57	0.57	0	99.31	99.31	0
Bonn	0.58	0.58	0.00	101.03	101.21	0.18
Sum of Laterals	0.00	0.00	0.00	0.16	0.34	0.18
I+SoL-O[1]	-0.01	-0.01	0.00	-1.56	-1.56	0.00

Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Ahr	0.95	0.79	-0.16	100.00	83.33	-16.67
MidRhine3	0	1.17	1.17	0	123.59	123.59
Sum of Laterals	0.95	1.96	1.01	100.00	206.92	106.92

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.7.3 Lateral inflows

The measured discharge of Altenahr is being used both for the calibration set and HBV set. The hydrological factor is only 1.20 for the calibration set resulting in a relative volume difference of -16.67% as shown in Table 4.26. There are no measured data in the calibration set for MidRhine3.

Table 4.26. Overview statistical information regarding the laterals in Section 7: Andernach-Bonn. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Ahr	-	-16.67	29.60	1.24
MidRhine3[1]	na	na	na	na

[1]No measured data (calibration set) available for MidRhine3.

4.8 Section 8: Bonn-Köln

4.8.1 Overview

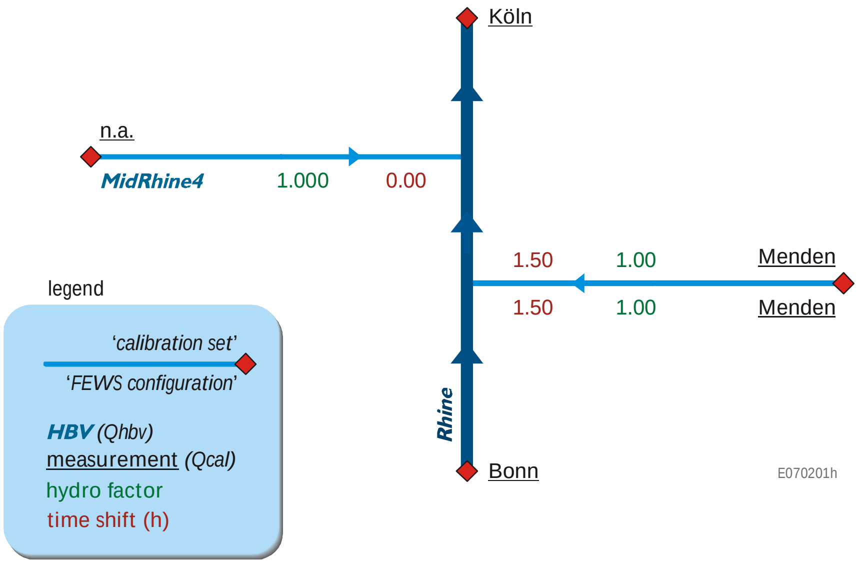

Figure 4.21. Overview Section 8: Bonn-Köln.

Figure 4.21 shows a schematic overview of the river section 8: Bonn-Köln. Two laterals are inserted on the way to Köln. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.27 shows the water balance of the section 8 Bonn-Köln. Detention does not occur in the section Bonn-Köln during the whole simulation period. Table 4.27, the following is observed

- the water balance at Köln is negative (-0.71 Bm^3/year), note that the behaviour of the water balance in time is fairly constant (see Appendix D);
- the inflow from Menden (Sieg) account for 2.41 of the flow volume at Köln;

- in the SOBEK simulations more water is leaving this section than is coming in from the upper boundary and the lateral inflows indicating that there is a net contribution from the groundwater to the discharge of the Rhine;
- the lateral inflows from the calibration set and HBV set are different (12%) because the lateral MidRhine4 is not available in the calibration set and is therefore replaced with zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis can be in the order of 40 m^3/s for Bonn and 100 for Köln.

Table 4.27. Overview water balance section 8: Bonn-Köln (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 8: Bonn - Köln
period: 1/11/1997 – 31/10/2004

Water balance from derived discharges

	Average volume (Bm^3/y)	Average volume relative to QH Köln (%)	QH (m^3/s)		
			max	mean	min
Bonn	70.48	96.62	9048	2234	628
Köln	72.94	100.00	9329	2312	637
Sum of Laterals	1.76	2.41			
I+SoL-O[1]	-0.71	-0.97			

Water balance from SOBEK calculations

	Average volume (Bm^3/y)			Average volume relative to QH Köln (%)			Maximal hysteresis (m^3/s)
	QcalQ	QhbvQ	Δ	QcalQ	QhbvQ	Δ	QcalH - QcalQ
Bonn	70.48	70.48	0	96.62	96.62	0	±40
Köln	72.48	72.68	0.20	99.36	99.64	0.28	±100
Sum of Laterals	1.76	1.96	0.21	2.41	2.69	0.28	
I+SoL-O[1]	-0.24	-0.24	0.00	-0.33	-0.33	0.00	

Overview laterals

	Average volume (Bm^3/y)			Average volume relative to Sum of Laterals QcalL (%)			QcalL (m^3/s)		
	QcalL	QhbvL	Δ	QcalL	QhbvL	Δ	max	mean	min
Menden	1.76	1.76	0	100	100	0	961	51.93	4.51
MidRhine4	0	0.21	0.21	0	11.70	11.70	-	-	-
Sum of Laterals	1.76	1.96	0.21	100	111.70	11.70			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.8.2 Periods of Interest

Table 4.28 and Figure 4.22 show results for a typical flood period for section 8. During this flood period not enough water is being measured at Köln (0.71%). For the low flow period more water is being simulated than can be explained on the basis of the inflows (upper boundary and sum of laterals) indicating a net contribution of the ground water to the Rhine flow. Ground water exchange during flood periods is not important in this section. Differences between the two SOBEK simulation are small both for the flood period and low flow period.

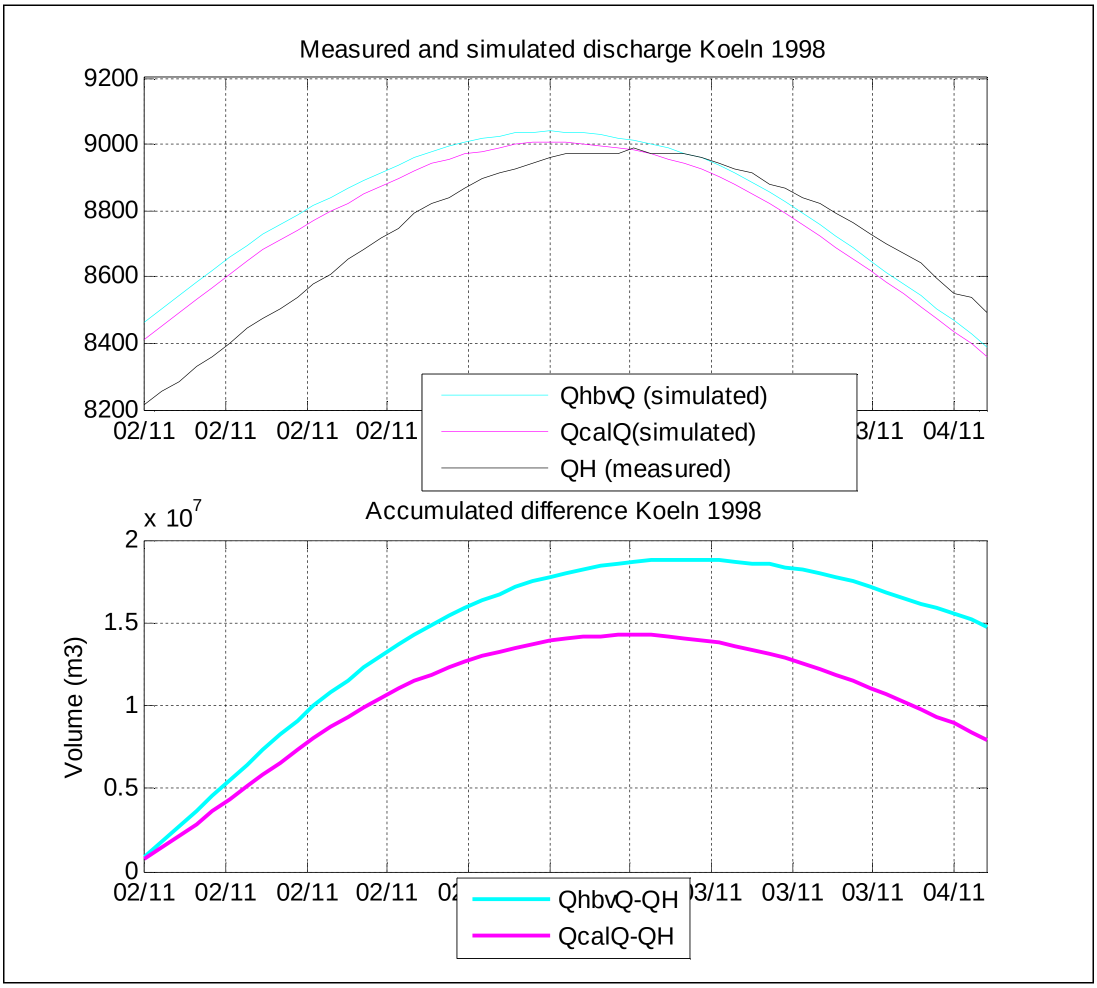

Figure 4.22. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Köln Köln, (b) accumulated difference at Köln for both the calibration set and the HBV set.

Table 4.28. Overview waterbalance section 8: Bonn-Köln for the flood period of 1998 (in B$m^3=10^9\ m^3$) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6\ m^3$) are the laterals from the calibration set and the HBV set, respectively.

Section 8: Bonn - Köln Flood period: 02/11/1998 00:00 – 04/11/1998 02:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Köln (%)**		
Bonn	1.54			96.15		
Köln	1.60			100.00		
Sum of Laterals	0.07			4.56		
I+SoL-O[1]	0.01			0.71		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Köln (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Bonn	1.54	1.54	0	96.15	96.15	0
Köln	1.61	1.62	0.01	100.50	100.92	0.43
Sum of Laterals	0.07	0.08	0.01	4.56	4.97	0.41
I+SoL-O[1]	0.00	0.00	0.00	0.22	0.20	-0.02
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Menden	73.10	73.10	0	100	100	0
MidRhine4	0	6.49	6.49	0	8.88	8.88
Sum of Laterals	73.10	79.60	6.49	100	108.88	8.88

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

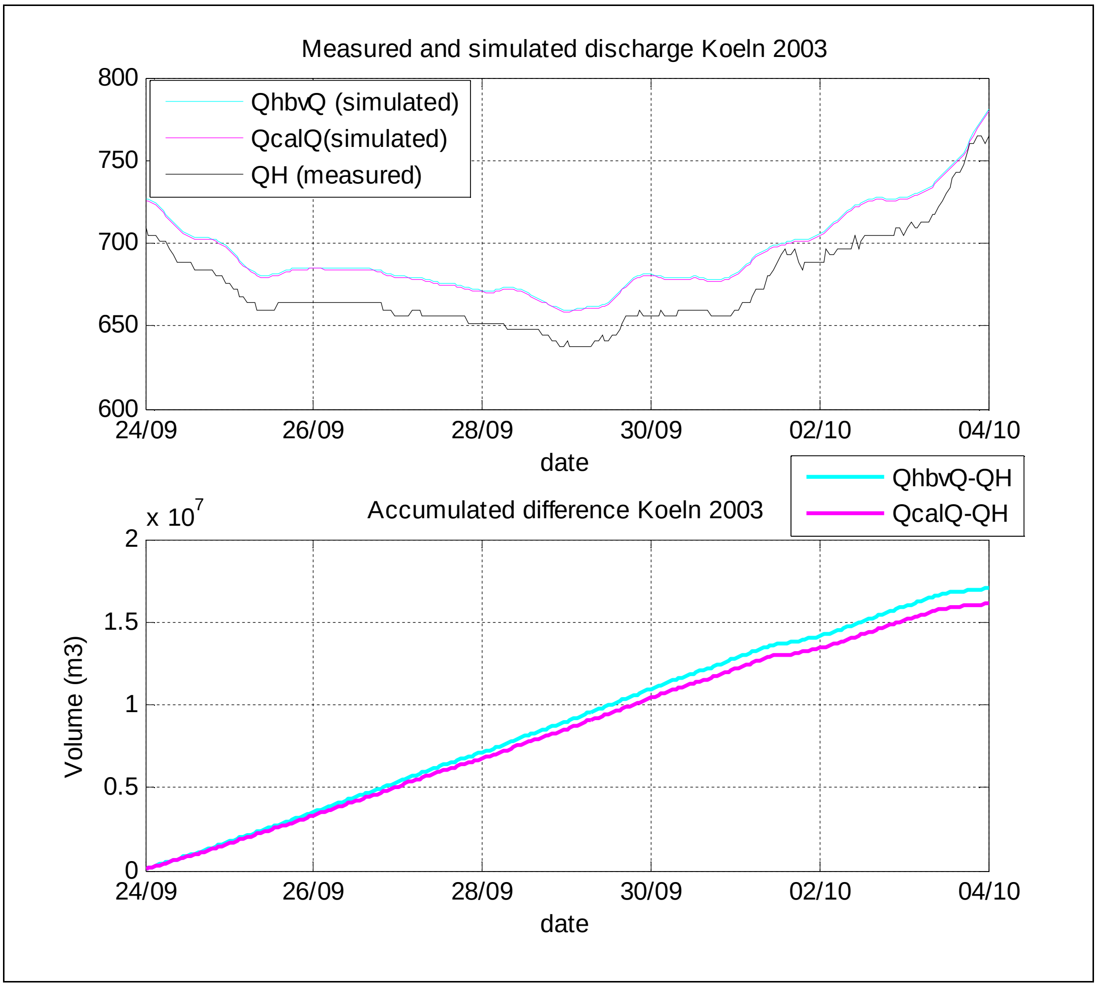

Figure 4.23. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Köln Köln, (b) accumulated difference at Köln for both the calibration set and the HBV set.

Table 4.29. Overview waterbalance section 8: Bonn-Köln for the low flow period of 2003 (in B$m^3=10^9\ m^3$) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6\ m^3$) are the laterals from the calibration set and the HBV set, respectively.

Section 8: Bonn – Köln Low flow period: 24/09/2003 – 04/10/20030						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Köln (%)**		
Bonn	0.58			98.47		
Köln	0.58			100.00		
Sum of Laterals	0.01			1.54		
I+SoL-O[1]	0.00			0.01		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Köln (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Bonn	0.58	0.58	0	98.47	98.47	0
Köln	0.60	0.60	0.00	102.76	102.92	0.16
Sum of Laterals	0.01	0.01	0.00	1.54	1.70	0.17
I+SoL-O[1]	-0.02	-0.02	0.00	-2.75	-2.75	0.00
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Menden	9.00	9.00	0	100	100	0
MidRhine4	0	0.97	0.97	0	10.76	10.76
Sum of Laterals	9.00	9.97	0.97	100	110.76	10.76

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.8.3 Lateral inflows

The measured discharge at Menden is being used in both the calibration set and the HBV set. There are no measured data in the calibration set for MidRhine4.

Table 4.30. Overview statistical information regarding the laterals in Section 8: Bonn- Köln. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Menden	-	-	-	-
MidRhine4[1]	na	na	na	na

[1]No measured data (calibration set) available for MidRhine4.

4.9 Section 9: Köln-Düsseldorf

4.9.1 Overview

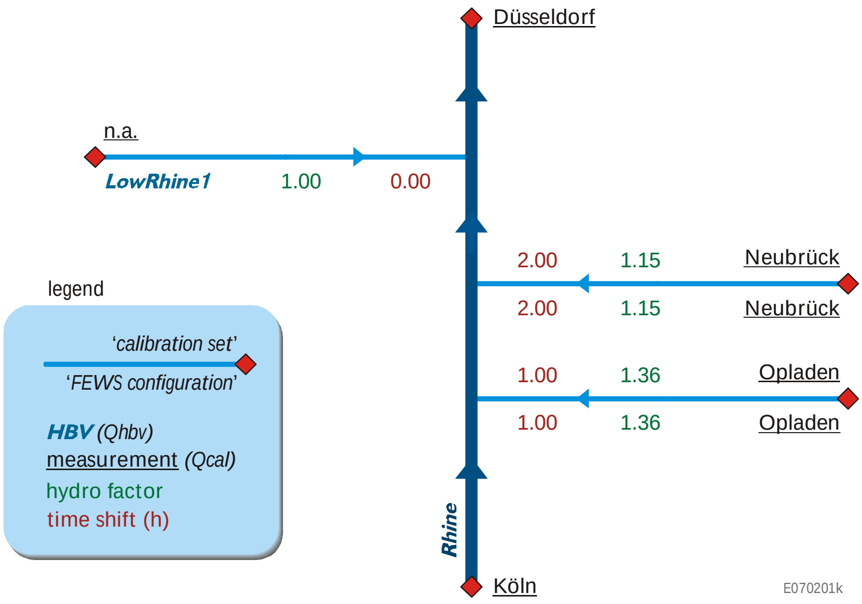

Figure 4.24. Overview Section 9: Köln-Düsseldorf.

Figure 4.24 shows a schematic overview of the river section 9: Köln-Düsseldorf. Three lateral inflows contribute to the Rhine flow in this river section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.31 shows the water balance of section 9: Köln-Düsseldorf. Detention does not occur in the section Köln-Düsseldorf during the whole simulation period. From Table 4.31, the following is observed

- the water balance at Düsseldorf is positive (0.49 Bm^3/year), note that the behaviour of the water balance in time is fairly constant (see Appendix D);
- in the SOBEK simulations much more water is leaving this section than is coming in from the upper boundary and the lateral inflows indicating that there is a considerable net contribution (1.3 - 1 Bm^3/y) from the groundwater to the discharge of the Rhine;
- the lateral inflows from the calibration set and HBV set are different (33%) because the lateral LowRhine1 is not available in the calibration set and is therefore replaced with zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis is estimated at 100 m^3/s for both Köln and Düsseldorf.

Table 4.31. Overview water balance section 9: Köln-Düsseldorf (in B$m^3/y=10^9$ m^3/y) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 9: Köln – Düsseldorf
period: 1/11/1997 – 31/10/2004

Water balance from derived discharges

	Average volume (Bm^3/y)	Average volume relative to QH Düsseldorf (%)	QH (m^3/s)		
			max	mean	min
Köln	72.94	99.20	9329	2312	637
Düsseldorf	73.53	100.00	9263	2331	672
Sum of Laterals	1.08	1.47			
I+SoL-O[1]	0.49	0.66			

Water balance from SOBEK calculations

	Average volume (Bm^3/y)			Average volume relative to QH Düsseldorf (%)			Maximal hysteresis (m^3/s)
	QcalQ	QhbvQ	Δ	QcalQ	QhbvQ	Δ	QcalH - QcalQ
Köln	72.94	72.94	0	99.20	99.20	0	±100
Düsseldorf	75.32	75.43	0.11	102.42	102.58	0.16	±100
Sum of Laterals	1.08	1.44	0.36	1.47	1.96	0.49	
I+SoL-O[1]	-1.29	-1.05	0.24	-1.76	-1.43	0.33	

Overview laterals

	Average volume (Bm^3/y)			Average volume relative to Sum of Laterals QcalL (%)			QcalL (m^3/s)		
	QcalL	QhbvL	Δ	QcalL	QhbvL	Δ	max	mean	min
Opladen	0.72	0.72	0	66.34	66.34	0	257.8	22.15	3.23
Neubrueck	0.36	0.36	0	33.66	33.66	0	43.45	11.62	4.18
LowRhine1	0	0.36	0.36	0	33.26	33.26	0	0	0
Sum of Laterals	1.08	1.44	0.36	100.00	133.26	33.26			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.9.2 Periods of Interest

Figure 4.25 and Table 4.32 show the results for a typical flood period for section 9. During a flood period less water is being measured than is provided by the upper boundary and the lateral inflows. Differences between the two SOBEK simulations are small. For the low flow period the results of the measurements compare well. From the two SOBEK simulations it is clear that water from the groundwater is entering the river during the low flow period.

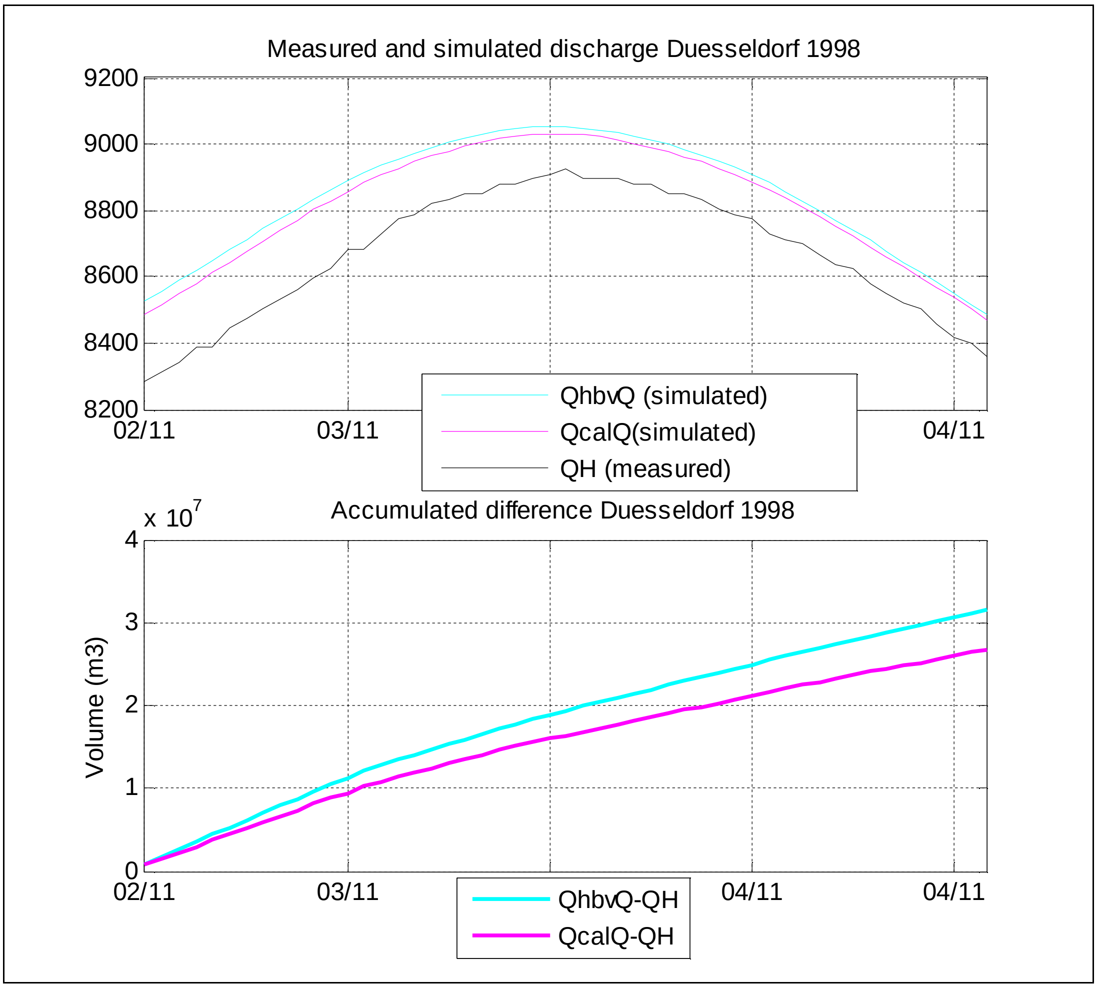

Figure 4.25. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Düsseldorf, (b) accumulated difference at Düsseldorf for both the calibration set and the HBV set.

Table 4.32. Overview waterbalance section 9: Köln-Düsseldorf for the flood period of 1998 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 9: Köln - Düsseldorf Flood period: 02/11/1998 12:00 – 04/11/1998 14:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Düsseldorf (%)**		
Köln	2.24			100.16		
Düsseldorf	2.24			100.00		
Sum of Laterals	0.03			1.17		
I+SoL-O[1]	0.03			1.32		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Düsseldorf (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Köln	2.24	2.24	0	100.16	100.16	0
Düsseldorf	2.26	2.27	0.01	101.15	101.49	0.34
Sum of Laterals	0.03	0.03	0.01	1.17	1.52	0.36
I+SoL-O[1]	0.00	0.00	0.00	0.17	0.19	0.02
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Opladen	21.39	21.39	0	82.09	82.09	0
Neubrueck	4.67	4.67	0	17.91	17.91	0
LowRhine1	0	7.96	7.96	0	30.55	30.55
Sum of Laterals	26.06	34.02	7.96	100.00	130.55	30.55

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

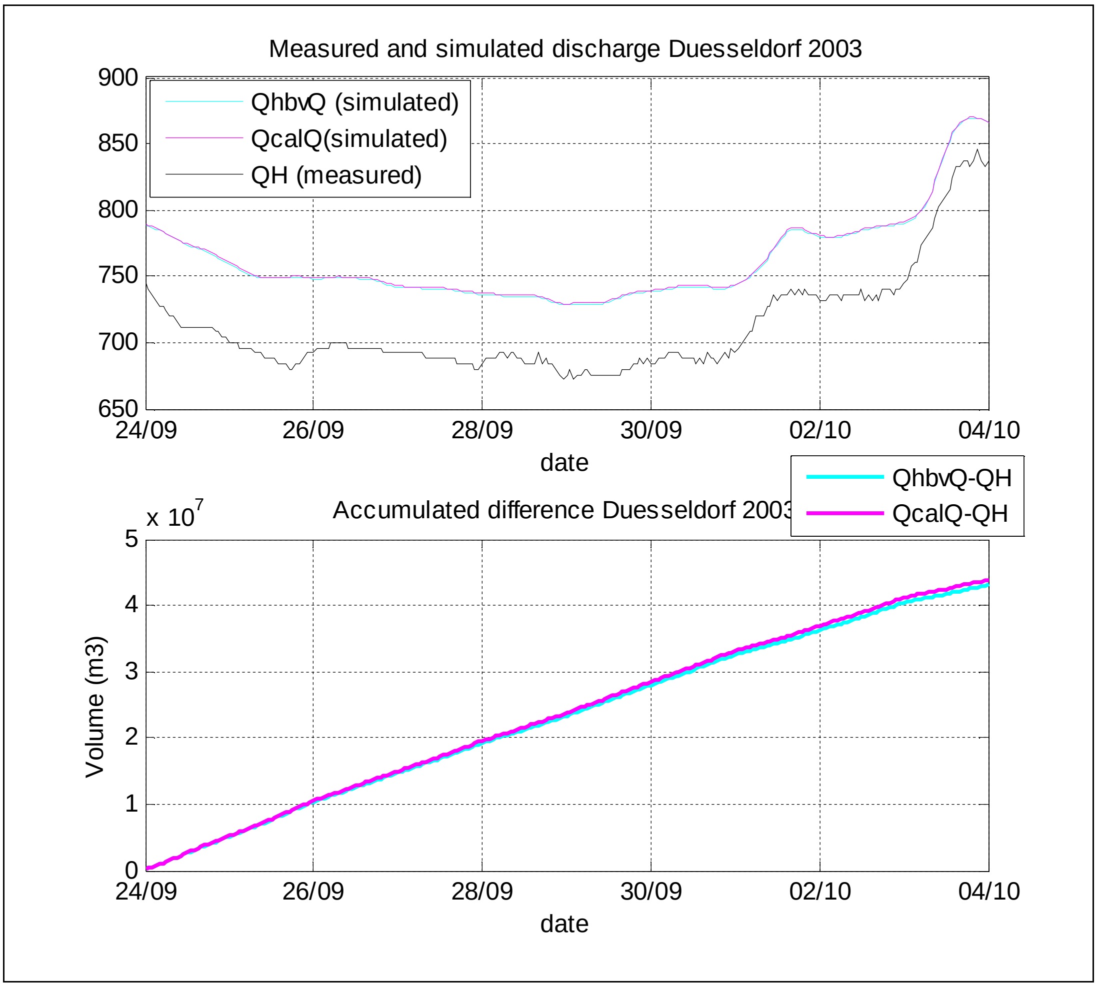

Figure 4.26. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Düsseldorf, (b) accumulated difference at Düsseldorf for both the calibration set and the HBV set.

Table 4.33. Overview waterbalance section 9: Köln-Düsseldorf for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 9: Köln – Düsseldorf Low flow period: 24/09/2003 – 04/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Düsseldorf (%)**		
Köln	0.59			95.16		
Düsseldorf	0.62			100.00		
Sum of Laterals	0.02			2.82		
I+SoL-O[1]	-0.01			-2.02		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Düsseldorf (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Köln	0.59	0.59	0	95.16	96.16	0
Düsseldorf	0.66	0.66	0.00	107.11	106.98	-0.13
Sum of Laterals	0.02	0.02	0.00	2.82	3.29	0.47
I+SoL-O[1]	-0.06	-0.05	0.00	-9.13	-8.54	0.59
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Opladen	9.54	9.54	0	54.80	54.80	0
Neubrueck	7.87	7.87	0	45.20	45.20	0
LowRhine1	0	2.88	2.88	0	16.57	16.57
Sum of Laterals	17.40	20.29	2.88	100.00	116.57	16.57

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.9.3 Lateral inflows

The measured discharge series at both Opladen and Neubrück are being used in the calibration set and HBV set. There are no measured data in the calibration set for LowRhine1.

Table 4.34. Overview statistical information regarding the laterals in Section 9: Köln-Düsseldorf. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
Opladen	-	-	-	-
Neubrueck	-	-	-	-
LowRhine1	na	na	na	na

[1]No measured data (calibration set) available for LowRhine1.

4.10 Section 10: Düsseldorf - Ruhrort

4.10.1 Overview

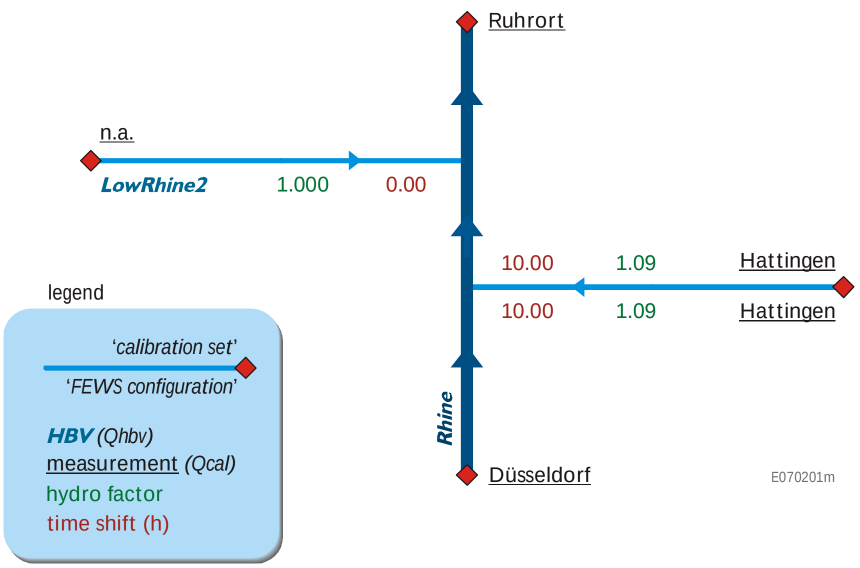

Figure 4.27. Overview Section 10: Düsseldorf-Ruhrort.

Figure 4.27 shows a schematic overview of the river section 10: Düsseldorf-Ruhrort. Three lateral inflows are contributing to the Rhine flow in this river section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.35 shows the water balance of the section 10: Düsseldorf-Ruhrort. Detention does not occur in the section Düsseldorf-Ruhrort during the whole simulation period. From Table 4.35, the following is observed

- the water balance at Ruhrort is negative (-2.01 Bm^3/year), note that the behaviour of the water balance in time is not constant(see Appendix D);
- effect groundwater exchange is small in this section;
- the lateral inflows from the calibration set and HBV set are different (7%) because the lateral LowRhine2 is not available in the calibration set and is therefore taken as zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis can be in the order of 100 m^3/s for Düsseldorf and 200 m^3/s for Ruhrort.

Table 4.35. Overview water balance section 10: Düsseldorf-Ruhrort (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 10: Düsseldorf – Ruhrort period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Ruhrort (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Düsseldorf	73.53			94.07			9263	2331	672
Ruhrort	78.17			100.00			9730	2478	779
Sum of Laterals	2.63			3.36					
I+SoL-O[1]	-2.01			-2.57					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Ruhrort (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH - QcalQ**		
Düsseldorf	73.53	73.53	0	94.07	94.07	0	±100		
Ruhrort	76.16	76.24	0.08	97.43	97.54	0.11	±200		
Sum of Laterals	2.63	2.82	0.19	3.36	3.60	0.24			
I+SoL-O[1]	0.00	0.11	0.11	0.00	0.14	0.13			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
Hattingen	2.63	2.63	0.00	100.00	100.00	0.00	982.09	81.30	8.54
LowRhine2	0	0.19	0.19	0	7.21	7.21	0	0	0
Sum of Laterals	2.63	2.82	0.19	100.00	107.21	7.21			

[1] I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.10.2 Periods of Interest

Figure 4.28 and Table 4.36 show results for a typical flood period for section 10. During a flood period less water is being measured than is provided by the upper boundary and the lateral inflows. Differences between the two SOBEK simulations are small. For the low flow period, see Figure 4.29 and Table 4.37, more water is being measured than is provided by the upper boundary and sum of the lateral inflows. From the two SOBEK simulations it is clear that water from the groundwater is entering the river during the low flow period.

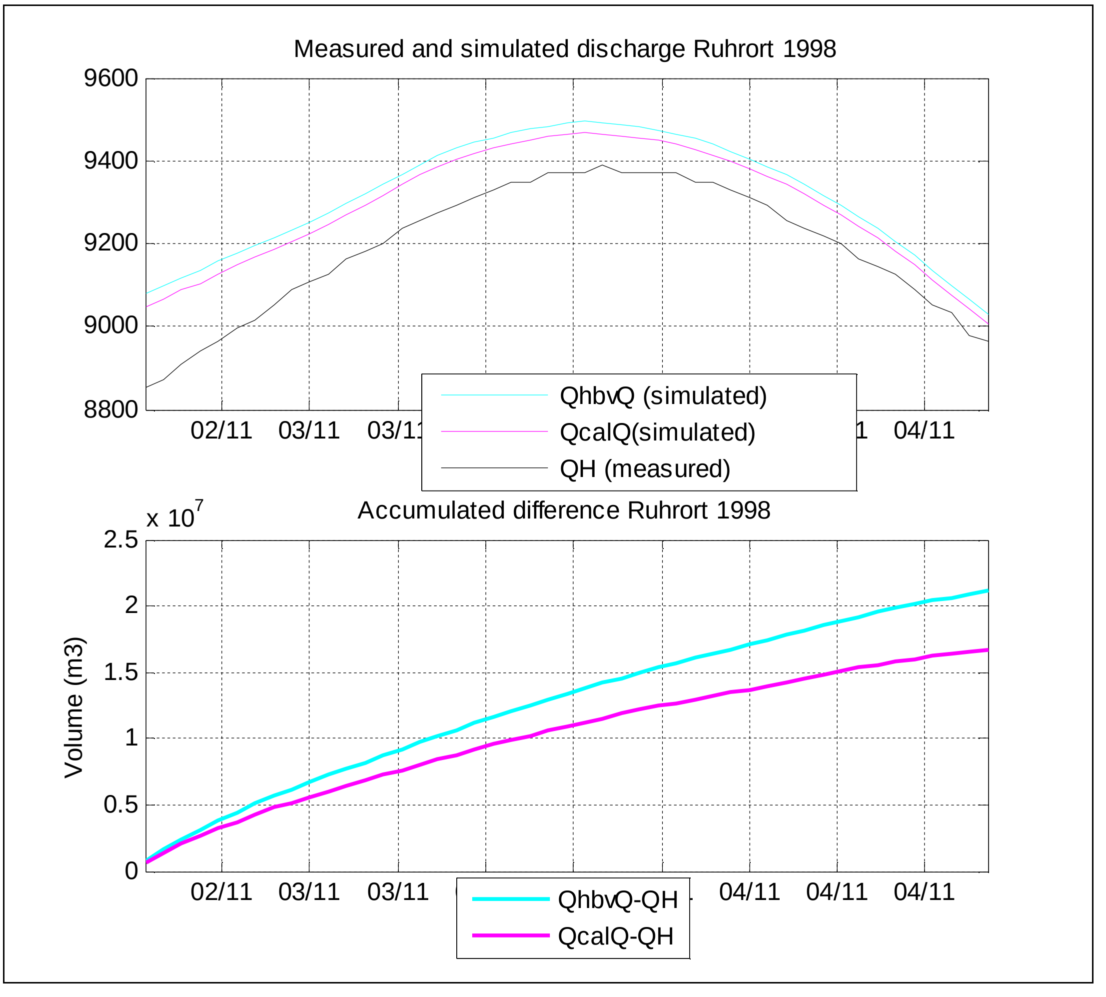

Figure 4.28. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Ruhrort, (b) accumulated difference at Ruhrort for both the calibration set and the HBV set.

Table 4.36. Overview waterbalance section 10: Düsseldorf-Ruhrort for the flood period of 1998 (in B$m^3=10^9$ m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6$ m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 10: Düsseldorf – Ruhrort Flood period: 2/11/1998 15:00 – 4/11/1998 13:00		
Water balance from derived discharges		
	Average volume (Bm^3)	**Average volume relative to QH Ruhrort (%)**
Düsseldorf	1.47	94.65
Ruhrort	1.56	100.00
Sum of Laterals	0.11	7.15
I+SoL-O[1]	0.03	1.80

Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Ruhrort (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Düsseldorf	1.47	1.47	0	94.65	94.65	0
Ruhrort	1.57	1.58	0.00	101.07	101.36	0.29
Sum of Laterals	0.11	0.12	0.00	7.15	7.47	0.31
I+SoL-O[1]	0.01	0.01	0.00	0.73	0.76	0.03

Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Hattingen	111.23	111.23	0	100	100	0
LowRhine2	0	4.90	4.90	0	4.40	4.40
Sum of Laterals	111.23	116.13	4.90	100	104.40	4.40

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

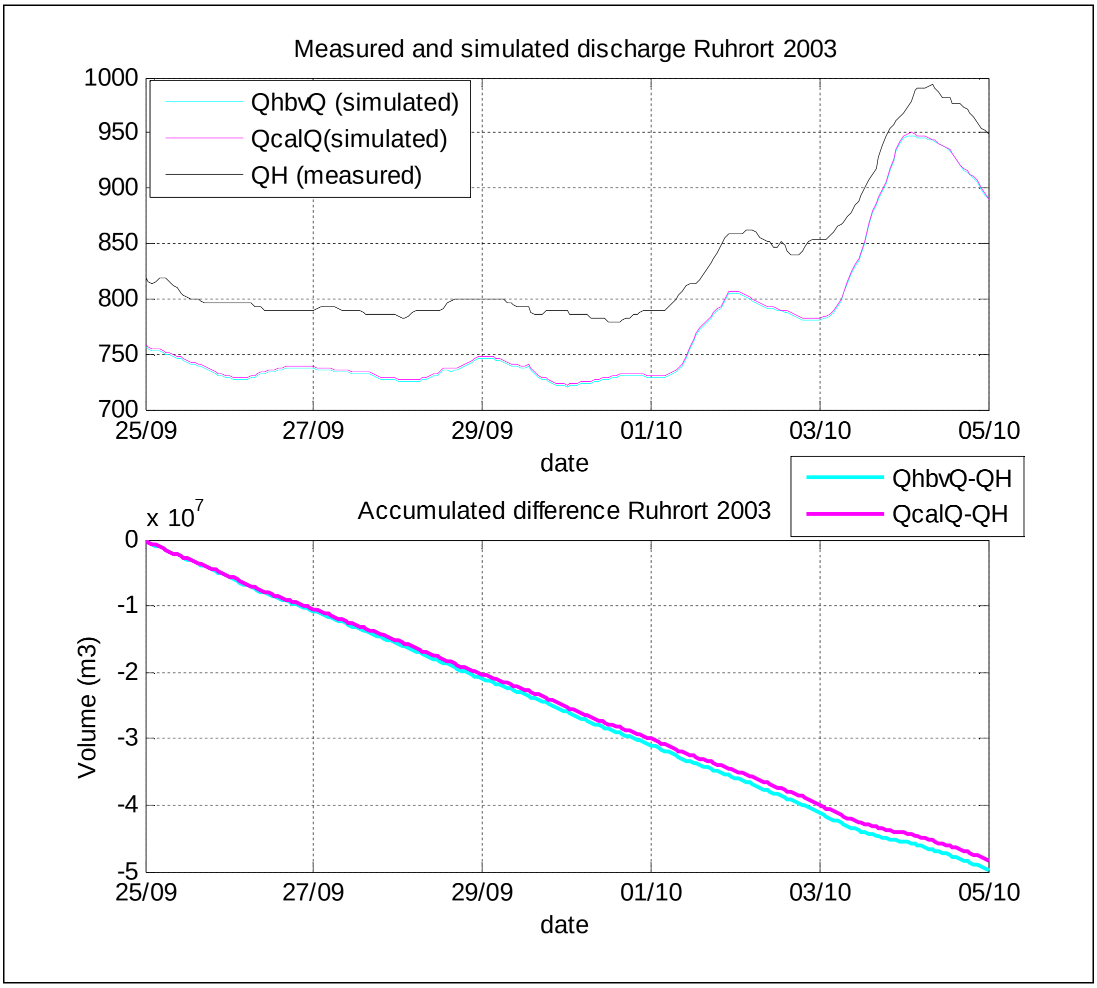

Figure 4.29. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Ruhrort, (b) accumulated difference at Ruhrort for both the calibration set and the HBV set.

Table 4.37. Overview waterbalance section 10: Düsseldorf-Ruhrort for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 10: Düsseldorf – Ruhrort Low flow period: 25/09/2003 – 05/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Ruhrort (%)**		
Düsseldorf	0.62			86.68		
Ruhrort	0.72			100.00		
Sum of Laterals	0.04			5.02		
I+SoL-O[1]	-0.06			-8.31		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Ruhrort (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Düsseldorf	0.62	0.62	0	86.68	86.68	0
Ruhrort	0.67	0.67	0.00	93.30	93.10	-0.20
Sum of Laterals	0.04	0.04	0.00	5.02	5.21	0.20
I+SoL-O[1]	-0.01	-0.01	0.00	-1.61	-1.21	0.40
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Hattingen	36.16	36.16	0	100	100	0
LowRhine2	0	1.41	1.41	0	3.90	3.90
Sum of Laterals	36.16	37.57	1.41	100	103.90	3.90

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.10.3 Lateral inflows

The measured discharge is being used at Hattingen in the calibration set and HBV set. There are no measured data in the calibration set for LowRhine2.

Table 4.38. Overview statistical information regarding the laterals in Section 10: Düsseldorf-Ruhrort. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
LowRhine2	na	na	na	na
Hattingen	-	-	-	-

[1]No measured data (calibration set) available for LowRhine2.

4.11 Section 11: Ruhrort - Wesel

4.11.1 Overview

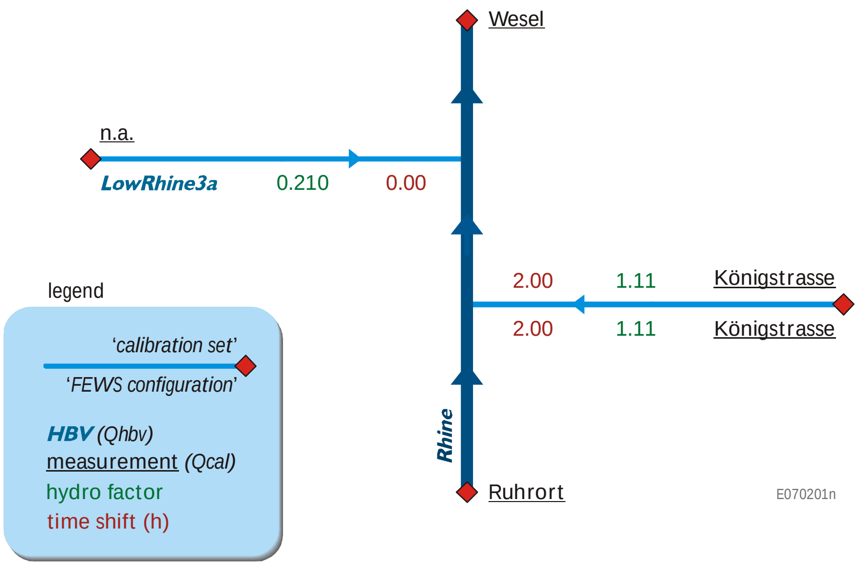

Figure 4.30. Overview Section 11: Ruhrort-Wesel.

Figure 4.30 shows a schematic overview of the river section 11: Ruhrort-Wesel. Two lateral inflows contribute to the Rhine flow in this river section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.39 shows the water balance of the section 11: Ruhrort-Wesel. Detention does not occur here during the whole simulation period. From Table 4.39, the following is observed:

- the water balance at Wesel is negative (-0.77 Bm^3/year), note that the behaviour of the water balance in time is not constant (see Appendix D);
- there is a net flux of water from the river to the groundwater in the SOBEK models;
- the lateral inflows from the calibration set and HBV set are different (10%) because the lateral LowRhine3a is not available in the calibration set and is therefore taken as zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis is estimated at 200 m^3/s for Ruhrort and 500 m^3/s for Wesel.

Table 4.39. Overview water balance section 11: Ruhrort-Wesel (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 11: Ruhrort – Wesel period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Wesel (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Ruhrort	78.17			98.34			9730	2478	779
Wesel	79.49			100.00			10266	2519	768
Sum of Laterals	0.55			0.69					
I+SoL-O[1]	-0.77			-0.97					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Wesel (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH - QcalQ**		
Ruhrort	78.17	78.17	0	98.34	98.34	0	±200		
Wesel	78.54	78.68	0.13	98.81	98.98	0.17	±500		
Sum of Laterals	0.55	0.60	0.05	0.69	0.76	0.07			
I+SoL-O[1]	0.17	0.09	-0.08	0.21	0.11	-0.10			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
Königstrasse	0.55	0.55	0.00	100.00	100.00	0.00	277.22	17.30	6.25
LowRhine3a	0	0.05	0.05	0	9.70	9.70	0	0	0
Sum of Laterals	0.55	0.60	0.05	100.00	109.70	9.70			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.11.2 Periods of Interest

Figure 4.31 and Table 4.40 show results for a typical flood period for section 11. During a flood period much more water is being measured than is provided by the upper boundary and the lateral inflows. Differences between the two SOBEK simulations are small. For the low flow period, see Figure 4.32 and Table 4.41, slightly less water is being measured than is provided by the upper boundary and sum of the lateral inflows. From the two SOBEK simulations, it is clear that water from the groundwater is entering the river during the low flow period.

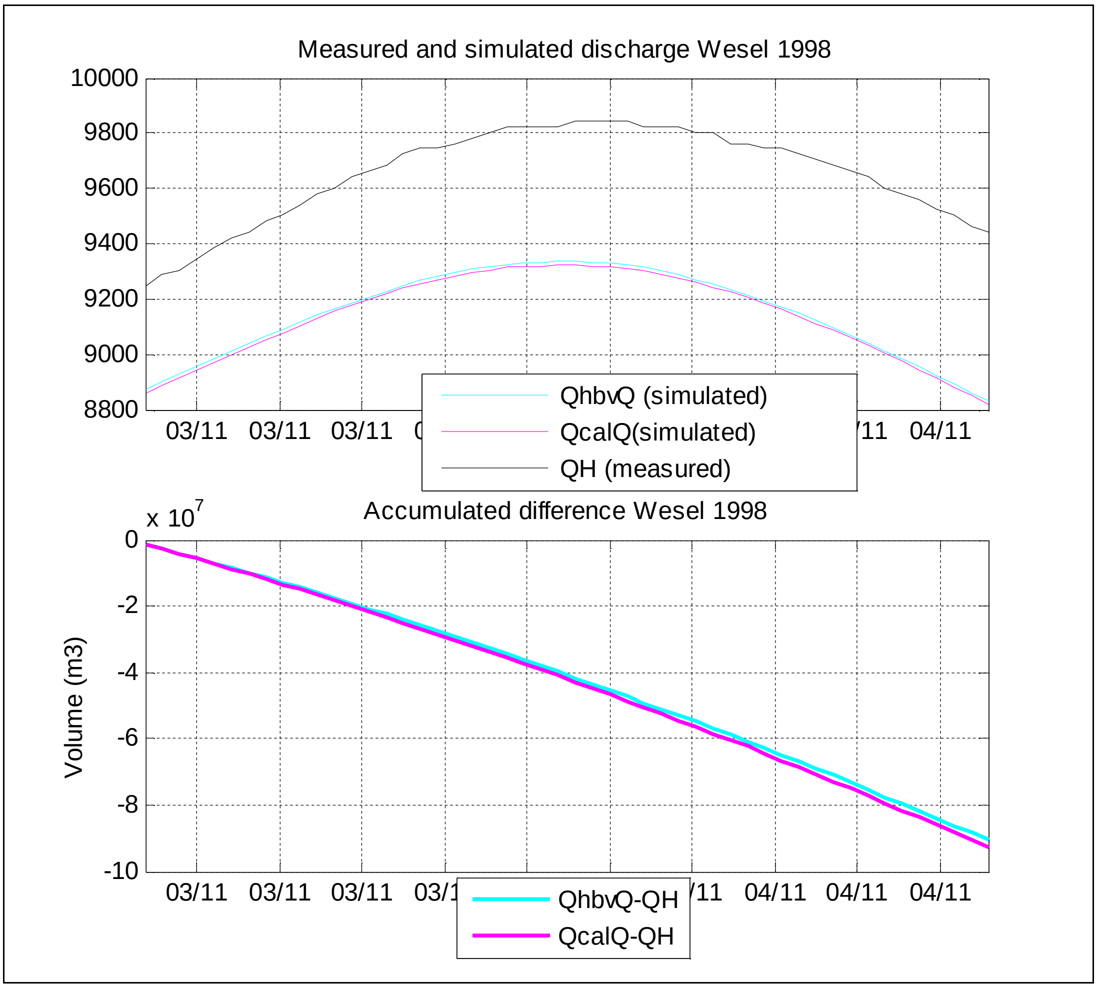

Figure 4.31. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Wesel, (b) accumulated difference at Wesel for both the calibration set and the HBV set.

Table 4.40. Overview waterbalance section 11: Ruhrort-Wesel for the flood period of 1998 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 11: Ruhrort - Wesel Flood period: 02/11/1998 21:00 – 04/11/1998 22:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Wesel (%)**		
Ruhrort	1.65			94.80		
Wesel	1.74			100.00		
Sum of Laterals	0.01			0.42		
I+SoL-O[1]	-0.08			-4.79		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Wesel (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Ruhrort	1.65	1.65	0	94.80	94.80	0
Wesel	1.64	1.65	0.00	94.66	94.79	0.12
Sum of Laterals	0.01	0.01	0.00	0.42	0.50	0.09
I+SoL-O[1]	0.01	0.01	0.00	0.55	0.51	-0.04
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Königstrasse	7.22	7.22	0	100	100	0
LowRhine3a	0	1.53	1.53	0	21.26	21.26
Sum of Laterals	7.22	8.75	1.53	100	121.26	21.26

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

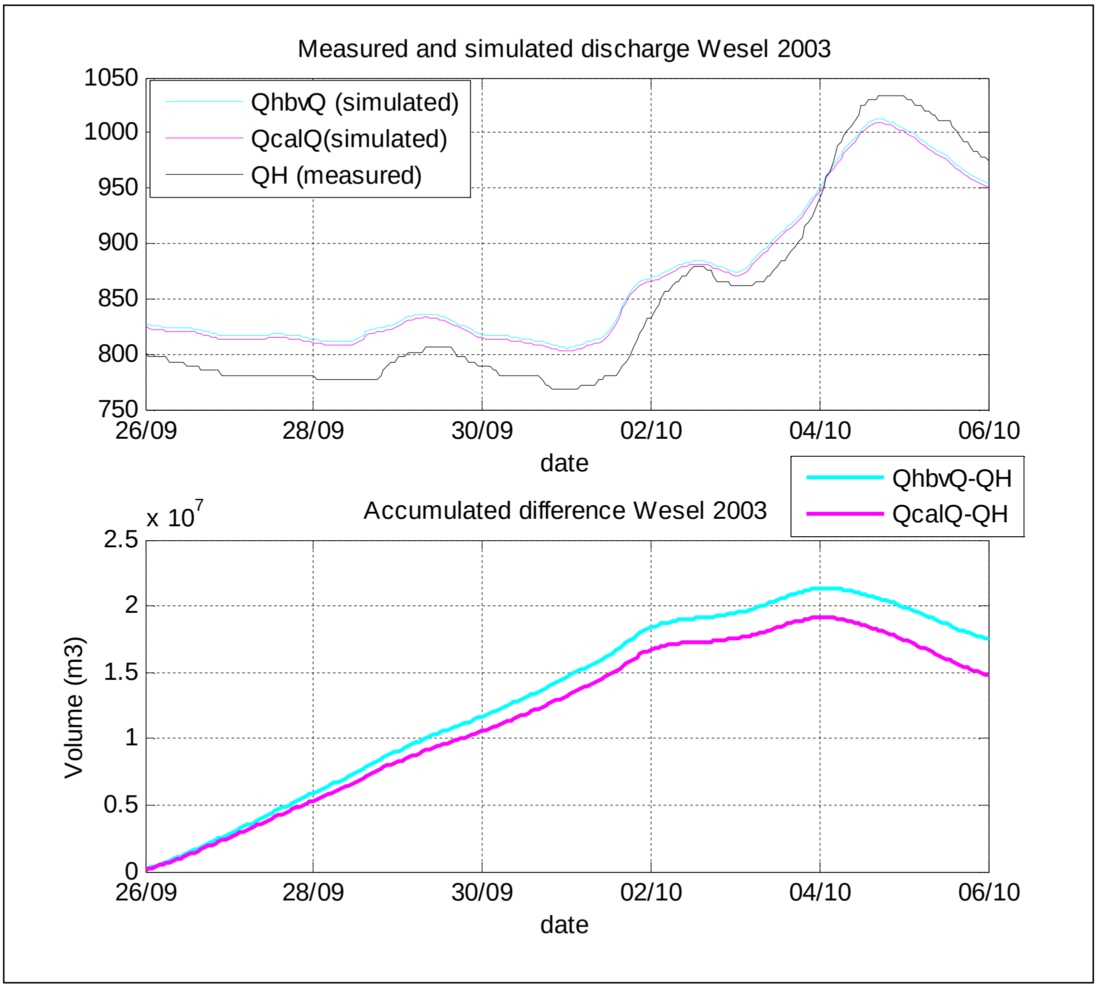

Figure 4.32. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Wesel, (b) accumulated difference at Wesel for both the calibration set and the HBV set.

Table 4.41. Overview waterbalance section 11: Ruhrort-Wesel for the low flow period of 2003 (in B$m^3=10^9$ m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6$ m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 11: Ruhrort - Wesel Low flow period: 26/09/2003 – 06/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Wesel (%)**		
Ruhrort	0.73			99.10		
Wesel	0.74			100.00		
Sum of Laterals	0.02			2.09		
I+SoL-O[1]	0.01			1.19		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Wesel (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Ruhrort	0.73	0.73	0	99.10	99.10	0
Wesel	0.75	0.75	0.00	102.00	102.38	0.37
Sum of Laterals	0.02	0.02	0.00	2.09	2.18	0.09
I+SoL-O[1]	-0.01	-0.01	0.00	-0.82	-1.11	-0.29
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Königstrasse	15.39	15.39	0	100	100	0
LowRhine3a	0	0.64	0.64	0	4.16	4.16
Sum of Laterals	15.39	16.03	0.64	100	104.16	4.16

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.11.3 Lateral inflows

The measured discharge at Königstrasse is being used in the calibration set and in the HBV set. There are no measured data in the calibration set for LowRhine3a.

Table 4.42. Overview statistical information regarding the laterals in Section 11: Ruhrort-Wesel. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	**NSE**	**relative volume difference %**	**maximum absolute difference (m^3/s)**	**mean absolute difference (m^3/s)**
LowRhine3a	na	na	na	na
Königstrasse	-	-	-	-

[1]No measured data (calibration set) available for LowRhine3a.

4.12 Section 12: Wesel - Rees

4.12.1 Overview

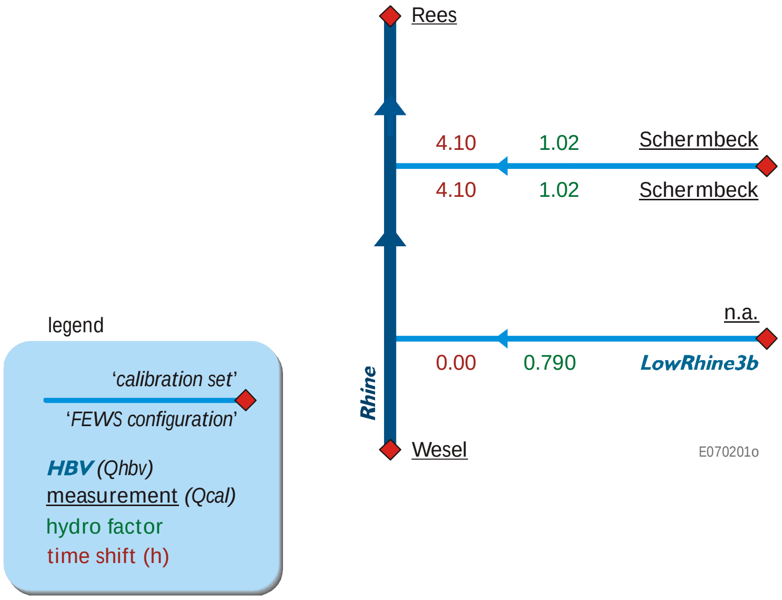

Figure 4.33. Overview Section 12: Wesel-Rees.

Figure 4.33 shows a schematic overview of the river section 12: Wesel-Rees. Two lateral inflows contribute to the Rhine flow in this river section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.43 shows the water balance of the section 12: Wesel-Rees. Detention does not occur in this section during the whole simulation period. From Table 4.43, the following is observed

- the water balance at Rees is positive (1.29 Bm^3/year), note that the behaviour of the water balance in time is fairly constant (see Appendix D);
- the maximum discharge at Rees is 330 m^3/s smaller than the maximum discharge at Wesel;
- there is a net flux of water from the ground water to the river in the SOBEK models;
- the lateral inflows from the calibration set and HBV set are different (13%) because the lateral LowRhine3b is not available in the calibration set and is therefore taken as zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis is estimated at 500 m^3/s for both Wesel and Rees.

Table 4.43. Overview water balance section 12: Wesel-Rees (in B$m^3/y=10^9$ m^3/y) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

<table>
<tr><th colspan="10">Section 12:Wesel – Rees
period: 1/11/1997 – 31/10/2004</th></tr>
<tr><th colspan="10">Water balance from derived discharges</th></tr>
<tr><th rowspan="2"></th><th colspan="3" rowspan="2">Average volume (Bm³/y)</th><th colspan="3" rowspan="2">Average volume relative to QH Rees (%)</th><th colspan="3">QH (m³/s)</th></tr>
<tr><th>max</th><th>mean</th><th>min</th></tr>
<tr><td>Wesel</td><td colspan="3">79.49</td><td colspan="3">99.73</td><td>10266</td><td>2519</td><td>768</td></tr>
<tr><td>Rees</td><td colspan="3">79.70</td><td colspan="3">100.00</td><td>9931</td><td>2526</td><td>832</td></tr>
<tr><td>Sum of Laterals</td><td colspan="3">1.50</td><td colspan="3">1.89</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>I+SoL-O[1]</td><td colspan="3">1.29</td><td colspan="3">1.61</td></tr>
<tr><th colspan="10">Water balance from SOBEK calculations</th></tr>
<tr><th rowspan="2"></th><th colspan="3">Average volume (Bm³/y)</th><th colspan="3">Average volume relative to QH Rees (%)</th><th colspan="3">Maximal hysteresis (m³/s)</th></tr>
<tr><th>QcalQ</th><th>QhbvQ</th><th>Δ</th><th>QcalQ</th><th>QhbvQ</th><th>Δ</th><th colspan="3">QcalH - QcalQ</th></tr>
<tr><td>Wesel</td><td>79.49</td><td>79.49</td><td>0</td><td>99.73</td><td>99.73</td><td>0</td><td colspan="3">±500</td></tr>
<tr><td>Rees</td><td>81.20</td><td>81.36</td><td>0.15</td><td>101.88</td><td>102.07</td><td>0.19</td><td colspan="3">±500</td></tr>
<tr><td>Sum of Laterals</td><td>1.50</td><td>1.70</td><td>0.20</td><td>1.89</td><td>2.14</td><td>0.25</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>I+SoL-O[1]</td><td>-0.21</td><td>-0.17</td><td>0.05</td><td>-0.27</td><td>-0.21</td><td>0.06</td></tr>
<tr><th colspan="10">Overview laterals</th></tr>
<tr><th rowspan="2"></th><th colspan="3">Average volume (Bm³/y)</th><th colspan="3">Average volume relative to Sum of Laterals QcalL (%)</th><th colspan="3">QcalL (m³/s)</th></tr>
<tr><th>QcalL</th><th>QhbvL</th><th>Δ</th><th>QcalL</th><th>QhbvL</th><th>Δ</th><th>max</th><th>mean</th><th>min</th></tr>
<tr><td>Schermbeck</td><td>1.50</td><td>1.50</td><td>0.00</td><td>100.00</td><td>100.00</td><td>0</td><td>466.44</td><td>46.11</td><td>14.99</td></tr>
<tr><td>LowRhine3b</td><td>0</td><td>0.20</td><td>0.20</td><td>0</td><td>13.32</td><td>13.32</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Sum of Laterals</td><td>1.50</td><td>1.70</td><td>0.20</td><td>100.00</td><td>113.32</td><td>13.32</td><td colspan="3"></td></tr>
</table>

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.12.2 Periods of Interest

Figure 4.34 and Table 4.44 show results for a typical flood period for section 12. During a flood period much less water is being measured than is provided by the upper boundary and the lateral inflows. This is probably due to an overestimation of the discharge in the Rhine at gaugingstation Wesel, which is situated net upstream the mouth of the Lippe, where backwater-effects during floods are likely to occur. Differences between the two SOBEK simulations are small. For the low flow period, see Figure 4.35 and Table 4.45, slightly more water is being measured than is provided by the upper boundary and sum of the lateral inflows. From the two SOBEK simulations, it is clear that water from the groundwater is entering the river during the low flow period.

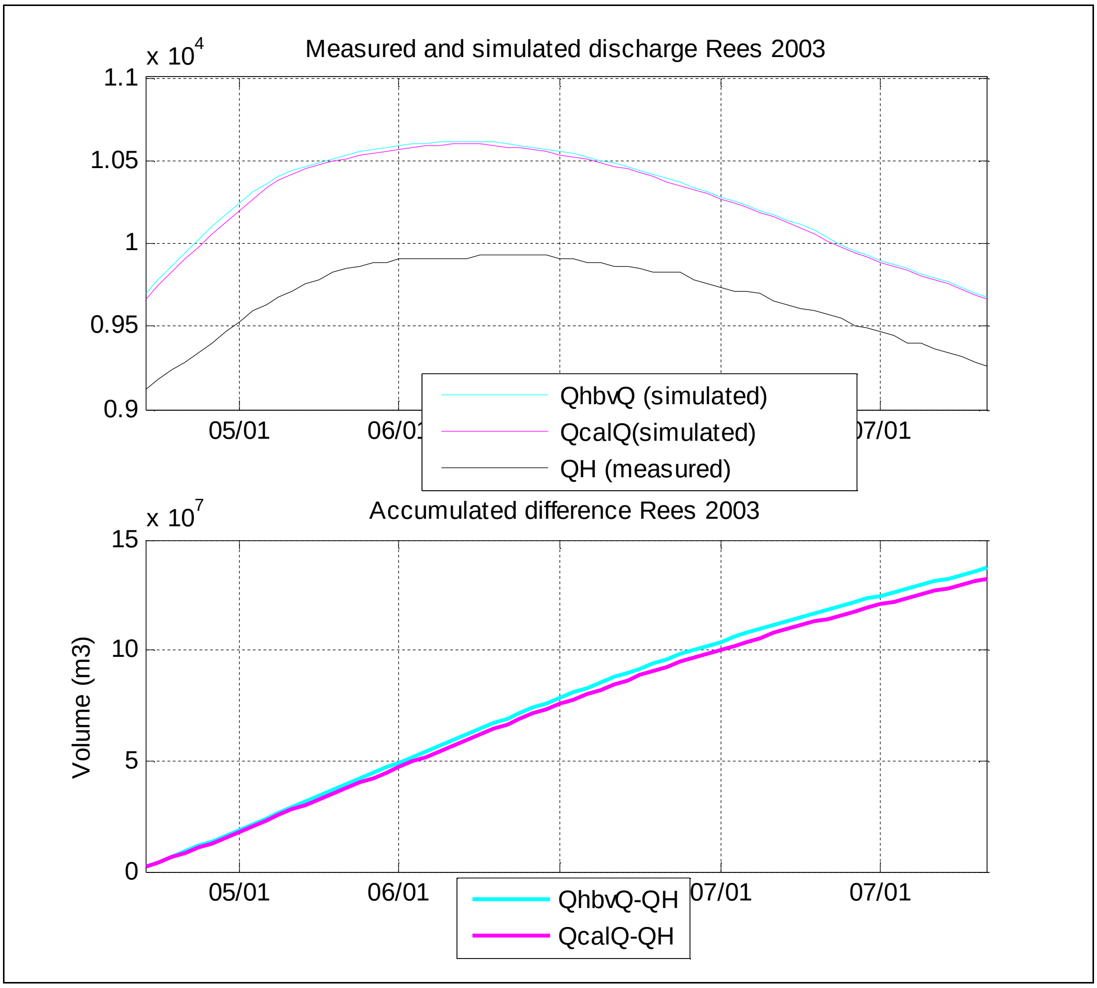

Figure 4.34. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Rees, (b) accumulated difference at Rees for both the calibration set and the HBV set.

Table 4.44. Overview waterbalance section 12: Wesel-Rees for the flood period of 2003 (in B$m^3=10^9$ m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6$ m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 12: Wesel – Rees Flood period: 05/01/2003 05:00 – 07/01/2003 20:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Rees(%)**		
Wesel	2.28			102.52		
Rees	2.23			100.00		
Sum of Laterals	0.09			3.88		
I+SoL-O[1]	0.14			6.40		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Rees (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Wesel	2.28	2.28	0	102.52	102.52	0
Rees	2.36	2.37	0.00	105.95	106.15	0.20
Sum of Laterals	0.09	0.09	0.00	3.88	4.04	0.16
I+SoL-O[1]	0.01	0.01	0.00	0.46	0.42	-0.04
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Schermbeck	86.47	86.47	0	100	100	0
LowRhine3b	0	3.60	3.60	0	4.16	4.16
Sum of Laterals	86.47	90.06	3.60	100	104.16	4.16

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

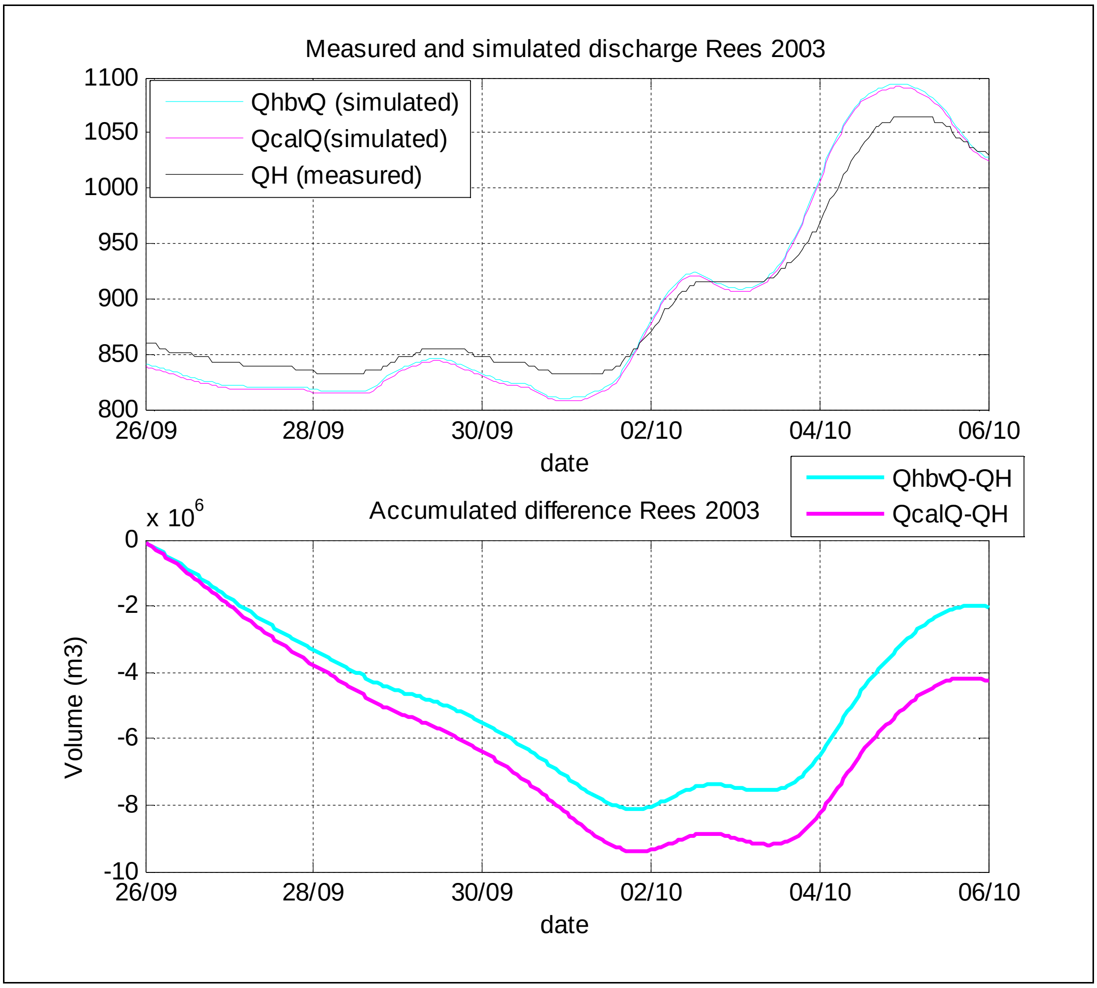

Figure 4.35. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Rees, (b) accumulated difference at Rees for both the calibration set and the HBV set.

Table 4.45. Overview waterbalance section 12: Wesel-Rees for the low flow period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 12: Wesel – Rees Low flow period:26/09/2003 – 06/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Rees(%)**		
Wesel	0.74			94.97		
Rees	0.78			100.00		
Sum of Laterals	0.02			3.18		
I+SoL-O[1]	-0.01			-1.86		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Rees (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Wesel	0.74	0.74	0	94.97	94.97	0
Rees	0.77	0.78	0.00	99.46	99.74	0.28
Sum of Laterals	0.02	0.03	0.00	3.18	3.49	0.31
I+SoL-O[1]	-0.01	-0.01	0.00	-1.31	-1.29	0.03
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
Schermbeck	24.72	24.72	0	100	100	0
LowRhine3b	0	2.42	2.42	0	9.77	9.77
Sum of Laterals	24.72	27.14	2.42	100	109.77	9.77

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.12.3 Lateral inflows

The measured discharge is being used at Schermbeck in the calibration set and HBV set. There are no measured data in the calibration set for LowRhine3b.

Table 4.46. Overview statistical information regarding the laterals in Section 12: Wesel-Rees. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
LowRhine3b	na	na	na	na
Schermbeck	-	-	-	-

[1]No measured data (calibration set) available for LowRhine3b.

4.13 Section 13: Rees - Emmerich

4.13.1 Overview

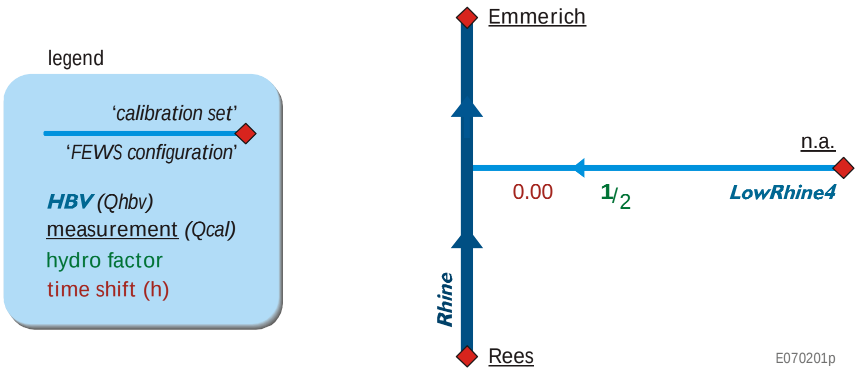

Figure 4.36. Overview Section 13: Rees-Emmerich.

Figure 4.36 shows a schematic overview of the river section 13: Rees-Emmerich. One lateral inflow contributes to the Rhine flow in this river section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.47 shows the water balance of the section 13: Rees-Emmerich. Detention does not occur in the section Rees-Emmerich during the whole simulation period. From Table 4.47, the following is observed

- the water balance at Emmerich is positive (0.95 Bm^3/year), note that the behaviour of the water balance in time is fairly constant (see Appendix D);
- the maximum discharge at Emmerich is 160 m^3/s smaller than the maximum discharge at Rees;
- there is a net flux of water from the ground water to the river in the SOBEK models;
- the lateral inflows from the calibration set and HBV set are different because the lateral LowRhine4 is not available in the calibration set and is therefore taken as zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis is estimated at 500 m^3/s for Rees and 350 m^3/s for Emmerich.

Table 4.47. Overview water balance section 13: Rees-Emmerich (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 13: Rees – Emmerich period: 1/11/1997 – 31/10/2004									
Water balance from derived discharges									
	Average volume (Bm^3/y)			**Average volume relative to QH Emmerich (%)**			**QH (m^3/s)**		
							max	**mean**	**min**
Rees	79.70			101.21			9931	2526	832
Emmerich	78.75			100.00			9770	2496	772
Sum of Laterals	0			0					
I+SoL-O[1]	0.95			1.21					
Water balance from SOBEK calculations									
	Average volume (Bm^3/y)			**Average volume relative to QH Emmerich (%)**			**Maximal hysteresis (m^3/s)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH - QcalQ**		
Rees	79.70	79.70	0	101.21	101.21	0	±500		
Emmerich	79.77	79.96	0.19	101.29	101.53	0.24	±350		
Sum of Laterals	0	0.16	0.16	0	0.20	0.20			
I+SoL-O[1]	-0.07	-0.09	-0.03	-0.08	-0.12	-0.04			
Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
LowRhine4	0	0.16	0.16	-	-	-	-	-	-
Sum of Laterals	0	0.16	0.16	-	-	-			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.13.2 Periods of Interest

Figure 4.37 and Table 4.48 show results for a typical flood period for section 13. During a flood period slightly less water is being measured than is provided by the upper boundary and the lateral inflows. Differences between the two SOBEK simulations are small. For the low flow period, see Figure 4.38 and Table 4.49, much less water is being measured than is provided by the upper boundary and sum of the lateral inflows. From the two SOBEK simulations, it is clear that water from the groundwater is entering the river during the low flow period.

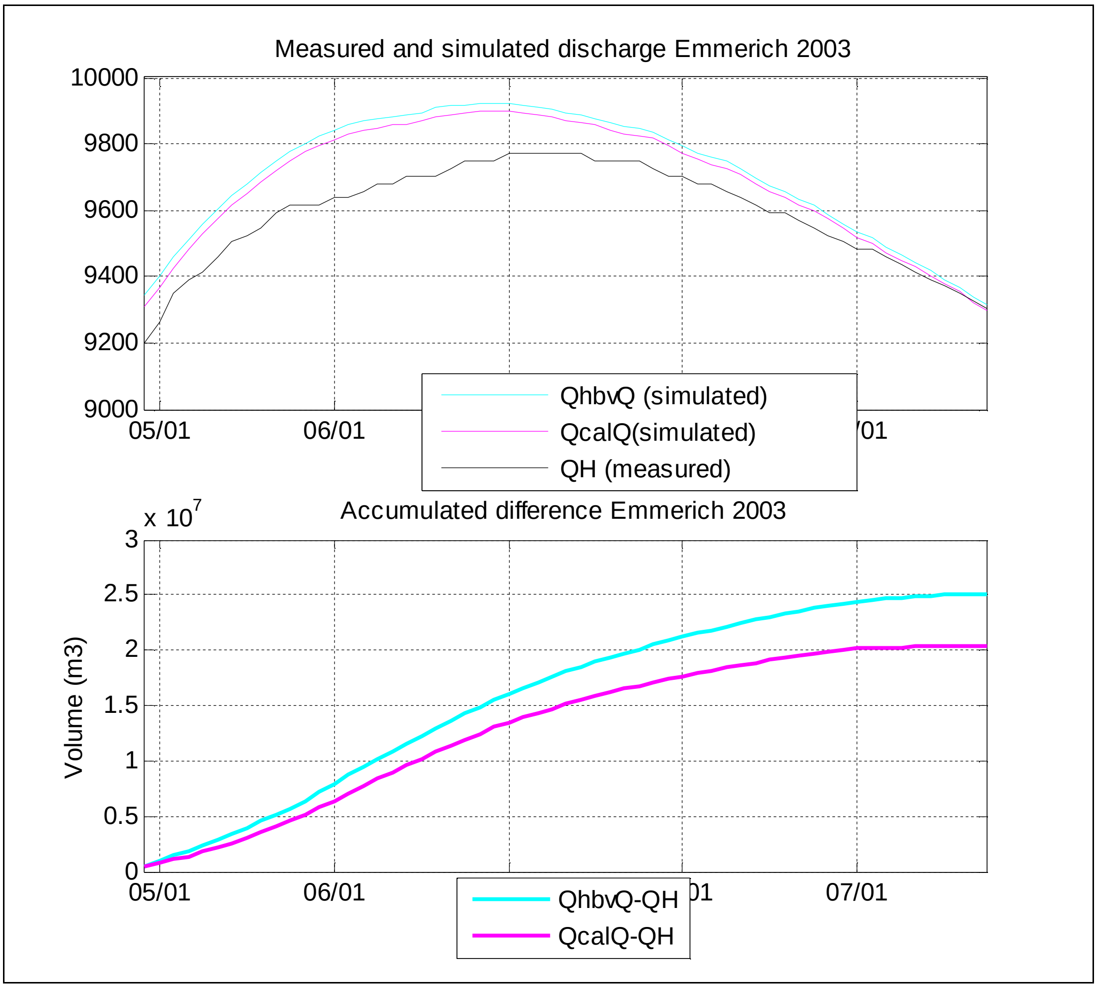

Figure 4.37. (a)` Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Emmerich, (b) accumulated difference at Emmerich for both the calibration set and the HBV set.

Table 4.48. Overview waterbalance section 13: Rees-Emmerich for the flood period of 2003 (in B$m^3=10^9\ m^3$) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6\ m^3$) are the laterals from the calibration set and the HBV set, respectively.

Section 13: Rees - Emmerich Flood period: 05/01/2003 11:00 – 07/01/2003 21:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Emmerich(%)**		
Rees	2.06			101.21		
Emmerich	2.04			100.00		
Sum of Laterals	0			0		
I+SoL-O[1]	0.02			1.21		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Emmerich (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Rees	2.06	2.06	0	101.21	101.21	0
Emmerich	2.06	2.06	0.00	101.00	101.23	0.23
Sum of Laterals	0	0.00	0.00	0	0.19	0.19
I+SoL-O[1]	0.00	0.00	0.00	0.21	0.16	-0.05
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
LowRhine4	0	3.83	3.83	-	-	-
Sum of Laterals	0	3.83	3.83	-	-	-

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

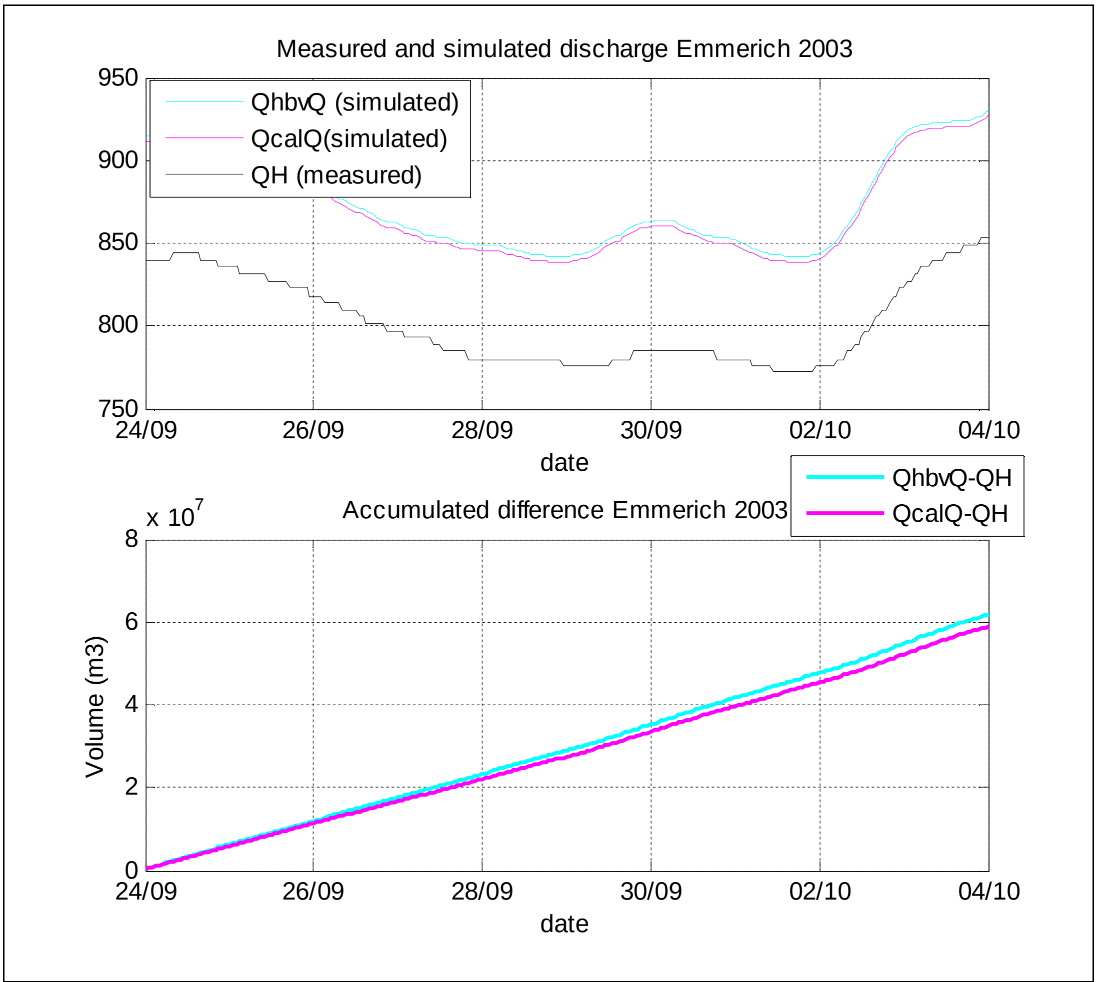

Figure 4.38. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Emmerich, (b) accumulated difference at Emmerich for both the calibration set and the HBV set.

Table 4.49. Overview waterbalance section 13: Rees-Emmerich for the low flow period of 2003 (in B$m^3=10^9$ m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in M$m^3=10^6$ m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 13: Rees - Emmerich Low flow period: 24/09/2003 – 04/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Emmerich(%)**		
Rees	0.75			107.73		
Emmerich	0.70			100.00		
Sum of Laterals	0			0		
I+SoL-O[1]	0.05			7.73		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Emmerich (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Rees	0.75	0.75	0	107.73	107.73	0
Emmerich	0.75	0.76	0.00	108.47	108.89	0.41
Sum of Laterals	0	0.00	0.00	0	0.35	0.35
I+SoL-O[1]	-0.01	-0.01	0.00	-0.74	-0.80	-0.06
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
LowRhine4	0	2.45	2.45	-	-	-
Sum of Laterals	0	2.45	2.45	-	-	-

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.13.3 Lateral inflows

There are no measured data in the calibration set for LowRhine4.

Table 4.50. Overview statistical information regarding the laterals in Section 13: Rees-Emmerich. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	**NSE**	**relative volume difference %**	**maximum absolute difference (m^3/s)**	**mean absolute difference (m^3/s)**
LowRhine4	na	na	na	na

[1]No measured data (calibration set) available for LowRhine4.

4.14 Section 14: Emmerich – Lobith

4.14.1 Overview

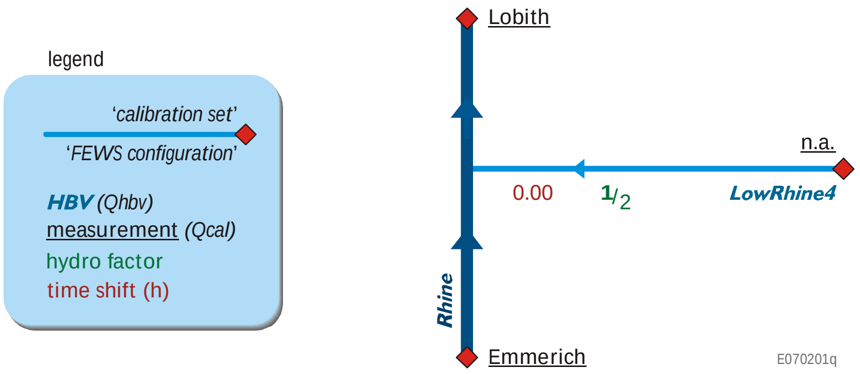

Figure 4.39. Overview Section 14: Emmerich.-Lobith

Figure 4.39 shows a schematic overview of the river section 14: Emmerich-Lobith. One lateral inflow contributes to the Rhine flow in this river section. In the SOBEK model exchange of water between the river and the groundwater reservoir is also being modelled.

Table 4.51 shows the water balance of the section 13: Rees-Emmerich. Detention does not occur in the section Rees-Emmerich during the whole simulation period. From Table 4.51, the following is observed

- the water balance at Lobith is positive (1.46 Bm^3/year), note that the behaviour of the water balance in time is not constant (see Appendix D);
- the maximum discharge at Lobith is 290 m^3/s smaller than the maximum discharge at Emmerich;
- there is a net flux of water from the ground water to the river in the SOBEK models;
- the lateral inflows from the calibration set and HBV set are different because the lateral LowRhine4 is not available in the calibration set and is therefore taken as zero.

The rating curves of the up- and downstream station together with the simulated hysteresis are given in Appendix A. The effect of the hysteresis is estimated at 350 m^3/s for both Emmerich and Lobith.

Table 4.51. Overview water balance section 14: Emmerich-Lobith (in B$m^3/y=10^9$ m^3/y) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set). An overview of both sets of laterals is also given. The maximum, mean and minimal discharge are determined from the calibration set over the period of investigation. Δ indicates the difference between results obtained using the calibration set and the HBV set. An estimate of the maximal hysteresis effect based on the SOBEK simulations is also provided.

Section 14: Emmerich – Lobith period: 1/11/1997 – 31/10/2004					
Water balance from derived discharges					
	Average volume (Bm^3/y)	**Average volume relative to QH Lobith (%)**	**QH (m^3/s)**		
			max	**mean**	**min**
Emmerich	78.75	101.89	9770	2496	772
Lobith	77.29	100.00	9487	2450	788
Sum of Laterals	0	0			
I+SoL-O[1]	1.46	1.89			

Water balance from SOBEK calculations						
	Average volume (Bm^3/y)			**Average volume relative to QH Lobith (%)**			**Maximal hysteresis (m^3/s)**
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**	**QcalH - QcalQ**
Emmerich	78.75	78.75	0	101.89	101.89	0	±350
Lobith	78.80	78.93	0.13	101.95	102.13	0.17	±350
Sum of Laterals	0	0.16	0.16	0	0.21	0.21	
I+SoL-O[1]	-0.05	-0.02	0.03	-0.06	-0.03	0.04	

Overview laterals									
	Average volume (Bm^3/y)			**Average volume relative to Sum of Laterals QcalL (%)**			**QcalL (m^3/s)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**	**max**	**mean**	**min**
LowRhine4	0	0.16	0.16	-	-	-	-	-	-
Sum of Laterals	0	0.16	0.16	-	-	-			

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.14.2 Periods of Interest

Figure 4.40 and Table 4.52 show results for a typical flood period for section 13. During a flood period much less water is being measured than is provided by the upper boundary and the lateral inflows. Differences between the two SOBEK simulations are small. For the low flow period, see Figure 4.41 and Table 4.53, slightly more water is being measured than is provided by the upper boundary and sum of the lateral inflows. From the two SOBEK simulations, it is clear that water from the groundwater is entering the river during the low flow period.

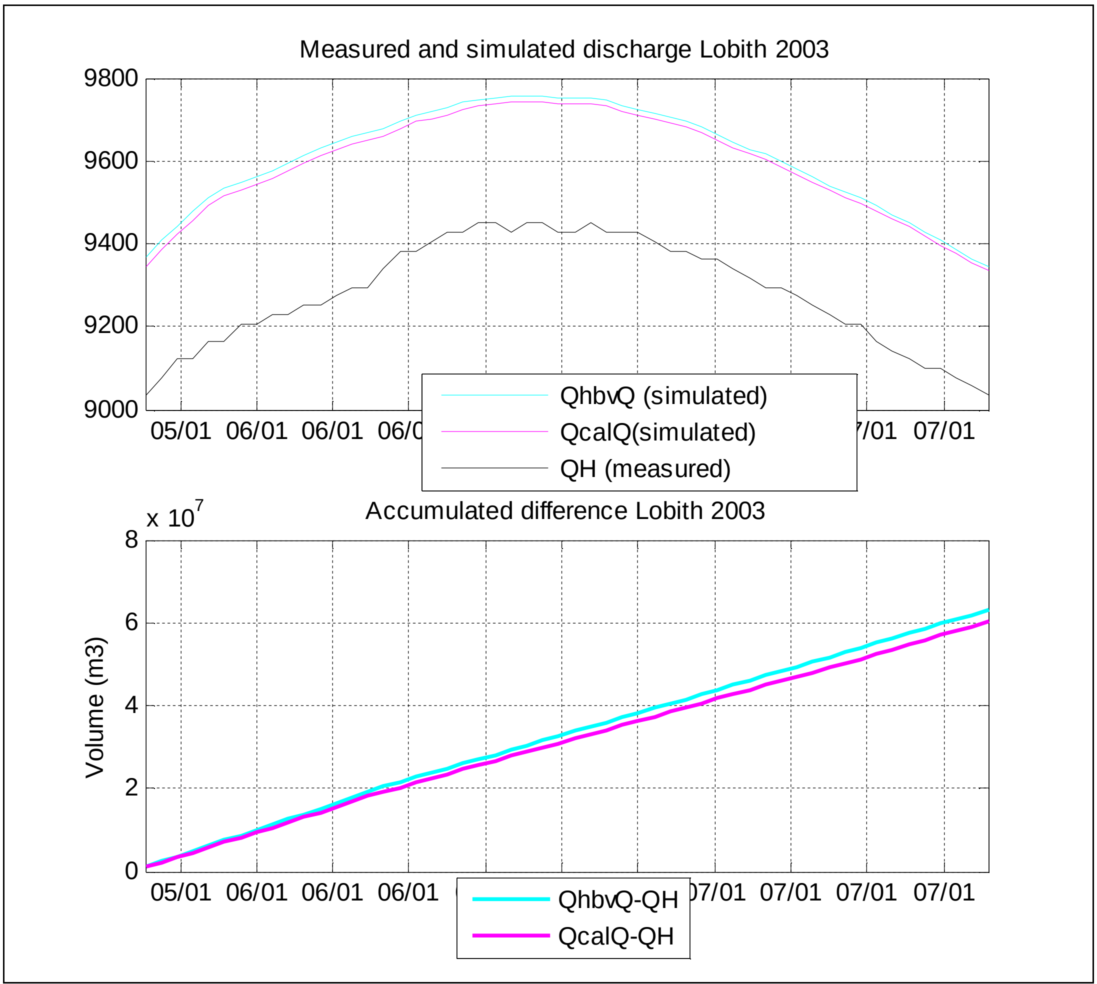

Figure 4.40. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Lobith, (b) accumulated difference at Lobith for both the calibration set and the HBV set.

Table 4.52. Overview waterbalance section 14: Emmerich-Lobith for the flood period of 2003 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 14: Emmerich - Lobith Flood period: 05/01/2003 17:00 – 07/01/2003 22:00						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Lobith (%)**		
Emmerich	1.87			103.55		
Lobith	1.80			100.00		
Sum of Laterals	0			0		
I+SoL-O[1]	0.06			3.55		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Lobtih (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Emmerich	1.87	1.87	0	103.55	103.55	0
Lobith	1.86	1.87	0.00	103.33	103.49	0.16
Sum of Laterals	0	0.00	0.00	0	0.18	0.18
I+SoL-O[1]	0.00	0.00	0.00	0.22	0.24	0.02
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
LowRhine4	0	3.29	3.29	-	-	-
Sum of Laterals	0	3.29	3.29	-	-	-

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

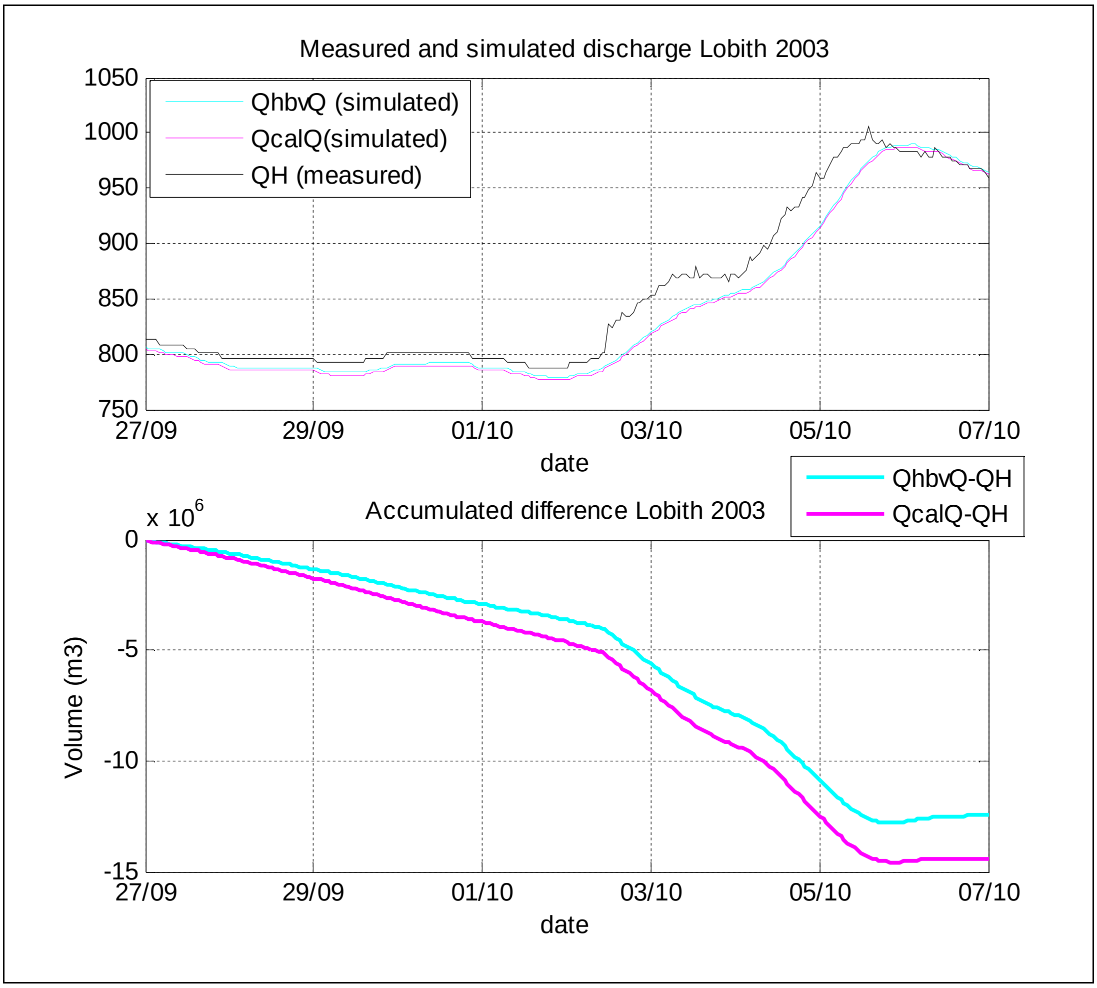

Figure 4.41. (a) Measured discharge (black line, QH) versus simulated discharge (QcalQ) using the calibration set (magenta line) and (QhbvQ) the HBV set (cyan line) at Lobith, (b) accumulated difference at Lobith for both the calibration set and the HBV set.

Table 4.53. Overview waterbalance section 14: Emmerich-Lobith for the flood period of 2002 (in Bm^3=10^9 m^3) based on measurements (QH) and two SOBEK simulations (QcalQ, laterals from calibration set) and (QhbvQ, laterals from HBV set). Δ indicates the difference between results obtained using the calibration set and the HBV set (HBV-cal). QcalL and QhbvL (in Mm^3=10^6 m^3) are the laterals from the calibration set and the HBV set, respectively.

Section 14: Emmerich - Lobith Low flow period: 27/09/2003 – 07/10/2003						
Water balance from derived discharges						
	Average volume (Bm^3)			**Average volume relative to QH Lobith (%)**		
Emmerich	0.72			97.74		
Lobith	0.74			100.00		
Sum of Laterals	0			0		
I+SoL-O[1]	-0.02			-2.26		
Water balance from SOBEK calculations						
	Average volume (Bm^3)			**Average volume relative to QH Lobtih (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Emmerich	0.72	0.72	0	97.74	97.74	0
Lobith	0.73	0.73	0.00	98.05	98.32	0.27
Sum of Laterals	0	0.00	0.00	0	0.33	0.33
I+SoL-O[1]	0.00	0.00	0.00	-0.32	-0.26	0.06
Overview laterals						
	Average volume (Mm^3)			**Average volume relative to sum of laterals QcalL (%)**		
	QcalL	**QhbvL**	**Δ**	**QcalL**	**QhbvL**	**Δ**
LowRhine4	0	2.44	2.44	-	-	-
Sum of Laterals	0	2.44	2.44	-	-	-

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

4.14.3 Lateral inflows

There are no measured data in the calibration set for LowRhine4.

Table 4.54. Overview statistical information regarding the laterals in Section 14: Emmerich-Lobith. The Nash-Sutcliffe Efficiency (NSE) is given together with the relative volume difference (QhbvL-QcalL)/QcalL, the maximal and mean absolute difference of QhbvL-QcalL.

Lateral	NSE	relative volume difference %	maximum absolute difference (m^3/s)	mean absolute difference (m^3/s)
LowRhine4	na	na	na	na

[1]No measured data (calibration set) available for LowRhine4.

5 Effect SOBEK Ground Water Module on Water Balance

5.1 Section 5/6: Kaub – Andernach

Table 5.1 shows the water balance result of running the SOBEK model with and without ground water exchange for section 5/6. It is clear that if the ground water module is switched off the calculated discharges at Andernach are higher. This means that there is a net loss of water from the river to the ground water.

Table 5.1. Overview water balance section 5/6: Kaub-Andernach (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 5/6: Kaub - Andernach period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Andernach (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Kaub	57.83	57.83	0	82.53	82.53	0
Andernach	71.65	72.08	0.43	102.26	102.87	0.62
Sum of Laterals	13.95	14.39	0.44	19.90	20.53	0.63
I+SoL-O[1]	0.13	0.14	0.01	0.18	0.19	0.01
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Andernach (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Kaub	57.83	57.83	0	82.53	82.53	0
Andernach	71.77	72.20	0.43	102.43	103.05	0.62
Sum of Laterals	13.95	14.39	0.44	19.90	20.53	0.63
I+SoL-O[1]	0.00	0.01	0.01	0.01	0.02	0.01

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.2 Section 7: Andernach – Bonn

Table 5.2 shows the water balance result of running the SOBEK model with and without ground water exchange for section 7. It is clear that if the ground water module is switched off the calculated discharges at Bonn are slightly higher. This means that there is a small net loss of water from the river to the ground water. However, for a low flow period (for instance 2003) it is the other way around (results not shown here).

Table 5.2. Overview water balance section 7: Andernach-Bonn (in $Bm^3/y = 10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 7: Andernach – Bonn period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Bonn (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Andernach	70.07	70.07	0	99.42	99.42	0
Bonn	70.29	70.46	0.17	99.73	99.97	0.24
Sum of Laterals	0.25	0.41	0.17	0.35	0.59	0.24
I+SoL-O[1]	0.02	0.02	0.00	0.03	0.03	0.00
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Bonn (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Andernach	70.07	70.07	0	99.42	99.42	0
Bonn	70.31	70.48	0.17	99.76	100.00	0.24
Sum of Laterals	0.25	0.41	0.17	0.35	0.59	0.24
I+SoL-O[1]	0.00	0.00	0.00	0.00	0.00	0.00

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.3 Section 8: Bonn – Köln

Table 5.3 shows the water balance result of running the SOBEK model with and without ground water exchange for section 8. It is clear that when the ground water module is switched off the calculated discharges at Köln are lower. This means that there is a net contribution from the ground water to the river.

Table 5.3. Overview water balance section 8: Bonn-Köln (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 8: Bonn – Köln period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Köln (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Bonn	70.48	70.48	0	96.62	96.62	0
Köln	72.48	72.68	0.20	99.36	99.64	0.28
Sum of Laterals	1.76	1.96	0.21	2.41	2.69	0.28
I+SoL-O[1]	-0.24	-0.24	0.00	-0.33	-0.33	0.00
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Köln (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Bonn	70.48	70.48	0	96.62	96.62	0
Köln	72.23	72.44	0.21	99.03	99.31	0.28
Sum of Laterals	1.76	1.96	0.21	2.41	2.69	0.28
I+SoL-O[1]	0.00	0.00	0.00	0.00	0.00	0.00

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.4 Section 9: Köln – Düsseldorf

Table 5.4 shows the water balance result of running the SOBEK model with and without ground water exchange for section 9. It is clear that when the ground water module is switched off the calculated discharges at Düsseldorf are much lower. This means that there is a big net contribution of water from the ground water to the river. This net contribution occurs during low flow periods but also during intermediate flows.

Table 5.4. Overview water balance section 9: Köln-Düsseldorf (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 9: Köln – Düsseldorf period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Düsseldorf (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Köln	72.94	72.94	0	99.20	99.20	0
Düsseldorf	75.32	75.43	0.11	102.42	102.58	0.16
Sum of Laterals	1.08	1.44	0.36	1.47	1.96	0.49
I+SoL-O[1]	-1.29	-1.05	0.24	-1.76	-1.43	0.33
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Düsseldorf (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Köln	72.94	72.94	0	99.20	99.20	0
Düsseldorf	74.02	74.38	0.36	100.66	101.15	0.49
Sum of Laterals	1.08	1.44	0.36	1.47	1.96	0.49
I+SoL-O[1]	0.00	0.00	0.00	0.00	0.00	0.00

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.5 Section 10: Düsseldorf – Rurhort

Table 5.5 shows the water balance result of running the SOBEK model with and without ground water exchange for section 10. It is clear that when the ground water module is switched off the calculated discharge at Ruhrort is only slightly higher for the HBV set. This means that there is a small net loss for the HBV set of water from the river to the ground water.

Table 5.5. Overview water balance section 10: Düsseldorf-Ruhrort (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 10: Düsseldorf – Ruhrort period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Ruhrort (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Düsseldorf	73.53	73.53	0	94.07	94.07	0
Ruhrort	76.16	76.24	0.08	97.43	97.54	0.11
Sum of Laterals	2.63	2.82	0.19	3.36	3.60	0.24
I+SoL-O[1]	0.00	0.11	0.11	0.00	0.14	0.13
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Ruhrort (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Düsseldorf	73.53	73.53	0	94.07	94.07	0
Ruhrort	76.16	76.35	0.19	97.43	97.67	0.24
Sum of Laterals	2.63	2.82	0.19	3.36	3.60	0.24
I+SoL-O[1]	0.00	0.00	0.00	0.00	0.00	0.00

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.6 Section 11: Ruhrort – Wesel

Table 5.6 shows the water balance result of running the SOBEK model with and without ground water exchange for section 11. It is clear that when the ground water module is switched off the calculated discharges at Wesel are somewhat higher. This means that there is a small net loss from the river to the ground water when the ground water module is active in this section.

Table 5.6. Overview water balance section 11: Ruhrort-Wesel (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 11: Ruhrort – Wesel period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Wesel (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Ruhrort	78.17	78.17	0	98.34	98.34	0
Wesel	78.54	78.68	0.13	98.81	98.98	0.17
Sum of Laterals	0.55	0.60	0.05	0.69	0.76	0.07
I+SoL-O[1]	0.17	0.09	-0.08	0.21	0.11	-0.10
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Wesel (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Ruhrort	78.17	78.17	0	98.34	98.34	0
Wesel	78.71	78.77	0.05	99.03	99.09	0.07
Sum of Laterals	0.55	0.60	0.05	0.69	0.76	0.07
I+SoL-O[1]	0.00	0.00	0.00	0.00	0.00	0.00

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.7 Section 12: Wesel – Rees

Table 5.7 shows the water balance result of running the SOBEK model with and without ground water exchange for section 12. It is clear that when the ground water module is switched off the calculated discharges at Rees are lower. This means that there is a net loss of water from the ground water to the river.

Table 5.7. Overview water balance section 12: Wesel-Rees (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 12: Wesel – Rees period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Rees (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Wesel	79.49	79.49	0	99.73	99.73	0
Rees	81.20	81.36	0.15	101.88	102.07	0.19
Sum of Laterals	1.50	1.70	0.20	1.89	2.14	0.25
I+SoL-O[1]	-0.21	-0.17	0.05	-0.27	-0.21	0.06
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Rees (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Wesel	79.49	79.49	0	99.73	99.73	0
Rees	80.99	81.19	0.20	101.61	101.87	0.25
Sum of Laterals	1.50	1.70	0.20	1.89	2.14	0.25
I+SoL-O[1]	0.00	0.00	0.00	0.00	0.00	0.00

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.8 Section 13: Rees – Emmerich

Table 5.8 shows the water balance result of running the SOBEK model with and without ground water exchange for section 13. It is clear that when the ground water module is switched off the calculated discharges at Emmerich are lower. This means that there is a net contribution of water from the ground water to the river.

Table 5.8. Overview water balance section 13: Rees-Emmerich (in $Bm^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 13: Rees – Emmerich period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Emmerich (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Rees	79.70	79.70	0	101.21	101.21	0
Emmerich	79.77	79.96	0.19	101.29	101.53	0.24
Sum of Laterals	0.00	0.16	0.16	0.00	0.20	0.20
I+SoL-O[1]	-0.07	-0.09	-0.03	-0.08	-0.12	-0.04
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Emmerich (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Rees	79.70	79.70	0	101.21	101.21	0
Emmerich	79.70	79.89	0.19	101.21	101.45	0.24
Sum of Laterals	0.00	0.16	0.16	0.00	0.20	0.20
I+SoL-O[1]	0.00	-0.03	-0.03	0.00	-0.03	-0.04

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

5.9 Section 14: Emmerich – Lobith

Table 5.9 shows the water balance result of running the SOBEK model with and without ground water exchange for section 14. It is clear that when the ground water module is switched off the calculated discharges at Lobith are lower. This means that there is a net contribution of water from the ground water to the river.

Table 5.9. Overview water balance section 14: Emmerich-Lobith (in B$m^3/y=10^9\ m^3/y$) based on discharges derived from rating curves (QH) and two SOBEK simulations QcalQ (using the laterals , QcalL, from calibration set) and QhbvQ (using the laterals, QhbvL, from HBV set) with and without the groundwater.

Section 14: Emmerich – Lobith period: 1/11/1997 – 31/10/2004						
Water balance from SOBEK simulations with groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Lobith (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Emmerich	78.75	78.75	0	101.89	101.89	0
Lobith	78.80	78.93	0.13	101.95	102.13	0.17
Sum of Laterals	0.00	0.16	0.16	0.00	0.21	0.21
I+SoL-O[1]	-0.05	-0.02	0.03	-0.06	-0.03	0.04
Water balance from SOBEK calculations without groundwater						
	Average volume (Bm^3/y)			**Average volume relative to QH Lobith (%)**		
	QcalQ	**QhbvQ**	**Δ**	**QcalQ**	**QhbvQ**	**Δ**
Emmerich	78.75	78.75	0	101.89	101.89	0
Lobith	78.75	78.88	0.13	101.89	102.06	0.17
Sum of Laterals	0.00	0.16	0.16	0.00	0.21	0.21
I+SoL-O[1]	0.00	0.03	0.03	0.00	0.04	0.04

[1]I =inflow upstream, O=outflow downstream, SoL=Sum of Laterals.

6 Conclusions and Recommendations

6.1 Aggregated Overview

In this study a water balance was derived per section for the period 1/11/1997-31/10/2004 and for several selected events (chapter 4 and Appendix B and D). An overview is provided of all rating curves both measured and derived with the SOBEK model (Appendix A). An overview and a comparison of the laterals of the calibration set and the HBV set is also provided (Chapter 4 and Appendix C).

The overview of the water balance over all sections based upon the measurements (using QcalL that includes the effect of the hydrofactors) is given in Table 6.1. Table 6.1 has been constructed using the information in Chapter 4. From Table 6.1, it is observed that the negative water balance at Worms (section 2) is completely compensated for at Mainz (section 3) and the same is valid for Kaub (section 4) and Andernach (section 5/6). For the other stations this compensation does not occur and for these stations also big differences in the water balance can be observed. Table 6.1 also shows the comparison of the water balance per section with the difference between the two SOBEK simulations with the measurement at the downstream station (QcalQ-QH and QhbvQ-QH in %). It is to be expected that the water balance based upon the measurements of the different sections are comparable with the differences found between the SOBEK simulations and QH. It can be observed in Table 6.1 that this is the case. The biggest difference is found for section 9: Köln – Düsseldorf where the influence of the groundwater module present in the SOBEK models plays a big role as shown in Chapter 4 and 5.

Table 6.2 - Table 6.7 show the same information for several flood periods (1993, 1995, 1998, 2002 and 2003) and the low flow period of 2003. Because the timing of the flood periods of the different sections are not the same, the volumes (Bm^3) are converted to fluxes (m^3/s) using the length of the flood periods. As a consequence the cumulated water balance error is only indicative.

For the flood periods, it can be observed that the compensation, as seen in Table 6.1, for section 2 and 3 does not occur. However, for section 4 and 5/6 this compensation is still visible. The effect of the groundwater in the SOBEK models for the different flood peaks when compared to the water balance error is now also visible for section 10 and 11. However, for the low flow period of 2003 the effect of the groundwater module is again most notable for section 9. Table 6.2 - Table 6.7 further show that the indicative cumulated water balance error based upon the measurements is in the order of 500 - 900 m^3/s, which is substantial (5-9% of the discharge at Lobith).

Table 6.1. Water balance error per section (I+SoL-O) (Bm^3/y) based upon the measurements together with the cumulated water balance error (Bm^3/y) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulations (QcalQ and QhbvQ) and the measurement at the downstream station (QH, QH=100%) for the whole period 1/11/1997-31/10/2004. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Period	**1/11/1997 - 31/10/2004**				
Section	**Water balance error per section (I+SoL-O) (Bm^3/y)**	**cumulated water balance error (I+SoL-O) (Bm^3/y)**	**Water balance error (I+SoL-O) per section relative to downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau – Speyer	0.64	0.64	1.51	1.50	1.65
2: Speyer - Worms	-0.31	0.33	-0.65	-0.67	-0.02
3: Worms – Mainz	0.31	0.64	0.57	0.56	0.67
4: Mainz – Kaub	-1.71	-1.07	-2.95	-2.96	-2.67
5/6: Kaub – Ander.	1.71	0.64	2.44	2.26	2.87
7: Ander. – Bonn	-0.16	0.48	-0.23	-0.27	-0.03
8: Bonn – Köln	-0.71	-0.23	-0.97	-0.64	-0.36
9: Köln – Düssel.	0.49	0.26	0.66	2.42	2.58
10: Düssel. – Ruhrort	-2.01	-1.75	-2.57	-2.57	-2.46
11: Ruhrort – Wesel	-0.77	-2.52	-0.97	-1.19	-1.02
12: Wesel – Rees	1.29	-1.23	1.61	1.88	2.07
13: Rees – Emme.	0.95	-0.28	1.21	1.29	1.53
14: Emme. - Lobith	1.46	1.18	1.89	1.95	2.13

Table 6.2 . Water balance error per section (I+SoL-O) (m^3/s) based upon the measurements together with an indicative estimate of the cumulative water balance error (m^3/s) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulation (QcalQ) and the measurement at the downstream station (QH, QH=100%) for the flood period of December 1993. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Flood Period	**December 1993**				
Section	**Water balance error per section (I+SoL-O) (m^3/s)**	**Indicative estimate cumulated water balance error (I+SoL-O) (m^3/s)**	**Water balance error (I+SoL-O) per section relative to downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau - Speyer	-175	-175	-5.71	-3.29	
2: Speyer - Worms	380	205	8.51	9.04	
3: Worms - Mainz	210	415	3.88	5.29	
4: Mainz – Kaub	-477	-62	-7.48	-7.24	
5/6: Kaub – Ander.	464	402	4.42	4.96	
7: Ander. – Bonn	-32	370	-0.30	-0.46	
8: Bonn – Köln	85	455	0.79	0.61	
9: Köln – Düssel.	130	585	1.22	1.07	
10: Düssel. – Ruhrort	83	668	0.75	0.27	
11: Ruhrort – Wesel	-169	499	-1.51	-1.97	
12: Wesel – Rees	350	849	3.19	3.02	
13: Rees – Emme.	99	948	0.91	0.88	
14: Emme. – Lobith	-89	859	-0.82	-0.81	

Table 6.3 . Water balance error per section (I+SoL-O) (m^3/s) based upon the measurements together with an indicative estimate of the cumulative water balance error (m^3/s) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulation (QcalQ) and the measurement at the downstream station (QH, QH=100%) for the flood period of January 1995. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Flood Period	**January 1995**				
Section	**Water balance error per section (I+SoL-O) (m^3/s)**	**Indicative estimate cumulated water balance error (I+SoL-O) (m^3/s)**	**Water balance error (I+SoL-O) per section relative to QH downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau - Speyer	-222	-222	-4.28	-2.57	
2: Speyer - Worms	211	-11	5.03	5.22	
3: Worms - Mainz	58	47	0.97	2.01	
4: Mainz – Kaub	-256	-209	-3.83	-3.63	
5/6: Kaub – Ander.	469	260	4.58	4.68	
7: Ander. – Bonn	-222	38	-2.06	-2.29	
8: Bonn – Köln	173	211	1.57	1.31	
9: Köln – Düssel.	228	439	2.09	1.93	
10: Düssel. – Ruhrort	51	490	0.44	-0.03	
11: Ruhrort – Wesel	-162	328	-1.35	-1.77	
12: Wesel – Rees	384	712	3.23	2.89	
13: Rees – Emme.	-48	664	-0.40	-0.45	
14: Emme. – Lobith	-85	579	-0.71	-0.70	

Table 6.4. Water balance error per section (I+SoL-O) (m^3/s) based upon the measurements together with an indicative estimate of the cumulative water balance error (m^3/s) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulations (QcalQ and QhbvQ) and the measurement at the downstream station (QH, QH=100%) for the flood period of November 1998. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Flood period	**November 1998**				
Section	**Water balance error per section (I+SoL-O) (m^3/s)**	**Indicative estimate cumulated water balance error (I+SoL-O) (m^3/s)**	**Water balance error (I+SoL-O) per section relative to QH downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau - Speyer	69	69	2.43	2.89	2.63
2: Speyer - Worms	77	146	2.31	2.26	2.71
3: Worms - Mainz	52	198	1.05	1.79	2.47
4: Mainz – Kaub	-133	65	-2.48	-2.43	-1.58
5/6: Kaub – Ander.	363	428	4.39	4.51	5.52
7: Ander. – Bonn	-184	244	-2.06	-2.32	-2.00
8: Bonn – Köln	65	309	0.71	0.50	0.92
9: Köln – Düssel.	155	464	1.32	1.15	1.49
10: Düssel. – Ruhrort	169	633	1.80	1.07	1.36
11: Ruhrort – Wesel	-472	162	-4.79	-5.34	-5.21
12: Wesel – Rees	406	567	4.18	3.78	4.10
13: Rees – Emme.	181	748	1.87	1.70	2.09
14: Emme. – Lobith	120	867	1.26	1.09	1.36

Table 6.5. Water balance error per section (I+SoL-O) (m^3/s) based upon the measurements together with an indicative estimate of the cumulative water balance error (m^3/s) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulations (QcalQ and QhbvQ) and the measurement at the downstream station (QH, QH=100%) for the flood period of November 2002. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Flood period	November 2002				
Section	**Water balance error per section (I+SoL-O) (m^3/s)**	**Indicative estimate cumulated water balance error (I+SoL-O) (m^3/s)**	**Water balance error (I+SoL-O) per section relative to QH downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau - Speyer	-36	-36	-1.13	-0.39	-0.29
2: Speyer - Worms	169	133	4.08	4.80	6.97
3: Worms - Mainz	310	444	1.32	1.15	1.49
4: Mainz – Kaub	-235	209	-4.44	-4.23	-3.83
5/6: Kaub – Ander.	206	415	2.84	3.21	4.12
7: Ander. – Bonn	-38	376	-0.53	-0.83	-0.38
8: Bonn – Köln	37	413	0.48	0.23	0.59
9: Köln – Düssel.	88	501	1.17	1.14	1.53
10: Düssel. – Ruhrort	55	557	0.69	-0.04	0.23
11: Ruhrort – Wesel	-307	250	-3.67	-4.20	-4.10
12: Wesel – Rees	271	521	3.25	2.94	3.18
13: Rees – Emme.	-32	488	-0.39	-0.81	-0.71
14: Emme. – Lobith	266	755	3.29	3.13	3.23

Table 6.6. Water balance error per section (I+SoL-O) (m^3/s) based upon the measurements together with an indicative estimate of the cumulative water balance error (m^3/s) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulations (QcalQ and QhbvQ) and the measurement at the downstream station (QH, QH=100%) for the flood period of January 2003. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Flood period	**January 2003**				
Section	**Water balance error per section (I+SoL-O) (m^3/s)**	**Indicative estimate cumulated water balance error (I+SoL-O) (m^3/s)**	**Water balance error (I+SoL-O) per section relative to QH downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau - Speyer	-65	-65	-2.51	-1.96	-0.40
2: Speyer - Worms	-55	-120	-1.61	-1.94	-0.53
3: Worms - Mainz	200	80	3.97	3.76	3.77
4: Mainz – Kaub	-198	-118	-3.56	-3.82	-3.11
5/6: Kaub – Ander.	248	130	2.98	2.99	5.31
7: Ander. – Bonn	-205	-75	-2.39	-2.72	-2.44
8: Bonn – Köln	69	-6	0.76	0.45	0.81
9: Köln – Düssel.	119	113	1.32	1.15	1.49
10: Düssel. – Ruhrort	1	114	0.01	-0.69	-0.54
11: Ruhrort – Wesel	-573	-459	-5.67	-6.26	-6.17
12: Wesel – Rees	629	170	6.40	5.95	6.15
13: Rees – Emme.	118	288	1.21	1.00	1.23
14: Emme. – Lobith	336	624	3.55	3.33	3.49

Table 6.7. Water balance error per section (I+SoL-O) (m^3/s) based upon the measurements together with an indicative estimate of the cumulative water balance error (m^3/s) based upon the measurements, the water balance error (%) per section relative to the downstream station based upon the measurements and the difference (%) between the SOBEK simulations (QcalQ and QhbvQ) and the measurement at the downstream station (QH, QH=100%) for the low flow period of September-October 2003. Note that I is inflow upstream, SoL is sum of lateral inflows, and O is outflow downstream.

Low flow period	**September-October 2003**				
Section	**Water balance error per section (I+SoL-O) (m^3/s)**	**Indicative estimate cumulated water balance error (I+SoL-O) (m^3/s)**	**Water balance error (I+SoL-O) per section relative to QH downstream station (%)**	**Difference between QH and QcalQ per section relative to QH downstream station (%)**	**Difference between QH and QhbvQ per section relative to QH downstream station (%)**
1: Maxau - Speyer	0	0	0.01	1.17	1.73
2: Speyer - Worms	58	58	6.79	6.45	6.28
3: Worms - Mainz	-8	50	-0.78	-1.44	-1.29
4: Mainz – Kaub	57	107	5.81	5.33	5.69
5/6: Kaub – Ander.	25	132	2.23	2.77	3.20
7: Ander. – Bonn	-6	126	-0.53	1.03	1.21
8: Bonn – Köln	0	126	0.01	2.76	2.92
9: Köln – Düssel.	-25	101	-2.02	7.11	6.98
10: Düssel. – Ruhrort	-119	-18	-8.31	-6.70	-6.90
11: Ruhrort – Wesel	17	-1	1.19	2.00	2.38
12: Wesel – Rees	-29	-30	-1.86	-0.54	-0.26
13: Rees – Emme.	107	77	7.73	8.47	8.89
14: Emme. – Lobith	-33	44	-2.26	-1.95	-1.68

For all sections, it is clear that the two SOBEK simulations are very similar and deviate both more from the measured discharge than from each other. This is further illustrated by Figure 6.1 where the results of all 14 models (see Table 3.1) as used in Chapter 4 are aggregated as a function of the river kilometres. From Figure 6.1, it is clear that the two SOBEK simulations are very close together for each section. The clear bend visible in the Figure 6.1 from kilometre 837 (Rees) onwards is caused by the measured discharges used as upper boundary of the SOBEK models. The reason that the two SOBEK simulations are very close is also caused by the fact that in the calibration set and the HBV set only the small laterals inflows differ and that the larger tributaries (Neckar, Main, Mosel, Lahn, Sieg, Ruhr, Lippe) are the same (derived from measured data).

Figure 6.2 shows the average volumes at each location taken from the simulation obtained with the model for section 1 Maxau-Rhine branches (see Table 3.1). This figure makes clear that differences in lateral inflows accumulate during the transport of water from upstream to downstream (increasing difference between blue and red lines in downstream direction). This is further illustrated by Table 6.8 that gives an aggregated overview over the sections of the differences between the two SOBEK simulations and between the two sets of lateral inflows.

From Table 6.8, it can also be observed that the ground water starts playing a role in the section Köln – Düsseldorf and thereafter. The difference between the SOBEK simulations with the calibration set and HBV set (4th column) deviates from the difference between the direct comparison of the calibration set and HBV set (3rd column). This deviation can only be caused by another source or sink of water in the model and in this case that is it is the groundwater module.
Section 9 is indeed the section with the strongest ground water interaction as shown in Chapter 4.9 and Chapter 5. Ground water exchange plays a major role as shown in the cumulative effect of errors as shown in Figure 6.2. From this figure, it can be observed that the effect of the ground water exchange is in the same order of the differences present in the laterals of the HBV and calibration set. It is also visible that section 9 between Köln (688 River km) and Düsseldorf (744 River km) is the most important section for the groundwater exchange.

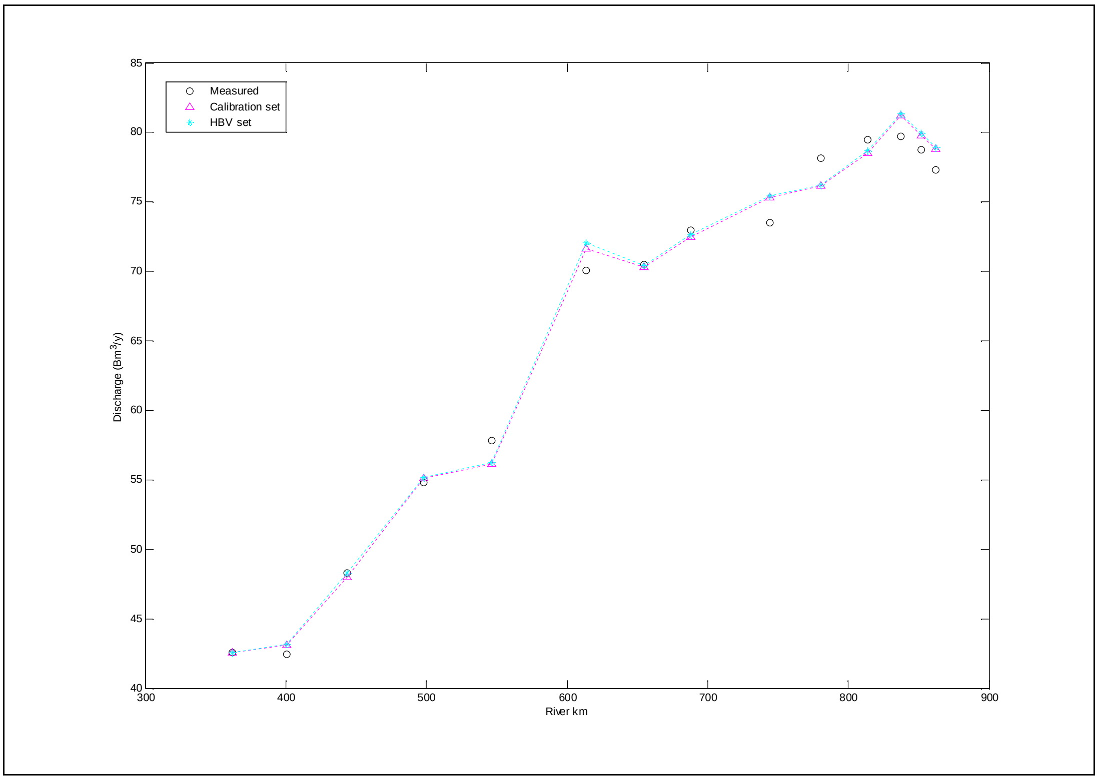

Figure 6.1. Overview of waterbalance results using model 1-14 (see Table 3.1) for each key measurement station along the Rhine.

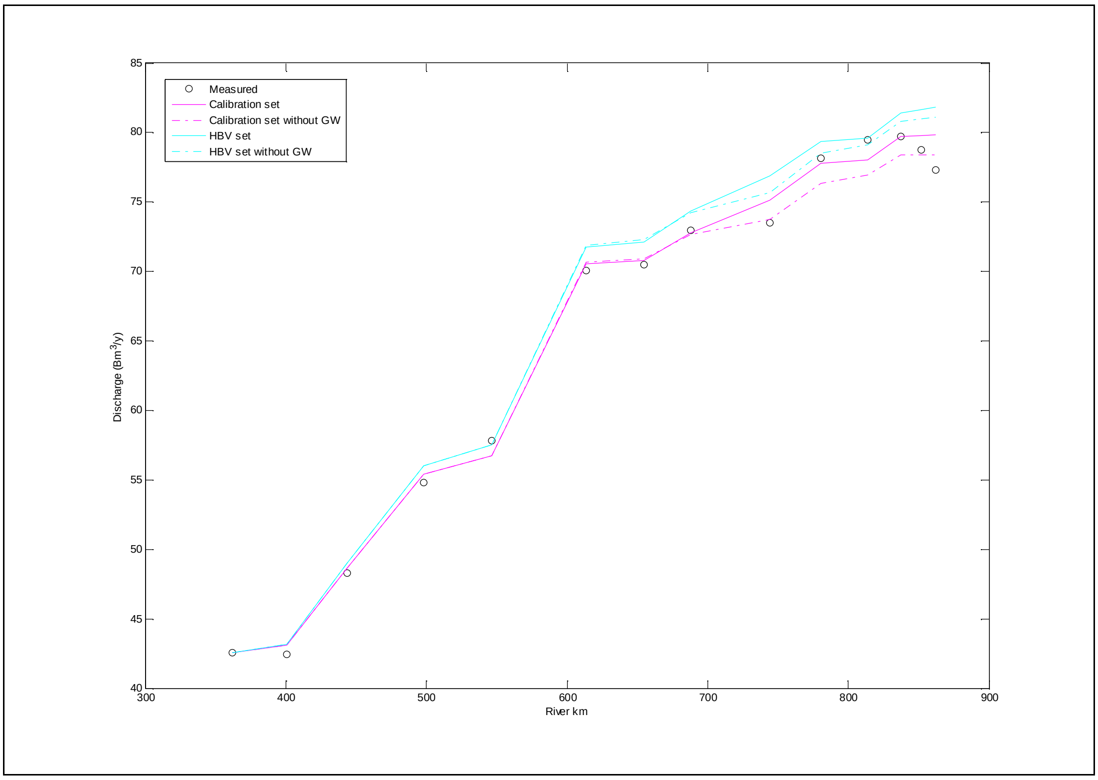

Figure 6.2. Overview of waterbalance results using model 1 (see Table 3.1) for each key measurement station along the Rhine.

Table 6.8. Overview of differences between the Sum of Laterals and the difference between the SOBEK simulations using the calibration set and HBV set per section, together with the cumulative difference between the SOBEK simulations using both sets of laterals all for the period 1/11/1997 – 31/10/2004**.**

Measurement station	**River Km**	**Differences calibration and HBV set (Bm^3/y)**	**Difference between calibration and HBV set as simulated with SOBEK (Bm^3/y)**	**Cumulative Difference between calibration and HBV set simulated with SOBEK (Bm^3/y)**
Maxau	362.23	-	-	-
Speyer	400.61	-0.06	-0.06	-0.06
Worms	443.37	-0.31	-0.31	-0.38
Mainz	498.27	-0.06	-0.06	-0.43
Kaub	546.23	-0.17	-0.17	-0.60
Andernach	613.78	-0.44	-0.43	-1.04
Bonn	654.78	-0.17	-0.17	-1.20
Koln	688.00	-0.21	-0.20	-1.41
Dusseldorf	744.20	-0.36	-0.11	-1.52
Ruhrort	780.80	-0.19	-0.08	-1.61
Wesel	814.00	-0.05	-0.13	-1.74
Rees	837.38	-0.20	-0.15	-1.89
Emmerich	851.96	-0.16	-0.19	-2.08
Lobith	862.22	-0.16	-0.13	-2.21

6.2 Overall Conclusions and Recommendations

The water balance analysis per section has shown that there are some sections, where the water balance is negative (this means at the downstream station more water is measured than could be expected from the input at the upstream station and the laterals) and others, where it is positive. In some cases errors in the water balance are totally compensated by the water balance of neighbouring sections, in other cases only partly.

The largest errors are probably present in the derived discharges of the main river. Strong deviations (see for instance Figure 4.6) exist between rating curves based on measurements and rating curves derived with the SOBEK model. This is partly caused by the fact that the rating curves do not include hysteresis effects. Besides the hysteresis effect, backwater effects of lateral inflows can influence the rating curve as well (see SOBEK rating curve Bonn in Appendix A). To investigate the rating curves of the key measurement stations the original data used for deriving the rating curves must be investigated. Furthermore, the calibration of the model versus the shifts and changes of the rating curves must be compared and investigated. Also the effect of the hysteresis which can conveniently be taken into account via a Jones correction should be investigated. Hysteresis will probably not affect the overall water balance but will have a significant effect on the fit to the measured discharges. This may be important for operational forecasting as the measured discharges may be used for state updating of the SOBEK model via Ensemble Kalman Filtering (see for instance Warmink, 2007).

There are differences between the lateral discharges from the calibration set and the HBV set. Between Andernach and Lobith this is mainly caused by the fact that there are no data available for the several diffuse inflows (Zwischeneinzugsgebiete) in the calibration set. The difference between the sum of laterals of the calibration set and the HBV set is similar for each section. However, the difference between individual lateral inflows of the two sets can be as large as 216%. The accumulated difference at Lobith between the calibration and HBV set when running the model for Maxau-Lobith is about 2 Bm^3/y (which is about 63 m^3/s). This difference is already occurring even when the main tributaries are not considered in the comparison, because they are the same for the calibration set and HBV set.

Currently, it is impossible to say which lateral from which set is good or bad. This is due to the fact that the SOBEK model deviates too much from the discharge derived from the rating curve and stage measurements. However, it is clear that strong deviations exist between the calibration and HBV set. This difference should be further investigated to make ascertain that the SOBEK model is fed with the right lateral inflow when using the model for investigations concerning the Rhine basin or during operational forecasting of floods and droughts for the Rhine basin.

In the current configuration groundwater is a large net contributor to the discharge of the Rhine. This net contribution happens especially during low flow periods and is probably one of the causes of the overestimation of the discharge during low flows (see also Warmink, 2007). Overall the effect of the ground water exchange is of the same order of magnitude as the difference between the calibration and HBV set. The effect of the ground water module on the model outcome should be further investigated.

6.3 Sensitivity Analysis Phase 3

In Phase 3, a sensitivity analysis into the sources of error will be carried out. As is clear from the conclusions of Phase 2 not all sources can be investigated in Phase 3, because they fall out of the scope of this study. The points below are suggested to be carried out in the analysis of Phase 3:

- Investigation into the difference between the rating curves derived with the SOBEK model and the rating curve used for stage transformation for all key measurement stations as was done for Worms already in Phase 2;

- Investigation into the effect of hysteresis on the water balance and on the comparison of the derived and simulated discharge for a selected section and one or two flood periods;

- Further investigation into the laterals of one section (for instance Speyer-Worms) that contribute most to the difference between the laterals of the HBV set and the calibration set (effect of the hydrofactors during a flood period and low flow period);

- Investigation into the lateral inflows of the large tributaries calibrations set vs the HBV-96 results as already has been done in phase 2 for the smaller tributaries and estimating the influence on the waterbalans;

- Investigation into the effect of the hydrofactors on the water balance purely based upon the measurements (comparison with Table 6.1);

- Further investigation into the effect of the SOBEK ground water module for several floods and a low flow period.

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