Prepared for:

Rijkswaterstaat RIZA

Effect of climate change on the rivers Rhine and Meuse

Applying the KNMI 2006 scenarios using the HBV model

Report

December, 2006

WL | delft hydraulics

Q4286

Prepared for:

Rijkswaterstaat RIZA

Effect of climate change on the rivers Rhine and Meuse

Applying the KNMI 2006 scenarios using the HBV model

Aline te Linde

Report

December, 2006

WL | delft hydraulics

CLIENT: Rijkswaterstaat RIZA

TITLE: Effects of climate change on the rivers Rhine and Meuse

ABSTRACT:

On 30 May 2006, the KNMI presented four new climate scenarios for the Netherlands which are referred to as KNMI'06 scenarios. These KNMI'06 scenarios will serve as the national standard in adaptation policies in the Netherlands for the coming years. It is in the interest of Dutch water managers, to have an idea of the impact of climate change on the discharge regime of the rivers Rhine and Meuse.

Van Deursen (2006) used the KNMI'06 climate scenarios to assess the effects of climate change on the discharge of the rivers Rhine and Meuse using the grid-based water balance models RhineFlow and MeuseFlow. To do this, the KNMI'06 scenarios were projected on the entire basin of the Rhine and Meuse.

In the current project the conceptual hydrological HBV models for both the Rhine and Meuse basins were used to assess the effects of climate change on the discharge, also projecting the KNMI'06 climate scenarios on the entire basin of the Rhine and Meuse. In this report, the predicted changes in discharge resulting from the new KNMI'06 scenarios are compared with the predicted changes resulting from the WB21 scenarios dating from the year 2000. Furthermore, the outcomes of RhineFlow and MeuseFlow and the HBV models are compared for the KNMI'06 scenarios. These comparisons are made at Lobith, Kaub and Rheinfelden in the Rhine basin and at Borgharen in the Meuse basin.

REFERENCES: ATB 10027559 WRR

VER	AUTHOR		DATE	REMARKS	REVIEW		APPROVED BY	
1.0	A.H. te Linde		December 11, 2006		J.C.J. Kwadijk		C.A. Bons	

PROJECT NUMBER:	Q4286
KEYWORDS:	Climate change, hydrology, modelling, Rhinebasin, Meuse basin
NUMBER OF PAGES:	
CONFIDENTIAL:	☒ YES, until January 2010 ☐ NO
STATUS:	☐ PRELIMINARY ☐ DRAFT ☒ FINAL

Contents

Appendix

1 Introduction

It is in the interest of Dutch water managers, to have an idea of the impact of climate change on the discharge regime of the rivers Rhine and Meuse.

World-wide climate change scenarios as being produced by IPCC mainly provide numbers for warming and sea-level rise at the global or continental scale, but do not provide sufficient information to determine the effects of climate change in a smaller area like the Rhine and Meuse river basins. The KNMI[1] therefore produces regional climate scenarios for the Netherlands, based on the global IPCC scenarios.

The KNMI presented in 1995 for the first time representative time series for future scenarios that could be used in impact studies that are relevant for the Netherlands, in particular in the area of water management. In 2000 under the framework of ‘Commissie Waterbeheer 21e eeuw (WB21)’ (Tielrooij *et al.*, 2000) a more formal set of climate scenarios for the Netherlands was produced. On 30 May 2006, the KNMI presented four new climate scenarios for the Netherlands which are referred to as KNMI'06 scenarios (Van den Hurk *et al.*, 2006). These KNMI’06 scenarios will serve as the national standard in adaptation policies in the Netherlands for the coming years.

Until now, the grid-based water balance models RhineFlow and MeuseFlow have been used to determine the impact of climate on the discharge of the rivers Rhine and Meuse (Buishand & Lenderink, 2003; Van Deursen, 2002; Tielrooij *et al.*, 2000). Flood forecasting in the Rhine and Meuse basins is done using the hydrological HBV model (Bergström, 1976) combined with the Sobek hydraulic model (WL | Delft Hydraulics, 2001). This model suite is also used tot assess the design discharges for the Rhine branches in the Netherlands. For this last application the precipitation is provided by a stochastic weather generator (Beersma *et al.*, 2001; Bergström, 1996; Eberle, 2005).

Van Deursen (2006) assessed the effects of climate change on the discharge of the rivers Rhine and Meuse using the models RhineFlow and MeuseFlow. He projected the KNMI’06 scenarios on the entire basin of the Rhine and Meuse.

The current project aims performing a comparable analysis, now using the HBV models for the Rhine and Meuse, instead of RhineFlow and MeuseFlow. The predicted changes in discharge resulting from the new KNMI’06 scenarios will be compared with the predicted changes resulting from the WB21 scenarios dating from the year 2000. Furthermore, the outcomes of RhineFlow and MeuseFlow and the HBV models will be compared for the KNMI’06 scenarios. These comparisons will be made at Lobith, Kaub and Rheinfelden in the Rhine basin and at Borgharen in the Meuse basin.

1 *KNMI is the Royal Dutch Meteorological Institute.*

The National Institute for Inland Water Management and Waste Water Treatment (Rijkswaterstaat/RIZA), which is part of the Ministry of Transport, Public Works and Water Management, commissioned WL | Delft Hydraulics to execute this project (ATB 10027559 WRR).

Chapter 2 describes the methods used to perform the data transformation and the model runs. In Chapter 3 the modeling results are discussed for a selection of discharge stations. Finally, in Chapter 4 conclusions are drawn. Appendix A contains all modeling results in graphs.

2 Methods

2.1 Introduction

To assess the effects of climate change on the discharge of the rivers Rhine and Meuse, the following procedure was applied:

1. The HBV model requires air temperature data, precipitation data and mean monthly values of potential evaporation. In the current project daily values of historical precipitation, temperature and evaporation values will be used for the period 1961 to 1995 for the Rhine basin and the period 1967 to 1998 for the Meuse basin.
2. These historical series are transformed to create four KNMI and two WB21 scenarios of future precipitation, temperature and evaporation were used as input of the HBV model. The different climate scenarios are constructed by applying simple transformation rules to observed temperature, precipitation and evaporation, also referred to as the delta change approach (Lenderink *et al.*, 2004).
3. To simulate the discharge for all climate scenarios, the hydrological model HBV (Bergström, 1976) is used, both for the Meuse basin and the Rhine basin. This results in a historical discharge series and six scenario discharge series for all climate scenarios at Lobith, Kaub, Rheinfelden and Borgharen.

2.2 Data transformation

2.2.1 Available data

RIZA provided the following data:

- Interpolated time series of measured data: daily values of precipitation and temperature for all HBV sub basins. For the Rhine for the period of 1961 – 1995 and for the Meuse for the period of 1967 – 1998.
- The average decade values (10 or 11 days) describing the changes in precipitation, temperature and evaporation for the following climate scenarios:
    - WB21 scenarios: +1 ºC and +2 ºC.
    - KNMI'06 scenarios: G, G plus, W and W plus.
- The results of the RhineFlow and MeuseFlow scenario runs, performed by Van Deursen (2006).

2.2.2 Climate scenarios

The KNMI presented in 1995 for the first time representative time series for future scenarios that could be used in impact studies that are relevant for the Netherlands, in particular in the area of water management.

In 2000 under the framework of ‘Commissie Waterbeheer 21^{e} eeuw (WB21)’ (Tielrooij *et al.*, 2000) a more formal set of climate scenarios for the Netherlands was produced. These scenarios are referred to as WB21 scenarios and based on the IPCC projections of a mean change in temperature, it contains three scenarios for 2050 of +0.5, +1 ºC and +2 ºC. In the current project only the +1 ºC and +2 ºC are considered, because only these two IPCC projections are used in the new KNMI’06 scenarios.

On 30 May 2006, the KNMI presented four new climate scenarios for the Netherlands which are referred to as KNMI'06 scenarios (Van den Hurk *et al.*, 2006). These KNMI’06 scenarios will serve as the national standard in adaptation policies in the Netherlands for the coming years. The climate change scenarios for the Netherlands for 2050 have been constructed by KNMI using a range of data sources and techniques. Temperature and circulation were used as steering parameters for four different scenarios for temperature, precipitation and potential evaporation.

General Circulation Model (GCM) simulations show changes in the strength of seasonal mean western component of the large scale atmospheric flow in the area around the Netherlands. That is why besides temperature the circulation is used as steering parameter, which has a great impact on the number of precipitation days, the seasonal mean precipitation, and the intensity of the 10-year precipitation event. Also potential evaporation is affected greatly by the assumed circulation change. The values chosen for global temperature increase and atmospheric circulation change as steering parameters to discriminate the four scenarios for the Netherlands are summarized in Table 1.

Table 1: Values for the steering parameters used to identify the four KNMI’06 climate scenarios for 2050 relative to 1990.

Scenario	**Global Temperature Increase**	**Change of atmospheric circulation**
G	+1 ºC	weak
G+	+1 ºC	strong
W	+2 ºC	weak
W+	+2 ºC	strong

For an elaborate description of the motivation and construction of the new climate change scenarios 2006 for the Netherlands, see the scientific report published by KNMI (Van den Hurk *et al.*, 2006).

KNMI produced the following decade values of predicted changes in precipitation and temperature for all scenarios, which were used in this project.

Table 2: Change in precipitation (%)

	KNMI 06				WB21	
decade	G	G+	W	W+	+1 gr C	+2 gr C
1	3.57	6.97	7.13	13.93	10.25	20.50
2	3.70	7.50	7.40	15.00	9.75	19.50
3	3.73	7.57	7.47	15.13	9.00	18.00
4	3.77	7.63	7.53	15.27	8.25	16.50
5	3.80	7.70	7.60	15.40	7.75	15.50
6	3.62	7.63	7.23	15.27	7.25	14.50
7	3.43	7.57	6.87	15.13	6.75	13.50
8	3.25	7.50	6.50	15.00	6.25	12.50
9	3.17	6.42	6.33	12.83	5.50	11.00
10	3.08	5.33	6.17	10.67	5.00	10.00
11	3.00	4.25	6.00	8.50	3.50	7.00
12	2.92	2.17	5.83	4.33	2.00	4.00
13	2.83	0.08	5.67	0.17	0.50	1.00
14	2.75	-2.00	5.50	-4.00	0.25	0.50
15	2.78	-3.83	5.57	-7.67	0.00	0.00
16	2.82	-5.67	5.63	-11.33	0.00	0.00
17	2.85	-7.50	5.70	-15.00	-0.50	-1.00
18	2.82	-8.67	5.63	-17.33	-1.00	-2.00
19	2.78	-9.83	5.57	-19.67	-1.50	-3.00
20	2.75	-11.00	5.50	-22.00	-2.00	-4.00
21	2.73	-11.00	5.47	-22.00	-2.75	-5.50
22	2.72	-11.00	5.43	-22.00	-3.25	-6.50
23	2.70	-11.00	5.40	-22.00	-3.75	-7.50
24	2.77	-10.17	5.53	-20.33	-4.25	-8.50
25	2.83	-9.33	5.67	-18.67	-4.75	-9.50
26	2.90	-8.50	5.80	-17.00	-2.00	-4.00
27	2.90	-6.58	5.80	-13.17	0.75	1.50
28	2.90	-4.67	5.80	-9.33	3.50	7.00
29	2.90	-2.75	5.80	-5.50	2.50	5.00
30	2.93	-1.17	5.87	-2.33	1.75	3.50
31	2.97	0.42	5.93	0.83	0.75	1.50
32	3.00	2.00	6.00	4.00	2.75	5.50
33	3.17	3.57	6.33	7.13	4.75	9.50
34	3.33	5.13	6.67	10.27	7.00	14.00
35	3.50	6.70	7.00	13.40	8.00	16.00
36	3.57	6.97	7.13	13.93	9.25	18.50

Table 3: Temperature change (degr Celcius)

	KNMI 06				WB21	
decade	G	G+	W	W+	+1 gr C	+2 gr C
1	0.88	1.18	1.77	2.36	1.45	2.90
2	0.93	1.13	1.85	2.26	1.50	3.00
3	0.91	1.12	1.83	2.24	1.53	3.05
4	0.90	1.11	1.81	2.22	1.58	3.15
5	0.89	1.10	1.78	2.20	1.48	2.95
6	0.89	1.14	1.78	2.27	1.38	2.75
7	0.89	1.17	1.77	2.35	1.28	2.55
8	0.88	1.21	1.77	2.42	1.20	2.40
9	0.88	1.23	1.76	2.46	1.10	2.20
10	0.88	1.25	1.76	2.50	1.03	2.05
11	0.88	1.27	1.75	2.54	0.98	1.95
12	0.87	1.29	1.74	2.58	0.90	1.80
13	0.87	1.31	1.74	2.63	0.88	1.75
14	0.87	1.34	1.73	2.67	0.80	1.60
15	0.86	1.35	1.73	2.69	0.78	1.55
16	0.86	1.36	1.72	2.72	0.75	1.50
17	0.86	1.37	1.72	2.74	0.73	1.45
18	0.86	1.38	1.71	2.76	0.70	1.40
19	0.85	1.39	1.71	2.78	0.70	1.40
20	0.85	1.40	1.70	2.80	0.80	1.60
21	0.85	1.42	1.71	2.83	0.93	1.85
22	0.86	1.43	1.71	2.87	1.05	2.10
23	0.86	1.45	1.72	2.90	1.05	2.10
24	0.86	1.41	1.72	2.82	1.08	2.15
25	0.86	1.37	1.73	2.75	1.08	2.15
26	0.87	1.34	1.73	2.67	1.05	2.10
27	0.87	1.31	1.74	2.63	1.00	2.00
28	0.87	1.29	1.74	2.58	0.95	1.90
29	0.88	1.27	1.75	2.54	0.88	1.75
30	0.87	1.25	1.74	2.51	0.78	1.55
31	0.87	1.24	1.74	2.47	0.68	1.35
32	0.87	1.22	1.73	2.44	0.80	1.60
33	0.86	1.21	1.73	2.42	0.93	1.85
34	0.86	1.20	1.72	2.40	1.03	2.05
35	0.86	1.19	1.72	2.38	1.18	2.35
36	0.88	1.17	1.76	2.34	1.33	2.65

Table 4: Change in evaporation (%)

	KNMI 06				WB21	
month	G	G+	W	W+	+1 gr C	+2 gr C
1	0.00	0.00	0.00	0.00	8.15	16.30
2	0.22	0.17	0.44	0.33	5.30	10.60
3	1.92	1.50	3.83	3.00	4.55	9.10
4	3.17	3.00	6.33	6.00	4.00	8.00
5	3.69	4.63	7.39	9.26	3.45	6.90
6	3.78	6.91	7.56	13.82	3.25	6.50
7	4.00	7.65	8.00	15.30	3.25	6.50
8	4.04	7.92	8.09	15.84	3.65	7.30
9	2.76	6.59	5.51	13.19	4.25	8.50
10	2.00	5.01	4.00	10.02	5.55	11.10
11	1.27	3.28	2.54	6.56	6.40	12.80
12	0.25	0.20	0.50	0.40	12.05	24.10

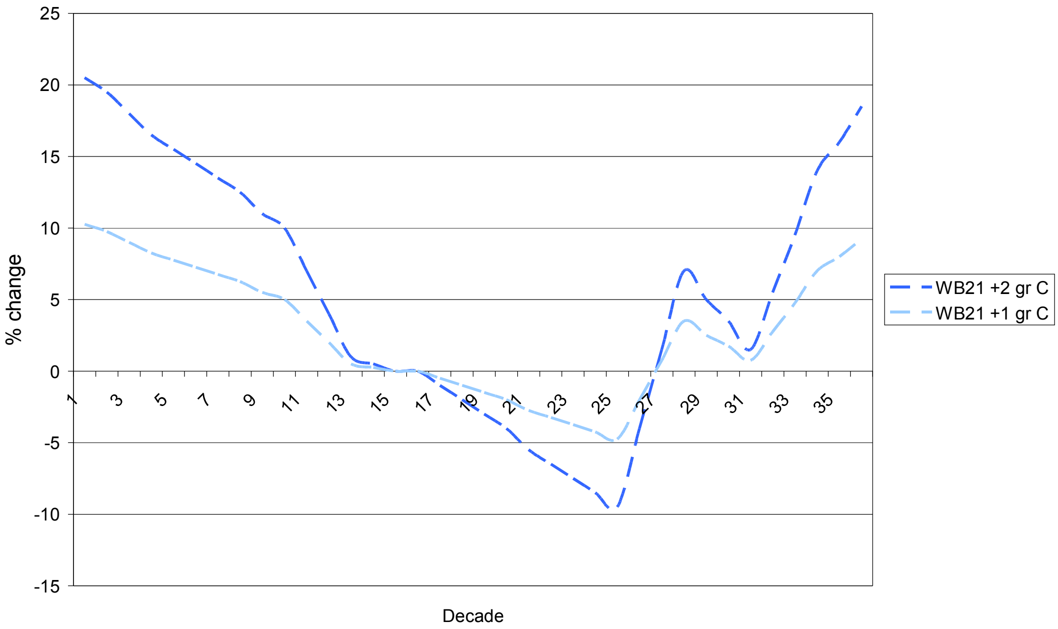

Figure 1: Change in precipitation (%), WB21 +1 ºC and WB21 +2 ºC

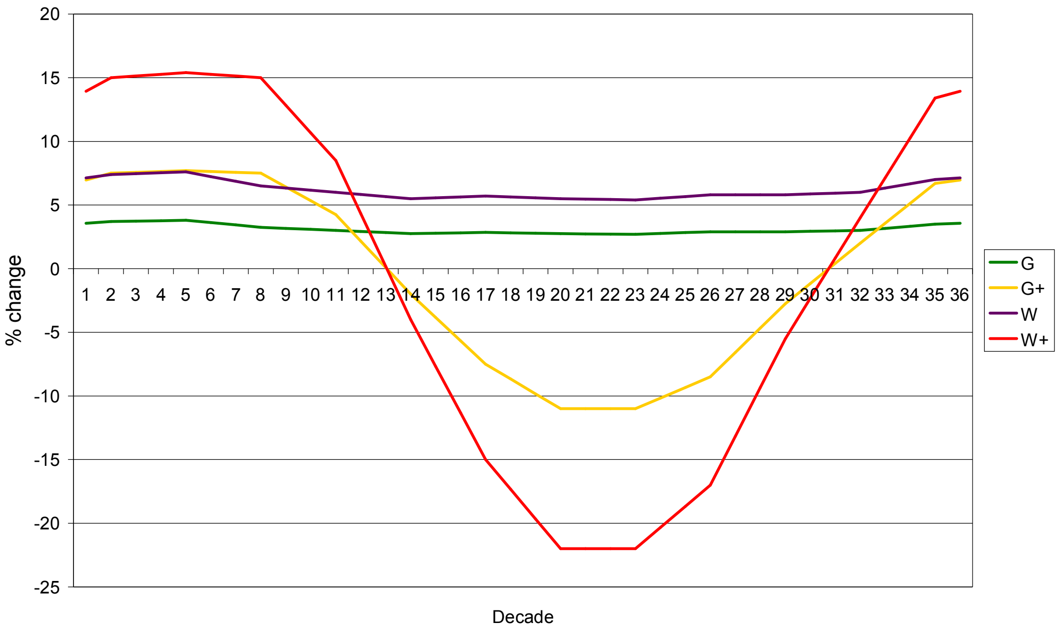

Figure 2: Change in precipitation (%), KNMI'06 G, G+, W, W+.

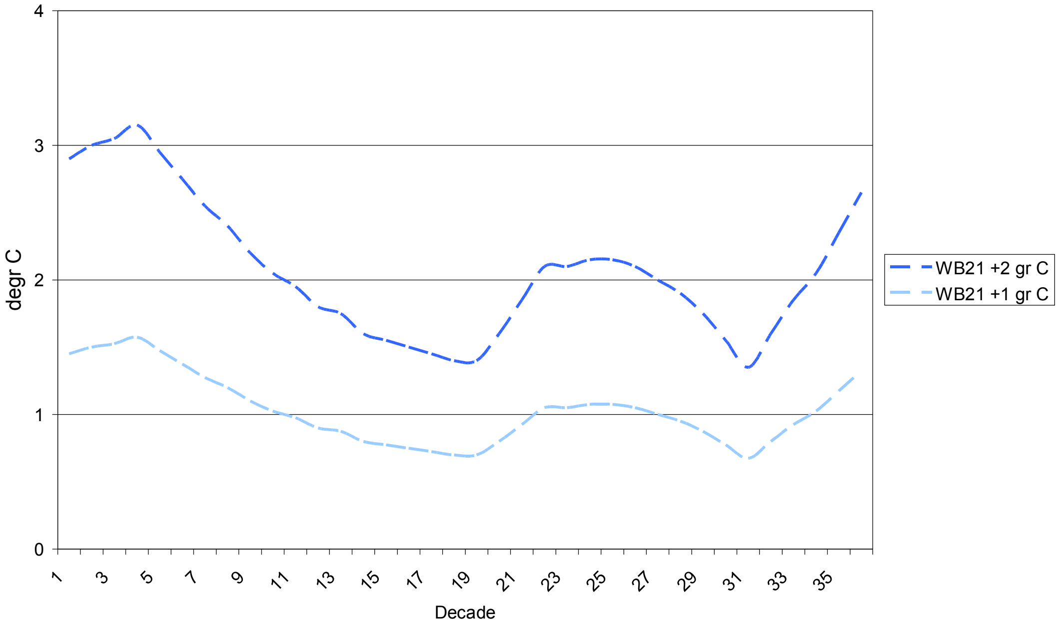

Figure 3: Temperature change (degr Celcius), WB21 +1 ºC and WB21 +2 ºC

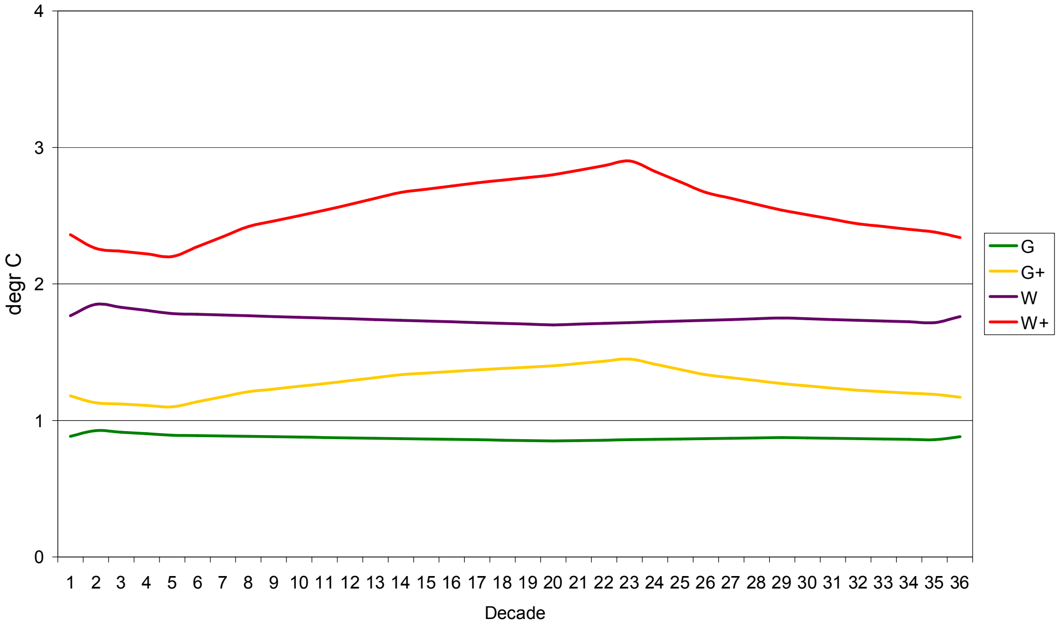

Figure 4: Temperature change (degr Celcius), KNMI'06 G, G+, W, W+.

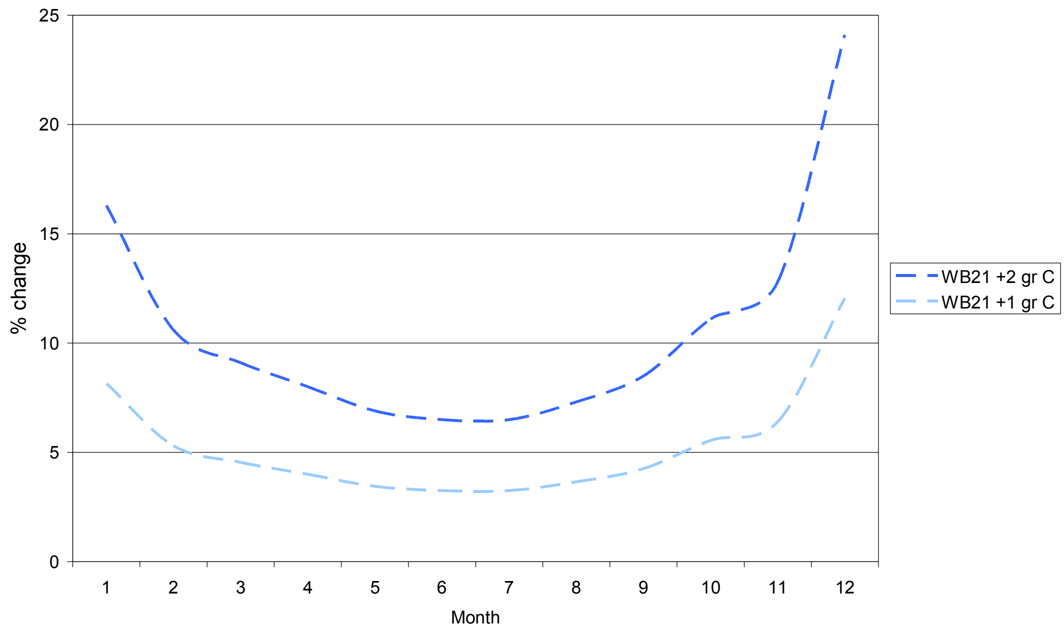

Figure 5: Evaporation change (%), WB21 +1 ºC and WB21 +2 ºC

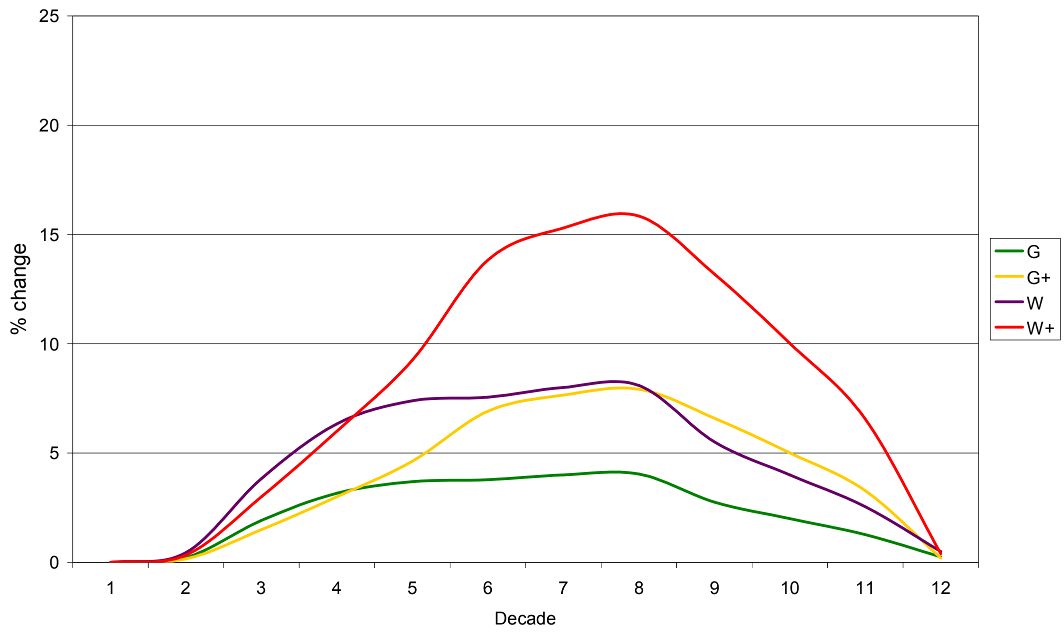

Figure 6: Evaporation change (%), KNMI'06 G, G+, W, W+.

2.2.3 Delta approach

For comparison reasons, the same method for data transformation as applied by Van Deursen (2006) was applied in this study. Four KNMI and two WB21 scenarios of future precipitation, temperature and evaporation were used as input of the HBV model. These different climate scenarios were constructed by applying simple transformation rules to observed temperature and precipitation, also referred to as the delta change approach (Lenderink *et al.*, 2004). A simple delta approach for temperature just adds an expected temperature increase to the observed temperature record to obtain a future temperature series. Precipitation was perturbed by a fraction. These rules leave the present day variance of temperature and the coefficient of variation of precipitation unchanged. Also, changes in the number of precipitation days and potential changes in the correlation between different variables are not considered. Furthermore, the transformation was applied for the whole Rhine basin, not taking into account possible geographical differences.

For every decade, the scenario time series is given by:

$$
\begin{aligned}
T_{scen}(t) &= T_{his}(t) + \left(\overline{T}_{scen} - \overline{T}_{his}\right) \\
P_{scen}(t) &= P_{his}(t) \times \left(\frac{\overline{P}_{scen}}{\overline{P}_{his}}\right)
\end{aligned}
\tag{1.1}
$$

where T_{scen} is the scenario temperature in ºC, T_{his} the historical temperature in ºC, P_{scen} the scenario precipitation in mm, P_{his} the historical precipitation in mm and t the timestep in days.

Evaporation in HBV is implemented by a file `evap.dat` describing mean monthly values for all HBV sub catchments. To transform the evaporation data this file was perturbed by a fraction.

The input files for precipitation and temperature are defined in a file containing the variable value for all time steps and locations in a matrix. For the Meuse input files, with 15 sub basins, the transformation was executed in Matlab.

A software package "backtr_wl_Rhine.exe" is available for data transformation, which contains an Euclidean distance model (Beersma *et al.*, 2001). The program converts a small index file into a large database with area-average precipitation and temperature for the 134 HBV sub basins (Werner and Reggiani, 2002). The small index files contain standardization coefficients for precipitation and temperature and the large database contains standardized historical (1961-1995) precipitation amounts and temperatures.

For the data transformation of the Rhine input files, only the small index files were transformed whereafter the rainfall generator was run to create a dataset of 35 years for each scenario.

This resulted in the following scenario time series that were used as input data for the HBV models.

Table 5: Input time series.

	Rhine		Meuse	
	P	T	P	T
Reference	1961 – 1995	1961 – 1995	1967 – 1998	1967 – 1998
WB21 +1 ºC	35 yrs ~2050	35 yrs ~2050	32 yrs ~2050	32 yrs ~2050
WB21 +2 ºC	35 yrs ~2050	35 yrs ~2050	32 yrs ~2050	32 yrs ~2050
KNMI'06 G	35 yrs ~2050	35 yrs ~2050	32 yrs ~2050	32 yrs ~2050
KNMI'06 G+	35 yrs ~2050	35 yrs ~2050	32 yrs ~2050	32 yrs ~2050
KNMI'06 W	35 yrs ~2050	35 yrs ~2050	32 yrs ~2050	32 yrs ~2050
KNMI'06 W+	35 yrs ~2050	35 yrs ~2050	32 yrs ~2050	32 yrs ~2050

2.3 Model runs

To simulate the runoff, the semi-distributed conceptual hydrological model HBV (Bergström, 1976) was used, both for the Meuse basin and the Rhine basin. Both model schematisations are available at WL | Delft Hydraulics.

The tool FEWSNL (Werner, 2005) was used to perform the model runs. The HBV models for both the Rhine and the Meuse are implemented in FEWSNL. FEWSNL was configured to import the reference and 6 scenario data sets and run HBV with these sets as input data. The HBV model normally runs at an hourly time step in FEWSNL, but was configured to run at a daily basis for both the Rhine and the Meuse in this project.

3 Results

Resulting discharge time series of all modelruns were analysed at the following locations:

Table 6: Locations selected for data analysis.

Rhine	**Meuse**
Lobith	Borgharen
Kaub	
Rheinfelden	

For these locations, the mean monthly discharge and the mean discharge per decade were calculated. Both the HBV results from the current study as well as the RhineFlow and MeuseFlow results produced by Van Deursen (2006) are presented in graphs in Appendix A and discussed in this chapter.

3.1 Rhine

3.1.1 Predicted change in mean discharges KNMI'06 scenarios

All three locations show comparable results. The mean rise in discharge in the winter months December, January and February varies from 10% rise for the G scenario to 20% for the W+ scenario.

In the summer months June, July and August, there is barely any change in discharge in the G and W scenarios. The G+ and W+ scenarios (strong change of atmospheric circulation) though, show a decrease in mean discharge of 20 – 35%.

3.1.2 Comparison between KNMI'06 and WB21 scenarios

When comparing the KNMI'06 scenarios with the former used WB21 scenarios, there are differences in predicted changes in discharges. These differences are alike for all locations and can be explained by the differences in precipitation input scenarios.

The main differences are less winter rise (~ - 10%) in discharge for all KNMI'06 scenarios when compared to the WB21 +2 ºC and a significant drop in discharge for the summer months for the KNMI'06 scenarios G+ and W+, when compared to the WB21 +2 ºC. The W+ scenario, for example, shows a decrease of 35%, while the WB21 +2 ºC only shows a decrease of 12%.

3.1.3 Comparison between HBV and RhineFlow results

The difference between the HBV and the RhineFlow results are displayed in a separate graph. These differences vary between the locations and increase in upstream direction.

At Lobith, the difference between both model results vary between + or – 5 %. The trend for all scenarios can be described as a wave motion. In winter, the HBV results are slightly higher than the RhineFlow results, followed by a dip at March, where the HBV results are lower than the RhineFlow results. In April and May, the HBV results are again higher. In June and July, the HBV results are lower, rising in August and becoming higher than the RhineFlow results again in the months September and October.

This wave motion can be explained by a difference in timing between both models. The ‘summer dip’ is estimated approximately one month later by RhineFlow than by HBV.

At Kaub, these differences increase a little bit, showing the same wave motion. At Rheinfelden the wave motion is still visible. The differences between the model results and for different scenarios are increased, especially for the periods where the HBV results are lower than the RhineFlow results, such as June and July, and January, February and March, where HBV predicts 20% less increase in discharge than RhineFlow for the W+ scenario does.

3.2 Meuse

3.2.1 Predicted change in mean discharges KNMI’06 scenarios

The W+ scenario varies between + 15% winter and - 20% summer. The G and W scenarios remain very stable, also in summer. When compared to the results for the Rhine basin, it seems that in the Meuse basin, changes in evaporation in summer have a less significant impact on the mean discharge, resulting in relatively less decrease in summer discharges.

3.2.2 Comparison between KNMI’06 and WB21 scenarios

When comparing the KNMI’06 scenarios with the former used WB21 scenarios, there are differences in predicted changes in discharges. These differences can be explained by the differences in precipitation input scenarios.

The main differences are less winter rise (~ - 10%) in discharge for all KNMI’06 scenarios when compared to the WB21 +2 ºC and a significant drop in discharge for the summer months for the KNMI’06 scenarios G+ and W+, when compared to the WB21 +2 ºC. The W+ scenario, for example, shows a decrease of 21%, while the WB21 +2 ºC only shows a decrease of 8%.

3.2.3 Comparison between HBV and MeuseFlow results

HBV predicts more increase in discharge than MeuseFlow, for the months January until August, ranging from 0 – 2% more for the G and W scenarios, to 4 – 6% more for the G+ and W+ scenarios.

The timing of decrease in summer discharges is almost 2 months later in MeuseFlow than in HBV (October instead of August), resulting in HBV predicting more discharge than MeuseFlow, with a maximum difference of 16% for the G+ and 28% for the W+ scenario for the months October, November and December.

4 Conclusions

All climate runs using the KNMI’06 scenarios for the year 2050 as input data, show an increase in mean winter discharges and a decrease in mean summer discharges, both for the Rhine and the Meuse basins. There is a wide range in these predicted changes, especially in the summer decrease, depending on the input scenario.

At Lobith, the maximum increase in mean winter discharge is 18%, and the maximum summer decrease is 35%, both the result of the most extreme climate change scenario W+. The moderate climate scenario G shows at Lobith 8% increase in winter discharge and only 1% decrease in summer.

At Borgharen, the predicted winter increase varies from 4 – 15% and the predicted decrease in mean summer discharge vary from + 3% to – 21%.

When comparing the KNMI’06 scenarios with the former used WB21 scenarios, there are differences in predicted changes in discharges, which can be explained by the differences in precipitation input scenarios. The main differences are less increase in winter discharge for all KNMI’06 scenarios when compared to the WB21 +2 ºC (~ 10% less) and a significant drop in the predicted decrease in summer discharge for the KNMI’06 scenarios G+ and W+, when compared to the WB21 +2 ºC (up to 20% less).

The outcomes of RhineFlow and MeuseFlow models for the KNMI’06 scenarios when compared to the HBV results show the same trends and are of the same order of magnitude. The difference between the results of the models for most scenarios and locations stays below 5%, mainly due to a difference in timing.

For the Rhine basin, the differences in HBV and RhineFlow results increase in upstream direction. The maximum difference is at Rheinfelden in the winter months, where HBV predicts 20% less increase in discharge than RhineFlow does for the W+ scenario.

5 References

Aalders, P., Warmerdam, P.M.M. and Torfs, P.J.J.F., 200?. Rainfall Generator for the Meuse basin. 3,000 year discharge simulations in the Meuse basin. WAU report 124, Wageningen, the Netherlands.

Beersma, J.J., Buishand, T.A. and Wójckik, R., 2001. Rainfall generator for the Rhine basin: multi-site simulations of daily weather variables by nearest-neighbour resampling. In: Generation of hydrometeorological reference conditions for the assessment of flood hazard in large river basin, Krahe., P. and Herpertz, D. (Eds.), pp. 69-77, CHR-Report no. I-20. International commssion for the Hydrology of the Rhine Basin (CHR). P.O. Box 17, 8200 AA Lelystad, The Netherlands.

Beersma, J.J., 2004. Rainfall Generator for the Rhine Basin. Description of 1000-year simulations. KNMI-publication; 186-V, De Bilt, The Netherlands.

Bergström, S., 1976. The HBV Model. In: Computer Models of Watershed Hydrology. Edited by Singh, V.P. Colorado, USA.

Buishand, T.A. and Lenderink, G., 2003. Estimation of future discharges of the river Rhine in the SWURVE project. KNMI Technical Report TR-273.

Deursen, Van, W., 2002. Klimaatveranderingen in de stroomgebieden van Rijn en Maas. Modelstudeies met Rhineflow-3 en Meuseflow-2. Carthago Consultancy, Rotterdam, the Netherlands.

Deursen, Van, W., 2006. Rapportage Rhineflow / Meuseflow. Nieuwe KNMI scenario's mei 2006. Carthago Consultancy, Rotterdam, the Netherlands.

Eberle, M., 2005. Hydrological Modelling on the River Rhine Basin Part III – Daily HBV Model for the Rhine Basin. Cooperation Institute for Inland Water Management and Waste Water Treament (RIZA) and Federal Institute of Hydrology (BfG). BfG-JAP-No; 2555, Koblenz, Germany.

Hurk, Van den, B., Klein Tank, A., Lendering, G., Ulden, Van, A., Oldenborgh, Van, G.J., Katsman, C., Brink, Van den, H., Keller, F., Bessembinder, J., Burgers, G., Komen, G., Hazeleger, W. and Drijfhout, S., 2006. KNMI Climate Change Scenarios 2006 for the Netherlands. KNMI Scientific Report WR 2006-01.

Lenderink, G., Buishand, A. and Van Deurwen, W., 2004. Estimates of future discharges of the river Rhine using two scenario methodologies: direct versus delta approach. Submitted to HESS (revised version). KNMI, De Bilt, The Netherlands.

Tielrooij, F., Dijkoud, Van, J., Blécourt, De – Maas, J., Endeoud, Van den, A., Oosterbaan, G.A. and Overbeek, H.J., 2000. Waterbeleid voor de 21e eeuw. Advies van de Commissie Waterbeheer 21e eeuw uitgebracht op 31 augustus 2000 aan de staatssecretaris van Verkeer en Waterstaat en de voorzitter van de Unie van Waterschappen.

Werner, M.G.F. and Reggiani, P., 2002. FEWS Extreme discharges. WL | Delft Hydraulics (Q2967), Delft, The Netherlands.

Werner, M.G.F., 2005. FEWS NL. Versie 1. WL | Delft Hydraulics (Q3933), Delft, The Netherlands.

WL | Delft Hydraulics, 2001. Technical reference SOBEK River. Delft, The Netherlands.

A Results in figures

A.1 Climate scenarios

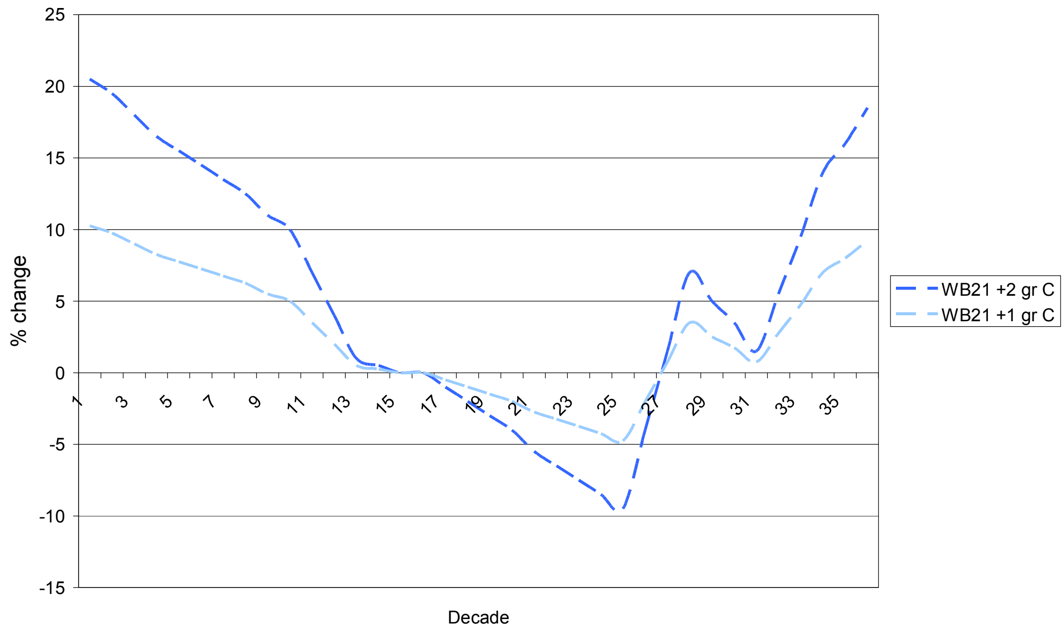

Figure 7: % Change in precipitation, WB21 +1 ºC and WB21 +2 ºC

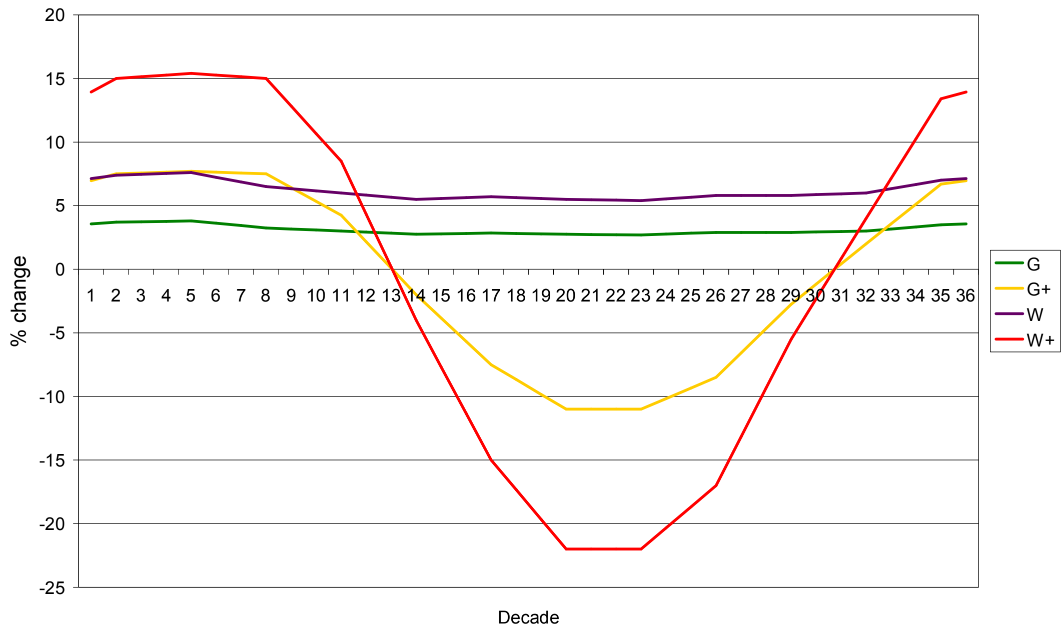

Figure 8: % Change in precipitation, KNMI'06 G, G+, W, W+.

A.2 Rhine basin

A.2.1 Lobith

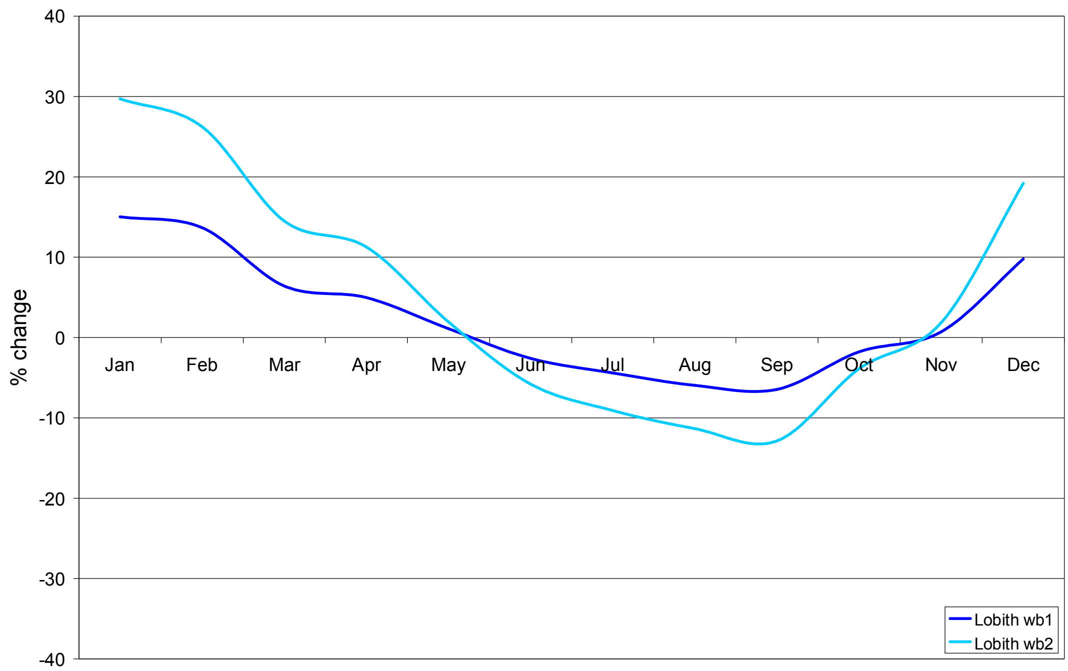

Figure 9: HBV WB21, month, Lobith

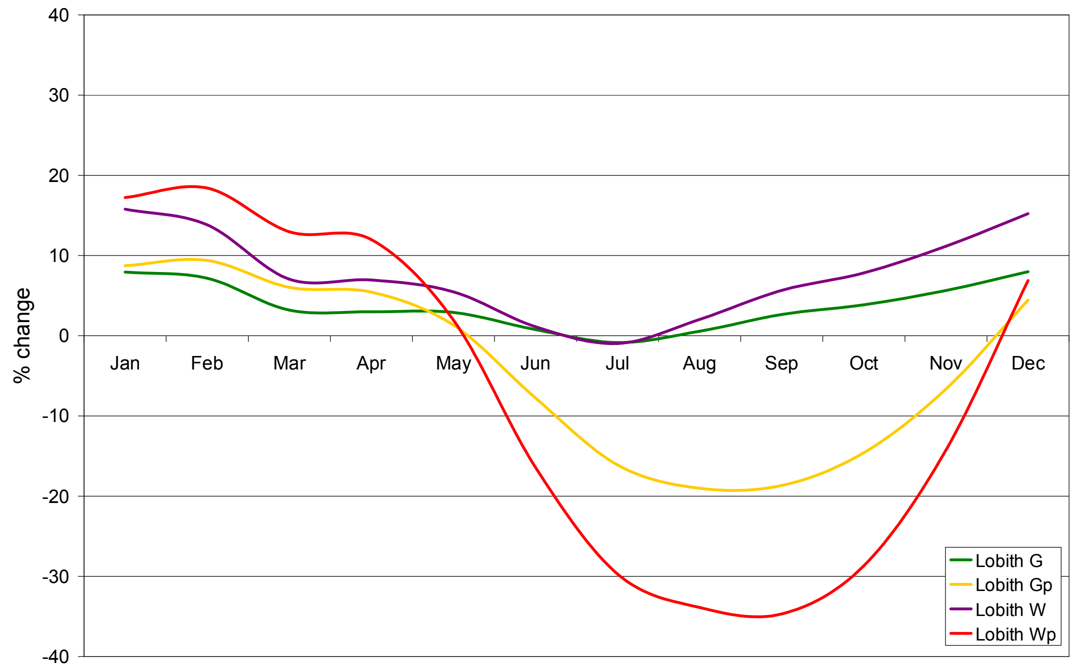

Figure 10: HBV KNMI'06, month, Lobith

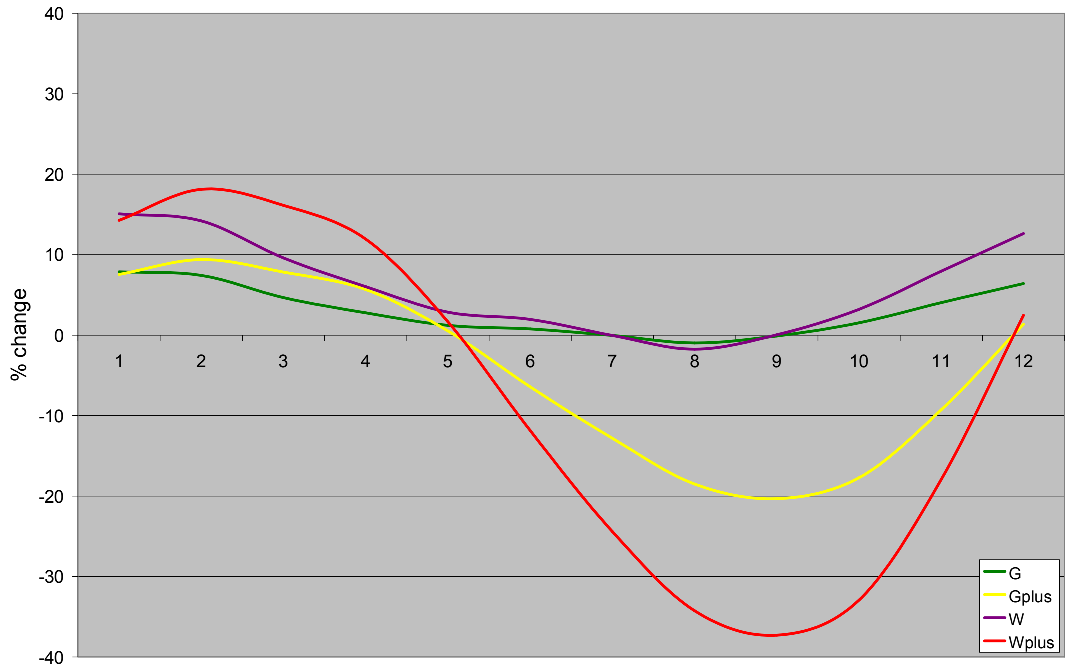

Figure 11: RhineFlow KNMI'06, month, Lobith

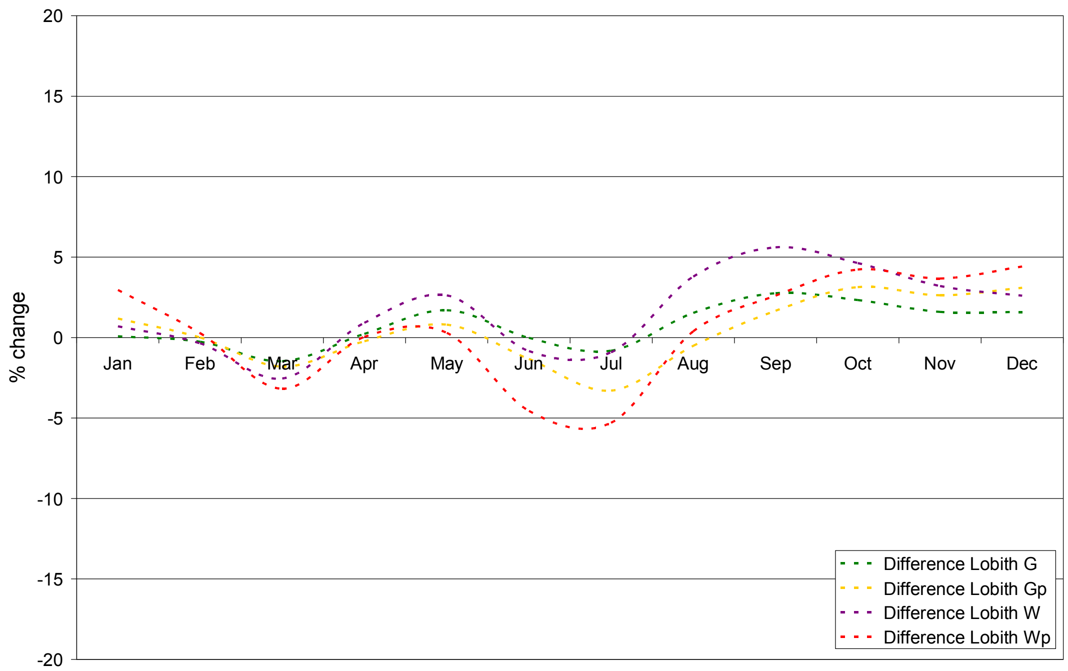

Figure 12: Difference HBV-RhineFlow KNMI'06, month, Lobith

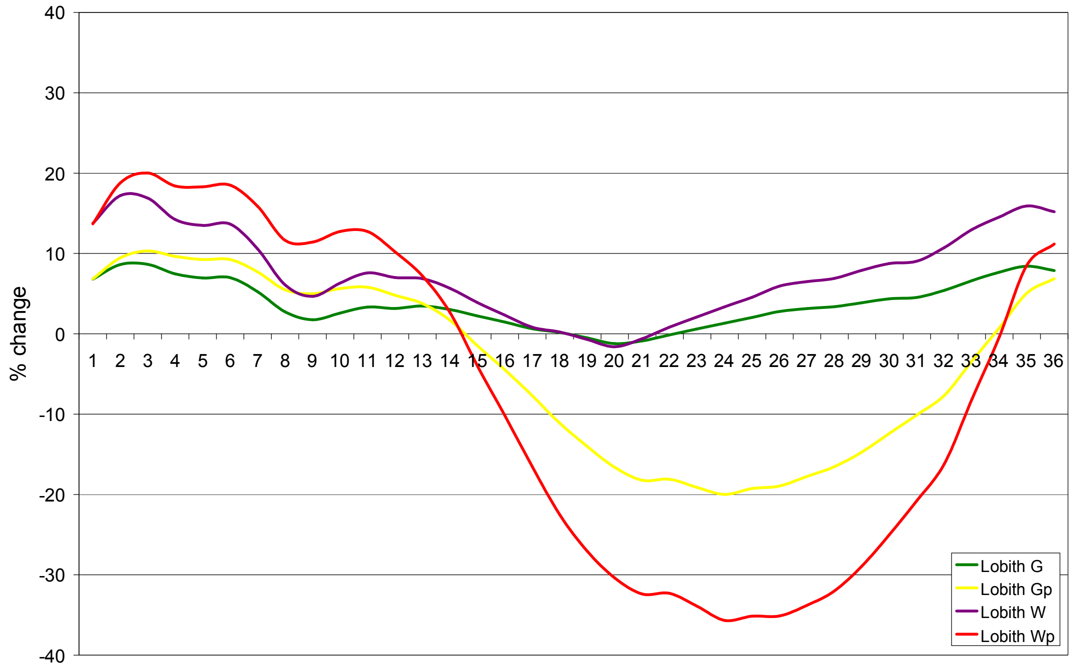

Figure 13: HBV KNMI'06, decade, Lobith

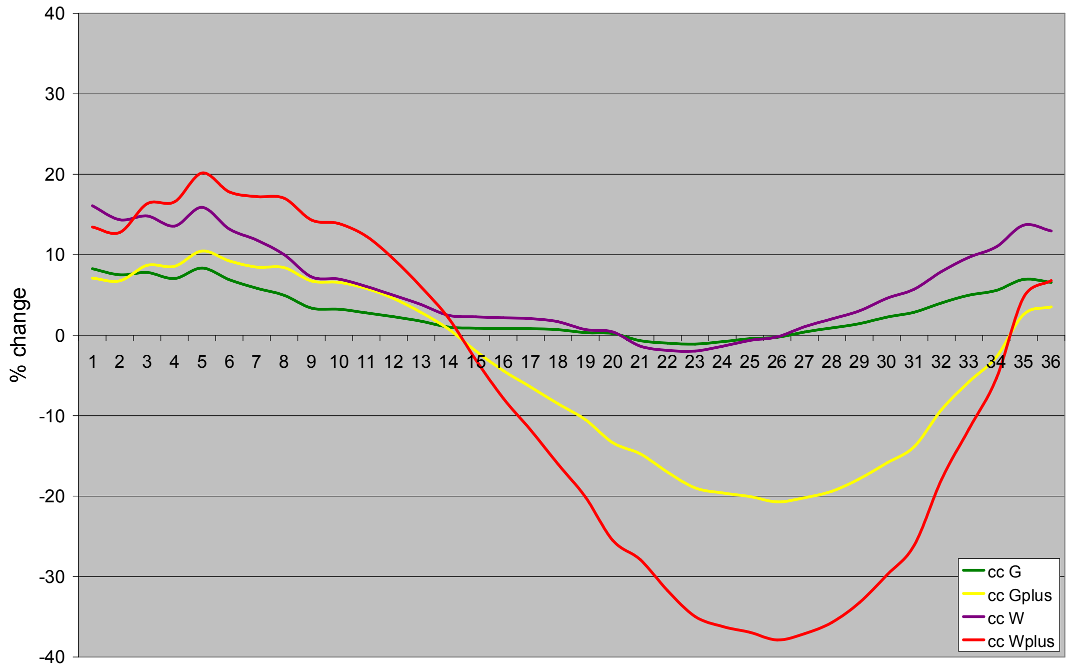

Figure 14: RhineFlow KNMI'06, decade, Lobith

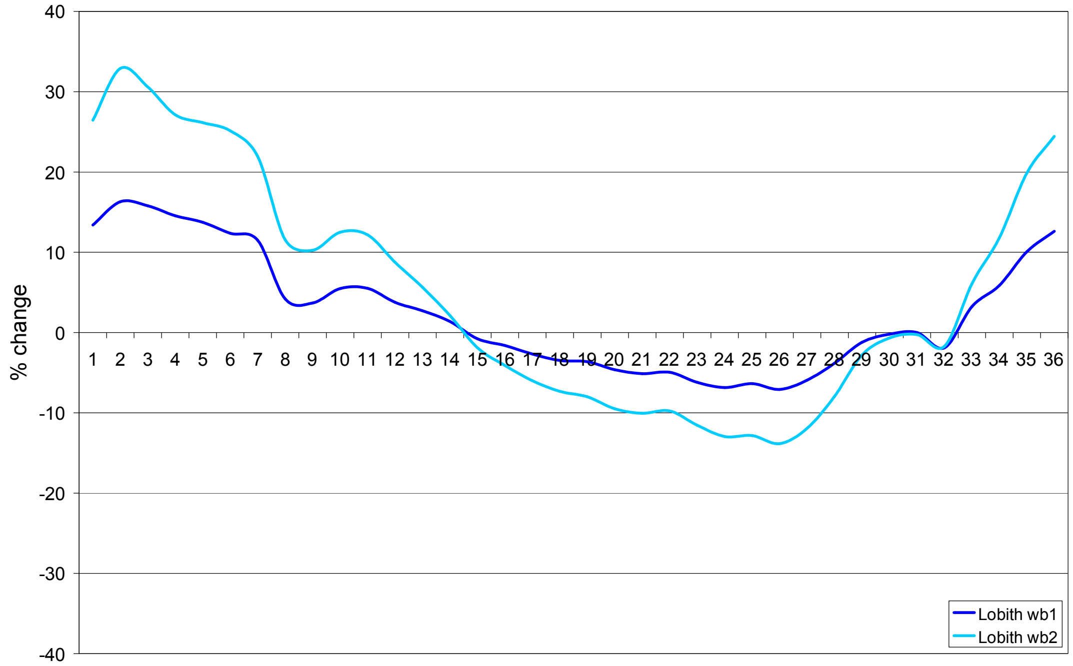

Figure 15: HBV WB21, decade, Lobith

A.2.2 Kaub

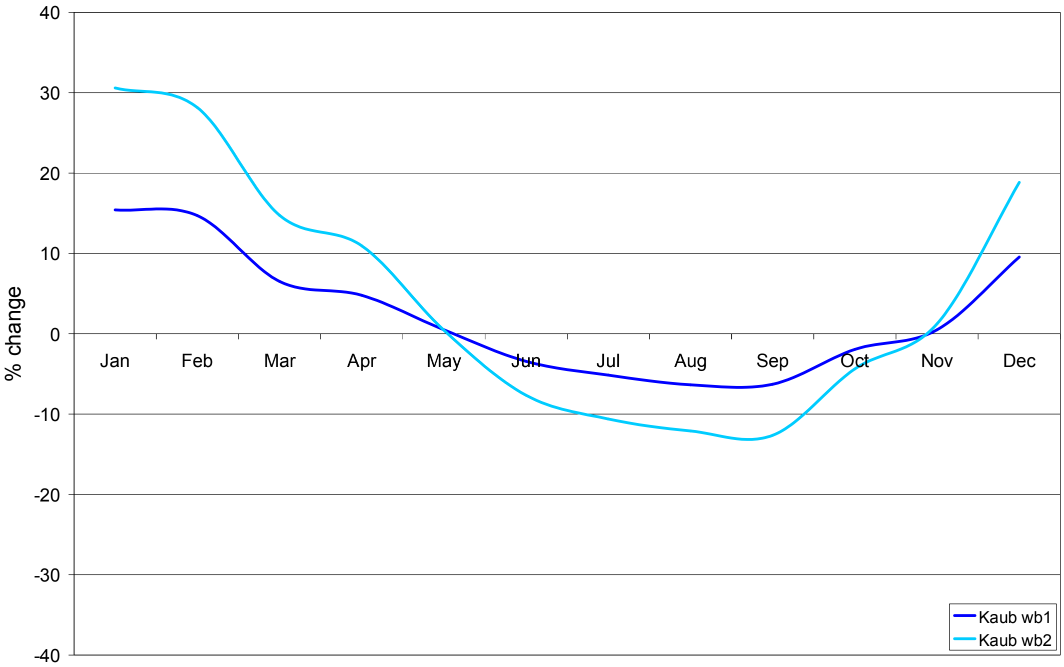

Figure 16: HBV WB21, month, Kaub

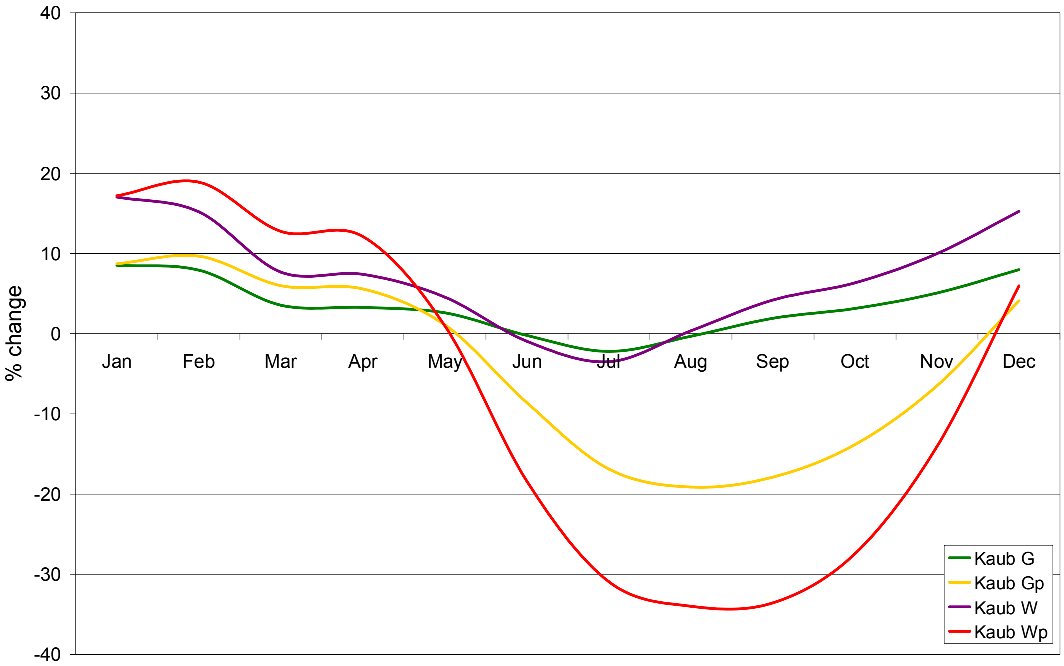

Figure 17: HBV KNMI'06, month, Kaub

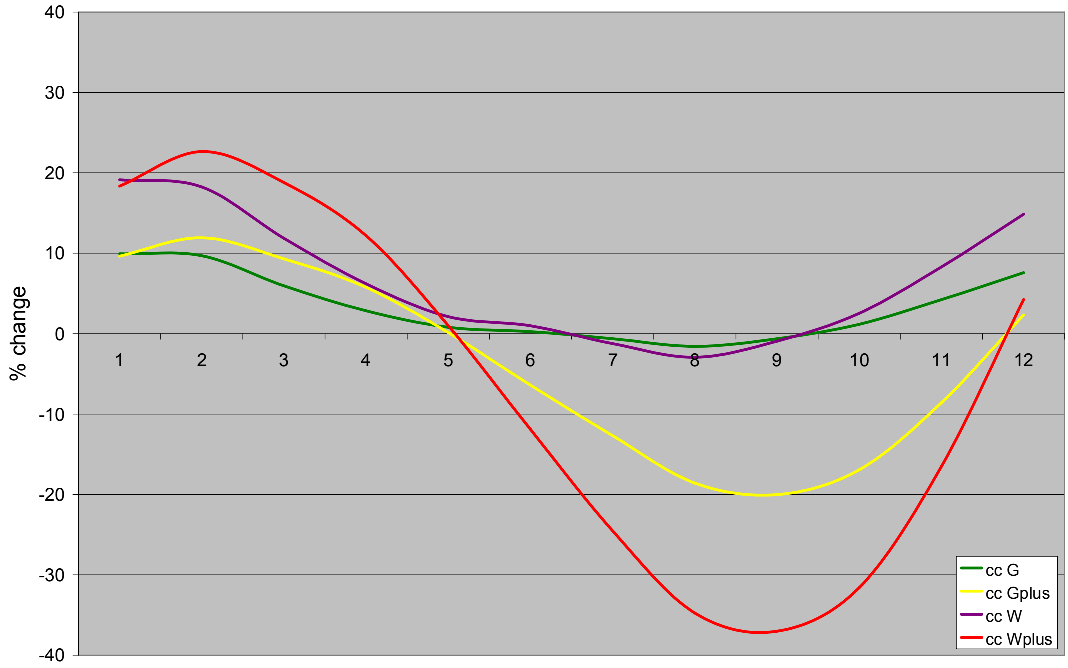

Figure 18: RhineFlow KNMI'06, month, Kaub

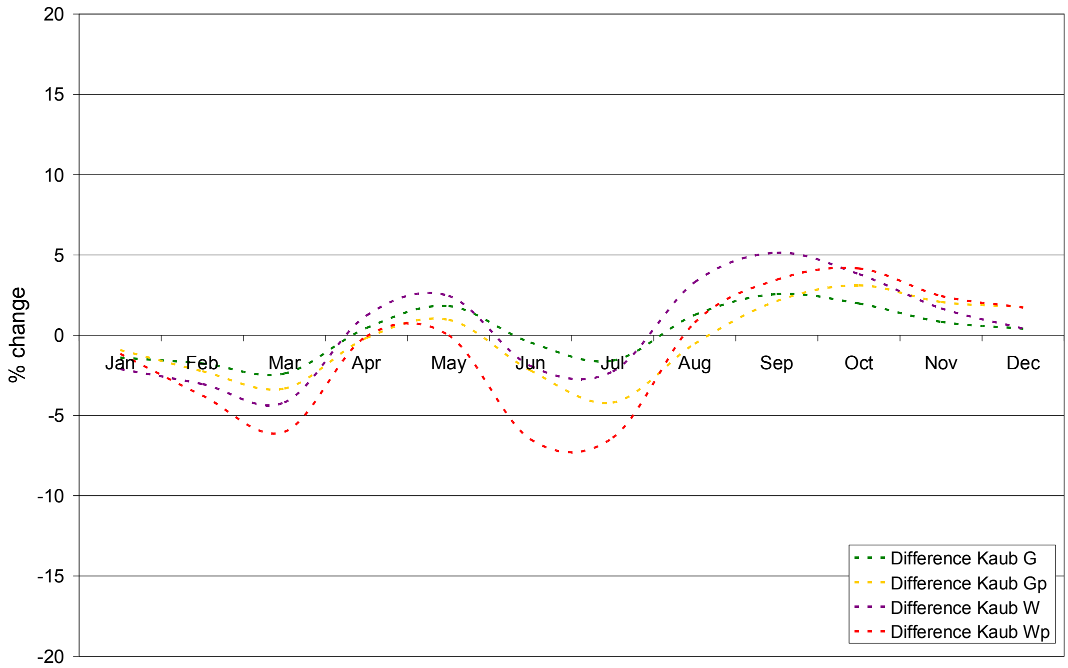

Figure 19: Difference HBV-RhineFlow KNMI'06, month, Kaub

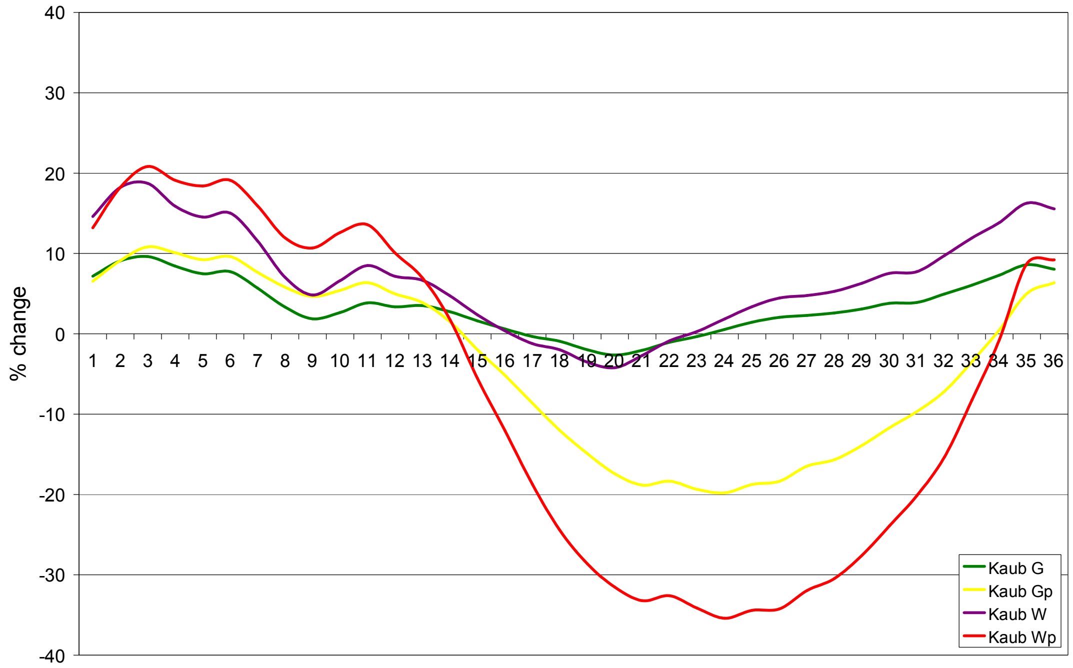

Figure 20: HBV KNMI’06, decade, Kaub

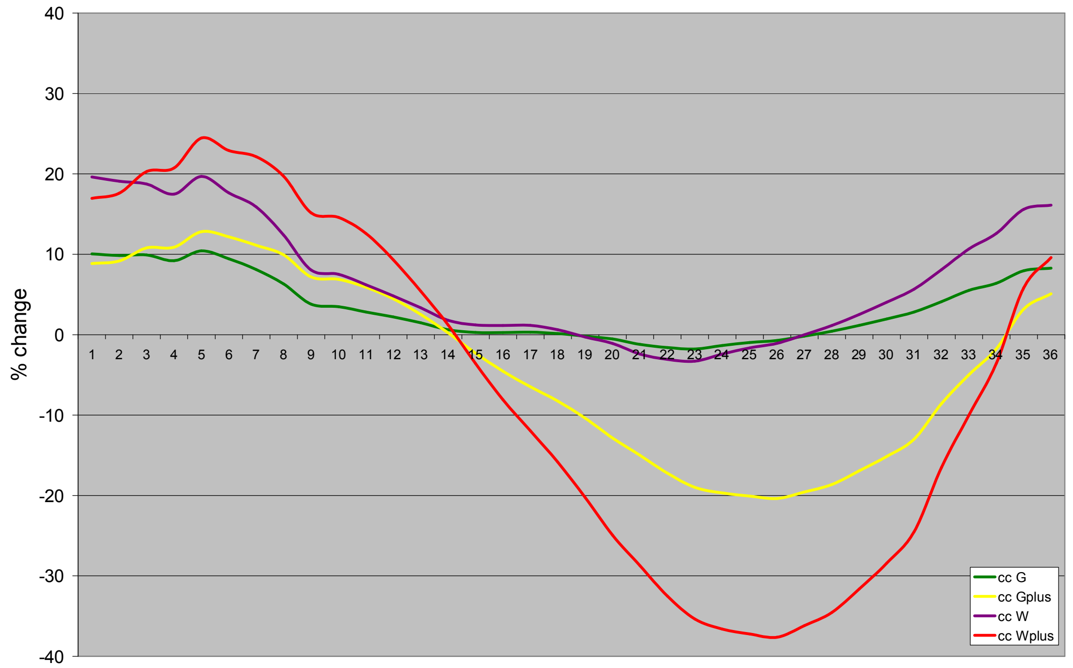

Figure 21: RhineFlow KNMI’06, decade, Kaub

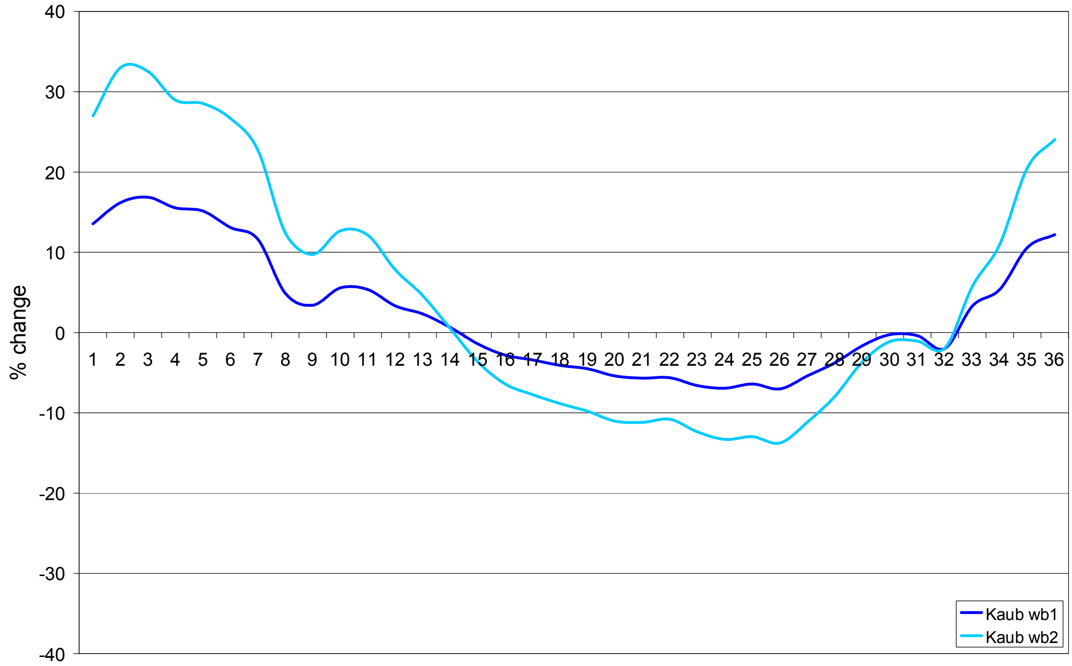

Figure 22: HBV WB21, decade, Kaub

A.2.3 Rheinfelden

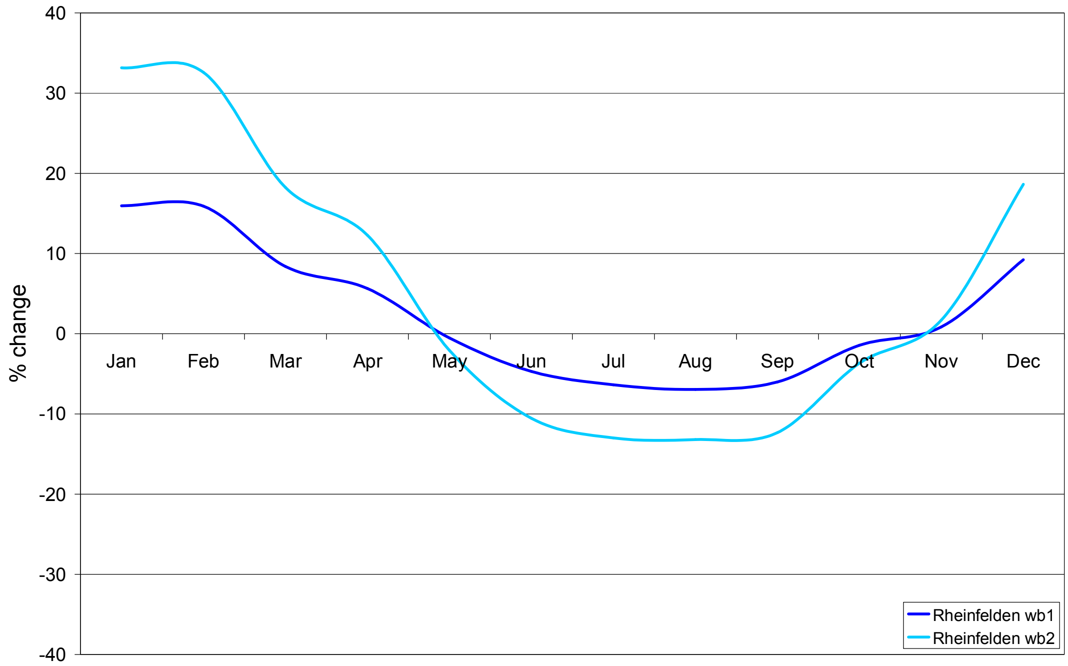

Figure 23: HBV WB21, month, Rheinfelden

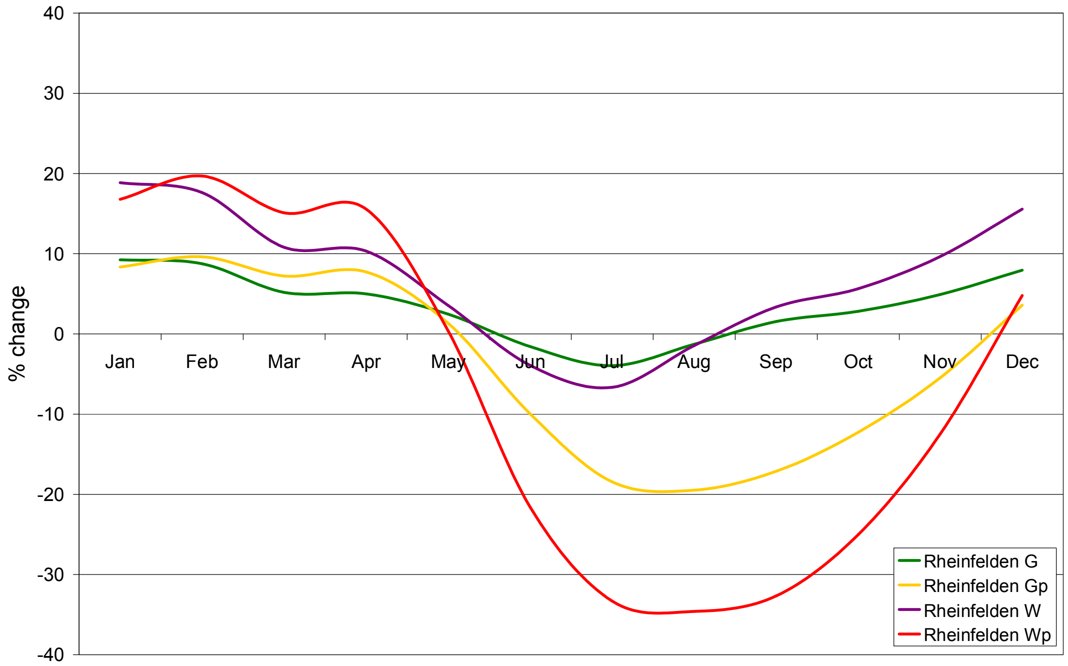

Figure 24: HBV KNMI'06, month, Rheinfelden

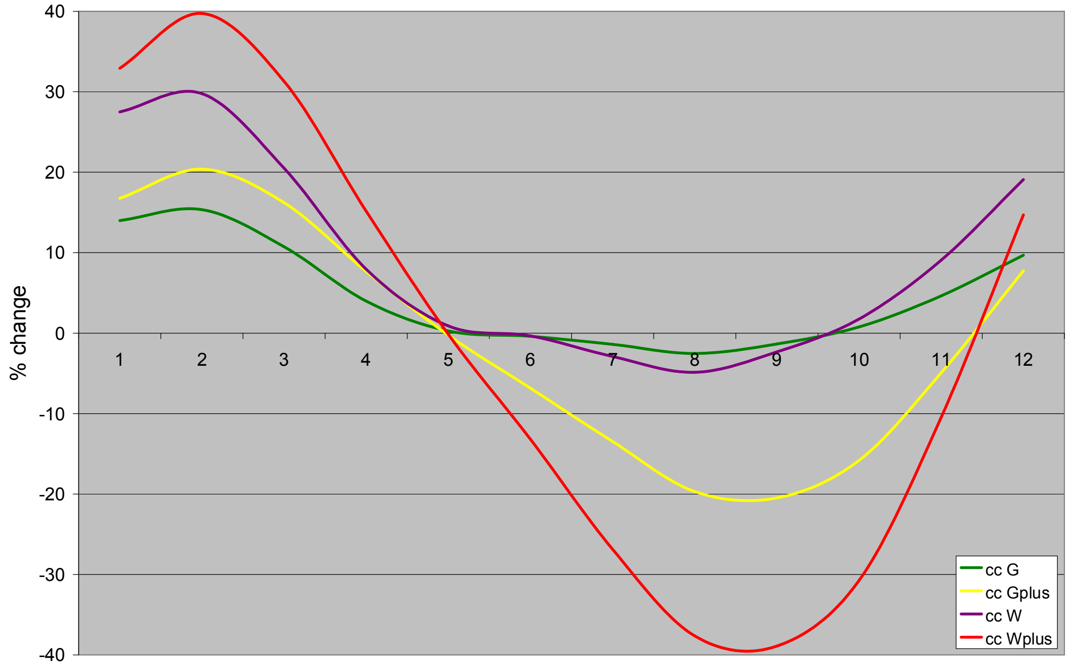

Figure 25: RhineFlow KNMI'06, month, Rheinfelden

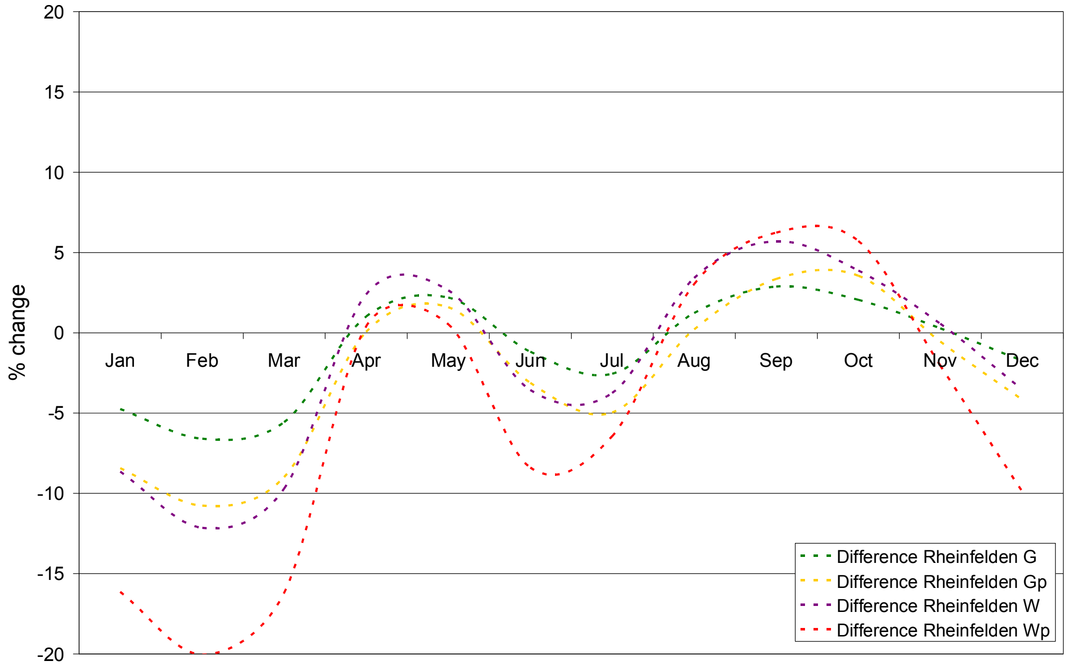

Figure 26: Difference HBV-RhineFlow KNMI'06, month, Rheinfelden

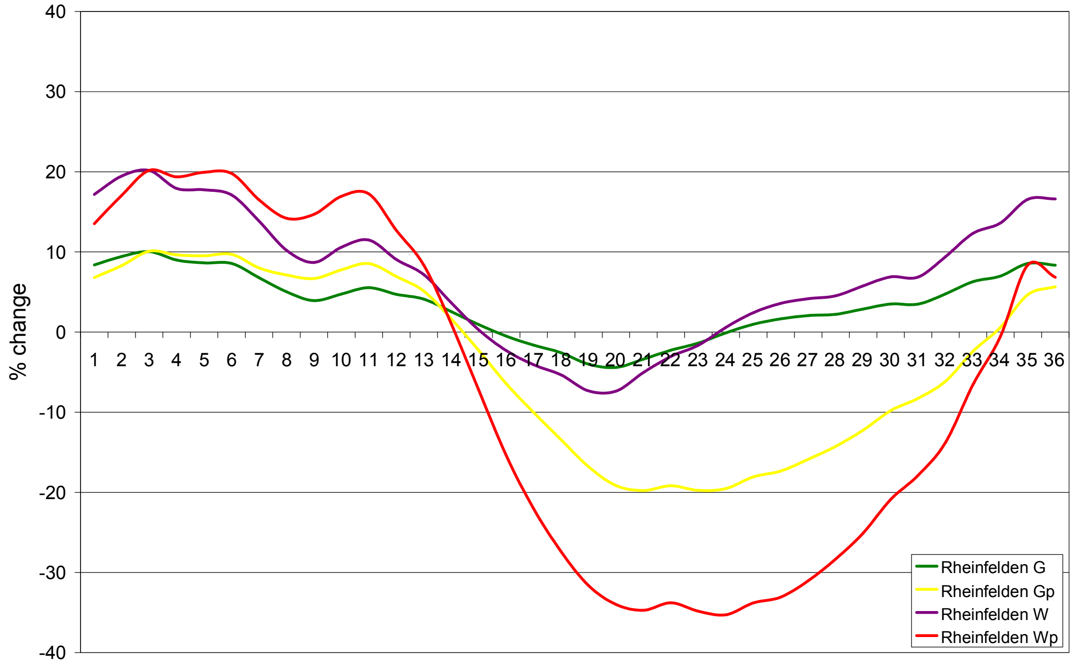

Figure 27: HBV KNMI'06, decade, Rheinfelden

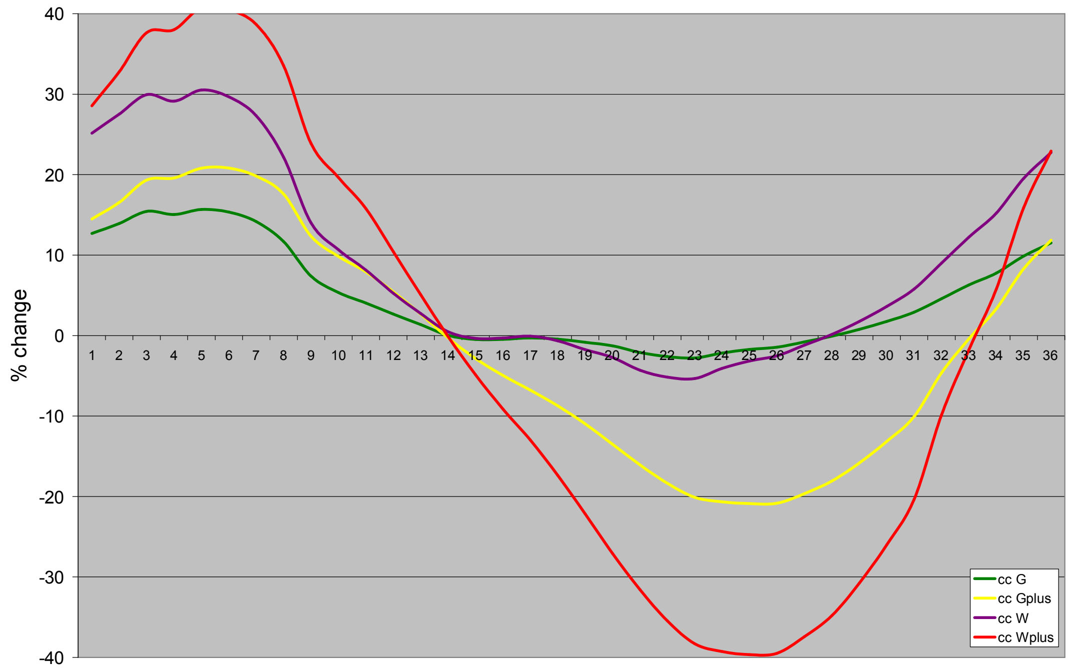

Figure 28: RhineFlow KNMI'06, decade, Rheinfelden

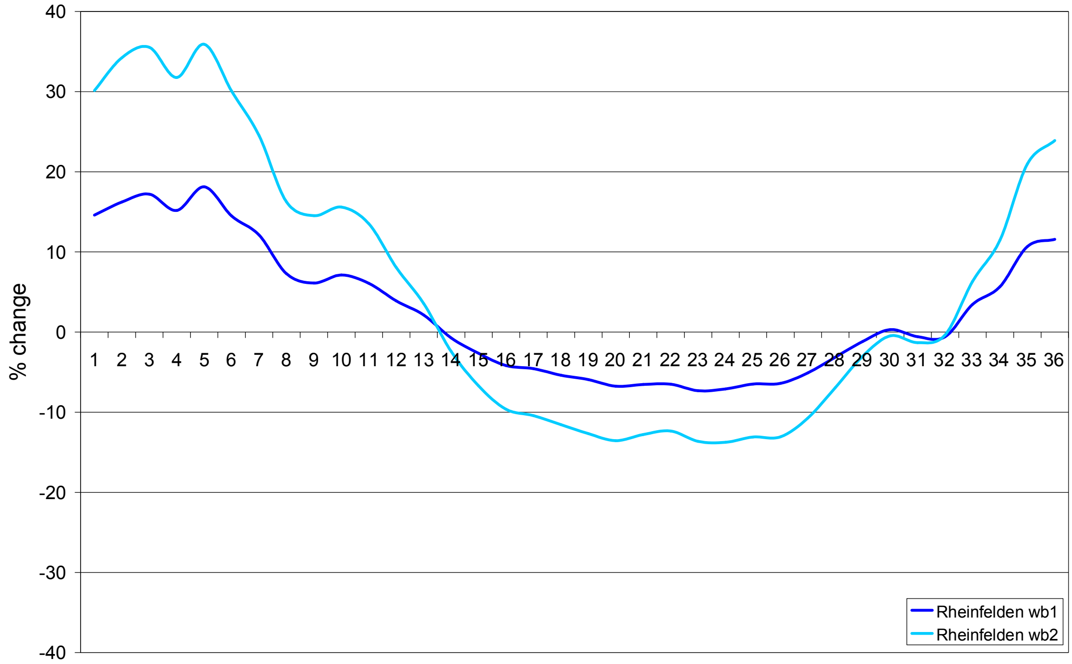

Figure 29: HBV WB21, decade, Rheinfelden

A.3 Meuse basin

A.3.1 Borgharen

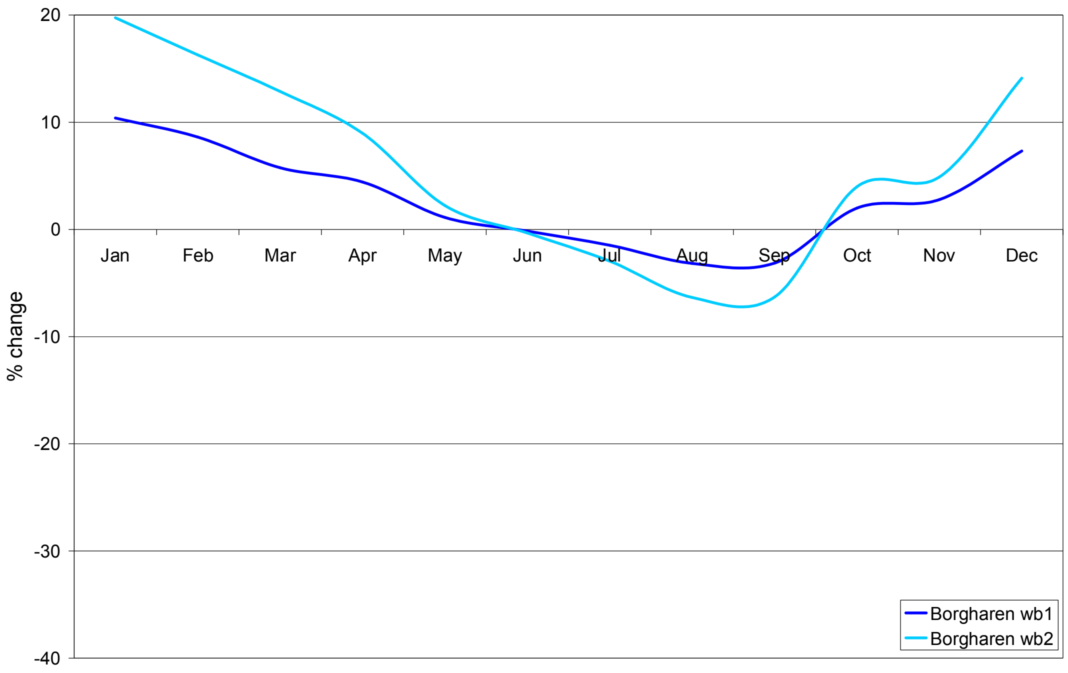

Figure 30: HBV WB21, month, Borgharen

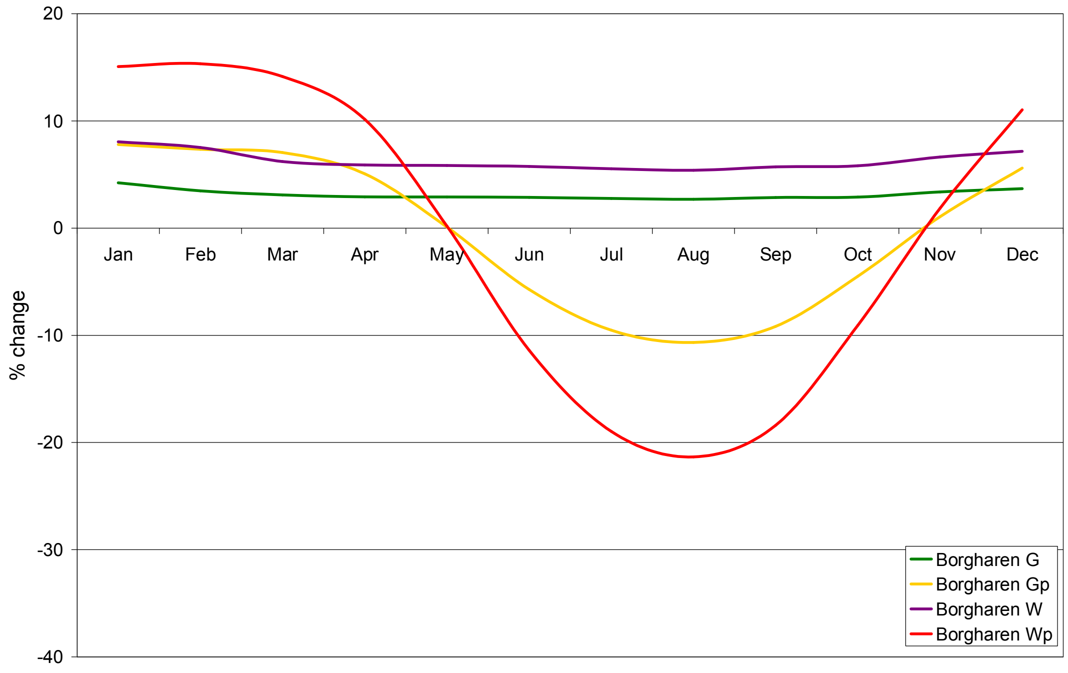

Figure 31: HBV KNMI'06, month, Borgharen

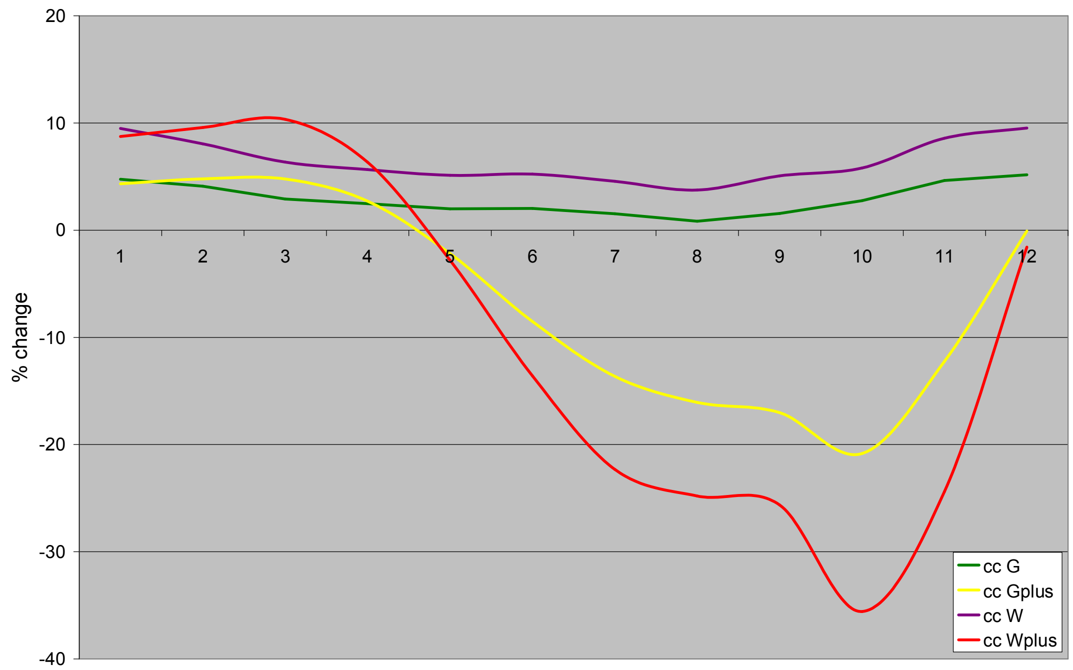

Figure 32: MeuseFlow KNMI’06, month, Borgharen

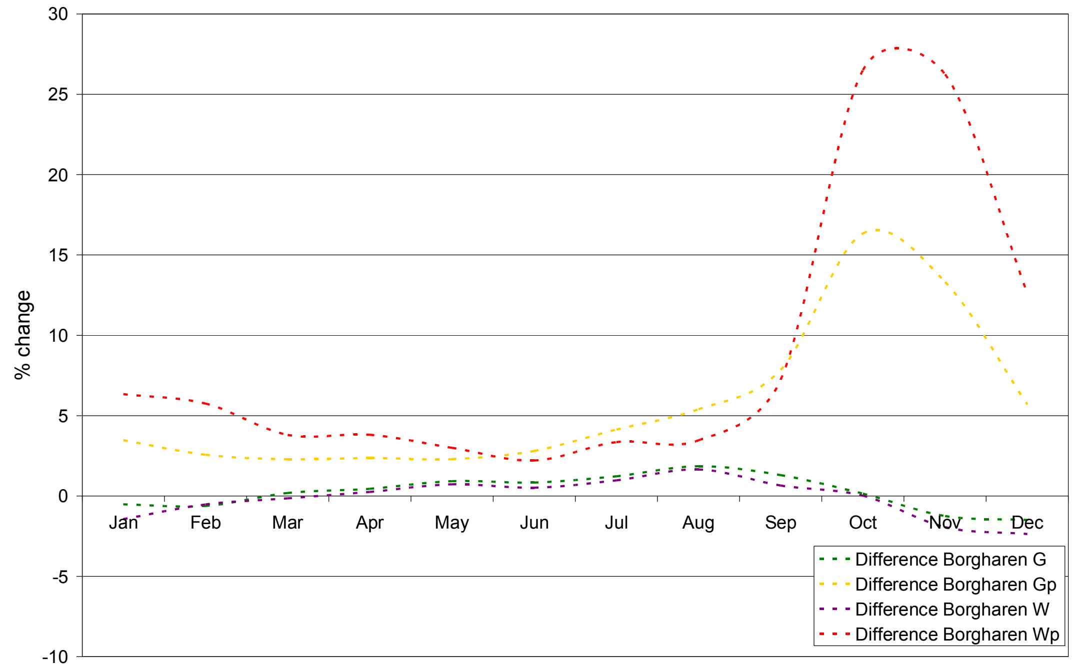

Figure 33: Difference HBV-MeuseeFlow KNMI’06, month, Borgharen

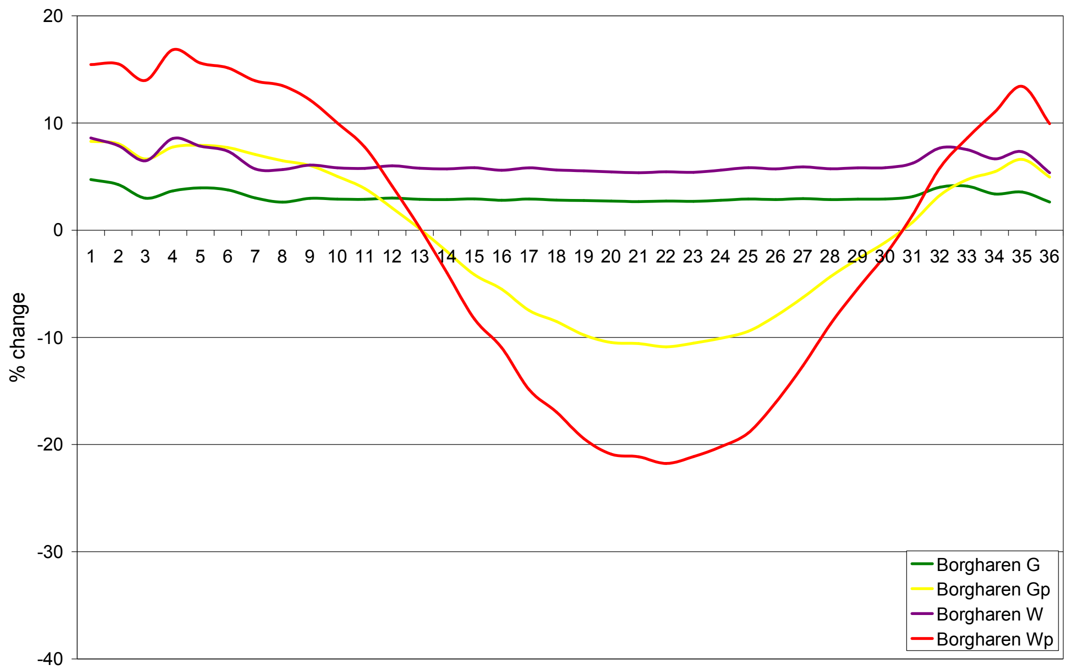

Figure 34: HBV KNMI'06, decade, Borgharen

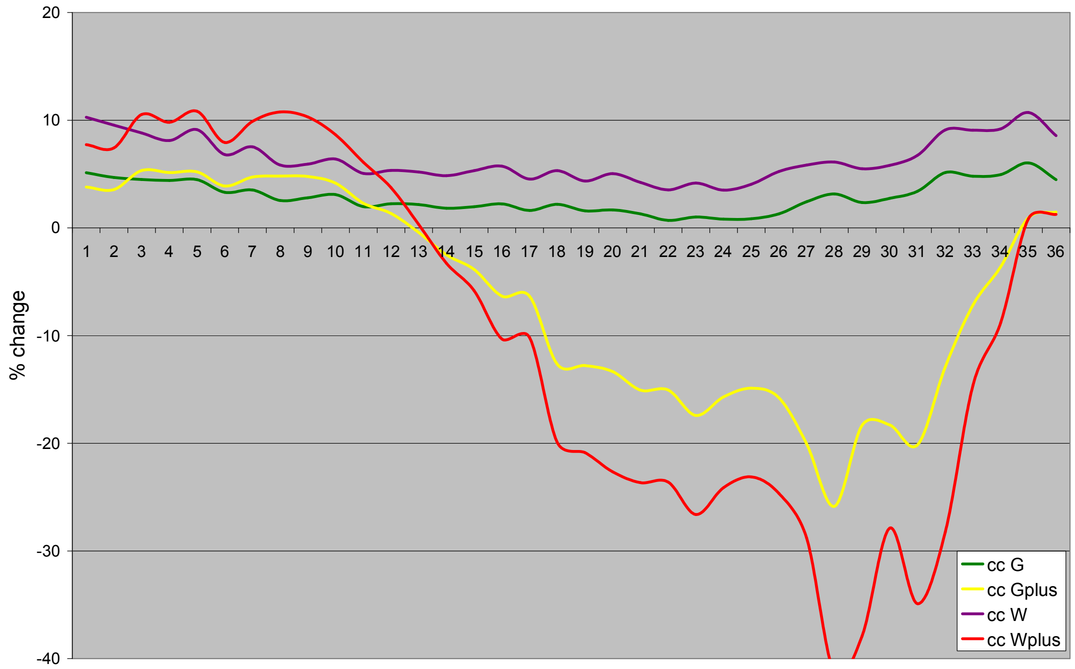

Figure 35: MeuseFlow KNMI'06, decade, Borgharen

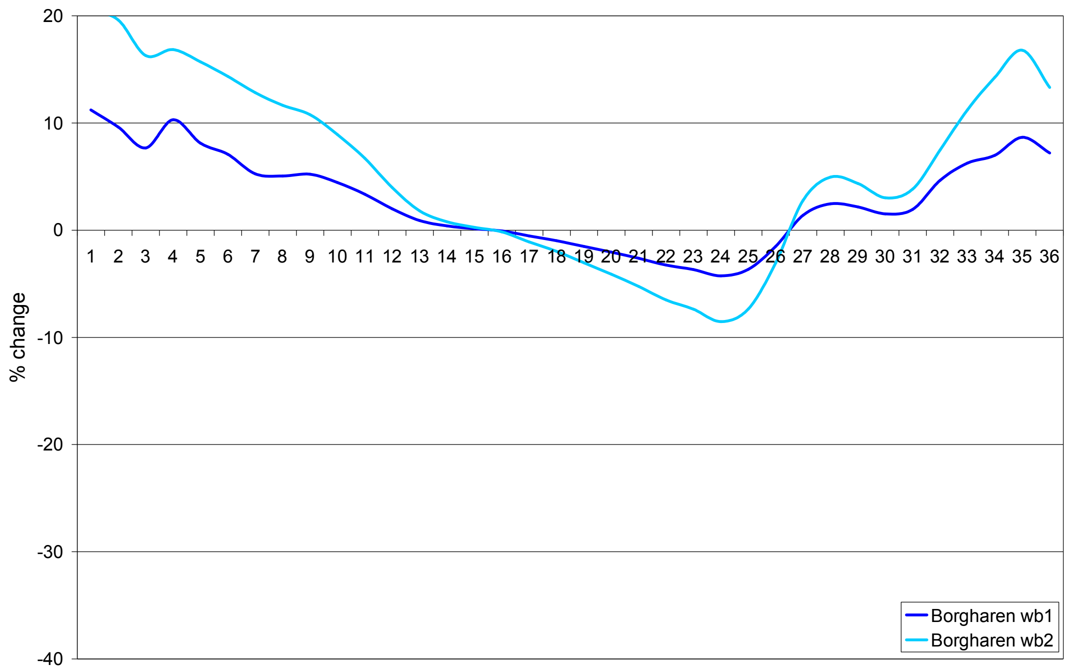

Figure 36: HBV WB 21, decade, Borgharen