Coupling WALRUS to SOBEK

Wageningen Lowland Runoff Simulator to 1D open water model

MSc Internship

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Frontpage picture: Retention reservoir Mallum in the Berkel catchment (made by Jurriaan ten Broek)

Preface

My internship started in April 2014, for me the first challenge to work at a company. I wanted to improve my skills and gain experience in programming with SOBEK. I worked almost all the time at the office of waterboard Rijn en IJssel in Doetinchem. This internship serves the completion of the master phase of the master Earth and Environment at the Wageningen University. Working on this internship has been an experience for me. The research process was not always easy and interesting, but in general the topic, especially SOBEK, keep me enthusiastic. This thesis became possible with the help of a few persons. At first I would like to thank ir. Gert van den Houten for his assistance during the process of my internship. Furthermore I would like to thank drs. Paul Torfs of the chair group Hydrology and Quantitative Water Management (HWM) for his guidance and tips for WALRUS and SOBEK. I also want to thank Claudia Brauer of the chair group HWM for helping me with WALRUS. Finally I would like to thank my girlfriend and parents for their support during this period.

Enjoy reading this report!

Jurriaan ten Broek, Wageningen, September 2014.

Summary

The objective of this study is to couple Wageningen Lowland Runoff Simulator (WALRUS) with a 1D open water model (SOBEK) for the catchment of the Berkel in Germany and The Netherlands. We were interested to see which parameters are best available and most important for hydrologic analysis, hydraulic analysis and coupling between both analysis.

WALRUS is recently developed and has some advantages compared to existing lumped rainfall-runoff models. There is a coupling between the unsaturated and saturated zone, a wetness-dependent divider and the inclusion of a surface water reservoir. Time series of precipitation, potential evaporation and discharge were used for the calibration of WALRUS. We tested WALRUS for three locations within the Berkel catchment: 1) steep sloping area of Lutum; 2) slightly sloping area of Stadtlohn and; 3) the flat area of Waterleiding. WALRUS performed well with an average Nash-Sutcliffe efficiency of 0.79 which is quite good. WALRUS has difficulties in reaching the peaks of the high discharges and recession limbs decrease too fast. Furthermore the groundwater level in WALRUS is difficult to relate to groundwater levels measured in the field.

A 1D-SOBEK model of the Dutch part of the Berkel catchment is made by Waterboard Rijn en IJssel and for the German part of the Berkel catchment a new 1D schematisation was added. We need to understand the weaknesses of the parameters in SOBEK for coupling WALRUS to SOBEK. The resistance of a river bed has a significant influence on the peak of the discharge and the inundation period (amount of storage). A higher resistance results in an increasing water level, but the peak discharge decreases. On the other hand the storage in the profile becomes larger when the resistance increases because the vegetation retains the water. The implementation of the retention reservoir Mallum has an important effect on the discharge downstream when a flood event occurs in the upstream area of Rekken. The top of the flood wave is decreased due to the storage of the water in the reservoir.

The simulated output of WALRUS is used as input for the sub-catchments of the Berkel in the SOBEK model. The hydraulic routing component in SOBEK provides a phase shift of the discharge. Generated parameter sets have a major influence on validation of the discharge (included the limitations of WALRUS) in SOBEK. The coupling of WALRUS and SOBEK can be used as early warning tool for the prediction of floods and drought, however further investigation is needed for the application of especially WALRUS in other large catchments.

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1 Introduction

According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) there are no widespread observations of changes in flood magnitude and frequency due to anthropogenic climate change, but projections imply variations in the frequency of floods. Global flood risk will increase in the future partly due to climate change (IPCC, 2014). Detected trends in streamflow are generally consistent with observed regional changes in precipitation and temperature. More intense precipitation results in the need to have a real-time simulation flood model. The rainfall-runoff relationship is comprehensive to simulate due to spatial and temporal variability of catchment characteristics and all variables involved in the model. The previous rainfall-runoff model developed by Wageningen University is called the Wageningen model and uses water balances of unsaturated, saturated and quick-flow reservoirs to compute the final discharge. The Wageningen model was developed by Hydrology and Quantitative Water Management Group (Stricker and Warmerdam, 1982). The model has two main disadvantages: disconnection exists between the unsaturated and saturated zone and no feedbacks are possible between groundwater and surface water. Furthermore users indicated the need to have more robust seasonal simulation capabilities. Therefore recently a new rainfall-runoff model for the application in lowland areas is developed by Brauer et al. (2014a) and is called the Wageningen Lowland Runoff Simulator (WALRUS). WALRUS has some advantages compared to existing lumped rainfall-runoff models; 1) a coupling between the unsaturated and saturated zone; 2) a wetness-dependent divider which conceptualises the varying contribution of fast flowroutes; and 3) the inclusion of a surface water reservoir, representing the channel network. WALRUS is applied in the Hupsel Brook catchment and the Cabauw polder (Brauer et al., 2014b). Some waterboards and MSc students of the Wageningen University are testing and calibrating WALRUS. This study focusses on the coupling of WALRUS with a surface water model of SOBEK. We are interested if the simulated output of WALRUS can be used as input in a SOBEK 1D Open Water model. Furthermore we are interested to see if hydrological or hydraulic parameters are more sensitive for changes.

1.1 Objective

The objective of this study is to make a real-time simulation of rainfall-runoff modeling with SOBEK 1D Open Water and Walrus. The Berkel catchment is used as representative catchment. The main research questions are:

1. Is a coupling between SOBEK 1D Open Water and WALRUS possible?
2. Which parameters are best available and most important for the hydrologic analysis (WALRUS), hydraulic analysis (SOBEK) and coupling between both analysis?

1.2 Outline

In Chapter 2 the topography, hydrogeology and landuse of the study site is described and in addition several measures for flood events are discussed. Chapter 3 describes data selection of precipitation, potential evaporation and discharge timeseries. Furthermore the water balance of the Berkel is mentioned. Chapter 4 describes the rainfall-runoff model WALRUS and Chapter 5 describes the 1D open water model SOBEK. The coupling of both models is discussed in Chapter 6. The report ends with a discussion (Chapter 7) and a conclusion together with recommendations (Chapter 8).

2 Study site

2.1 Introduction and topography

The Berkel catchment is situated in the western part of Germany and the eastern part of The Netherlands (Figure 2.1). The total area of the catchment is approximately 800 km^2 of which about 50 % is situated in Germany. The source of the Berkel is located in Billerbeck, flows through the Achterhoek to join the IJssel at Zutphen after about 110 kilometres. The elevation at the source is 127 m above mean sea level and at Zutphen the elevation is 8 m above mean sea level. The first tens of kilometres the Berkel is a meandering river, when the river crosses the border of The Netherlands the meandering stops. In the Dutch part the Berkel is canalised because in the past this area was prone to flooding and sedimentation. Several weirs were installed and a large flood retention reservoir with a sand catch was constructed in order to prevent the downstream area from flooding and to collect the sediment.

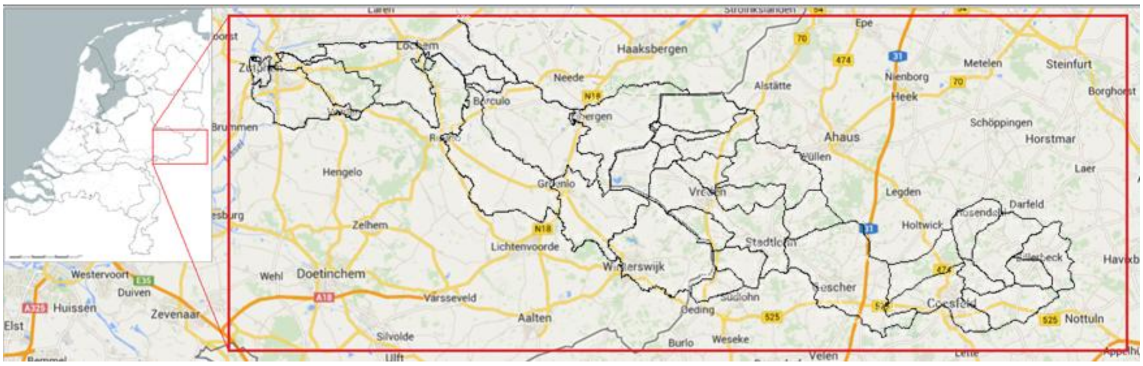

Figure 2.1: Catchment area of the Berkel in The Netherlands and Germany (Googlemaps, 2014).

2.2 Hydrogeology

The source of the Berkel is located in the *Baumberge*. The *Baumberge* is a low mountain range in Nordrhine-Westfalen originated in the Cretaceous. In the Lower-Cretaceous chalk and clay were deposited and in the Upper-Cretaceous sand and chalk were deposited. Today *Baumberge* consists of calcareous sandstone (high hydraulic conductivity) where a lot of springs are present as result of groundwater reservoirs beneath the calcareous layers (Mulder and Warmerdam, 2006).

During the epochs of the Tertiairy period slightly different heavy clay layers were deposited in the area. The area between Stadtlohn and Lochem is most influenced during the Pleistocene period. In the Pleistocene glacial periods were alternated by interglacial periods. The Saalien ice age was a glacial period, glaciers from Scandinavian reached the Netherlands (also the Berkel area) and left fractions of boulder clay. This deposition is dominated by chalk and silt, the hydraulic conductivity is low. The Weichselien ice age was again a glacial period, but the glaciers did not reach the Berkel area. In the Netherlands permafrost occurred during this period which limited the infiltration of water, as a result surface flow eroded slopes in the ice pushed hills. The sea-level was very low at that time, the circumstances changed the area into a polar desert where a strong western wind deposited (moved) a lot of sand and silt. In the most recent geological period, Holoceen, fluvial depositions can be found near the course of the Berkel with finer depositions downstream (WRIJ, 2008; Haaksma et al., 2012).

2.3 Land use

Different land use types are present in the catchment of the Berkel. Information about the land use was based on the report of Hobbelt et al. (2011) who used land use maps to calculate the different percentages based on different smaller sub-catchments within the Berkel catchment (Figure 2.2). The potential evaporation is dependent on the crops in the field. Table 2.1 indicates that agricultural is the most dominant type of land use in the area.

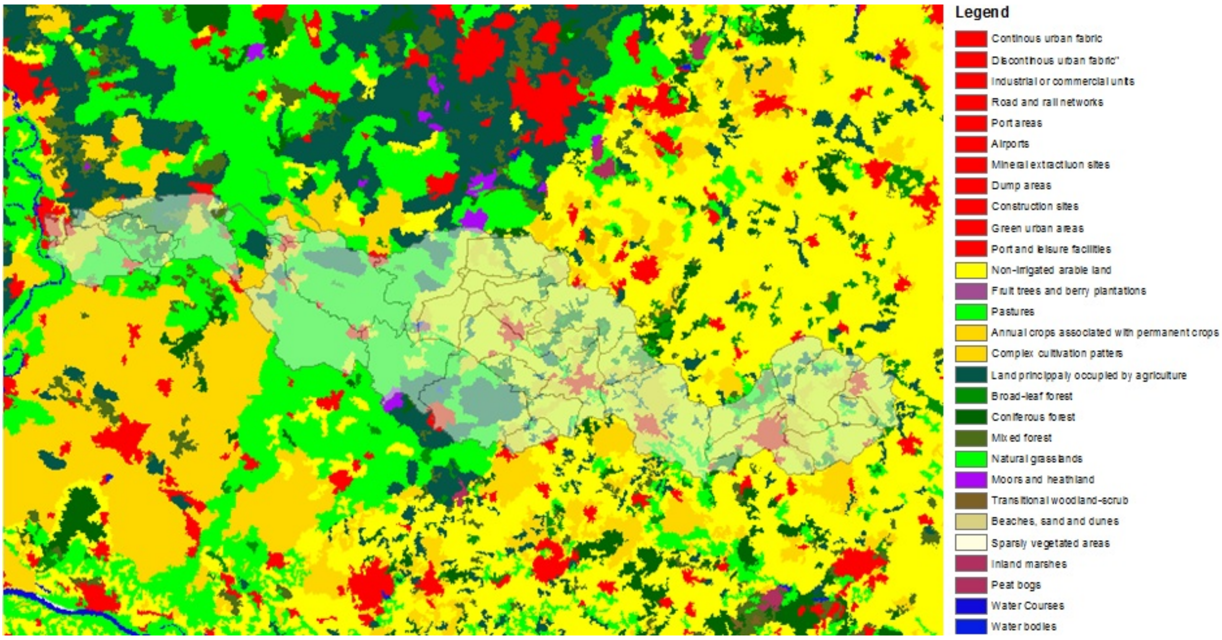

Figure 2.2: Land use in the Berkel catchment.

Table 2.1: Total area and land use covering percentages of Berkel sub-catchments

	Total area (km^2)	Urban area (%)	Agriculture (%)	Pastures (%)	Forest (%)
Lutum	38	9.5	79	3	8.5
Stadtlohn	231	7.5	78	6.5	8
Rekken	384	7	79	4	10
Haarlo	446	6	76	9	9
Lochem	709	5	63.5	25	6.5

2.4 Hydraulic structures

Along the Berkel several structures are realised in order to protect the downstream area from flooding. Three diversion channels exist between the Berkel and Twentekanaal, at Haarlo, Lochem and Eefde respectively. The maximum discharges of the two most upstream diversion channels are: Bolksbeek – 48 m^3/s and Lochem – 32 m^3/s (WRIJ, 2008). The third diversion channel at Eefde has no maximum discharge capacity, almost all the water of the Berkel is diverted directly to the Twentekanaal. Furthermore, a retention reservoir is build to store water for a couple of days to protect vulnerable areas downstream the weir of Mallum during extreme flood events. The maximum discharge capacity of the weir at Mallum is 81 m^3/s, above this discharge the water flows automatically into the reservoir (WRIJ, 2008). A total amount of $2.3*10^6$ m^3 can be stored (WRIJ, 2008). Until today the retention reservoir has never been used. The land owners do not receive compensation for possible losses when the reservoir will be used, although Waterboard Rijn en IJssel (WRIJ) must restore the damage, i.e. deposited sediment, remains of plants, etc.

3 Data Selection

For surface water and rainfall-runoff modelling three types of data are necessary: precipitation, potential evaporation and discharge. In Section 3.1 the precipitation time series are mentioned, followed by potential evaporation (Section 3.2) and discharge time series (Section 3.3). The chapter ends with a short description of the water balance of the German catchment area of the Berkel.

3.1 Precipitation time series

The precipitation time series were collected from previous surveys of the Berkel catchment (Hobbelt et al., 2011; Jansen et al., 2012; Haaksma et al., 2012). The actual precipitation in a catchment is not uniformly distributed due to catchment characteristics and seasonal effects. Hourly precipitation data were used and in Table 3.1 we see an overview of all measurement locations. Based on the length of the available precipitation records the start and end date were chosen. Starting point is 01-08-2002, since this is when the raingauge at Coesfeld started recording. The end of the period is 01-10-2008 since this is when the raingauge at Gescher stopped recording. In total 6 years of data were selected including extreme years, 2003 was a dry year and 2007 was a wet year (KNMI, 2014).

Table 3.1: Overview of the precipitation stations, the X and Y coordinates, data availability and the missing data

Station	X	Y	Data availability	Missing hours
Baumberg	294105	444787	01-01-1991 till 22-05-2011	0
Coesfeld	277532	440962	01-08-2002 till 22-05-2011	0
Legden	271578	452393	14-06-1996 till 10-04-2012	31
Gescher	266000	441500	27-05-1998 till 01-10-2008	0
Vreden	253764	450520	01-08-2002 till 22-05-2011	0
Hupsel	241397	454434	01-08-2002 till 22-05-2011	0

3.1.1 Verification

To check the consistency of precipitation records a ripple diagram is used. A ripple diagram shows the cumulative precipitation sums of the individual precipitation stations of the selected time period and helps to analyse the accuracy of the individual precipitation stations. Vreden deviates from the other stations from 2004 till the end of 2006, therefore this station was removed from the data (Figure 3.1). Furthermore, Baumberg and Coesfeld measures systematically more precipitation than the other rain gauges. The ridges (low mountain range *Baumberge*) are high enough to cause a small orographic effect on the precipitation distribution. A short statistical evaluation between station Baumberg (highest precipitation amount) and station Legden (lowest precipitation amount) of the time period 01-08-2002 till 01-10-2008 prove a maximum precipitation difference of 943 mm, a mean difference of 501 mm and standard deviation of 298 mm. Therefore all the precipitation stations (except station Vreden) are used for the calculation of areal precipitation.

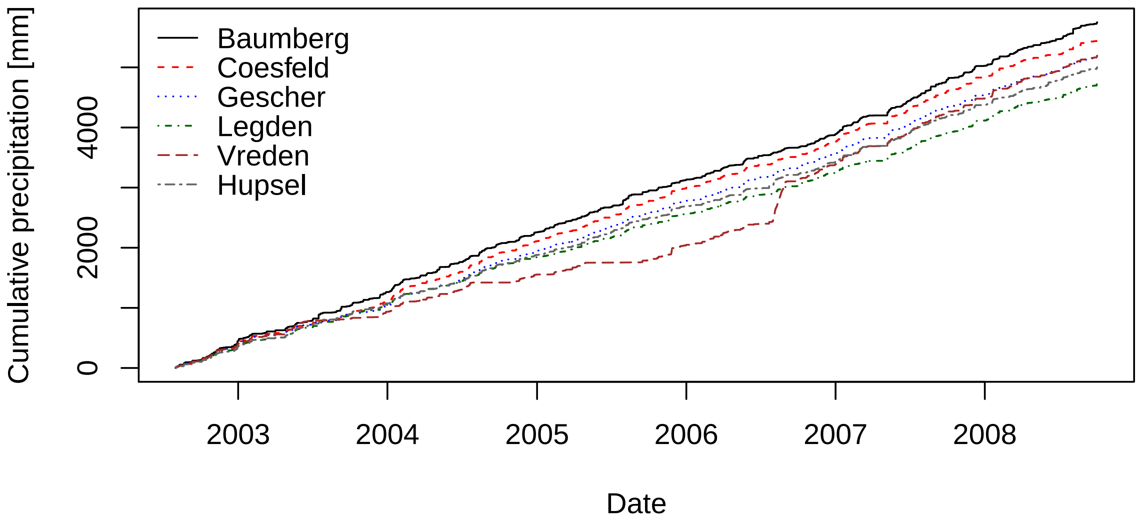

Figure 3.1: Ripple diagram of the cumulative precipitation sums of all the different precipitation stations.

3.1.2 Thiessen Polygons

Precipitation measured at one raingauge provides a point measurement. Several techniques exist to account for spatial and temporal variability of rainfall in a catchment. Mulder and Warmerdam (2006) showed that the Thiessen Polygons method is the most reliable methodology for the Berkel catchment, hence this method is used for the calculation of the areal precipitation. When Thiessen Polygons are used for interpolation, an interpolated field consists of polygons with boundaries at a distance halfway between the stations. Lines are drawn between the measurement stations and subsequently perpendicular bisectors are drawn to create the Thiessen polygons (Figure 3.2). The procedure was run using Voronoi polygons with a point coverage of the selected measurement stations. More information on Voronoi polygons can be found in Okabe et al. (2009).

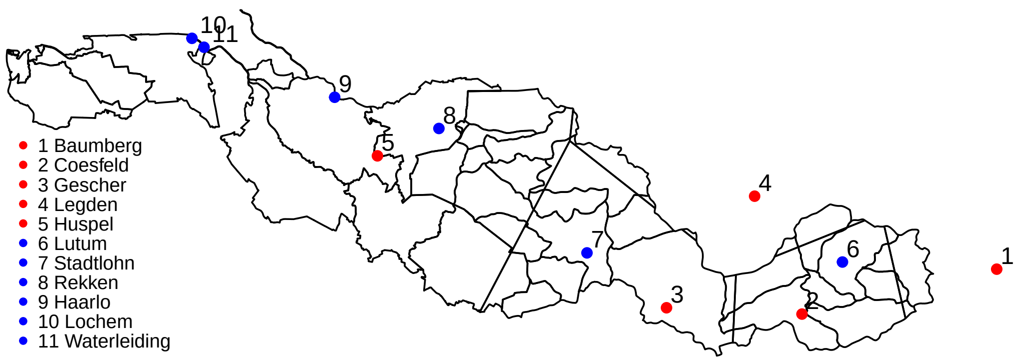

Figure 3.2: Calculated Thiessen polygons based on the 5 selected meteorological stations including names (red circles). Locations and names of the discharge stations (blue circles).

3.2 Potential evaporation time series

Potential evaporation is also necessary as input for rainfall-runoff modelling. Under Dutch conditions, potential evaporation is well described by the Makkink equation. The Makkink reference evaporation is mainly driven by incoming short-wave radiation and temperature (Makkink, 1957; Buishand and Velds, 1980; Hiemstra and Sluiter, 2011). The reference evaporation of the meteorological station Hupsel was used as representative for the Berkel catchment of the period 01-08-2002 till 01-10-2008. To calculate potential evaporation for a certain type of vegetation the reference evaporation is multiplied with a crop factor:

$$E_{pot} = k_c * E_{ref} \tag{1}$$

where E_{pot} is the potential evaporation (mm), E_{ref} is the reference evaporation (mm) and k_c is the cropfactor for optimal growth conditions (-). To calculate actual evaporation a reduction factor must be known of the potential evaporation, but this factor is unknown. Therefore only the potential evaporation is applied in our study. The catchment potential evaporation is determined with the following equation:

$$ET_{pot} = A_f * (K_f * E_{ref}) + A_a * (K_a * E_{ref}) \tag{2}$$

where ET_{pot} is the catchment average potential evaporation (mm), A_f is the percentage of forest in the catchment, K_f is the crop factor of forest (0.6), E_{ref} is the reference evaporation (mm), A_a is the percentage of agriculture in the catchment (-) and K_a is the crop factor of agriculture (1.0). The percentages of the different sub-catchments are summarised in Chapter 2.

3.3 Discharge time series

Five discharge stations along the Berkel were selected: Lutum, Stadtlohn, Rekken, Haarlo and Lochem. The characteristics of the selected discharge stations are summarised in Table 3.2. To compare the observed and simulated discharge values the same period is selected as for precipitation time series (01-08-2002 till 01-10-2008). The time series of the six locations including a return period of 1 year can be found in Figure A.1 till Figure A.6 in Appendix A.

Table 3.2: Characteristics of discharge stations

Station (-)	X (-)	Y (-)	Data availability (-)	Missing hours (% from total)
Lutum	280975	445935	30-10-1958 till 29-03-2011	0.005
Stadtlohn	259232	446172	01-01-2000 till 23-06-2011	1.9
Rekken	246631	456766	01-07-1971 till 29-02-2012	5.8
Haarlo	237758	459423	24-09-1999 till 29-02-2012	7.9
Lochem	225610	464440	24-09-1999 till 29-02-2012	6.6
Waterleiding	226635	464682	11-10-2011 till 01-05-2014	5.8

For the rainfall-runoff model and the open water model three stations were selected: Lutum, Stadtlohn and Grote Waterleiding. The most important criterion is the slope in the catchment (Chapter 2). This selection is further described in Section 4.2.

3.4 Selected hydrological years

We are interested in several hydrological years to include dry and wet periods in the simulation. The precipitation, potential evaporation and discharge time series were converted to UTC. Two separate hydrological years were selected for the calibration of WALRUS. We were interested in the simulation of extreme years with both high and low discharges in the selected period. For Lutum and Stadtlohn the hydrological years April 2003 – March 2004 and April 2007 – March 2008 (Figure 3.3 and Figure B.1 in Appendix B) were selected in order to have both low and high discharges in the time series. For Waterleiding the measurement period started later, therefore a different period is selected in comparison to Lutum and Stadtlohn, November 2011 – October 2012 and April 2013 – March 2014, still including low and high discharges (Figure B.2 and Figure B.3 in Appendix B).

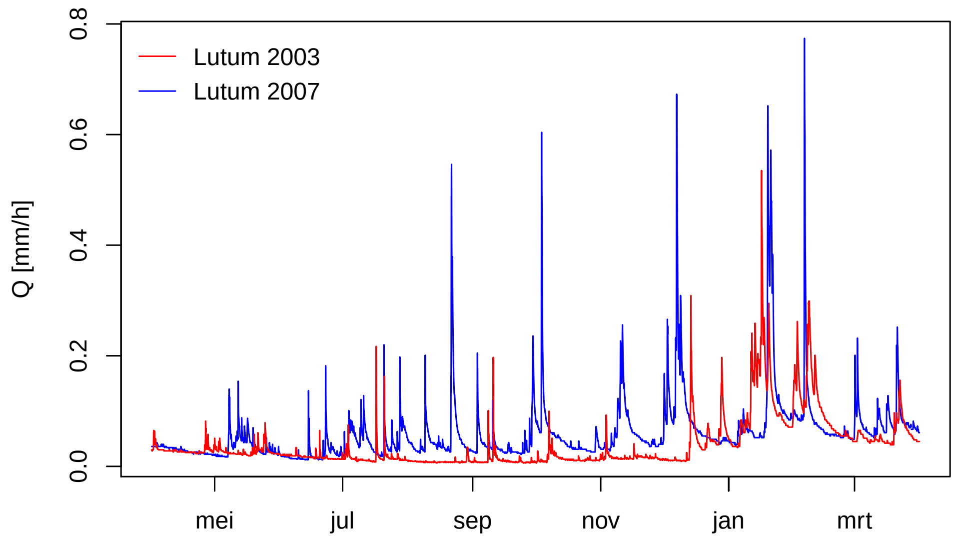

Figure 3.3: Two hydrological years for discharge station Lutum.

3.5 Water balance of the Berkel

In order to determine if the inflow equals outflow of the catchment a water balance is made. The water balance is a mass balance of the water that enters and leaves the catchment and the change of storage between start and end time of the time period. A longer time period will result in a smaller relative change of water storage. The balance equation is:

$$\Delta S = \int_{t_1}^{t_2} Q_{in}(t)\ dt - \int_{t_1}^{t_2} Q_{out}(t)\ dt \tag{3}$$

where ΔS is the water storage change in the selected period, $Q_{in}(t)$ is the amount of water that enters the catchment and $Q_{out}(t)$ is the amount of water that leaves the catchment. In reality the amounts of the different components are not exactly known. Precipitation enters the catchment while potential evaporation and discharge leave the catchment. The volume of seepage, infiltration or flow at the boundary is neglected (zero). These components are difficult to measure and a separate study can be necessary. The simplified water balance of the Berkel catchment is:

$$R = P - ET - Q - \frac{dS}{dT} \tag{4}$$

where P is precipitation (mm), ET is potential evaporation (mm), Q is discharge (mm), $\frac{dS}{dT}$ is the storage change (mm) and R is the rest term (mm). The potential evaporation equals actual evaporation because the reduction factor is unknown. The storage change in the catchment is negligible because we look at a long time period which makes the change in storage very small compared to the other components. Gap-free hydrological years are not present in the time series. For the area upstream of Rekken, Stadtlohn and Lutum a water balance for five hydrological years is calculated (Figure 3.4, 3.5 and 3.6). A negative rest term indicates that more water leaves than enters the system via precipitation. An explanation is for example that seepage is not taken into account. Furthermore the potential evaporation is calculated, the actual evaporation will be lower in dryer periods compared to the calculated potential evaporation which results in a smaller rest term. The positive rest terms of Lutum are the result of the high precipitation amounts. The hydrological year 03/04 is by far the driest year for Rekken and Stadtlohn.

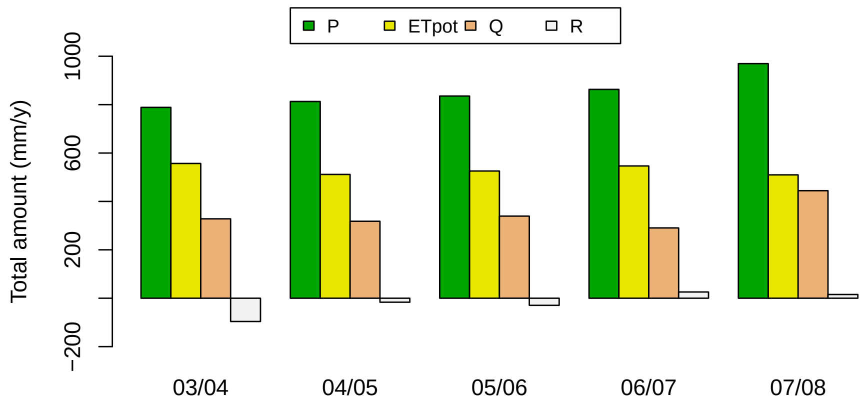

Figure 3.4: Water balance of the German catchment (upstream of Rekken). P is areal precipitation, ETpot is potential evaporation, Q is discharge of station Rekken and R is the rest term.

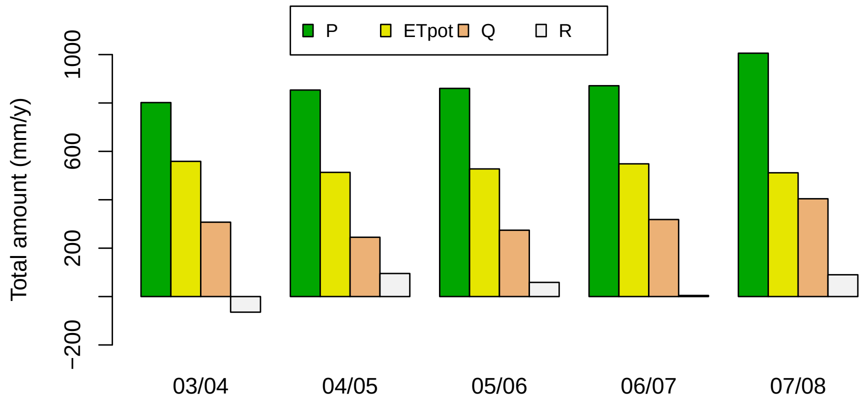

Figure 3.5: Water balance of the area upstream of Stadtlohn. P is areal precipitation, ETpot is potential evaporation, Q is discharge of station Stadtlohn and R is the rest term.

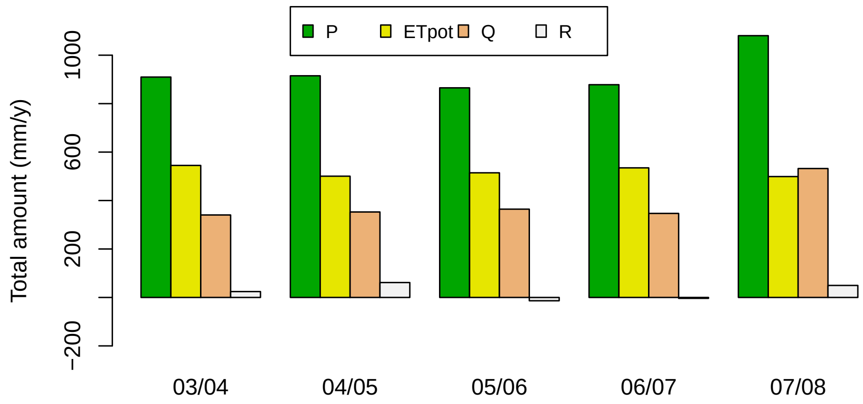

Figure 3.6: Water balance of the area upstream of Lutum. P is areal precipitation, ETpot is potential evaporation, Q is discharge of station Lutum and R is the rest term.

4 WALRUS

The Wageningen Lowland Runoff Simulator (WALRUS) is a water balance model developed by Claudia Brauer (Brauer et al., 2014a). WALRUS consists of three reservoirs: a soil reservoir, a quickflow reservoir and a surface water reservoir (Figure 4.1). The model can be split into 5 compartments: Land surface, vadose zone within the soil reservoir, groundwater zone within the soil reservoir, quickflow reservoir and surface water reservoir. External fluxes are seepage (f_{XG}) and extraction (f_{XS}). For a detailed model description readers are referred to Brauer et al. (2014a).

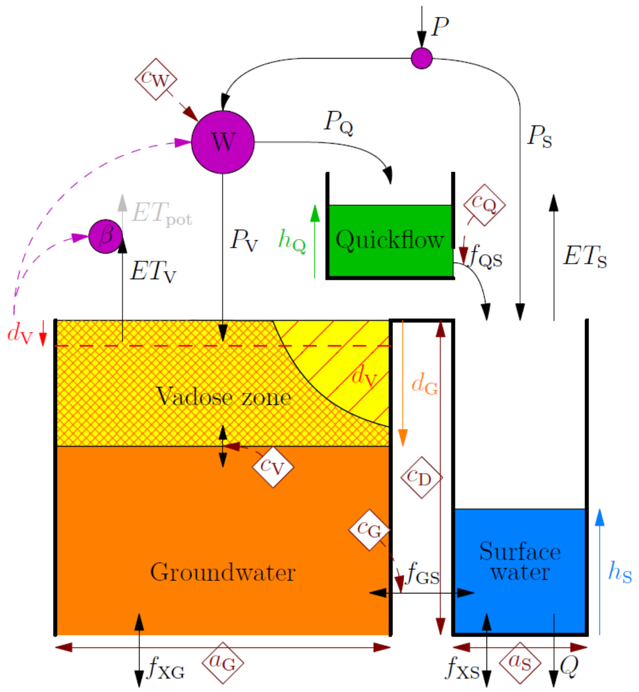

Figure 4.1: Overview of the model structure of WALRUS with the five compartments: land surface (purple), vadose zone within the soil structure (yellow/red hatched), groundwater zone (orange), quickflow reservoir (green) and surface water reservoir (blue). Fluxes are black arrows, model parameters are brown diamonds and states in the colour of the reservoir they belong to (Brauer et al., 2014a).

4.1 Assessment of model performance

The modelling performance of a hydrological model can be quantified. In our study the Nash-Sutcliffe Efficiency (NSE) is used to test the performance of a WALRUS (Nash and Sutcliffe, 1970):

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_{obs}(t_i) - Q_{mod}(t_i))^2}{\sum_{i=1}^{n}(Q_{obs}(t_i) - \overline{Q_{obs}(t_i)})^2} \tag{5}$$

where $Q_{obs}(t_i)$ is the observed discharge and $Q_{mod}(t_i)$ is the simulated discharge. NSE ranges from 1 to $-\infty$ where 1 represents a perfect match between observed and modelled discharge and a negative value indicates that the mean is a better predictor of the observed values. For all the optimised parameters the starting value was calculated based on the value with the lowest mean square error (MSE) within the chosen range of the parameters.

4.2 Calibration of WALRUS

WALRUS must be calibrated on historical data so that this model provide accurate simulations based on precipitation and potential evaporation. Calibration is adjusting parameters of a mathematically model in order to approximate the observed values. Parameters are not exchangeable between models of different catchments across a country because the heterogeneity in soil characteristics, geomorphology and geology are significant different. Some of the parameters in WALRUS can not be estimated from field observations because these parameters represent the total catchment or sub-catchments including heterogeneity and must therefore be calibrated. For the Berkel catchment six model parameters were optimised:

- Wetness parameter (cW) determines the soil wetness index which is the fraction of the remaining precipitation which percolates slowly through the soil matrix and the fraction which flows towards the surface water via quick flow routes.
- Groundwater reservoir constant (cG) represents the combined effect of all resistance and variability therein. Furthermore cG depends on soil type (hydraulic conductivity) and drainage density.
- Vadose zone relaxation time (cV) determines how quickly the system advances towards a new equilibrium.
- Quickflow reservoir constant (cQ) determines how fast outflow of the quick reservoir is decreased until the original value.
- Initial groundwater depth (dG0) below the soil surface.
- Bankfull discharge (cS) corresponds to the discharge at the catchment outlet when the surface water level reaches the soil surface. Calibration of cS is not necessary when a Q-h relation is present.

Two other parameters, aS and st are based on fieldwork observations (Appendix C and Appendix D). The ranges of different parameters are showed in Table 4.1. The user-defined functions with defaults of WALRUS remained the same.

Table 4.1: Parameters of WALRUS and minimum and maximum values for the calibration

Parameter	Unit	Minimum	Maximum
cW	mm	1	500
cG	mm	$10e^6$	$250e^6$
cV	h	1	200
cQ	h	1	200
dG0	mm	100	2000
cS	mmh^{-1}	1	30

An automatic calibration technique called hydroPSO is chosen which is a swarm optimisation technique developed by Zambrano-Bigiarini and Rojas (2013). In R the parameter optimisation algorithm is performed using the package "hydroPSO" to find the best fit parameter set. This calibration technique was also used in the application of WALRUS by Brauer et al. (2014b). The personal experience of hydroPSO is that this technique always produces results (simulated discharges), but the calculation takes a long time (almost one day). Other calibration techniques were not performed within this study and also the uncertainty of the different parameters was not investigated. In this study these applications were not feasible because the focus was on the coupling of SOBEK and WALRUS.

Figure D.1 in Appendix D shows the 28 sub-catchments within the Berkel catchment, but there are too few discharge time series to calibrate all these sub-catchments. So only the calibrated parameters sets of Lutum, Stadtlohn and Waterleiding are used for the calculation of the 28 sub-catchments. The steep sloping area (sub-catchments 1 till 9) is calibrated based on the observed discharge of measurement station Lutum, the slighty sloping area (sub-catchments 10 till 16 and 20 till 23) is calibrated with the observed discharge station of Stadtlohn and the flat area (sub-catchments 17 till 19 and 24 till 28) is calibrated with the discharge station of the small brook Waterleiding.

4.3 Results of calibration WALRUS

Lutum station April 2003 – March 2004
The hydrological year 2003 has a dry summer with a corresponding low observed discharge (Figure 4.2). WALRUS has difficulty with simulation the peak of high discharges because the observed peak is often underestimated. Furthermore the decline of discharge during the recession period is going too fast. The parameters calculated by hydroPSO are plotted inside Figure 4.2 (also valid for Figure 4.3 and 4.4).

Stadtlohn April 2003 – March 2004
Calibration of WALRUS for Stadtlohn has a good simulated discharge (ns=0.88). Peaks of the high discharges are underestimated and discharges during the recession periods decline too fast compared with the observed discharge (Figure 4.3) which corresponds to Figure 4.2. The dry summer period of 2003 is well simulated.

Grote Waterleiding
In Figure 4.4 we can see the period from November 2011 until October 2012. High discharges in the winter period are underestimated whereas lower discharges during the spring are overestimated. Other hydrological years can be found in Figures E.1, E.2 and E.3 in Appendix E.

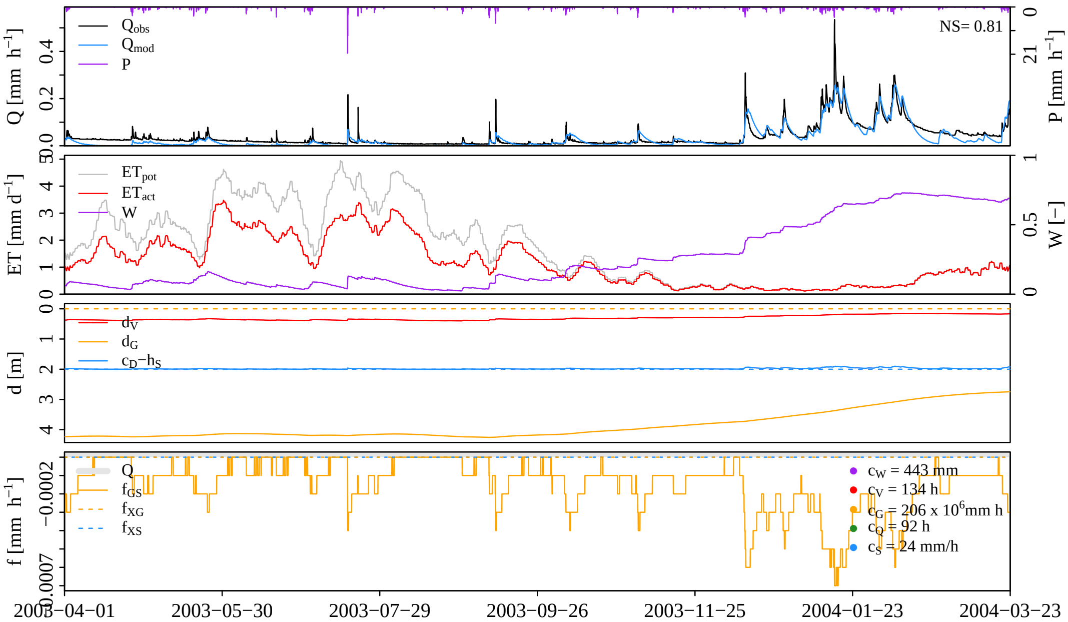

Figure 4.2: Model output of Lutum after calibration with observed discharge (Q_{obs}), simulated discharge (Q_{mod}), precipitation (P), potential evaporation (ET_{pot}), actual evaporation (ET_{act}) and wetness index (W). The surface water level (h_s) is measured with respect to the bottom, while the groundwater depth (d_G) is measured with respect to the soil surface. The channel depth (c_D) relates the two to each other. The storage deficit (d_v) is an effective thickness. External fluxes are seepage (f_{XG}) and surface water supply (f_{XS}). Internal flux is groundwater drainage / surface water infiltration (f_{GS}).

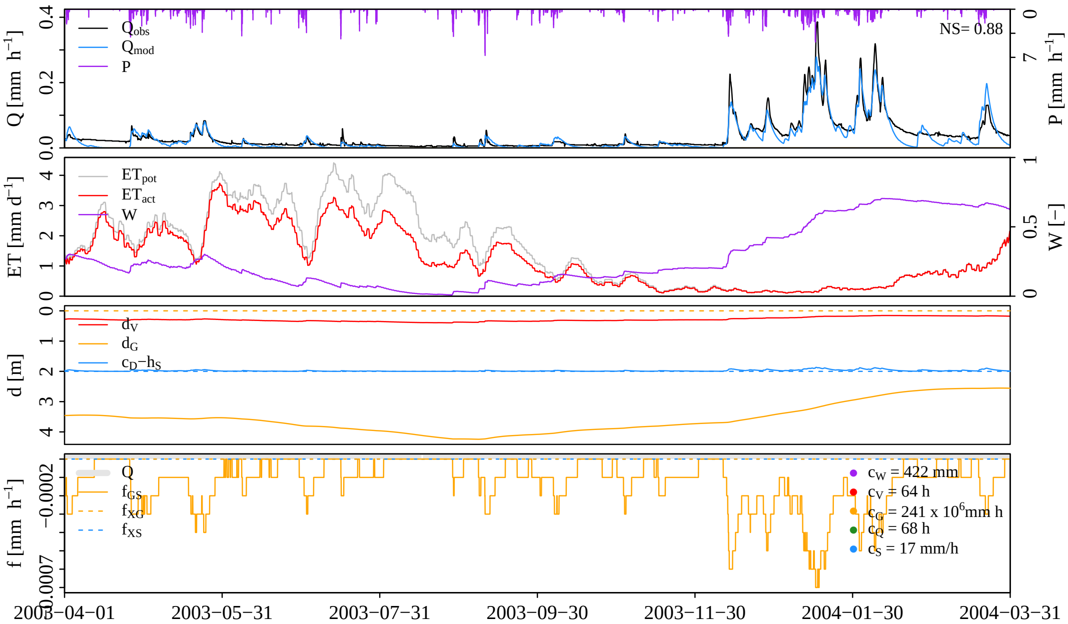

Figure 4.3: Model output of Stadtlohn after calibration with observed discharge (Q_{obs}), simulated discharge (Q_{mod}), precipitation (P), potential evaporation (ET_{pot}), actual evaporation (ET_{act}) and wetness index (W). The surface water level (h_s) is measured with respect to the bottom, while the groundwater depth (d_G) is measured with respect to the soil surface. The channel depth (c_D) relates the two to each other. The storage deficit (d_v) is an effective thickness. External fluxes are seepage (f_{XG}) and surface water supply (f_{XS}). Internal flux is groundwater drainage / surface water infiltration (f_{GS}).

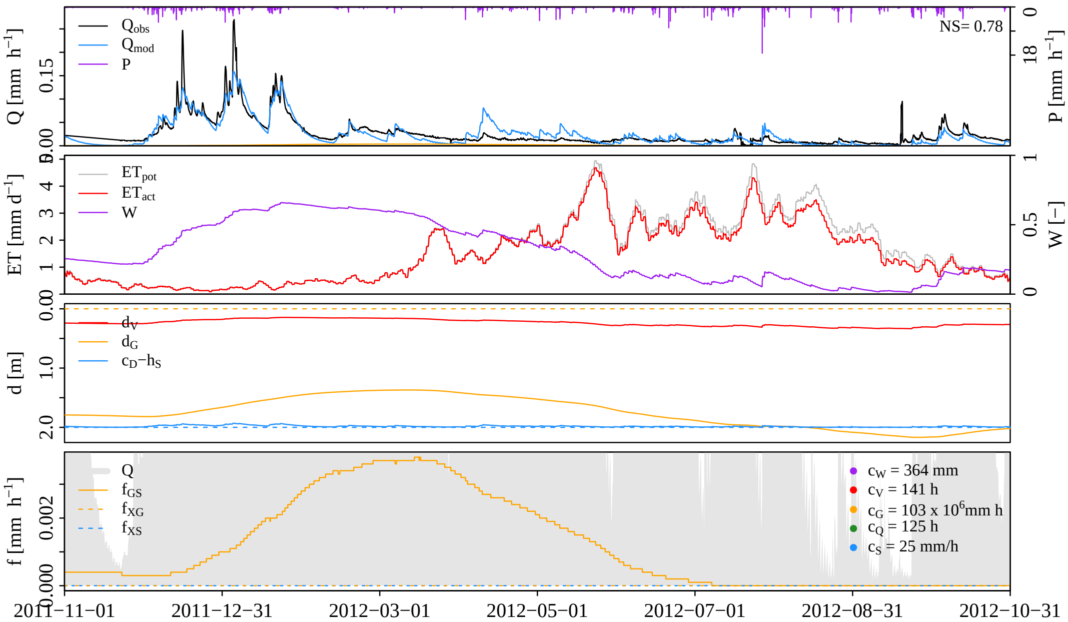

Figure 4.4: Model output of Waterleiding after calibration with observed discharge (Q_{obs}), simulated discharge (Q_{mod}), precipitation (P), potential evaporation (ET_{pot}), actual evaporation (ET_{act}) and wetness index (W). The surface water level (h_s) is measured with respect to the bottom, while the groundwater depth (d_G) is measured with respect to the soil surface. The channel depth (c_D) relates the two to each other. The storage deficit (d_v) is an effective thickness. External fluxes are seepage (f_{XG}) and surface water supply (f_{XS}). Internal flux is groundwater drainage / surface water infiltration (f_{GS}).

4.4 Conclusion

The best simulation runs calculated with the calibrated parameter sets as described in this chapter show that the simulated peak discharges and recession limbs deviate from the observed discharge. Furthermore at all discharge stations the surface water levels does not change during the year. In reality the surface water level fluctuates during the year (depending on the catchment characteristics). Most of the simulated groundwater levels ($\mathrm{d_G}$) are beneath the surface water level, physically this is not correct and is expected the other way around. Both issues are not further investigated because the focus is on the coupling. The parameter cS should not be calibrated because the value is very large. Automatic calibration for hydrological years is time consuming (making use of hourly time series more than one day).

5 SOBEK 1D Open Water model

SOBEK is a surface water modelling program developed by Deltares and can be used for flood modelling, sewer overflow design, river morphology, surface water quality, salt intrusion and drainage systems (Deltares, 2014). Within the SOBEK environment different programmes exist which can be used for integrated water systems. In this study only SOBEK 1D Open Water (Rural) is used and the RR module is replaced by WALRUS (Chapter 6).

5.1 Building 1D-model

In the schematisation of the channel flow module water branches are modelled with corresponding weirs, culverts, orifices etc. The schematisation of water branches is obtained by the use of connection nodes and reach segments. River profiles are adjusted to reach segments in order to define the shape of the water course. Friction, width of the river and channel depth below surface are properties of cross sections. Precipitation cannot directly fall on the developed schematisation. The discharge is triggered in two ways: 1) a constant or variable water height or discharge from the boundaries and; 2) lateral flow via a connection node. WALRUS is used as an indirect tool to calculate the lateral flow as input for further 1D schematisation.

5.2 The Berkel in SOBEK

A 1D-SOBEK model of the Dutch part of the Berkel catchment is made by WRIJ and was used as a starting point for the model of the total catchment. For the German catchment area of the Berkel a new 1D schematisation was added. Furthermore the Groenlosche Slinge, a main side-branch of the Berkel, was connected to the schematisation. The topographic map of Germany was used to determine the height above mean sea level. The dimensions of the German cross sections were estimated based on fieldwork, whereas the dimensions of Dutch cross sections were based on measured observations. Storage is included within the cross section of the model (Figure 5.1). All the 28 sub-catchments of the Berkel catchment (Figure D.1 in Appendix D) are represented by the use of single lateral flow nodes.

Boundary conditions

Each sub-catchment was adjusted to one connection node with lateral flow. Water is added to the main branch using the lateral flow nodes and the total discharge of the Berkel increases further downstream. The upstream boundary contains a constant discharge of 0.000001 m^3s^{-1}. The downstream boundaries at the outlet contain constant water levels of both 5.5 m above mean sea level (average water level IJssel). The three diversion channels to the Twentekanaal are also boundaries. Bolksbeek has a fixed water level of 16 m, Lochem has a fixed water level of 10 m and Eefde has a fixed water level of 5.5 m above mean sea level.

Weirs

All the weirs in the Dutch part of the catchment were determined using a GIS layer with detailed information about location, channel width and crest level. The few weirs in Germany were based on fieldwork which is less accurate then the Dutch weirs in the model. The weirs that control the water level in the diversion channels contain a controller function to check and divert the discharge.

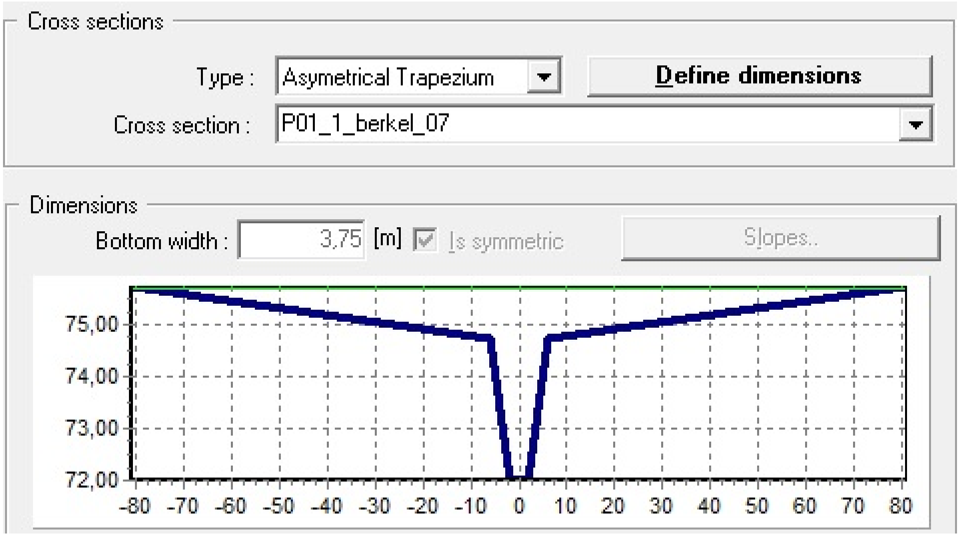

Figure 5.1: Example of a cross section (asymmetrical trapezium). Steep slope corresponds to the river bank and the slighting slope represents the inundation area.

Friction

There is large uncertainty about the right resistance coefficient. The resistance in the St-Venant equations is parametrized and not physically exact which means that there is an uncertainty about the resistance (Te Chow, 1959; Dingman, 1994). In our model we chose to use the friction calculation method of Strickler (Strickler, 1923). The mean flow velocity is calculated by:

$$v = K_s * R^{2/3} * S^{1/2} \tag{6}$$

where v is the mean flow velocity (ms^{-1}) K_s is the Strickler coefficient ($m^{1/3}s^{-1}$), R the hydraulic radius (m) and S the slope (-). The hydraulic radius is calculated by:

$$R = \frac{A}{P} \tag{7}$$

where R is the hydraulic radius (m), A is the cross sectional area of the flow (m^2) and P is the wetted parameter (m). In SOBEK rural a fixed Strickler coefficient is used which is in SOBEK converted to Chezy. To determine the magnitude of the Strickler friction in the SOBEK model Table 5.1 is used.

5.3 Retention reservoir Mallum

Close to the German border a retention reservoir is build to store water when a flood event from the upstream part of Germany enters The Netherlands. Until today the retention reservoir is never been used. In SOBEK the retention reservoir was build using different nodes to approach the working mechanism. In Figure 5.2 we can see a schematisation of retention reservoir Mallum. The node with the yellow colour represents the total storage of the inundation area. Waterboard Rijn and IJssel is interested how the reservoir works when a

Table 5.1: Vegetation rate and vegetation description related to the Strickler friction (CultuurtechnischeVereniging, 1958)

Vegetation rate (%)	Strickler Friction $(\frac{m^{\frac{1}{3}}}{s})$	Description (-)
0	34	Very clean
20	28	Clean
40	23	Slightly overgrown
60	15	Moderately overgrown
80	10	Strongly overgrown
100	5	Totally overgrown

virtual flood wave occurs in the upstream part of the Berkel. A virtual flood wave of 110 m^3s^{-1} is situated in SOBEK in order to see what the effect is downstream of the retention reservoir. Strickler resistances of 20 $m^{1/3}s^{-1}$ for the area upstream of Rekken and 33 $m^{1/3}s^{-1}$ for the area downstream of Rekken are used. The top of the flood wave is decreased significantly (around 30 m^3s^{-1}) when the water is stored in the retention reservoir (Figure 5.3). The water in the retention reservoir is released after a few days depending on how fast the water level drops which is clearly visible, the straight blue line increases again at August 29th compared to the dotted blue line (Figure 5.3). Without the reservoir a flood wave will be problematic for cities as Borculo and Lochem.

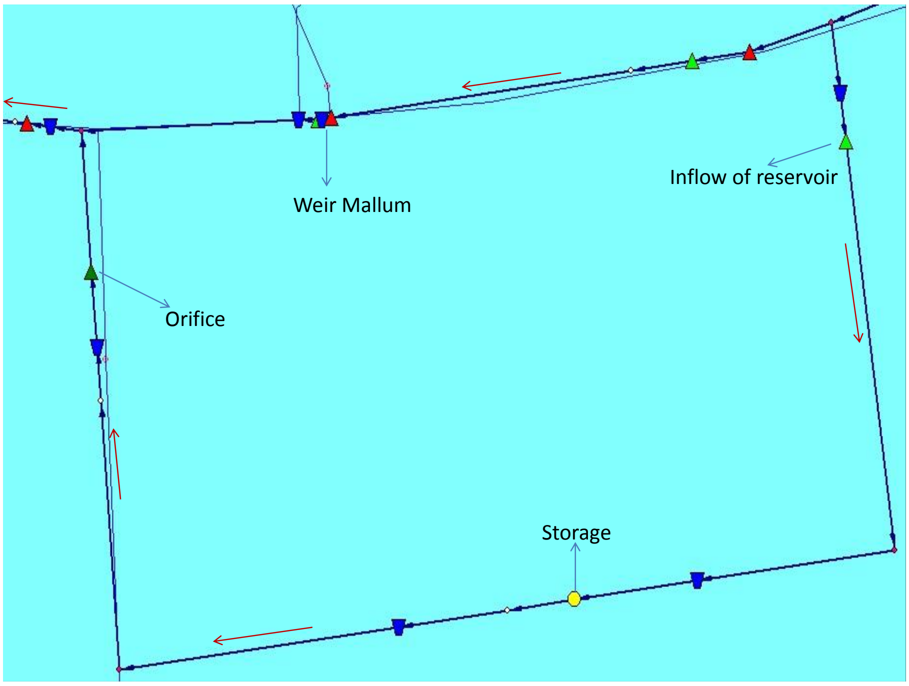

Figure 5.2: Schematisation of the retention reservoir Mallum. The blue triangles are cross sections, yellow circle is the water reservoir (storage), light green triangles are weirs, dark green triangle is a orifice and the red triangles are measurement stations. The brown arrows indicate the flow direction.

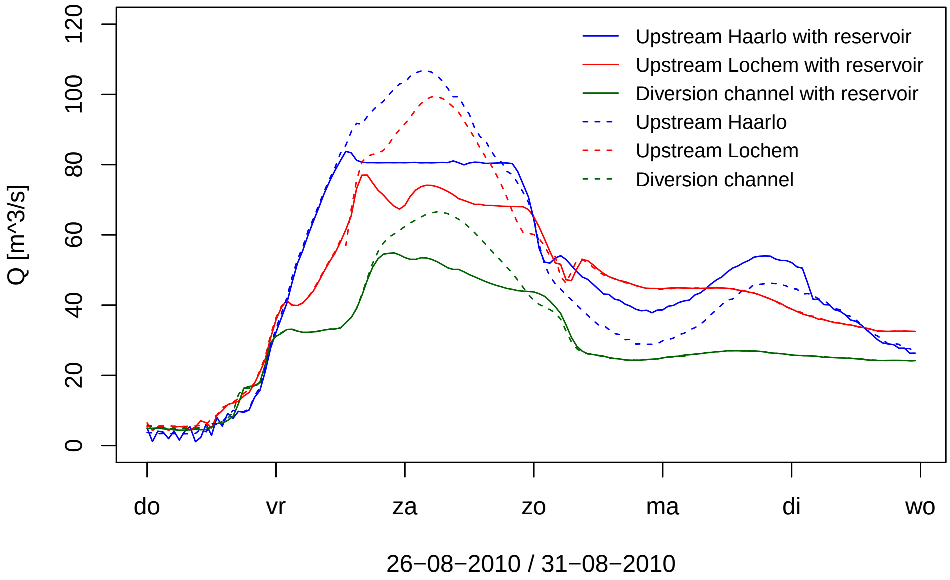

Figure 5.3: The discharge with or without the retention reservoir near Haarlo, Lochem and the diversion channel at Eefde. Straight lines indicate SOBEK with retention reservoir and dotted lines indicate SOBEK without retention reservoir.

5.4 Q-h relationship and storage

The resistance in a cross section has a major influence on th water level and discharge. The observed Q-h relation of Lutum (fixed and natural situation) is compared with the simulated Q-h relation using different Strickler resistances (Figure 5.4). A higher resistance causes an increase of the water level. A smoother profile has a higher discharge compared to a rough profile. High roughness in the profile prevents a quick flow in the river and as consequence the water level increases. The shape of the cross sections used in SOBEK also influence the Q-h relation, in the German part of the catchment the cross sections are estimated using fieldwork observations.

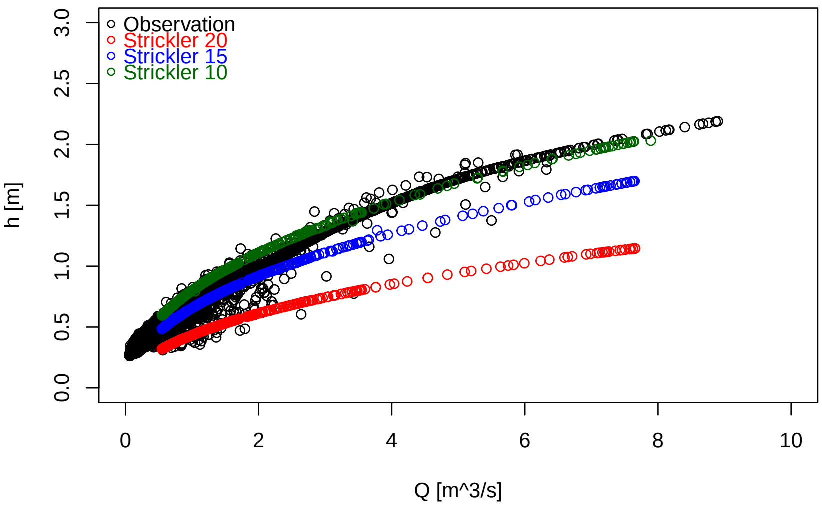

Figure 5.4: Q-h relation for different friction parameters of discharge station Lutum.

When applying a high resistance (rougher circumstances) the peak discharge of a flood event is lower (Figure 5.5). The duration of the flood event takes longer when the resistance is higher (more vegetation), but the peak discharge is relative low (Table 5.2). In a smoother profile the peak discharge of the flood event increases because water is discharged fast with only a short high peak.

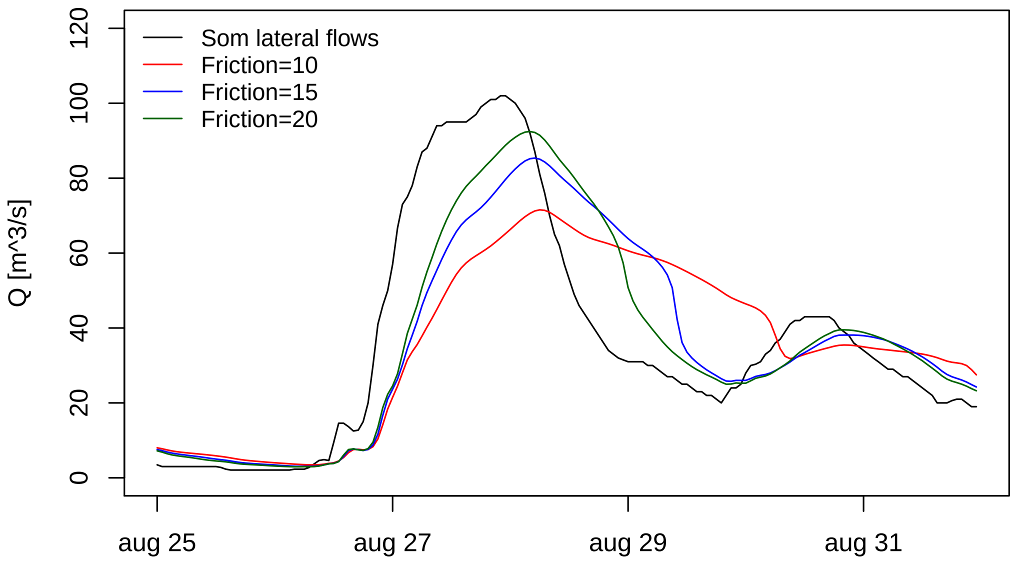

Figure 5.5: Discharge of the total amount of all lateral flow nodes (German catchment area of the Berkel) and the simulated discharge calculated with Strickler resistances of 10, 15 and 20 $m^{1/3}s^{-1}$ determined at the border of The Netherlands and Germany.

Table 5.2: Characteristics of flood waves calculated with different Strickler resistances

	Q-peak (m^3s^{-1})	Peak time (-)	Reduction Q-peak (%)	Lag time (hours)
Lateral flows	102	27-8-2010 22:00	-	-
Friction 20	92.4	28-8-2010 04:00	9.4	6
Friction 15	85.3	28-8-2010 05:00	16.4	7
Friction 10	71.5	28-8-2010 06:00	29.9	8

Due to a high resistance the flow velocity decreases in the Berkel. Vegetation in and along the Berkel lags flooding for a certain time and as consequence total storage increases when the resistance increases (Figure 5.6). First the water is stored in the river bed, after that the Berkel starts to inundate the flooding area. A transition zone (based on the dimensions of the cross sections) is included because there is no clear threshold between the storage in the river profile and inundation area. A smooth cross section causes a higher flow velocity and a corresponding lower storage.

5.5 Conclusion

When flood events occur in the German part of the Berkel catchment the retention reservoir Mallum can be used. The effect of the retention reservoir is significantly downstream of

Mallum, the top of the flood wave decreases. This study shows that the retention reservoir has an important contribution to protect the area downstream of Haarlo. Vegetation (roughness) increases the water level, but the total discharge decreases. A high roughness provides a slower velocity and a larger storage in the profile. Due to this high storage a lower flood wave occurs after a storm event, but the inundation time increases.

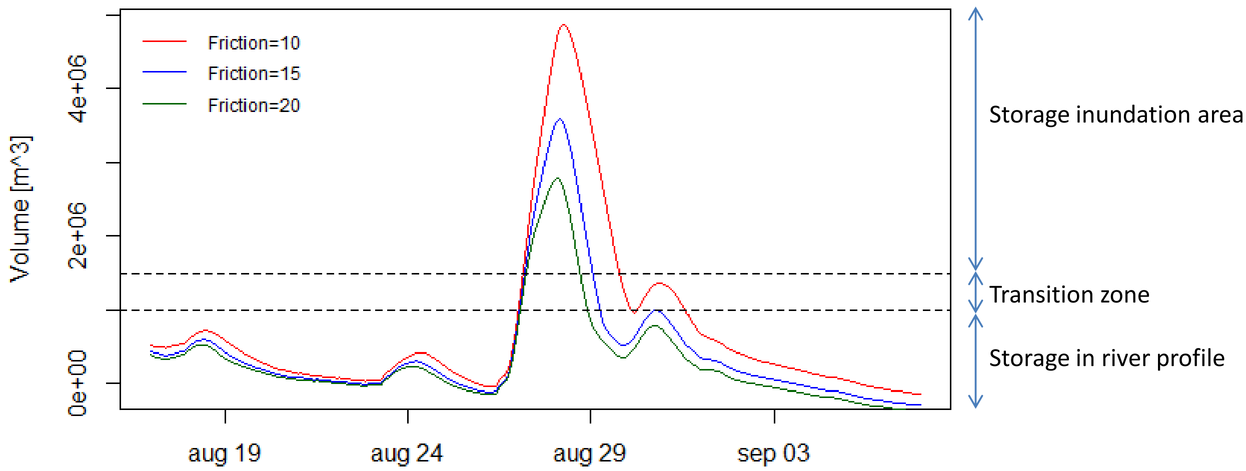

Figure 5.6: Water storage for the upstream area of Rekken with Strickler resistances of 10, 15 and 20 $m^{1/3}s^{-1}$. The transition zone indicates the area where the Berkel starts to inundate.

6 Coupling SOBEK and WALRUS

In this chapter the models described in Chapter 4 and Chapter 5 are coupled. In section 6.1 the technical aspects are mentioned. Section 6.2 discusses the sensitivity of the parameters.

6.1 WALRUS output as input SOBEK

The simulated discharges of the 28 sub-catchments are calculated with the calibrated parameter sets of Lutum, Stadtlohn and Waterleiding for the hydrological year 2005 (Section 4.2 and Figure D.1 in Appendix D). Each sub-catchment has an unique areal precipitation (Table D.1 in Appendix D). All 28 simulated discharge time series of WALRUS are coupled with corresponding lateral flow nodes in the SOBEK model. SOBEK uses all these lateral flows nodes to calculate the total discharge. Furthermore we are interested in the difference between the output of WALRUS and SOBEK.

6.2 Sensitivity of parameters

There are two main differences between SOBEK and WALRUS; maximum peak discharge and routing component. In SOBEK the peak discharges are slightly lower compared to WALRUS due to the resistance of the cross sections (Figure 6.1). The shape of the peaks is the almost the same, but the rising limbs and recession limbs are more smoothed in the SOBEK model. Furthermore a phase shifting is present in the SOBEK model induced by the hydraulic routing component (Figure 6.2). The generated calibrated parameter sets have a major influence on validation of the hydrological input records. The coupling procedure is most affected by these parameter sets, applying several parameter sets result in completely different simulated discharges. Finally the lateral flow nodes in SOBEK depends on the simulated discharge in WALRUS.

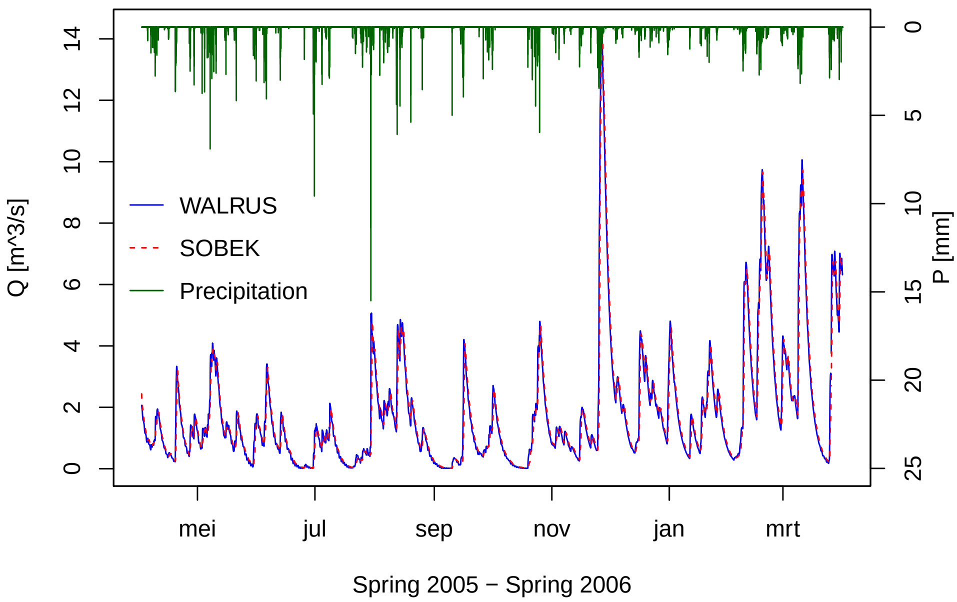

Figure 6.1: The hydrological year 2005–2006 of WALRUS (red) and SOBEK (blue) of discharge station Stadtlohn.

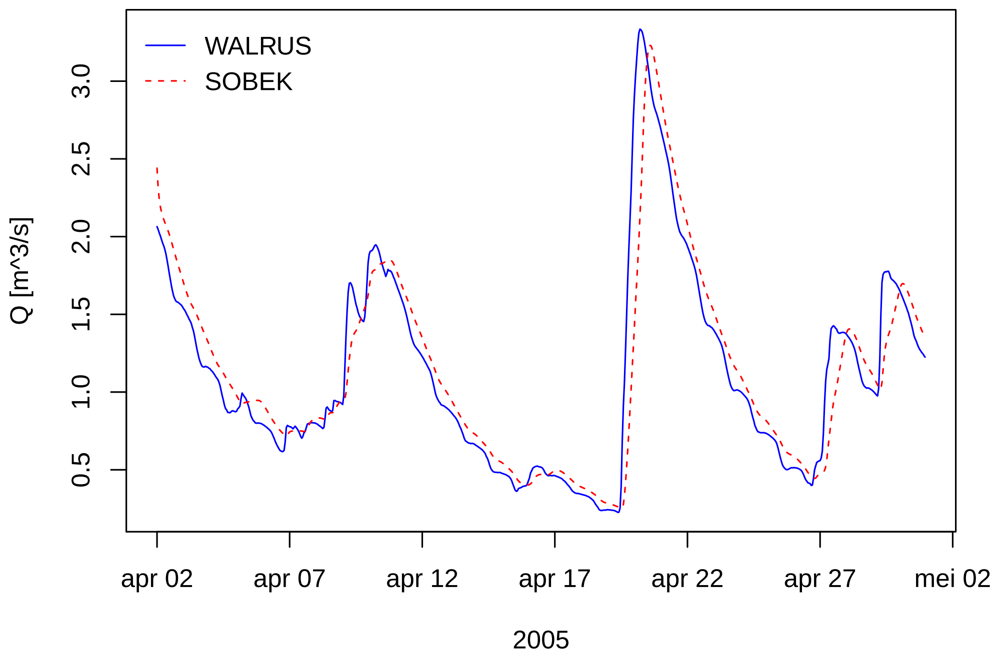

Figure 6.2: April 2005 of WALRUS (blue) and SOBEK (red) of discharge station Stadtlohn.

7 Discussion

7.1 WALRUS

Data quality

In WALRUS gaps in the time series are automatically interpolated which results into gap-free data for the SOBEK model. For the areal precipitation the Thiessen Polygons interpolation technique is used, however the effect of location and orographic effect is not taken into account. The limited amount of rain gauges (only six in this study, Table 3.1) can negatively influence the reliability of the areal precipitation. A better estimation of the areal precipitation is the use of radar rainfall data, although the observation record is limited (Krajewski and Smith, 2002). From January 2012 Waterboard Rijn and IJssel has access to radar time series, in the near future these radar rainfall data will be used to estimate the spatial distribution of precipitation. A recent technique is the use of mobile telephone networks to measure precipitation (Overeem et al., 2013). For the potential evaporation only the Hupsel station was selected, however the spatial variance of evapotranspiration is far less variable compared to precipitation (KNMI, 2014). Therefore one station of potential evaporation is representative to use in these models.

Calibration

WALRUS performed well, with Nash-Sutcliffe efficiencies of 0.81,0.88 and 0.78 for the calibration periods of Lutum, Stadtlohn and Waterleiding respectively (Figure 4.2, 4.3 and 4.3). The structure and characteristics of WALRUS influence the quality of the discharge predictions. A calibration model cannot not guarantee that model predictions will generate the same values compared to the values of the real-time measurements (Beven, 2011). In WALRUS the peaks of high discharges are often underestimated which is an example of an amplitude error (Serban and Askew, 1991). Deviations between simulated and observed discharge can be caused by the following aspects:

- WALRUS is a simplification of the reality (conceptual model). Both spatial variation of wet and dry conditions and response time of rainfall-runoff process are still difficult to simulate.
- Input data add uncertainty to the predictions (Vrugt et al., 2005). Checking and validation of these data helped to reduce errors in the input data (Chapter 3).
- Errors exist in simulation of the surface- and groundwater level. A solution might be the use of a fixed stage-discharge relation in order to skip the parameter cS. Furthermore initial groundwater level should be fixed (always start with a groundwater level above channel depth) which means that parameter cG needs no calibration. Only four parameters are left for optimization which ensures that the deviation will become smaller.
- The optimization technique can find a local optimum instead of the absolute optimum. Ensembles are generated for different forcing data or parameter sets to indicate predictive uncertainty (Krzysztofowicz, 2001).

7.2 SOBEK

Data quality
For the area upstream of Rekken fieldwork was necessary to estimate cross sections and crest levels of weirs, but fieldwork is rather subjective and not very reliable. For the Dutch part shapefiles are present (for example height of crest levels) which improves the quality of the model.

Q-h relation
The Strickler resistance is calibrated based on the observed Q-h relation of discharge station Lutum. Furthermore the Q-h relation depends on coarse estimated cross sections and channel depths. After application of the exact measured cross sections the calibration should be performed again. For comparison discharge station Stadtlohn should also be calibrated.
The water level increases when a higher resistance is used and in addition the amount of storage becomes larger. The peak discharge reduces, but the inundation period increases (area downstream is longer affected by high discharges). A study of Veldman et al. (2006) examined that the growing vegetation in the cross section has a negative influence on the water level which is in line with our results. In comparison to wide and deep streams, small streams are more vulnerable for growth of vegetation. The water plants are not rigid but will bend in the stream direction and water can flow between the leaves and stems. Therefore the resistance decreases and can be overestimated in a model (Freeman et al., 2000).

7.3 Coupling

The delay of a discharge event depends on the catchment characteristics and where the precipitation falls (Beven, 2011). WALRUS might give better results when a routing function of the rainfall-runoff process is taken into account. The routing function is included due to the coupling between WALRUS and SOBEK. A lag time is clearly visible when both simulated discharges are compared with each other (Figure 6.2). The generated parameter sets used for validation have difficulty to predict an event in another season, directly influence the SOBEK model which is dependent on the processes taking place in WALRUS.

8 Conclusions and recommendations

8.1 Conclusions

In this report we studied if a coupling is possible between WALRUS and SOBEK. We tested the newly developed rainfall-runoff model WALRUS for three locations within the Berkel catchment: steep sloping area of Lutum, slightly sloping area of Stadtlohn and the flat area of Waterleiding. WALRUS performed well, with an average Nash-Sutcliffe efficiency of 0.79 for the calibration periods (hydrological years). However, WALRUS has difficulties in reaching the peak of the high discharges and the recession limbs often decrease too fast. In SOBEK is indicated that the resistance of the cross sections has a significant influence on the water level and discharge. Therefore a high resistance results into a reduced peak of the flood event and an increased inundation time. During a virtual flood event the discharge decreases significantly when the water is temporary stored in a retention reservoir. The parameter sets obtained during calibration can have a major influence on the prediction of discharge in another season. Hydraulic routing provides an additional time lag before the water reaches the outlet of the catchment. WALRUS is suitable as rainfall-runoff model for SOBEK and investigation of other catchments is necessary in order to judge whether WALRUS in combination with SOBEK can be used as early warning tool for the prediction of floods and droughts.

8.2 Recommendations

This study leads to the following recommendations:

- To improve the calibration of WALRUS parameters dG0 and cS should be fixed. Both parameters need no calibration any more and the calculation time will decrease. Implement a stage-discharge relation to fix cS and a initial groundwater level to fix dG0.
- The geology can be taken into account in order to see where seepage and infiltration occur in the catchment. When the amounts are significant, both terms can be included in the water balance.
- To get an improved quality of both models complete time series are necessary. Hourly observations are recommended because of high temporal distribution.
- Investigate whether radar rainfall measurements are more accurate in prediction of areal precipitation compared to Thiessen Polygons interpolation technique.
- Compare WALRUS output with other rainfall-runoff models (HBV, sacramento) and investigate which model gives the best simulation of the discharge in order to get better predictions of floods and droughts.
- For more realistic results of the German part of the Berkel catchment a digital elevation map and cross sections (width of channel, slope, etc.) are necessary and should be implemented in the schematisation of SOBEK.

References

Beven, K. J. (2011). *Rainfall-runoff modelling: the primer.* John Wiley & Sons.

Brauer, C., Teuling, A., Torfs, P., and Uijlenhoet, R. (2014a). The wageningen lowland runoff simulator (walrus): a lumped rainfall-runoff model for catchments with shallow groundwater. *Geoscientific Model Development Discussions*, 7(1):1357–1411.

Brauer, C., Torfs, P., Teuling, A., and Uijlenhoet, R. (2014b). The wageningen lowland runoff simulator (walrus): application to the hupsel brook catchment and cabauw polder. *Hydrology and Earth System Sciences Discussions*, 11(2):2091–2148.

Buishand, T. and Velds, C. (1980). *Klimaat van Nederland 1: Neerslag en verdamping.* KNMI.

CultuurtechnischeVereniging (1958). *Richtlijnen voor het ontwerpen van open waterlopen en sommige bijbehorende kunstwerken.* Assen: van Gorcum.

Deltares (2014). Sobek suite. `www.deltaressystems.com`.

Dingman, S. (1994). *Physical hydrology*, volume 575. Prentice Hall Englewood Cliffs, NJ.

Freeman, G. E., Rahmeyer, W. H., and Copeland, R. R. (2000). Determination of resistance due to shrubs and woody vegetation. Technical report, DTIC Document.

Googlemaps (2014). Topographic maps. `www.googlemaps.nl`.

Haaksma, H., Torfs, P., Brauer, C., van den Houten, G., and Koskamp, M. (2012). Ensemble flood forecasting for the berkel: a practical implementation study. Master's thesis, Wageningen University.

Hiemstra, P. and Sluiter, R. (2011). *Interpolation of Makkink evaporation in the Netherlands.* KNMI.

Hobbelt, L., Teuling, A., and Brauer, C. (2011). Extreme neerslag en overstromingen in oost-nederland en delen van duitsland. BSc thesis, Wageningen University.

IPCC (2014). Climate change 2014: Impacts, adaptation, and vulnerability. part a: Global and sectoral aspects. contribution of working group ii to the fifth assessment report of the intergovernmental panel on climate change. [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jansen, F., Teuling, A., and Brauer, C. (2012). Relation between catchment characteristics and peak discharges. BSc thesis, Wageningen University.

KNMI (2014). Climatological data bank. `www.knmi.nl`.

Krajewski, W. and Smith, J. (2002). Radar hydrology: rainfall estimation. *Advances in water resources*, 25(8):1387–1394.

Krzysztofowicz, R. (2001). The case for probabilistic forecasting in hydrology. *Journal of Hydrology*, 249(1):2–9.

Makkink, G. (1957). Testing the penman formula by means of lysimeters. *J. Inst. Water Eng*, 11(3):277–288.

Mulder, M. and Warmerdam, P. (2006). Neerslag-afvoer modellmodel van stroomgebied de berkel in duitsland. Master's thesis, Wageningen University.

Nash, J. and Sutcliffe, J. (1970). River flow forecasting through conceptual models part ia discussion of principles. *Journal of hydrology*, 10(3):282–290.

Okabe, A., Boots, B., Sugihara, K., and Chiu, S. (2009). *Spatial tessellations: concepts and applications of Voronoi diagrams*. John Wiley & Sons.

Overeem, A., Leijnse, H., and Uijlenhoet, R. (2013). Country-wide rainfall maps from cellular communication networks. *Proceedings of the National Academy of Sciences*, 110(8):2741–2745.

Serban, P. and Askew, A. (1991). Hydrological forecasting and updating procedures. *IAHS Publ*, (201):357–369.

Stricker, J. N. M. and Warmerdam, P. M. M. (1982). Estimation of the water balance in the hupselse beek basin over a period of three years and first report to simulate the rainfall runoff process for a complete year. In *Proceedings of the International Symposium on Hydrological Research Basins and their Use in Water Resources Planning*, Bern, Switzerland.

Strickler, A. (1923). *Beiträge zur Frage der Geschwindigkeitsformel und der Rauhigkeitszahlen für Ströme, Kanäle und geschlossene Leitungen*. Eidg. Amt für Wasserwirtschaft Bern.

Te Chow, V. (1959). *Open channel hydraulics*. McGraw-Hill Book Company, Inc; New York.

Veldman, W., Augustijn, D., Huthoff, F., and Visser, M. (2006). Maaien of niet? effect van de flora en faunawet op het peilbeheer. Master's thesis, Universiteit Twente.

Vrugt, J. A., Diks, C. G., Gupta, H. V., Bouten, W., and Verstraten, J. M. (2005). Improved treatment of uncertainty in hydrologic modeling: Combining the strengths of global optimization and data assimilation. *Water Resources Research*, 41(1).

WRIJ (2008). Waterrapport 2006-2008. Technical report, Waterschap Rijn en IJssel.

Zambrano-Bigiarini, M. and Rojas, R. (2013). A model-independent particle swarm optimisation software for model calibration. *Environmental Modelling & Software*, 43:5–25.

Appendices

A Time series discharge stations

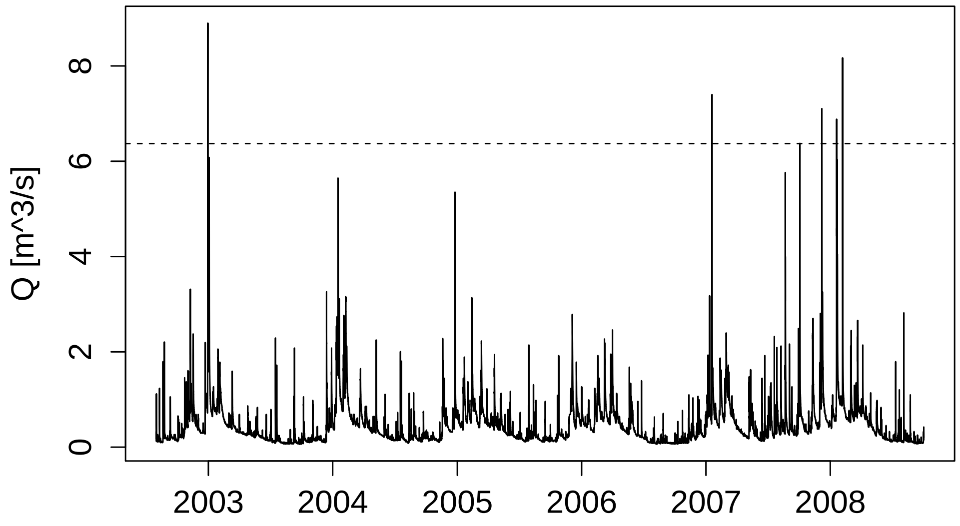

Figure A.1: Time series of discharge station Lutum. The dotted line corresponds to a return period of 1x a year.

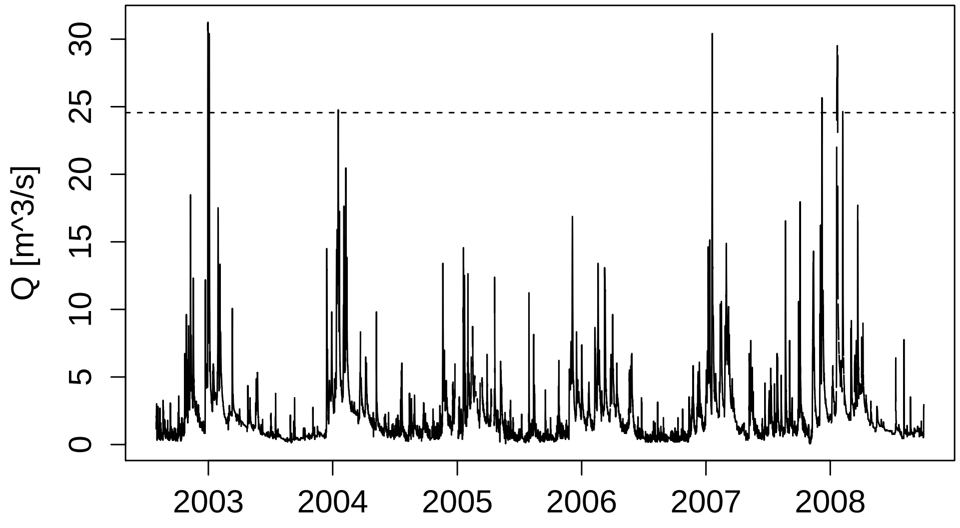

Figure A.2: Time series of discharge station Stadtlohn. The dotted line corresponds to a return period of 1x a year.

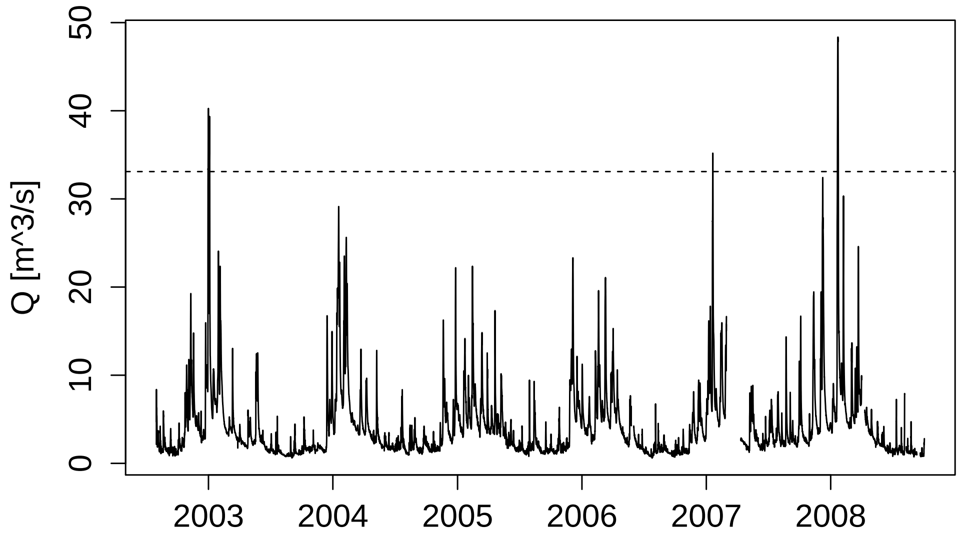

Figure A.3: Time series of discharge station Rekken. The dotted line corresponds to a return period of 1x a year.

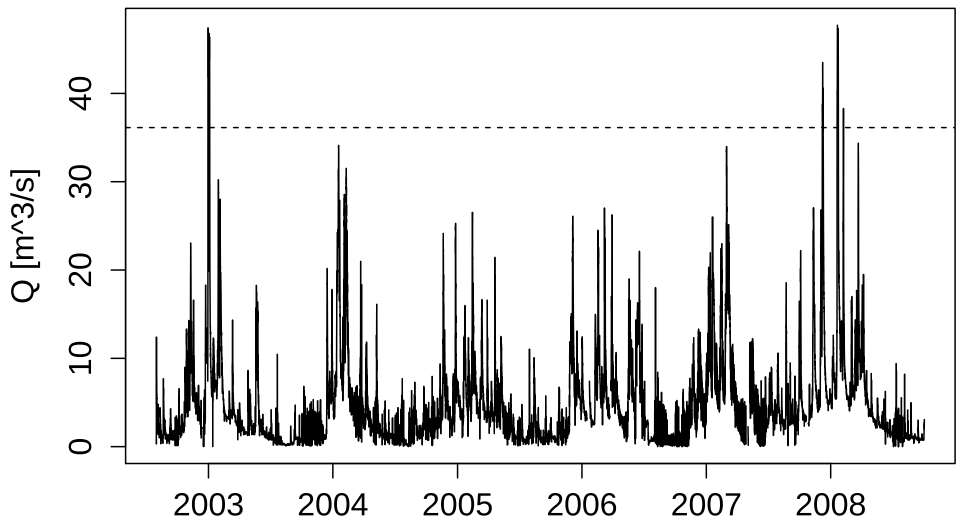

Figure A.4: Time series of discharge station Haarlo. The dotted line corresponds to a return period of 1x a year.

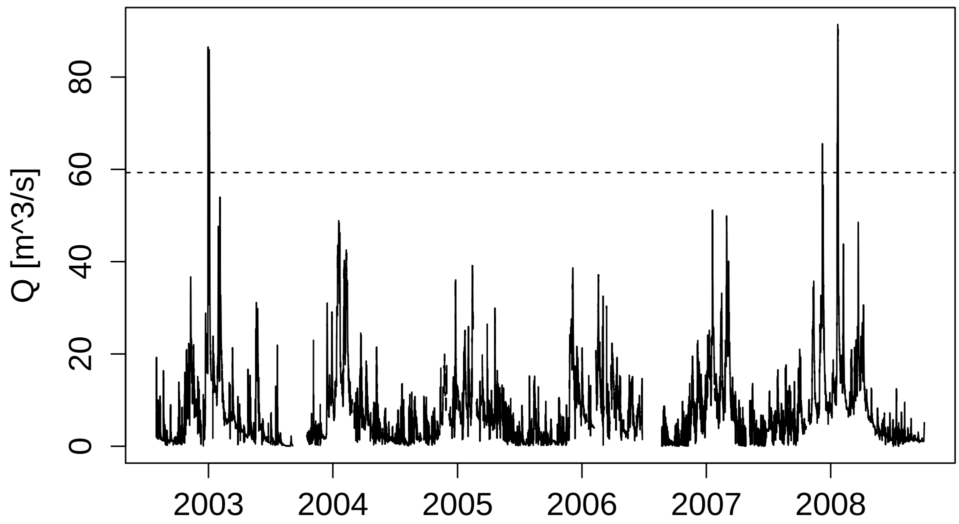

Figure A.5: Time series of discharge station Lochem. The dotted line corresponds to a return period of 1x a year.

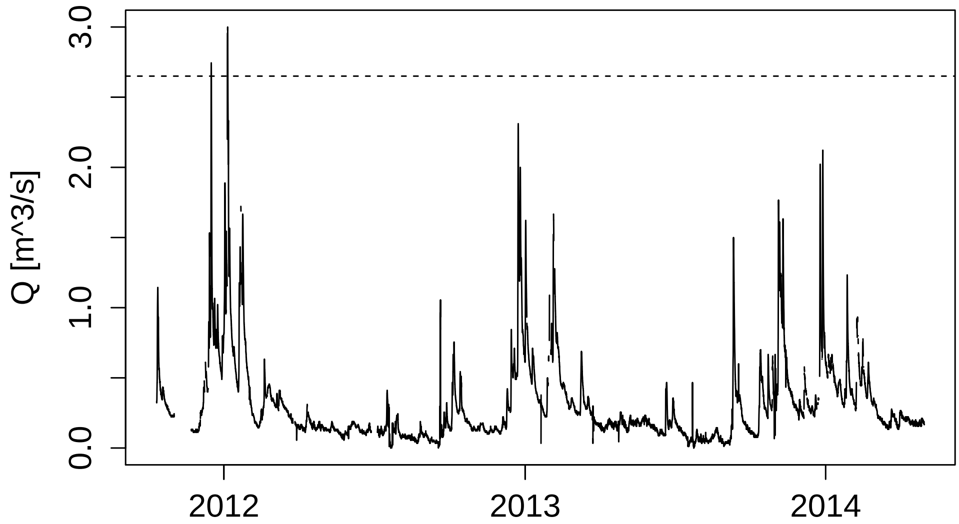

Figure A.6: Time series of discharge station Waterleiding. The dotted line corresponds to a return period of 1x a year.

B Selection hydrological years

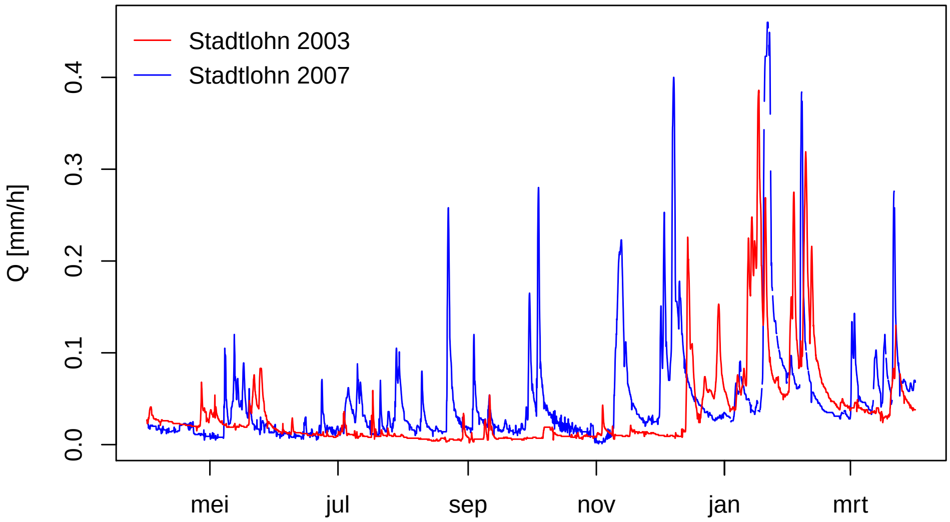

Figure B.1: Hydrological years 2003–2004 and 2007–2008 of discharge station Stadtlohn.

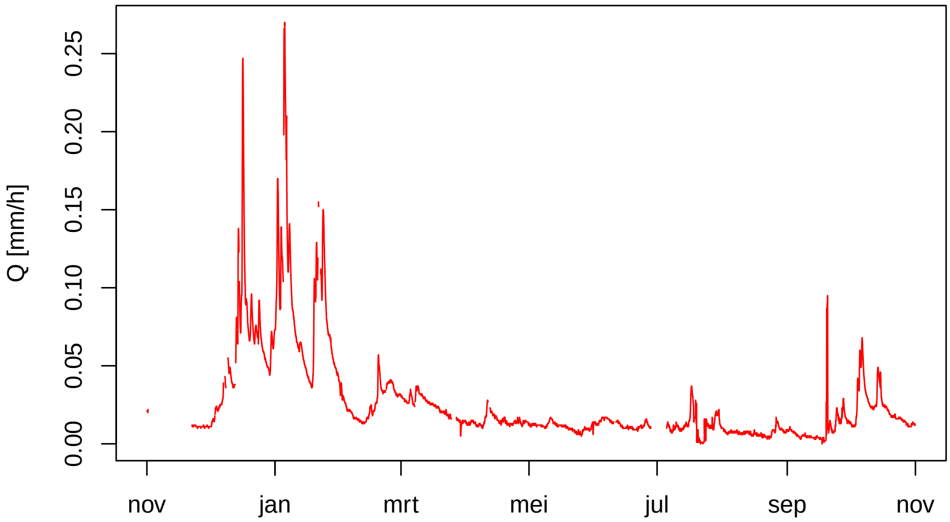

Figure B.2: Period November 2011–October 2012 of discharge station Waterleiding.

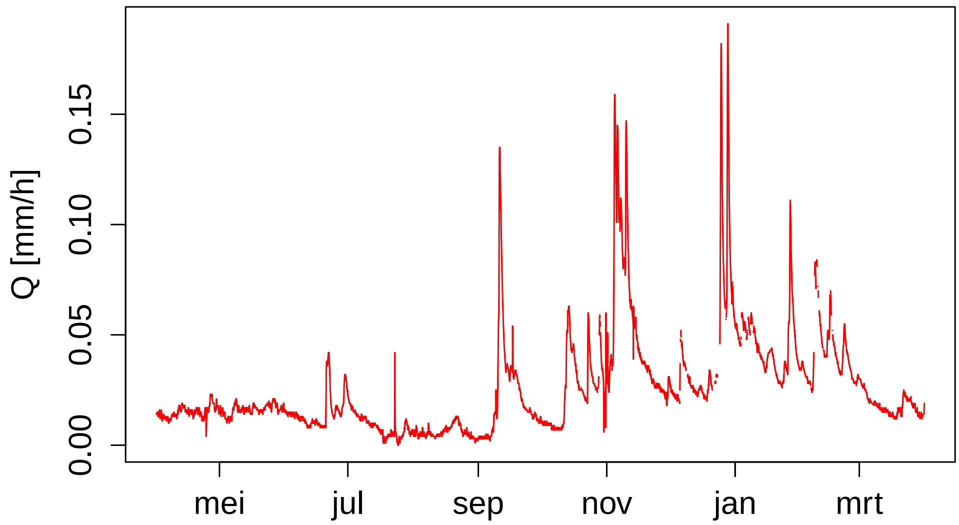

Figure B.3: Hydrological year 2013–2014 of discharge station Waterleiding.

C Fieldwork Berkel catchment

The objective of the fieldwork was to describe the Berkel catchment. The programs ArcGIS and Google Maps were used to select the most interesting locations for the fieldwork. The 10th of April Gert van den Houten and I visited the Berkel catchment. We started at the source of the Berkel and followed the Berkel downstream. The most important characteristics of the different stops are shortly summarised:

1. The source of the Berkel is located at the western side of the Baumberge. Seepage from the aquifers causes the start of the Berkel (Figure C.1).

Figure C.1: Source of the Berkel catchment (spring).

2. As second stop we visited the discharge station Lutum (Figure C.2). The LANUV is responsible for the measurements and maintenance.

Figure C.2: Berkel at discharge station Lutum.

3. In the German part of the catchment several weirs are installed, but not all of them are used any-more. Some of the weirs are in a very poor ure condition (Figure C.3).

4. A sand trap at Rekken was build to prevent that sand settles in undesirable places in the Netherlands. Some structural works are installed and a local widening exists.

5. The flood retention basin of the Berkel is located at Mallum and has a storage capacity of $2.3 * 10^6$ m^3, complete surrounded by dikes. The basin can be emptied by a sluice in the Ramsbeek, this river flows downstream Mallum into the Berkel.

Figure C.3: Example of the poor conditions of a weir in Germnay.

6. Three weirs are installed along the Dutch part of the Berkel and automatically programmed to divert the water between the Twentekanaal and the Berkel. As result the Berkel narrows further downstream and a significant amount of water is diverted during the year to the Twentekanaal.

7. Re-meandering of the *Berkel* is under construction and will be finished at the end of 2014 (Figure C.4). Several meander loops are built and when these meanders are finished nature development will take place without any human interference.

Figure C.4: Re-meandering of the Berkel.

D Characteristics sub-catchments Berkel

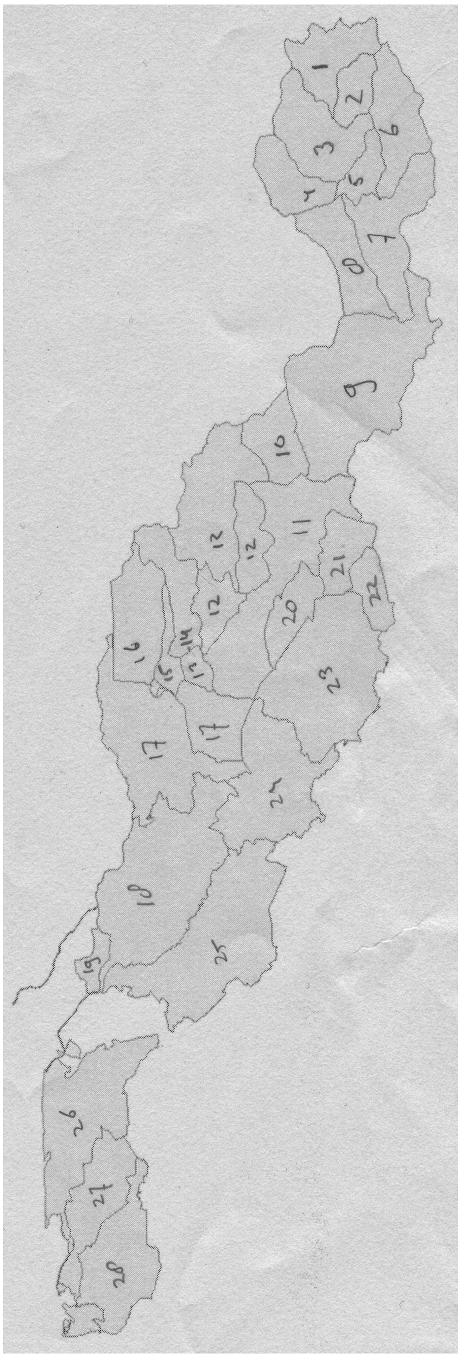

Figure D.1: Different sub-catchments of the Berkel. The numbers correspond to Table D.1

Table D.1: Characteristics of the different sub-catchments of the Berkel

Location (-)	aS (-)	cD (mm)	Soil Type (-)	Area (km^2)	Thiessen Polygons (-)
1	0.01	2000	sandy-clay-loam	17.87	1/5 Coesfeld, 4/5 Baumberg
2	0.01	2000	sandy-clay-loam	8.8	4/5 Coesfeld, 1/5 Baumberg
3	0.01	2000	sandy-clay-loam	25.01	7/8 Coesfeld, 1/8 Baumberg
4	0.01	2000	sandy-clay-loam	14.64	2/5 Coesfeld, 3/5 Legden
5	0.01	2000	sandy-clay-loam	7.65	Coesfeld
6	0.01	2000	sandy-clay-loam	21.59	1/9 Baumberg, 8/9 Coesfeld
7	0.01	2000	sandy-clay-loam	26.93	1/15 Gescher, 14/15 Coesfeld
8	0.01	2000	sandy-clay-loam	19.45	1/15 Legden, 3/15 Gescher, 11/15 Coesfeld
9	0.01	2000	sandy-clay-loam	65.86	11/15 Gescher, 3/15 Coesfeld, 1/15 Legden
10	0.01	2000	sandy-clay-loam	15.01	1/10 Legden, 9/10 Gescher
11	0.01	2000	sandy-clay-loam	48.66	2/5 Hupsel, 3/5 Gescher
12	0.01	2000	sandy-clay-loam	58.09	1/5 Hupsel, 3/5 Gescher, 1/5 Legden
13	0.01	2000	sandy-clay-loam	3.91	Hupsel
14	0.01	2000	sandy-clay-loam	16.24	9/10 Hupsel, 1/10 Legden
15	0.01	2000	sandy-clay-loam	5.92	Hupsel
16	0.01	2000	sandy-clay-loam	24.00	Hupsel
17	0.01	2000	sand	62.17	Hupsel
18	0.01	2000	sand	63.12	Hupsel
19	0.01	2000	sand	5.93	Hupsel
20	0.01	2000	sandy-clay-loam	12.32	3/5 Hupsel, 2/5 Gescher
21	0.01	2000	sandy-clay-loam	12.49	Gescher
22	0.01	2000	sandy-clay-loam	8.94	Gescher
23	0.01	2000	sandy-clay-loam	54.64	1.5 Gescher, 4/5 Hupsel
24	0.01	2000	sand	40.57	Hupsel
25	0.01	2000	sand	60.22	Hupsel
26	0.01	2000	sand	43.49	Hupsel
27	0.01	2000	sand	26.76	Hupsel
28	0.01	2000	sand	30.29	Hupsel

E Results of calibration

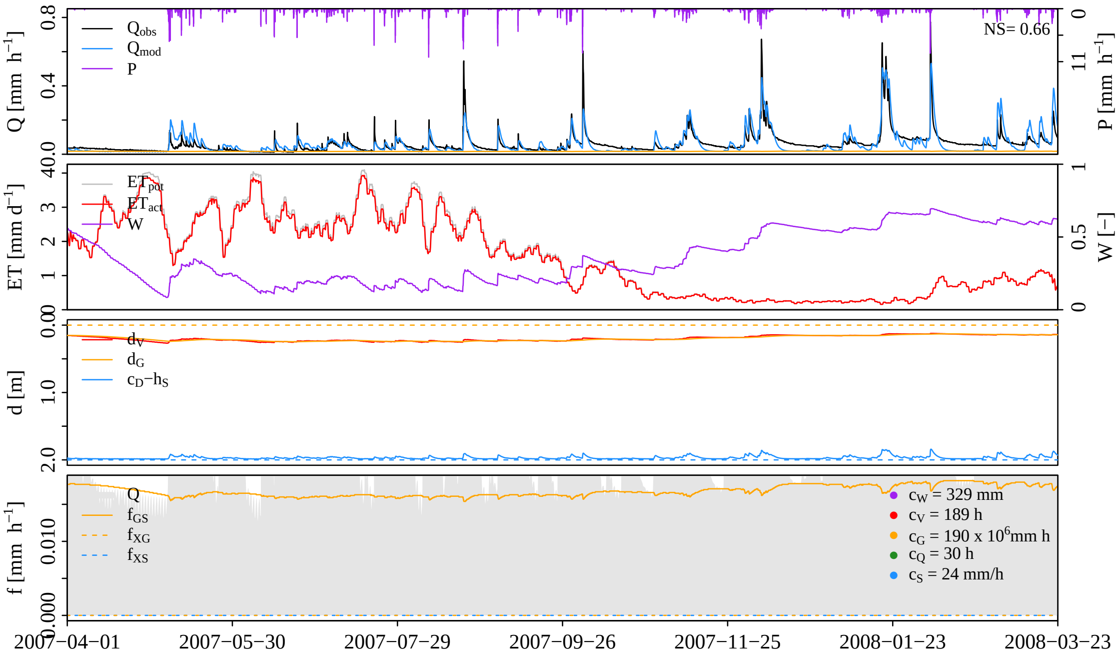

Figure E.1: Calibration (with hydroPSO) of the hydrological year 2007 for discharge station Lutum.

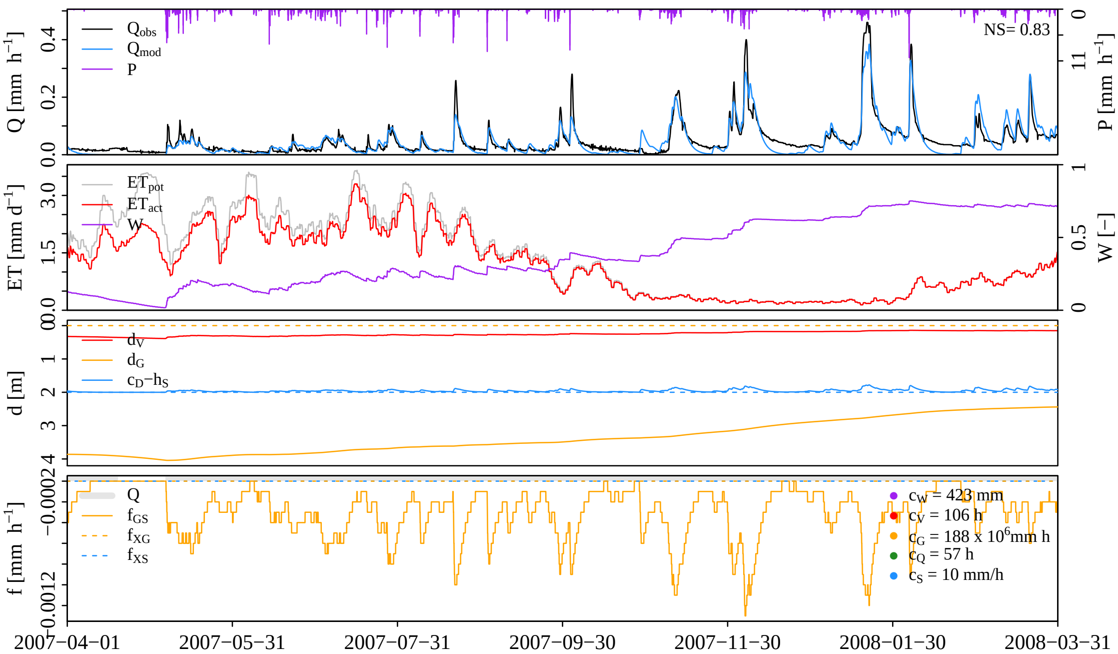

Figure E.2: Calibration (with hydroPSO) of the hydrological year 2007 for discharge station Stadtlohn.

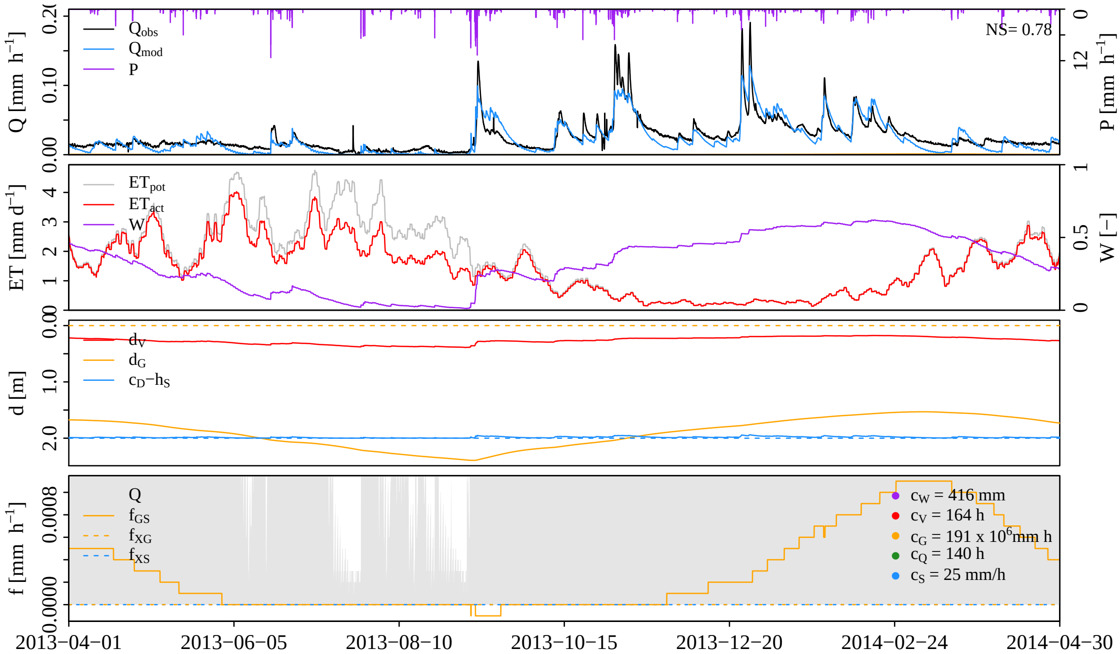

Figure E.3: Calibration (with hydroPSO) of the hydrological year 2013 for discharge station Waterleiding.