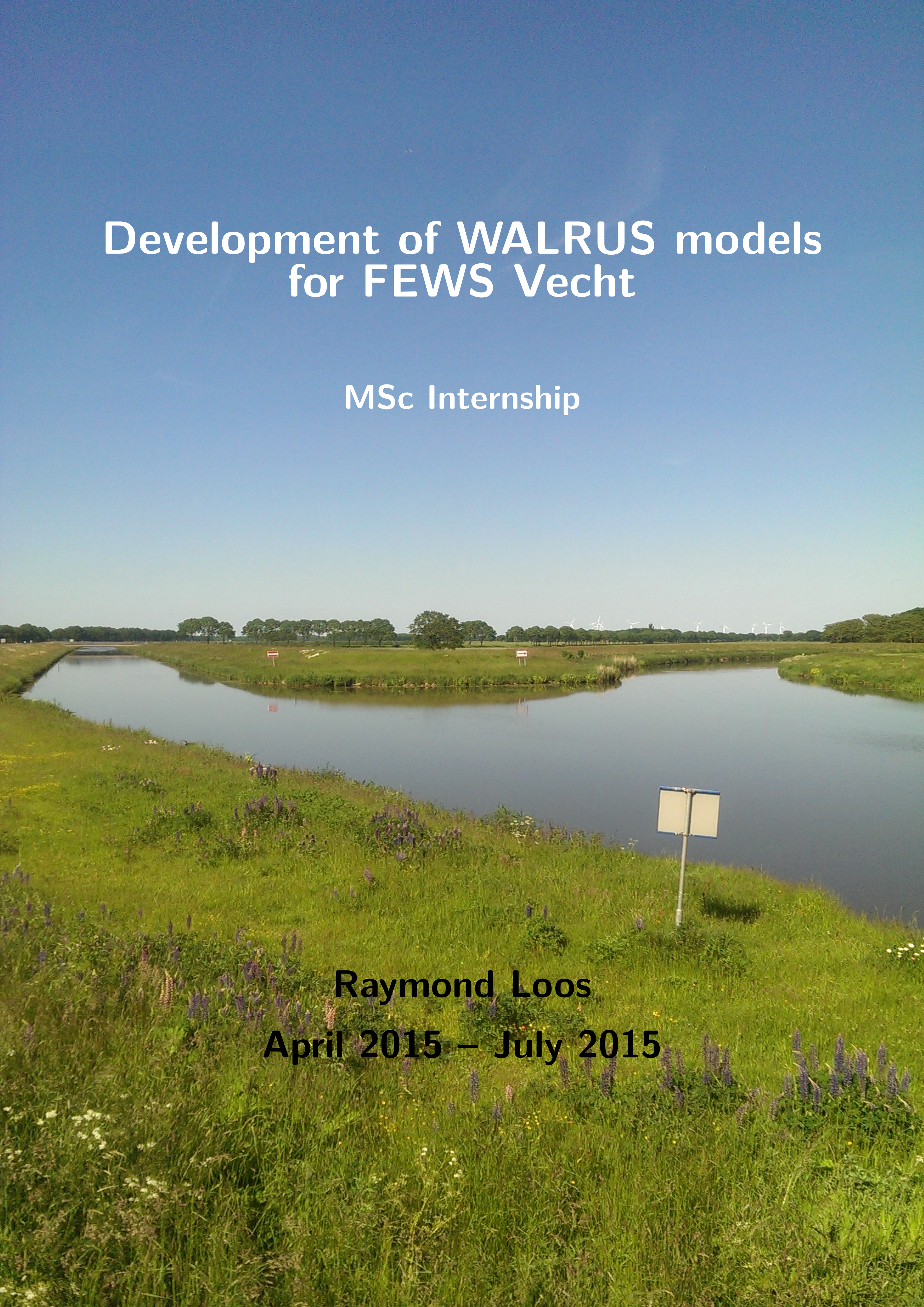
Development of WALRUS models for FEWS Vecht

MSc Internship



Raymond Loos

April 2015 – July 2015

Development of WALRUS models for FEWS Vecht

MSc Internship

Raymond Loos

Registration number: 910830528010

Hydrology and Quantitative Water Management Group

Wageningen University

April 2015 – July 2015

Preface

This report is the result of an internship at water board Vechtstromen in order to finish my MSc Earth & Environment (specialization Hydrology and Quantitative Water Management) at the Wageningen University. First of all, I would like to thank two persons in special: Pieter Filius (my supervisor at water board Vechtstromen) for giving me the opportunity to do an internship, being interested in the WALRUS concept and the professional and enthusiastic supervision during my internship. Claudia Brauer (Hydrology and Quantitative Water Management Group at Wageningen University) is the other person I would like to thank in special. She introduced me as an internship searching student during her WALRUS workshop and there I met Pieter. I would also like to thank Claudia for the interesting discussions we had about WALRUS and giving advice on some topics in this study. Furthermore, I would also like to thank Paul Torfs (supervisor at the Wageningen University), Gerben Tromp (water board Groot Salland) for providing data, Henk Top (water board Vechtstromen) and Tineke Wijnands (water board Vechtstromen), also for providing data and other useful information and Jeroen van der Scheer (water board Vechtstromen) for giving me feedback on the report that you can all read now. Finally, I like to thank my family, friends and all other people I met during my internship at water board Vechtstromen for their interest and support during this four months of work.

Abstract

The flood warning tool FEWS Vecht is developed in order to get one forecast system for the entire basin of the Vecht, which is located in Germany and the (East of) Netherlands. HBV models are currently implemented in this flood warning tool, but it has been observed that those models are not accurate enough during a first peak discharge after a longer dry period. Users of FEWS Vecht are looking for alternative rainfall-runoff models that are performing better. The Wageningen Lowland Runoff Simulator (WALRUS) is a possible alternative and is tested in this study. A model comparison study was executed in order to see which model performs better. WALRUS was calibrated on the same winter periods and validated on the same periods as selected by the development of the HBV models in a previous study. The model comparison was done for three subcatchments of the Vecht basin: Dinkel, Steinfurter Aa and Afwateringskanaal. WALRUS performed better (in terms of Nash-Sutcliffe) in 7 out of 10 selected periods. In the other periods HBV was performing better (in two periods only slightly better). Based on this model comparison study, it can be concluded that WALRUS performs (on average) better than the HBV model. After the model comparison study, a WALRUS model was also developed for subcatchment Regge and the three other WALRUS models were improved by decreasing the time resolution, applying a recently developed snow algorithm, using available waste water treatment plants data or correcting the potential evapotranspiration for land use. Average Nash-Sutcliffe efficiencies of 0.71 (WALRUS Dinkel), 0.67 (WALRUS Steinfurter Aa), 0.81 (WALRUS Afwateringskanaal) and 0.78 (WALRUS Regge) were found. It was found that WALRUS performed better using different parameter sets, depending on the hydrological conditions. A first step was made in finding a relation between the parameters of WALRUS and the Standardized Precipitation Index, a well-known drought index, which gives an indication of the hydrological conditions. Further research needs to be done in order to draw reliable conclusions on that topic.

Contents

1 Introduction **1**

1.1 Introduction 1

1.2 Objective and research questions 2

1.3 Outline 2

2 Study area **3**

2.1 Vecht catchment 3

2.2 Subcatchments 3

3 Data **5**

3.1 Precipitation 5

3.2 Evapotranspiration 7

3.3 Discharge 8

3.4 Snow 8

3.5 Waste water treatment plants 9

4 Methods **13**

4.1 Comparison of HBV and WALRUS 13

4.1.1 HBV 13

4.1.2 WALRUS 14

4.1.3 Assumptions 16

4.2 Calibration 17

4.3 WALRUS subcatchments 18

4.4 Season dependent parameter sets 18

5 Results **21**

5.1 Comparison of HBV and WALRUS 21

5.2 WALRUS Dinkel 23

5.3 WALRUS Steinfurter Aa 24

5.4 WALRUS Regge 26

5.5 WALRUS Afwateringskanaal 28

5.6 Season dependent parameter sets 29

6 Discussion **33**

7 Conclusions & recommendations **37**

Bibliography **39**

A Results comparison HBV and WALRUS **i**

B Simulations WALRUS Dinkel **v**

C Simulations WALRUS Steinfurter Aa **xi**

D Simulations WALRUS Regge **xvii**

E Simulations WALRUS Afwateringskanaal **xxix**

F Crop factors Regge **xxxv**

1 | Introduction

1.1 Introduction

Good hydrological models are becoming more and more important in terms of forecasting high water peaks in rivers. Changing climate results in more severe weather conditions, e.g. more intense rainfall events or droughts. Water boards in the eastern part of the Netherlands are also searching for ways in which they can collaborate in those extreme situations. It could occur that one water board has to much water in its system, while a neighboring water board has enough retention areas to store extra water. When a good forecasting system is available, one can decide on beforehand how to divide the water in cases of high flows or in dry periods. The flood warning tool FEWS Vecht is developed in order to get one forecast system for the entire basin of the Vecht, which is located in Germany and the (East of) Netherlands, see Figure 1.1.

Figure 1.1: Overview of all subcatchments of the Vecht. The black borders mark the border of the management area of water board Vechtstromen. The area on the right side of this management area is located in Germany. Table 2.1 gives an overview of the area of the subcatchments.

At this moment, FEWS Vecht runs with HBV rainfall-runoff models that are developed by HKV (2012). The models are calibrated on peak discharges. It has been observed that those HBV models are not accurate enough during a first peak discharge after a longer dry period, especially in summer. Therefor, the users of FEWS Vecht at water board Vechtstromen are searching for alternative rainfall-runoff models, which are performing better, during summer peak discharges as well as during winter peak discharges. The Wageningen Lowland Runoff Simulator (WALRUS), developed by (Brauer et al., 2014a) is a possible alternative rainfall-runoff model. A model comparison study will be executed in order to see if WALRUS can perform better in situations of peak discharges.

Model comparison studies are already performed in several studies. Kloosterman (2012) compared five lumped hydrological models on a big peak discharge that occurred on 27 August 2010 in the Hupsel Brook catchment in the Netherlands. The conclusion of this study was that the model with the lowest amount of parameters, could simulate the timing and peak that was observed best. Vansteenkiste et al. (2014) tested five hydrological models with different spatial resolutions and complexity on a catchment in Belgium. It was found that the calibration of the lumped models is less time consuming in comparison to the more complex distributed models. The model performance was on average also higher for these lumped models.

It is important to have good hydrological models for making water level predictions, especially during high flows. A short computation time is also important, especially when running the model in an ensemble mode. Then, decisions on water management can be made by water managers at an earlier stage. WALRUS contains less parameters than the HBV model (five against seven), so it has probably a shorter computation time. A model comparison will be done in order to see if WALRUS also performs better than HBV in terms of discharge simulations.

1.2 Objective and research questions

The objective of this study is to develop WALRUS models for several subcatchments of the Vecht and to compare the results to current model results. The following research questions are formulated in order to reach the objective:

- To what extent is WALRUS able to simulate the discharges in the subcatchments?
- What are the differences between the results of WALRUS and the already existing models?

1.3 Outline

The subcatchments that are selected for this study are Afwateringskanaal, Dinkel, Regge and Steinfurter Aa. Some information on these subcatchments can be found in Chapter 2. Chapter 3 describes the available and used data of these subcatchments. In Chapter 4, the methods are described, followed by the results in Chapter 5. Some points of discussion are presented in Chapter 6 and finally the overall conclusions and some recommendations are showed in Chapter 7.

2 | Study area

This chapter gives a brief introduction on the Vecht catchment and the corresponding subcatchments.

2.1 Vecht catchment

The Vecht catchment is located in West-Germany and the East of the Netherlands (see Figure 1.1). The Vecht starts as a small stream (called Vechte) around the village of Darfeld in Germany (165 meter a.s.l.). The Vecht merges with the stream Steinfurter Aa close to the village of Bilk. At the city of Neuenhaus, the Dinkel joins in and then the Vecht is heading towards the Netherlands. Several streams drain on the Vecht and there are some canals which are connected to the Vecht. Finally, the Vecht flows into river Zwarte Water, which ends up in Lake Ijssel (at sea level). The total length of the river Vecht is 167 km and the total area is around 4925 km^2.

2.2 Subcatchments

The total area of the Vecht catchment is divided into several subcatchments which are maintained by several water boards. All subcatchments of the Vecht catchment can be found in Table 2.1. For this study, the only investigated subcatchments are: Afwateringskanaal, Dinkel, Regge and Steinfurter Aa.

Table 2.1: Overview of the size and the operating organizations in the subcatchments of the Vecht.

Subcatchment	Area [km^2]	Water board
Afwateringskanaal	579	WS Vechtstromen
Dinkel	643	WS Vechtstromen & NLWKN
Itterbeek	337	WS Vechtstromen & NLWKN
Mastenbroek	126	WS Groot Salland
Ommerkanaal	171	WS Vechtstromen
Radewijkerbeek	154	WS Vechtstromen & NLWKN
Regge	1015	WS Vechtstromen
Sallandse Wetering	499	WS Groot Salland
Steinfurter Aa	205	NRW
Stouwe	20	WS Groot Salland
Streukelerzijl	268	WS Groot Salland
Vechte A	183	NRW
Vechte B	316	NLWKN
Vechte C	409	NLWKN
Total	4925	

Afwateringskanaal

Subcatchment Afwateringskanaal has an area of 579 km^2 and is located in the most northern part of the Vecht in the Netherlands (see Figure 1.1). Coevorden and Emmen are the biggest cities in this area and besides sandy soils that are used for agriculture, some peat areas are also present. The surface water system at the outlet of the catchment is a bit complex. Figure 2.1 shows an overview of the situation. River Afwateringskanaal and canal Coevorden-Vechtkanaal are separated from each other by a railway (black line). The only connections between these two streams are indicated with the orange lines in the red circles, of which the upper connection (in the city of

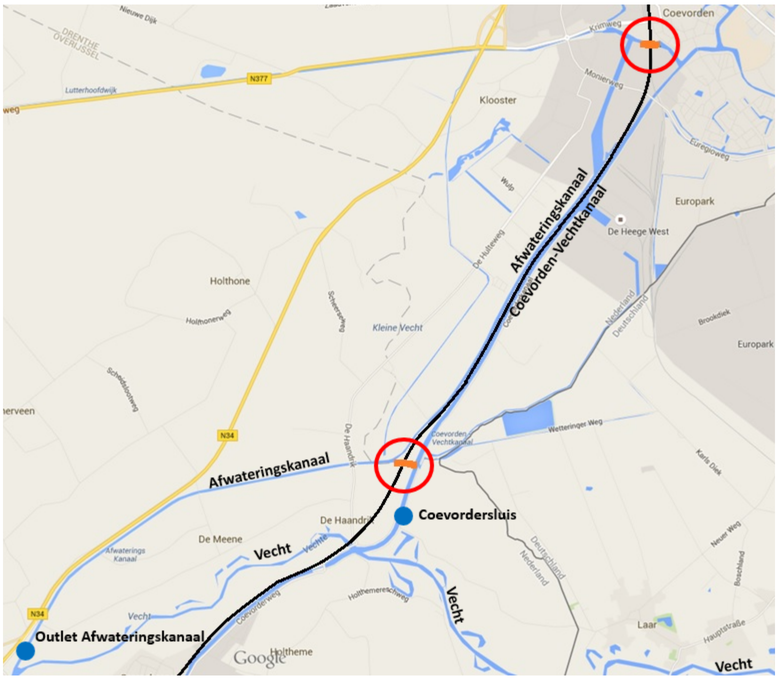


Figure 2.1: Overview of the surface water system at the outlet of subcatchment Afwateringskanaal.

Coevorden) is always present. The other connection (close to sluice Coevordersluis) is only used in case of too high water levels in the Coevorden-Vechtkanaal. No discharge measurements at the location of this connection are done. Sluice Coevordersluis is the connection between the river Vecht and canal Coevorden-Vechtkanaal. Water can flow in both directions and discharge measurements are quite inaccurate. The outlet of the subcatchment is located in the bottom left corner of the figure. There, the water from is flowing into the river Vecht (see cover page figure).

Dinkel

Subcatchment Dinkel is located partly in the Netherlands and partly in Germany. The total area is 643 km^2 and the subcatchment is freely draining. The total length of the stream is around 93 km. The discharge at the outlet of the subcatchment consists of three measurement locations (Lage I, II and III) and is called "Lage (gesamt)".

Regge

Subcatchment Regge is located in the Netherlands and has an area of 1015 km^2. The stream is divided in three parts, upper Regge, middle Regge and lower Regge and has a total length of around 50 km. The discharge of this subcatchment also consists of different measurement locations, namely Archem and Linderbeek.

Steinfurter Aa

The Steinfurter Aa with an area of 205 km^2 is the smallest subcatchment of the four investigated subcatchments. It is the most eastern part of the Vecht catchment, completely located in Germany. The catchment is freely draining and discharge is measured in Wettringen.

More details on the available data and information of these subcatchments can be found in Chapter 3 and Chapter 4 of this report.

3 | Data

This chapter presents all data that is used in this study.

3.1 Precipitation

The first part of the research consists of a comparison of two models (see Section 4.1). A precipitation dataset is delivered by the water board. For the German subcatchments, the precipitation data originate from meteorological station St. Arnold which is located just outside the northeastern boundaries of subcatchment Steinfurter Aa. Precipitation data is available for the period 1998–2012 and is used for subcatchments Dinkel, Steinfurter Aa and Afwateringskanaal.

After the comparison study, the WALRUS model is build with hourly data of the Dutch subcatchments Regge and Afwateringskanaal. New datasets of precipitation need to be prepared. Hourly precipitation time series are available at the website of the KNMI (KNMI, 2015). Four stations are located in (or closely to) the management area of water board Vechtstromen: Heino, Hoogeveen, Hupsel and Twenthe (see Figure 1.1).

First the precipitation data were analyzed to recognize strange patterns or gaps in the time series. This was done by making a plot of the cumulative precipitation for the period 1999–2011 (Figure 3.1). Station Hoogeveen is systematically measuring higher precipitation amounts, compared to the other three measurement locations. Stations Heino, Hupsel and Twenthe are measuring more or less the same amounts of precipitation. These three stations are used to determine the catchment average precipitation for subcatchment Regge.

A catchment averaged precipitation time series is made for subcatchment Afwateringskanaal as well. Since station Hoogeveen is the only station in the neighborhood of subcatchment Afwateringskanaal and because of the fact that hourly observations of station Hoogeveen are consequently higher than other stations in the neighborhood, there is a doubt on the quality of this time series. Therefor, a second analysis is carried out with the use of several daily precipitation time series, also from the KNMI.

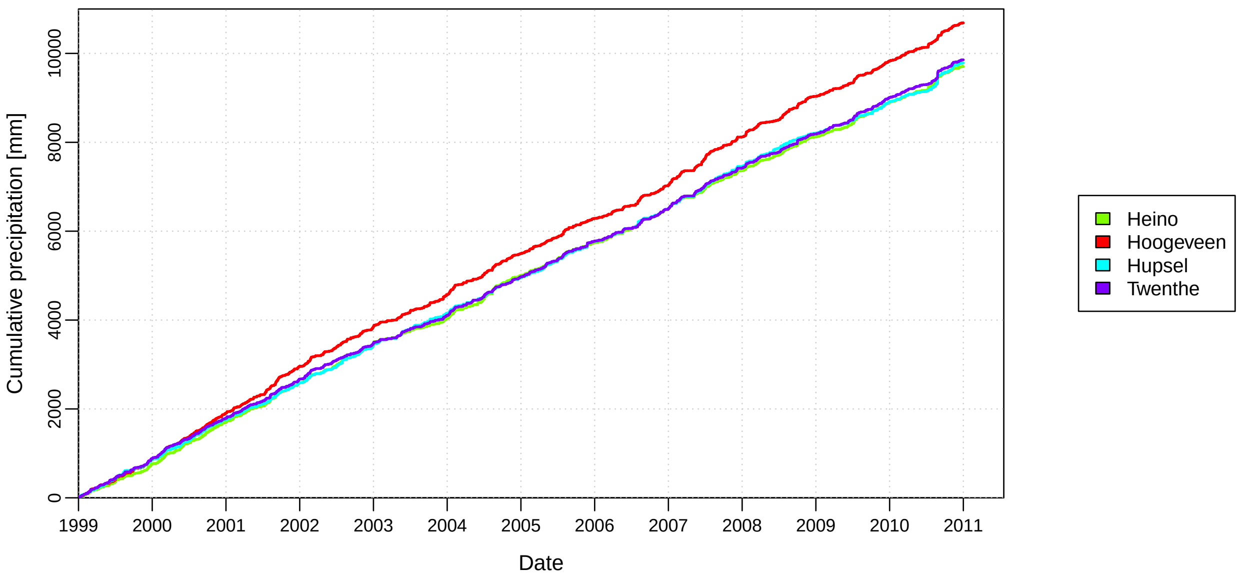


Figure 3.1: Cumulative precipitation of four KNMI stations with hourly measurements for the period 1999–2011.

The same method is applied for the hourly time series. A plot of the cumulative precipitation is made for the period 2006–2011 (see Figure 3.2). In this plot, the hourly observations of the stations used for the Regge are also plotted (in grey) and station Hoogeveen is plotted (in red) to compare the cumulative amounts in this period with the daily observations. Daily observations at five locations are plotted in the other different colors. What can be concluded is that station Hoogeveen (hourly time series) still has the highest amounts of precipitation, but the total amounts at daily station Emmen does not deviate much from this red line. Stations Klazienaveen and Schoonebeek are showing a more or less equal pattern compared to the hourly stations of the Regge and station Steenwijksmoer is recording a little bit less precipitation. The lines behave in the same way, so no big gaps or deviations from other stations are clearly visible. Therefor, all five daily precipitation stations are used for preparing the precipitation time series of subcatchment Afwateringskanaal.

The daily precipitation observations are compared to the hourly precipitation data from station Hoogeveen. The amount of precipitation on a certain day is divided over the hours of the day where rainfall was observed at the hourly station. When no rainfall was observed at hourly station Hoogeveen, the sum of the daily station was equally divided over the 24 hours of that day. In this way, hourly time series can be derived from daily data.

After creating hourly time series of precipitation, the catchment averaged precipitation is calculated by creating Thiessen polygons. This method divides the subcatchments in parts, by assigning land to the nearest measurement station. The area of the subcatchment that belongs to each measurement station can be measured using ArcGIS. Table 3.1 shows the percentages of the share of each station to the total subcatchment. Those percentages are multiplied with the time series of the corresponding stations and then summed in order to obtain the catchment averaged precipitation time series.

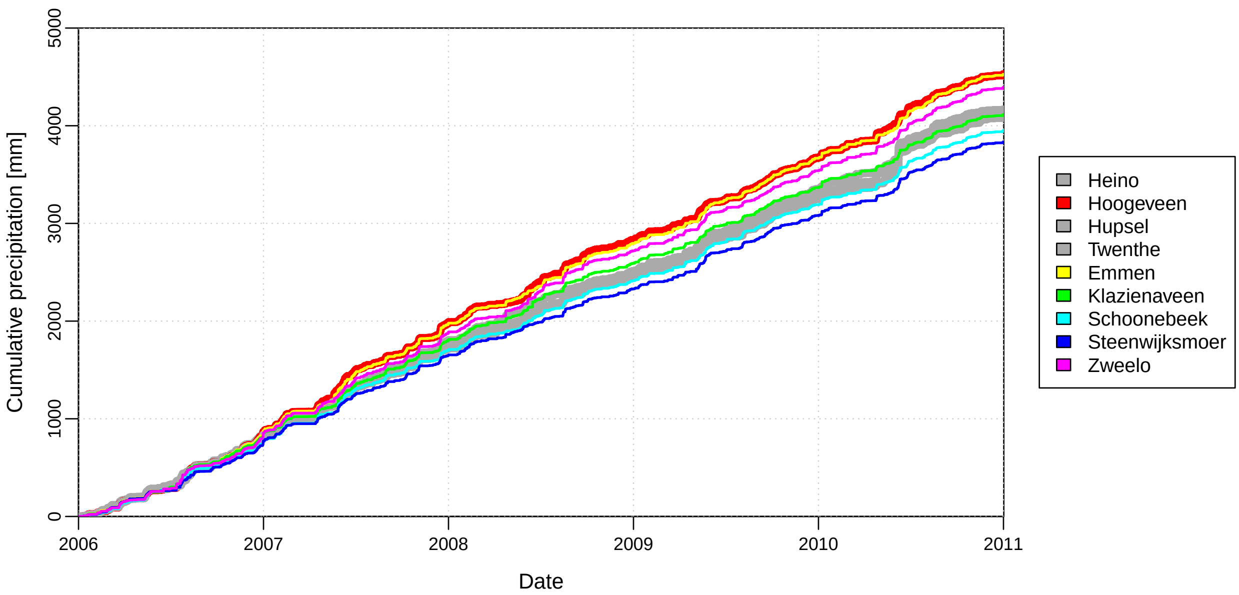


Figure 3.2: Cumulative precipitation of five daily measurement stations belonging to subcatchment Afwateringskanaal for the period 2006–2011. The hourly measurement stations (see Figure 3.1) used for subcatchment Regge are plotted in grey. Hourly station Hoogeveen is plotted in red.

Table 3.1: Percentage of each measurement location that is used to create the catchment averaged precipitation time series for subcatchments Regge and Afwateringskanaal.

(a) Regge

Station	Percentage
Heino	26.8%
Hupsel	14.3%
Twenthe	58.9%

(b) Afwateringskanaal

Station	Percentage
Emmen	13.4%
Klazienaveen	14.0%
Schoonebeek	32.9%
Steenwijksmoer	19.6%
Zweelo	20.1%

3.2 Evapotranspiration

The HBV model uses the Makkink reference evapotranspiration (Makkink, 1957; Hiemstra and Sluiter, 2011) data from KNMI station Hoogeveen for all Dutch and all German subcatchments. For the comparison of the two models (see Section 4.1), an evapotranspiration time series (on daily time scale) was created for WALRUS, using the data from station Hoogeveen as well.

When building two WALRUS models on an hourly time scale for subcatchments Regge and Afwateringskanaal, other time series were derived. The reference evapotranspiration time series of subcatchment Regge was created with the data of the same three meteorological stations as for the precipitation time series (Heino, Hupsel, Twenthe), using the same proportions as in Table 3.1. For subcatchment Afwateringskanaal, station Hoogeveen was used.

In order to see the effects of land use on evapotranspiration in WALRUS, an extra evapotranspiration set was created using information on land use and crop factors, which compensates the evapotranspiration for the land use. This has been done for the Regge subcatchment only. The general method is that the reference evapotranspiration ET_{ref} time series from the KNMI are multiplied by a crop factor *f*, leading to the potential evapotranspiration ET_{pot} (see Equation 3.1).

$$ET_{\text{pot}} = f * ET_{\text{ref}} \tag{3.1}$$

This crop factor *f* is fluctuating during the year and needs to be derived. First of all, land use maps are studied and the fractions of each land use type in the subcatchment are calculated. Feddes (1987) developed a table with crop factors during the growing season (April–September). This table can be found in Appendix F. Crop factors in the other months of the year are assumed to be equal to the crop factor of bare soil, while other crop factors (mixed/deciduous/coniferous forest and water) are equal to the crop factor of that land use type in September. For urban areas, a reduction factor of 0.5 has been assumed, since no crop factors were available.

The crop factors per month are multiplied by the fraction of the associated land use type and summed per month, leading to a catchment averaged evapotranspiration crop factor *f* per month (see Table 3.2). The original reference evapotranspiration of subcatchment Regge is multiplied with this crop factor for each specific month. Section 5.4 shows the results of WALRUS Regge, using the original evapotranspiration time series and the evapotranspiration time series corrected for land use.

Table 3.2: Catchment averaged evapotranspiration crop factors for subcatchment Regge.

Month	f	Month	f
January	0.83	July	0.98
February	0.83	August	0.94
March	0.83	September	0.90
April	0.85	October	0.83
May	0.88	November	0.83
June	0.95	December	0.83

3.3 Discharge

Discharge observations are necessary to quantify the performance of WALRUS. Discharge data of four subcatchments were available (see Table 3.3). It must be noticed that the dataset of station Afwateringskanaal consists of 15 minute records, but a large part of the dataset gives only a real value once every 1.5 hour. Station Coevordersluis is a measurement point at the location of a sluice, which acts as outlet as well as inlet (e.g. positive and negative discharges are recorded). The data is not very reliable but the data is investigated because on the yearly water balance, the total discharge of the sluice can be up to 30% of the measured discharge at the outlet of catchment (station Afwateringskanaal).

Irregular time series are converted to hourly or daily discharge time series. This can be done by assuming that the observed discharge is constant until the next observation is stored in the dataset. The time (in seconds) between observation t_{n-1} and t_n is calculated and multiplied with the associated discharge Q_{n-1}, leading to a volume of water V_n. The total volume since the start of the time series is calculated for every time step and a linear interpolation function is applied. Then, an empty time series is made with constant time steps of one hour or one day. With use of the linear interpolation function, cumulative volumes are calculated at each specific time step. Then for each record in the dataset, volume V_{n-1} is subtracted from V_n and converted to a discharge by using dt (which is the constant time step in seconds).

Table 3.3: Availability of discharge data of four subcatchments.

Subcatchment	Station name	Period	Time step
Dinkel	Lage(gesamt)	1998–2011	1 day
Steinfurter Aa	Wettringen	1975–2010	irregular
Regge	Archem + Linderbeek	1999–2011	1 hour
Afwateringskanaal	Afwateringskanaal	2006–2011	15 minutes
	Coevordersluis	1999–2011	15 minutes

3.4 Snow

For the two Dutch subcatchments (Regge and Afwateringskanaal), the effects of snow are investigated. Due to snowfall, the peak discharge after a precipitation event is delayed and rainfall-runoff models do not always simulate this correctly. Wendt (2015) developed an algorithm which accounts for the effects of snow accumulation and snow melt and the delay in peak discharge. Therefor, time series of temperature and radiation need to be added to the current input dataset for WALRUS.

First of all, the precipitation time series is split into two new time series: one for precipitation which falls as rain and one for precipitation which falls as snow (based on temperature criteria which can be specified in the algorithm).

If the temperature at a certain time is below a threshold (minimum rain temperature), all precipitation falls as snow. If the temperature at a certain time is between the minimum rain temperature and the maximum snow temperature, precipitation falls partly as snow.

The snow has to melt when the temperature is rising again. This melt can be determined by two methods: the degree hour factor method (DHF method) or the shortwave radiation factor method (SRF method). The DHF method only needs temperature data, while the SRF method needs temperature data as well as global radiation data.

In the end, the original precipitation time series is replaced by a new time series, consisting of a combination of the (real) rainfall time series and the calculated snow melt time series. More details about these snow melt methods can be found in Wendt (2015).

Temperature and radiation time series are available by the website of the KNMI (KNMI, 2015). For subcatchment Afwateringskanaal, these data originate from station Hoogeveen and for subcatchment Regge, the same method is applied as when calculating the catchment average precipitation time series (see Section 3.1). Section 4.3 describes how the snow algorithm is used in this study.

3.5 Waste water treatment plants

Several waste water treatment plants (WWTP) are present in the Vecht catchment. Figure 3.3 shows the WWTP located in the Dutch part of the catchment. From a previous study, it is known that adding WWTP data can improve model results, because water from those WWTP can consist of 10% of the total discharge of a catchment (Loos, 2015). Since data from WWTP located in Germany are not available, the data from WWTP located in the Dutch subcatchments Regge and Afwateringskanaal are only used. Effluent data are available on a daily scale for subcatchment Afwateringskanaal in the period 2006–2011, while only monthly effluents are available for subcatchment Regge in the period 2007–2011.

WWTP time series of three locations in subcatchment Afwateringskanaal are used: Coevorden, Sleen and Emmen. Data of the location Emmen is only available from 2011 until 2015, but data from 2006–2011 is necessary, because of the availability of discharge time series in the same period. First, the three time series are analyzed for the period 2011–2015. When studying the total effluent of each station and compare it to the total effluent of all three stations, the proportion of the total effluent is as follows: Coevorden 19%, Sleen 9% and Emmen 72%. WWTP Emmen has the biggest share to the total effluent. It can be concluded that the effluent of WWTP Emmen needs to be included in the dataset of the period 2006–2011 as well.

Therefor, correlations between the three stations are calculated. WWTP effluents consist of an almost constant base flow, this is sewage water from for instance households. The peaks in the effluent time series are caused by rainfall. Since the baseflow is different for each WWTP (depending on the size of the WWTP and the controlled area), these values are subtracted from the time series. It was observed that WWTP Emmen always peaked one day later than the other two WWTP, so the time series of Emmen were shifted in order to reach a higher correlation. The effluents of WWTP Sleen were divided by the total effluent of WWTP Sleen and each fraction was (for each time step) multiplied with the total effluent of WWTP Emmen. This was also done for WWTP Coevorden. In this way, two new time series were generated which are in proportion with WWTP Emmen. The Nash-Sutcliffe of the two time series (compared to the real data of WWTP Emmen) was derived. The simulated time series of WWTP Emmen, based on the data of WWTP Sleen had a Nash-Sutcliffe of 0.88. The simulated time series of WWTP Emmen, created with the data of WWTP Coevorden had a Nash-Sutcliffe of 0.84. In this way, it is concluded that WWTP Sleen correlates better with WWTP Emmen. Then, a time series of WWTP Emmen for the period 2006–2011 is derived from the data of WWTP Sleen.

The effluent data for all WWTP locations are summed for each subcatchment and analyzed. It must be noted that in the second half of 2009, no effluent data was available for the three WWTP in subcatchment Afwateringskanaal. The gap in the time series is filled with a constant effluent which equals the baseflow earlier mentioned. Table 3.4 shows the water balances of subcatchments Regge and Afwateringskanaal, including the WWTP data, which is implemented in WALRUS as f_{XS}. As can be concluded from the table, the share of WWTP to the total discharge in subcatchment Regge is around 4% and in subcatchment Afwateringskanaal around 11%.

Please note that the water balance of subcatchment Regge is almost always strongly negative in these years. A clear reason for that fact can not directly be given, but it could be that the discharge observations are not accurate enough or that some other external water fluxes are influencing the water balance in the catchment. Further research needs to be done in order to tackle this problem.

Table 3.4: Water balance of the subcatchments Regge and Afwateringskanaal, including a flux from the waste water treatment plants (WWTP) in the two subcatchments (showed in column f_{XS}). Water balances of subcatchments Dinkel and Steinfurter Aa can be found in Section 5.2 and 5.3, respectively.

(a) Regge

Year	P [mm]	ET_{pot} [mm]	Q [mm]	f_{XS} [mm]	$Balance$ [mm]
2007–2008	871	569	316	13	-1
2008–2009	700	572	251	11	-112
2009–2010	777	607	238	11	-57
2010–2011	786	587	323	11	-113

(b) Afwateringskanaal

Year	P [mm]	ET_{pot} [mm]	Q [mm]	f_{XS} [mm]	$Balance$ [mm]
2006–2007	862	602	261	30	29
2007–2008	912	562	236	34	148
2008–2009	699	568	229	29	-69
2009–2010	778	598	252	24	-48
2010–2011	729	586	299	29	-127

Figure 3.3: Overview of all waste water treatment plant locations (brown dots) in the management area of water board Vechtstromen (inside the black border lines). Since data from WWTP located in Germany are not available, the data from WWTP located in the Dutch subcatchments Regge and Afwateringskanaal are only used.

4 | Methods

This chapter describes the methods that are used in this study. Section 4.1 will introduce the model comparison study that has been performed. The applied calibration methods can be found in Section 4.2. After the model comparison study, the WALRUS model has been (further) developed for the subcatchments. Those methods can be found in Section 4.3. A side step is made in order to find a first approach in choosing different parameter sets throughout the year (Section 4.4).

4.1 Comparison of HBV and WALRUS

In the following subsections, the two models are described. First a description of the HBV model is given in Subsection 4.1.1, then a description of the WALRUS model will be given in Subsection 4.1.2 and Subsection 4.1.3 will give an overview of all assumptions that are made in order to compare the two models.

4.1.1 HBV

The HBV-model (Hydrologiska ByrÃěns Vattenbalansavdelning) is a conceptual rainfall-runoff model, developed in the 70's by Bergström and Forsman (1973). The model consists of three main components: a subroutine for snow accumulation and melt, a subroutine for soil moisture accounting and a response and river routing subroutine (Figure 4.1).

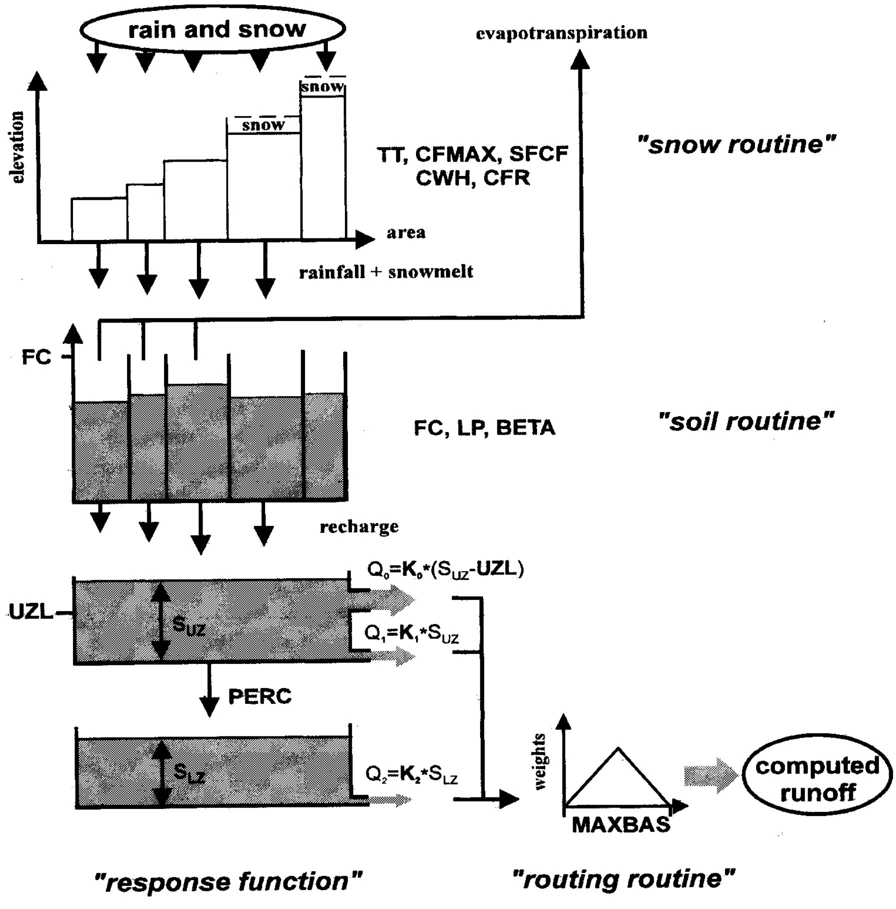


Figure 4.1: The HBV model structure (Seibert, 2000).

The snow routine determines when precipitation occurs as snow or as rain, using a threshold temperature (TT). The amount of snow is adjusted with a snow-correction factor ($SFCF$). The amount of snow melt is determined by multiplying the degree-day factor ($CFMAX$) with the difference between the temperature and the threshold temperature (T-TT). CWH and CFR are the water holding capacity and refreezing coefficient, respectively.

The soil moisture routine mainly controls the runoff formation and is based on three parameters: field capacity FC, fraction of the field capacity, for determining the reduction of evaporation LP, and an empirical parameter β which determines the amount of recharge towards the response function routine.

The response routine transforms excess water from the soil moisture zone to runoff. This includes the effect of direct precipitation and evaporation on wet areas (e.g. rivers, lakes). It consists of a nonlinear upper and linear lower reservoir. The upper reservoir is filled with water from the soil moisture routine and as long as there is water in this upper zone, the lower reservoir will be filled with percolated water from the upper zone (depending on parameter $PERC$). There are three reservoir parameters (K_0,K_1 and K_2), controlling the speed of outflow of water from the upper and lower zone. UZL is a threshold for the outflow Q_0 (see Figure 4.1). Q_0, Q_1 and Q_2 are representing the quick, intermediate and slow runoff components.

The runoff that is generated in the respons routine is routed with a transformation function in order to get a proper shape at the outlet of the catchment. It is a simple filter technique with a triangular distribution of weights, depending on parameter $MAXBAS$. A complete description can be found in Bergström et al. (1995).

4.1.2 WALRUS

The Wageningen Lowland Runoff Simulator (WALRUS) is a lumped rainfall-runoff model, developed by Brauer et al. (2014a). It is model that is suitable for lowland catchments with shallow groundwater and there are only five parameters that need to be calibrated (HBV has seven parameters which require calibration). In comparison to HBV, in WALRUS it is also possible to calibrate on channel depth and initial groundwater level. The model is programmed in R, an open source programming environment for statistical computing and graphics. Figure 4.2 shows a schematic overview of WALRUS. A complete description can be found in (Brauer et al., 2014a). The next sections will give a brief introduction.

The model consists of five compartments: land surface, vadose zone, groundwater zone, quickflow reservoir and surface water reservoir (see Figure 4.2). Precipitation (P) enters the model in the land surface compartment. A certain amount is directly falling on the surface water reservoir (P_S). The soil wetness index (W) determines which part of the remaining amount of precipitation is going to the vadose zone (P_V) and which part is going directly to the quickflow reservoir (P_Q). The vadose zone is, together with the groundwater zone, part of soil reservoir (slow reservoir). The quickflow reservoir represents overland flow and flow through drainage pipes and soil cracks. The wetness index (W) ranges between 0 (all water to the soil reservoir) and 1 (all water to the quickflow reservoir) and is a function of storage deficit (d_V). The storage deficit is expressed as the volume of empty soil pores per unit area, e.g. the depth of water needed to reach saturation. This storage deficit also controls the reduction of evapotranspiration (β). There is a coupling between the vadose zone and the groundwater table and between the surface water reservoir and groundwater zone. There can be a flux from the quickflow reservoir into the surface water reservoir (f_QS), but not the other way around. Internal fluxes such as surface water infiltration and drainage of groundwater (f_GS) are depending on groundwater depth (d_G) and surface water level (h_S). The groundwater depths in WALRUS represent the behavior of the catchment averaged groundwater table. External fluxes are upward/downward seepage (f_XG), surface water supply/extraction (f_XS) and discharge (Q). Discharge is determined from the surface water level (h_S) with use of a default stage-discharge relation. This stage-discharge relation can be changed by the user. The change of water level in the quickflow reservoir (h_Q) is determined by the difference between the water that is flowing into

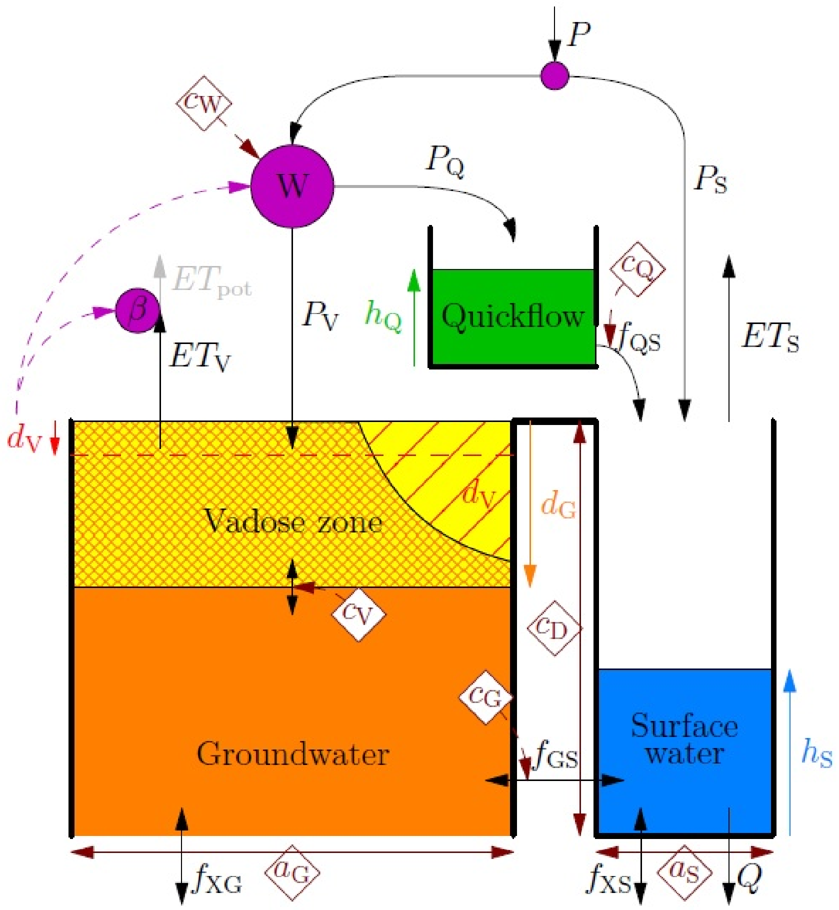


Figure 4.2: Schematic overview of WALRUS with all internal and external fluxes, states and parameters (Brauer et al., 2014a). A short explanation is given in the text.

the quickflow reservoir (P_{Q}) and the water that is leaving the reservoir (f_{QS}) divided by the groundwater reservoir area fraction (a_{G}). The surface water area fraction is denoted by a_{S}.

WALRUS needs as input a dataset with time series of precipitation (P), potential evapotranspiration (ET_{pot}) and observed discharge (Q). When time series of seepage or groundwater extraction (f_{XG}) or surface water supply/extraction (f_{XS}) are available, those can be added to the dataset.

For the simulation, values for channel depth (c_{D}), initial groundwater depth (d_{G0}) (which can also be calibrated), soil type and the fraction of surface water need to be given. The initial surface water level is determined with use of the first discharge observation and the stage-discharge relation. Depending on the parameter set, WALRUS gives a simulation of the discharge as output. The model performance is quantified by the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970), see also Section 4.1.3. The actual evapotranspiration, wetness index, storage deficit, groundwater depth, and the external fluxes are stored for each time step in a text file, as well as in a figure. Selected parameters and initial conditions are stored in an another file. Another file contains the terms of the water balance. This balance is computed as:

$$\Sigma P - \Sigma ET_{\mathrm{act}} - \Sigma Q + \Sigma f_{\mathrm{XG}} + \Sigma f_{\mathrm{XS}} = -\Delta d_{\mathrm{V}} \cdot a_{\mathrm{G}} + \Delta h_{\mathrm{Q}} \cdot a_{\mathrm{G}} + \Delta h_{\mathrm{S}} \cdot a_{\mathrm{S}}. \tag{4.1}$$

The water balance should always close, but sometimes small deviations from zero are caused by rounding errors.

There are five parameters that require calibration: the wetness index parameter (c_W), vadose zone relaxation time (c_V), groundwater reservoir constant (c_G), the quickflow reservoir constant (c_Q) and the bankfull discharge (c_S; only when the default stage-discharge relationship is used). These parameters are representative for the catchment characteristics.

4.1.3 Assumptions

For the comparison of the two models, the model results of the HBV model from a previous study (HKV, 2012) were delivered by the water board. Since subcatchment Regge is not included in the study of (HKV, 2012), the model comparison is only executed for subcatchments Dinkel, Steinfurter Aa and Afwateringskanaal. To compare the performance of the two models, the same assumptions as applied to HBV are made by setting up the WALRUS model. These assumptions are:

- The model output is on daily basis.
- The input precipitation for WALRUS is the same as for the HBV model, which means that daily precipitation data from St. Arnold is used for the German subcatchments and radar data is used for the Dutch subcatchments.
- Evapotranspiration data of both models and for all subcatchments originates from KNMI station Hoogeveen.
- The snow routine from the HBV model is not used in comparison study. In the Netherlands, snowfall is often not recorded sufficiently, e.g. measurement errors could be quite large. Therefor, the input of snow in the model could be not accurate. Because the HBV simulation results are very sensitive for the settings of the snow parameters, all precipitation input was assumed to be rain. This is also the case for WALRUS (despite the fact that a snow algorithm can be applied).
- The observed discharge of subcatchment Afwateringskanaal consists of the discharge time series of ADM Afwateringskanaal and Coevordersluis (sluice with positive and negative values for discharge).
- The same calibration and validation periods are chosen (see Table 4.1).

Table 4.1: Calibration and validation periods of the HBV model. The same periods are chosen for the comparison with WALRUS.

	Dinkel		Steinfurter Aa		Afwateringskanaal	
	start	end	start	end	start	end
Calibration	01-11-2006	30-04-2007	01-11-2006	30-04-2007	01-11-2006	30-04-2007
Validation 1	01-11-2002	30-04-2003	01-09-1998	28-02-1999	01-11-2007	30-04-2008
Validation 2	01-11-2003	30-04-2004	01-11-2001	30-04-2002	01-11-2009	30-04-2010
Validation 3	-	-	01-11-2003	30-04-2004	-	-

After calibrating of the WALRUS model, a parameter set will be chosen and tested on several validation years. The performance of the two models will be quantified by the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970). The Nash-Sutcliffe efficiency (NS) is based on the difference between the modeled and observed discharge and is determined with the following formula:

$$NS = 1 - \frac{\sum(Q_{obs} - Q_{mod})^2}{\sum(Q_{obs} - \overline{Q_{obs}})^2}, \tag{4.2}$$

where Q_{obs} is the observed discharge and Q_{mod} is the modeled discharge. Nash-Sutcliffe efficiencies can vary between $-\infty$ and 1. When NS=1, the modeled discharge is exactly the same as the observed discharge. When NS=0, the modeled discharge is as good as the mean of the observations and when NS<0, the model is even worse.

4.2 Calibration

Each subcatchment has its own hydrological characteristics. Therefor, WALRUS requires a specific parameter set that represents the characteristics of the subcatchment. Finding an optimal parameter set for a subcatchment is not always obvious (Melsen et al., 2014). It is possible to find two or more parameter sets which give equally good results in terms of Nash-Sutcliffe. Three different calibration techniques are used in order to find the best parameter set for each subcatchment: HydroPSO, Levenberg-Marquardt and Monte Carlo.

HydroPSO is a stochastic optimization software developed by Zambrano-Bigiarini and Rojas (2013). A swarm of a chosen number of particles is trying to find the optimal parameter value (between given boundaries) by searching for the lowest sum of residuals in the model outcome. The particles are communicating with each other, so the more particles are chosen, the higher the chance that the real lowest sum of residuals is found (and not a local minimum). HydroPSO is the standard calibration method which is implemented in the WALRUS calibration script.

The Levenberg-Marquardt algorithm (Moré, 1977) differs from the HydroPSO calibration technique. Given the start and boundary values of the parameters for the calibration, the Levenberg-Marquardt calibration searches with one particle and follows the same path each time the calibration has been executed (with the same start and boundary values), searching for the parameter set with the lowest sum of residuals. It is known from a previous study (Loos, 2015) that Levenberg-Marquardt calibrations can result in parameter sets where more parameters are equal to their boundary values, which is not really reliable. This has been taken into account by evaluating the calibration results.

The Monte Carlo calibration technique is the most simple one. A certain number of parameters sets (at least 5000) are created randomly and tested in WALRUS. The ten parameter sets with the lowest sum of squares are selected and the one with the best simulation results (evaluated with the experience of the modeler) is chosen as the optimal set for that subcatchment.

The five parameters of WALRUS (c_{W}, c_{V}, c_{G}, c_{Q}, c_{S}) are calibrated, together with the initial groundwater depth (d_{G0}) and channel depth (c_{D}). The boundary values for all subcatchments are mostly the same (see Table 4.2). After a first rough calibration (all parameters and general boundary values), the results are evaluated. In case the three previously mentioned calibration techniques lead to a more or less equal value of one or more parameters, an average parameter value is chosen. If the calibration results of the other parameters are not leading to an almost similar value, a next calibration run is executed with the remaining parameters only and if possible, the ranges of the boundary values are narrowed. After calibration, the parameter sets are sometimes manually fine-tuned in order to get better simulation results.

Table 4.2: Boundary values for calibration of the five parameters (c_{W}, c_{V}, c_{G}, c_{Q}, c_{S}), the initial groundwater depth (d_{G0}) and the channel depth (c_{D}) for the three different calibration techniques.

	c_{W}	c_{V}	c_{G}	c_{Q}	c_{S}	d_{G0}	c_{D}
Lower boundary	100	0.1	0.1×10^6	1	0.1	400	400
Upper boundary	400	100	100×10^6	200	25	2500	2500

4.3 WALRUS subcatchments

Each subcatchment gets its own WALRUS model. Tables 4.3 gives an overview of the available data (precipitation, potential evapotranspiration and discharge) and time resolution of the WALRUS model. Depending on the availability of data, other approaches are also investigated, this is also shown in the table. All steps that are taken and the results are presented separately for each subcatchment in Sections 5.2 (WALRUS Dinkel), 5.3 (WALRUS Steinfurter Aa), 5.4 (WALRUS Regge) and 5.5 (WALRUS Afwateringskanaal).

Table 4.3: Overview of the time resolution, available data and other approaches for each subcatchment.

	Dinkel	Steinfurter Aa	Regge	Afwateringskanaal
Time resolution	day	day	hour	hour
Available necessary time series	1998–2008	1998–2008	1999–2011	2006–2011
WWTP data included	no	no	2007–2011	2006–2011
Evapotranspiration corrected for land use	no	no	yes	no
Snow algorithm applied	no	no	yes	yes

4.4 Season dependent parameter sets

It is known that different combinations of parameter values can give equal results in terms of Nash-Sutcliffe efficiency (Brauer, 2014). On average, WALRUS performs better in periods with above average amounts of precipitation. In more dry periods WALRUS behaves differently. Choosing another parameter set for those periods can improve the simulation results. The main question is: on which criteria can the selection of the parameter set for a certain period be based? Seasons are not always starting at the same date, and summers can be wet, while winters are dry. Since WALRUS is a rainfall-runoff model and fed with precipitation as most important input, the Standardized Precipitation Index (SPI), developed by McKee et al. (1993), is investigated as an indicator.

In this study, the Standardized Precipitation Index (SPI) is applied on precipitation data of subcatchment Regge. For each day, the sum of the precipitation of the previous 30 days is calculated. This data is fitted to a probability function and then transformed to a normal distribution, leading to values of the SPI. Because the SPI is normally distributed, the mean SPI becomes zero and the SPI can be used to monitor wet as well as dry periods (McKee et al., 1993). Table 4.4 shows the complete classification of the SPI.

Table 4.4: Classification of the Standardized Precipitation Index, by McKee et al. (1993).

SPI			Category
	$\leq$	-2.00	Extremely dry
-1.99	–	-1.50	Severely dry
-1.49	–	-1.00	Moderately dry
-0.99	–	0.99	Near normal
1.00	–	1.49	Moderately wet
1.50	–	1.99	Severely wet
	$\geq$	2.00	Extremely wet

For this experiment, only a division is made between negative and positive SPI values. Ten periods of at least 30 days are selected with a continuous positive or negative SPI value. These ten periods are calibrated by using the Monte Carlo calibration technique with 50.000 different parameter sets and applying the snow algorithm as well. Since the channel depth was already known from previous calibrations (see Section 5.4), this value was fixed on

Table 4.5: Boundary values for calibration of four parameters (c_W, c_G, c_Q, c_S) and the initial groundwater depth (d_{G0}). Parameter c_V and the channel depth (c_D) are fixed at 45 h and 2450 mm, respectively.

	c_W	c_G	c_Q	c_S	d_{G0}
Lower boundary	200	1×10^7	1	0.1	1000
Upper boundary	400	1×10^8	200	25	2450

beforehand. Parameter c_V was also fixed, since it was found that the same Nash-Sutcliffe efficiencies can be obtained over the whole range of this parameter (Brauer et al., 2014b). All boundary conditions can be found in Table 4.5.

After the calibration of the ten selected periods, the best 20 out of 50.000 are selected, based on the sum of squares. This parameter sets are analyzed in Section 5.6.

5 | Results

This chapter presents the results of this study. Section 5.1 shows the comparison of the HBV and WALRUS model runs. In the subsequent Sections 5.2–5.5, the WALRUS results of four subcatchments are given. Section 5.6 gives the results of the small experiment with the season dependent parameter sets.

5.1 Comparison of HBV and WALRUS

After calibrating the WALRUS model on the preselected periods (see Table 4.1), a parameter set is chosen, based on high Nash-Sutcliffe efficiencies, but also based on own interpretations of the model results, displayed in the four panels of the standard WALRUS output. It is known from previous studies that models can be right for the wrong reasons (Kirchner, 2006), so a high Nash-Sutcliffe not always means that the simulation is good. The selected parameter sets can be found in Table 5.1.

Table 5.1: Overview of WALRUS model parameters, states and soil type of the subcatchments used for the model comparison study.

Subcatchment	c_{W}	c_{V}	c_{G}	c_{Q}	c_{S}	d_{G0}	c_{D}	a_{S}	st
Dinkel	207	0.1	9200000	1.5	0.4	1500	1900	0.01	sand
Steinfurter Aa	275	9.3	8400000	1.7	1.2	1900	1850	0.01	sand
Afwateringskanaal	247	14	50000000	38	24	1850	2500	0.01	sand

The parameter sets are validated on several other periods (see Table 4.1). Figure 5.1 shows the result of the calibration of the Steinfurter Aa and Figure 5.2 shows the result of one of the validation years of the same subcatchment. All figures can be found in Appendix A. The WALRUS results for subcatchment Steinfurter Aa are remarkably better than the results of the HBV model. Discharge peaks are better simulated with WALRUS, although they are still overestimated in periods with real high discharge (Figure 5.1 and 5.2). The Nash-Sutcliffe efficiencies are higher for WALRUS in all cases. WALRUS has some more problems with subcatchment Dinkel. Although the discharge peaks in the calibration period are all really good simulated (see Appendix A), the validation is a little bit disappointing and the HBV model performs better in terms of Nash-Sutcliffe. The calibration results of WALRUS for subcatchment Afwateringskanaal are good, a Nash-Sutcliffe of 0.81 is reached. The validations are less good, with Nash-Sutcliffe efficiencies of 0.56 and 0.43 against Nash-Sutcliffe efficiencies of 0.58 and 0.16 for the HBV model. Both models have problems with simulating the discharge for this subcatchment. This is probably caused by the fact that for the HBV model (and also for the WALRUS model), the discharge of the sluice (Coevordersluis), which can be positive and negative is summed with the discharge measured at the outlet of the subcatchment and this sum is used as discharge of the entire catchment. Since the data from the Coevordersluis is really unreliable and fluctuates sometimes quite strongly, both models can not model that correctly. These fluctuations are clearly visible in the observed discharge (dips in the black lines).

Table 5.2 gives an overview of all obtained Nash-Sutcliffe efficiencies. In general, it can be concluded that WALRUS is on average performing better than HBV. This positive result of the comparison gave way to further develop the WALRUS model for the subcatchments for complete hydrological years and without dealing with the same assumptions as for the comparison with the HBV model.

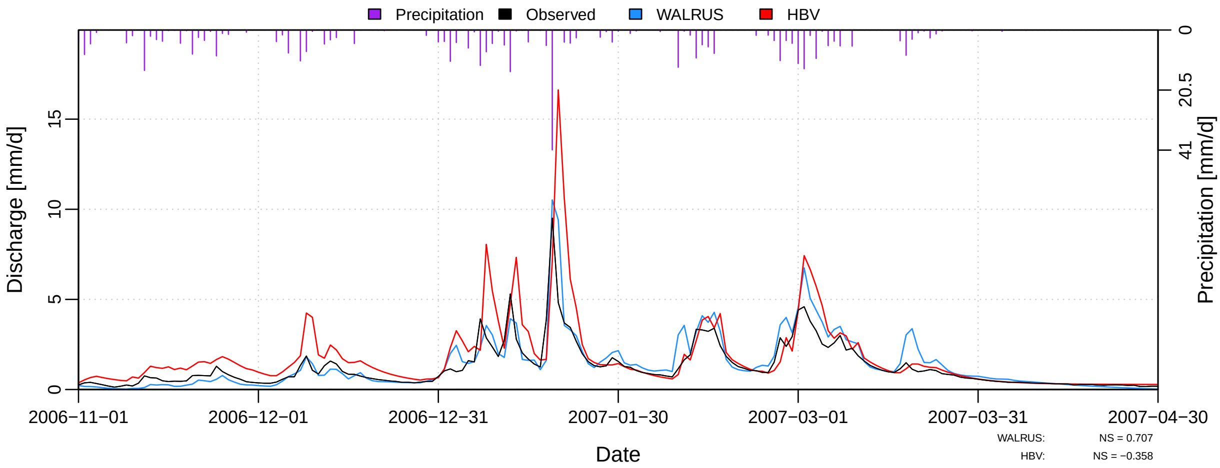


Figure 5.1: Results of WALRUS and the HBV model for subcatchment Steinfurter Aa for the calibration period.

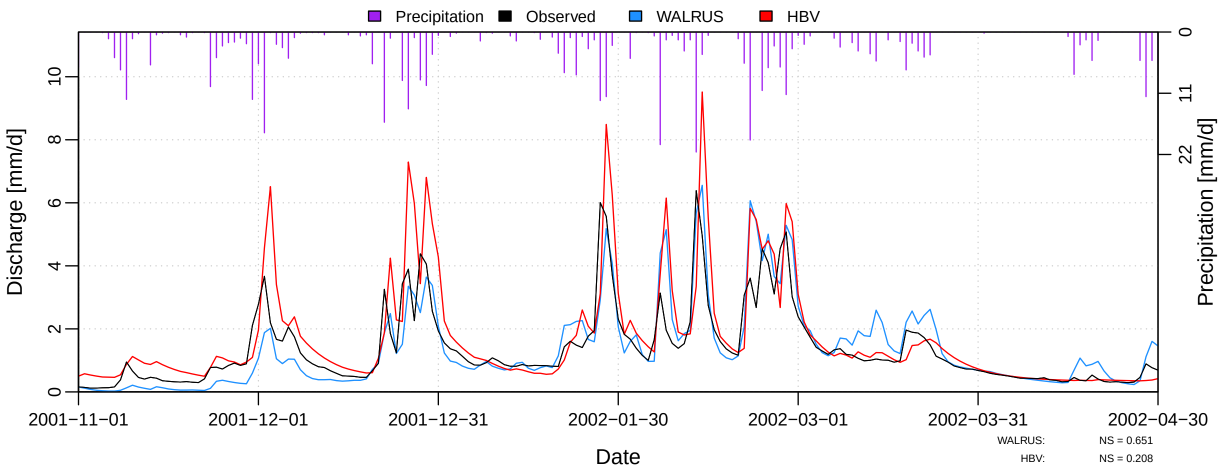


Figure 5.2: Results of WALRUS and the HBV model for subcatchment Steinfurter Aa for validation period 2.

Table 5.2: Nash-Sutcliffe efficiencies of WALRUS and HBV after calibrating and validating the WALRUS parameter set. The calibration and validation periods are the same as in Table 4.1.

	Dinkel		Steinfurter Aa		Afwateringskanaal	
	WALRUS	HBV	WALRUS	HBV	WALRUS	HBV
Calibration	0.875	0.597	0.707	-0.358	0.807	0.696
Validation 1	0.657	0.826	0.526	0.265	0.564	0.575
Validation 2	0.861	0.885	0.651	0.208	0.433	0.158
Validation 3	-	-	0.689	0.651	-	-

5.2 WALRUS Dinkel

Daily discharge observations of three stations close to the outlet of the Dinkel were used: Lage I, Lage II and Lage III (see Section 3.3). The same precipitation and evapotranspiration data were used as during the comparison study. WALRUS was calibrated on hydrological years 1998–1999 and 2006–2007. After calibration, the best parameter set was chosen, not only by choosing the parameter set which results in the highest Nash-Sutcliffe efficiency, but also by assessing the other processes (e.g. fluctuations in groundwater and surface water levels, flux of groundwater towards the surface water). After choosing a parameter set (which can be found in Table 5.3), this parameter set was validated on the other available hydrological years. Table 5.4 gives an overview of all available hydrological years for the Dinkel subcatchment. This table gives the obtained Nash-Sutcliffe efficiencies, the water balance of the observations and the simulated actual evapotranspiration and discharge of WALRUS, leading to a new water balance, based on the simulations and the precipitation.

Table 5.3: Overview of WALRUS model parameters, states and soil type used for subcatchment Dinkel.

c_{W}	c_{V}	c_{G}	c_{Q}	c_{S}	d_{G0}	c_{D}	a_{S}	st
335	15	13000000	49.0	15.0	1650	2000	0.01	sand

Table 5.4: Nash-Sutcliffe efficiencies (NS) of the WALRUS simulations of subcatchment Dinkel. All related figures can be found in Appendix B.

		Observations				Simulations	
Year	NS [-]	P [mm]	ET_{pot} [mm]	Q_{obs} [mm]	$Balance$ [mm]	ET_{act} [mm]	Q_{sim} [mm]
1998–1999	0.88	1067	492	589	-14	473	561
1999–2000	0.78	864	580	324	-41	526	287
2000–2001	0.77	820	525	292	3	494	276
2001–2002	0.84	893	577	388	-72	538	331
2002–2003	0.81	821	550	351	-80	522	306
2003–2004	0.78	778	611	289	-122	550	210
2004–2005	0.48	828	568	262	-2	537	263
2005–2006	0.14	721	574	242	-95	529	163
2006–2007	0.84	817	602	335	-120	520	273
2007–2008	0.80	916	562	357	-4	532	340

Figure 5.3 shows the WALRUS simulation for the hydrological year 1998–1999, one of the calibration years. This is a very good simulation, most peaks are well recognized. Some peaks are a little bit too peaky, but this can also be due to the use of daily data. When using hourly data, the blue line can be more detailed. The orange line in the top panel shows the flux from the groundwater towards the surface water level. This line represents the base flow in the system and after a longer period with (almost) no precipitation, the discharge should decrease until it reaches this orange line. This is clearly visible at the end of November. The third panel in Figure 5.3 shows the storage deficit (d_{V}) in red, the groundwater level (d_{G}) in orange and the surface water level (c_{D}-h_{S}) in blue. Normally, the groundwater level drops below the surface water level in summer. There was a lot of precipitation (1067 mm) measured in this specific year, so groundwater levels are almost the entire year above the surface water level.

The figures of the other years mentioned in Table 5.4, can be found in Appendix B. Overall, it can be concluded that the model works quiet well in this subcatchment. Winter peaks are well modeled after a summer period with low discharges (2006–2007 and 2007–2008 for instance). In some years, the recession curves do not show a natural

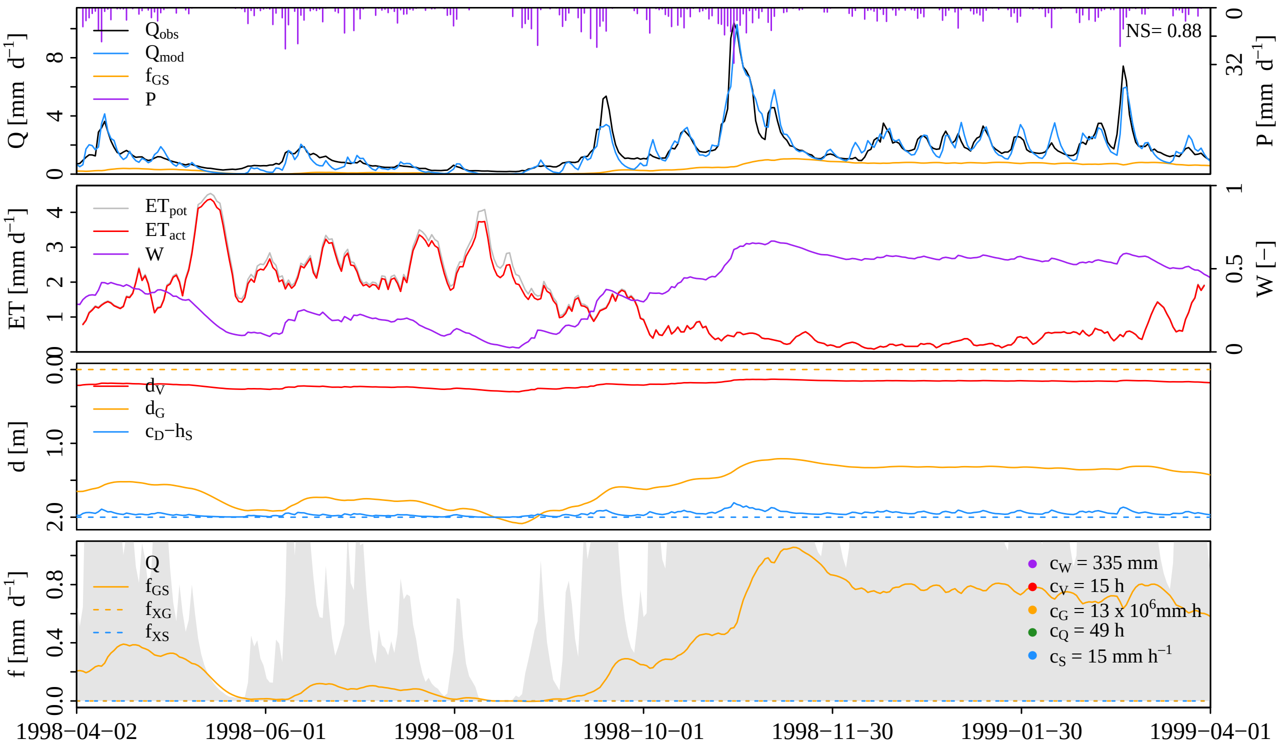


Figure 5.3: Simulation result of WALRUS Dinkel for the hydrological year 1998–1999.

behaviour (2005–2006). It seems that the discharges (e.g. water levels) are controlled. In those periods, WALRUS performs less in terms of Nash-Sutcliffe. It is possible to adapt the model for changes in for instance weir levels. Due to time limitations and missing information on water management in this area, no further investigation has been done in order to improve WALRUS results for this aspect.

5.3 WALRUS Steinfurter Aa

WALRUS is also tested on a daily time scale for subcatchment Steinfurter Aa. Precipitation and evapotranspiration data were the same as for the comparison study. A dataset of discharge observations at location Wettringen was available, but the time steps were irregular, so they first needs to be converted into daily discharges. After that, WALRUS was calibrated on the hydrological year 1998–1999 and 2006–2007. Calibration of this subcatchment was quite difficult. The initial groundwater depth was often far below the channel depth (on the first of April). This sounds not logical, since groundwater levels in lowland areas are normally above or around the channel depth in this time of the year. Optimal parameters were often boundary values, which makes them quite unreliable (because the optimal value was maybe not exactly at the boundary, but outside of the boundary values).

The parameter set of the comparison study in the Steinfurter Aa was also applied on the calibration years. It seemed that using this parameter set, Nash-Sutcliffe efficiencies were reached that were not reached during calibration.

Table 5.5: Overview of WALRUS model parameters, states and soil type used for subcatchment Steinfurter Aa.

c_W	c_V	c_G	c_Q	c_S	d_{G0}	c_D	a_S	st
275	9	8400000	1.7	1.2	1500	1850	0.01	sand

Table 5.6: Nash-Sutcliffe efficiencies (NS) of the WALRUS simulations of subcatchment Steinfurter Aa. All related figures can be found in Appendix C.

Year	NS [-]	P [mm]	ET_{pot} [mm]	Q_{obs} [mm]	$Balance$ [mm]	ET_{act} [mm]	Q_{sim} [mm]
		Observations				Simulations	
1998–1999	0.70	1068	492	484	93	481	550
1999–2000	0.57	890	580	246	64	549	286
2000–2001	0.72	827	525	257	45	508	263
2001–2002	0.73	884	577	319	−12	552	302
2002–2003	0.72	855	550	298	7	536	324
2003–2004	0.74	812	611	239	−38	577	212
2004–2005	0.65	869	568	253	48	552	281
2005–2006	0.42	743	574	272	−104	547	164
2006–2007	0.73	831	602	295	−66	548	256
2007–2008	0.73	937	562	422	−46	546	349

Therefor, the same parameter set is chosen as during the comparison study, only the initial groundwater depth was changed and set to 1500 mm (see Table 5.5).

Table 5.6 gives an overview of all Nash-Sutcliffe efficiencies that were reached after applying the chosen parameter set to all available data. All related figures can be found in Appendix C. One figure is shown in Figure 5.4. Despite the fact that the Nash-Sutcliffe is only 0.72, this is a quite good simulation. Most peaks (especially in winter) are recognized and also the small peaks in summer (August 2002) are well simulated. Surface water levels are fluctuating (due to a small value of parameter c_S) and a reasonable groundwater table creates a base flow, especially in winter (third panel). Compared to the results of the Dinkel, the base flow is more fluctuating in the Steinfurter Aa. This is

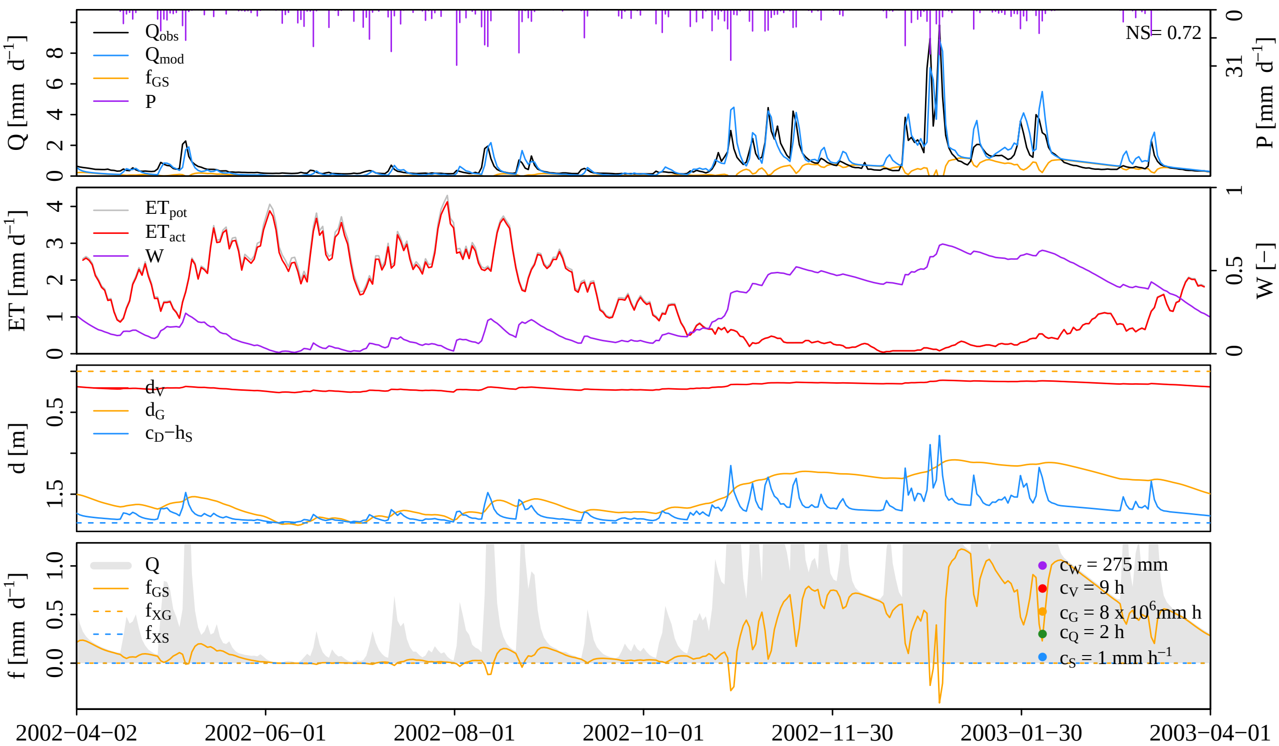


Figure 5.4: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2002–2003.

due to the fact that the groundwater reservoir constant (c_G) is lower, which means that there is less resistance for groundwater to create a flux towards the surface water (and vice versa). Because the surface water level is fluctuating quite rapidly, it could happen that the surface water level suddenly exceeds groundwater level. Then the groundwater drainage flux (f_{QS}) decreases to zero or becomes negative (infiltration of surface water), this is visible in the bottom panel of the WALRUS figures (orange line).

The simulation of 1998–1999 shows a summer with almost zero discharges (Figure C.1 in Appendix C). In September of 1998 the change from dry to wet is clearly visible in a big peak discharge in the observations. While the peak is recognized by WALRUS, the peak is not simulated that good, unfortunately. Other 'end of summer' peaks are better simulated. Maybe downscaling to hourly discharge observations could lead to a better simulation in this case.

At the end of the simulation of 2000–2001 (Figure C.3 in Appendix C), WALRUS simulates some 'extra' peaks, while observations do not show them. This could be caused by snowfall, which delays the discharge of precipitation. WALRUS is able to correct the simulated discharge for snowfall, but therefor time series of temperature and radiation are necessary (see also Section 3.4). Since daily data are used and no exact calculations can be made for snow melt (during daytime) or snow accumulation (during night when temperature drops below zero), no further investigation has been done in order to see the effects of snow. The last two (Dutch) subcatchments are modeled on a hourly time scale. In these two subcatchments, the effects of snowfall are investigated.

5.4 WALRUS Regge

Subcatchment Regge is calibrated and validated on hourly time scale. This subcatchment is used in a small test case in order to see the effects of the snow algorithm, potential evapotranspiration corrected for land use and the effects of adding WWTP data. WALRUS Regge was calibrated on the normal dataset on the hydrological year 1999–2000. The calibration resulted in a parameter set which was also changed by hand afterwards, in order to improve the simulation results.

Table 5.7: Overview of WALRUS model parameters, states and soil type used for subcatchment Regge.

c_W	c_V	c_G	c_Q	c_S	d_{G0}	c_D	a_S	st
396	45	16000000	7.5	0.2	1625	2450	0.01	loamy sand

Table 5.8: Nash-Sutcliffe efficiencies (NS) of the WALRUS simulations of subcatchment Regge. All related figures can be found in Appendix D.

Year	NS [-]	Observations P [mm]	ET_{pot} [mm]	Q_{obs} [mm]	$Balance$ [mm]	Simulations ET_{act} [mm]	Q_{sim} [mm]
1999–2000	0.82	898	583	265	50	512	284
2000–2001	0.76	863	537	328	−2	488	298
2001–2002	0.73	891	581	381	−72	515	313
2004–2005	0.69	822	566	302	−46	520	264
2005–2006	0.74	774	583	240	−50	527	212
2006–2007	0.78	863	604	301	−42	504	283
2007–2008	0.74	871	569	316	−14	519	273
2008–2009	0.57	700	572	251	−123	480	183
2009–2010	0.79	777	607	238	−68	515	216
2010–2011	0.74	786	587	323	−125	489	287

Table 5.7 shows the parameters that were chosen after calibration. The parameter set was validated on the other available years. All figures can be found in Appendix D. Table 5.8 gives an overview of the Nash-Sutcliffe efficiency and water balance of each of simulated hydrological years.

Looking to water balance of the observations used for the model, it can be concluded that (except for the calibration year), all water balances are negative. The average balance is -49 mm. Probably the evapotranspiration time series are overestimated. WALRUS reduces potential evapotranspiration by using a reduction factor which is depending on the storage deficit. When the storage deficit is almost zero (soil is saturated), the evapotranspiration reduction factor is 1.0 (no reduction). When the storage deficit increases, the reduction factor decreases (more reduction of potential evapotranspiration), since there is less water available in the vadose zone. Observing the water balances in Table 5.8, the actual evapotranspiration (potential evapotranspiration times the evapotranspiration reduction factor) is on average 12% lower.

The potential evapotranspiration that has been used is equal to the reference evapotranspiration of the KNMI (see Section 3.2). This evapotranspiration is derived from using incoming shortwave radiation and temperature measurements, but is not corrected for land use. In order to see if the average water balance is closing better, the evapotranspiration time series of subcatchment Regge is corrected for land use. This is already explained in Section 3.2. The average water balance, based on the same precipitation and discharge time series, but now using the corrected potential evapotranspiration time series is $+5$ mm, a substantial improvement of the water balance. Since there was only a good land use map available of the Regge catchment, this has only been done for WALRUS Regge.

After validating the same parameter set on the data with the adjusted potential evapotranspiration, significant improvements of the WALRUS simulations are visible. The Nash-Sutcliffe efficiencies are presented in Table 5.9, in column C. Note that column A contains the same Nash-Sutcliffe efficiencies as already presented in Table 5.8.

The effects of snowfall are also investigated. Wendt (2015) developed a snow algorithm for WALRUS (see Section 3.4) and this algorithm is implemented in the WALRUS code and can be used on demand. In that case, additional time series of temperature and global radiation are required. Column E shows the results (in terms of Nash-Sutcliffe). It is logical that the Nash-Sutcliffe efficiencies are not significantly higher than the normal simulation (column A), since the snow algorithm only influence the simulations when temperatures are below zero and precipitation occurs.

Table 5.9: Overview of the simulation results (in terms of Nash-Sutcliffe) of WALRUS Regge with different input datasets.

Dataset	A	B	C	D	E	F	G	H
WWTP data included	no	yes	no	yes	no	yes	no	yes
ET_{pot} corrected for land use	no	no	yes	yes	no	no	yes	yes
Snow algorithm applied	no	no	no	no	yes	yes	yes	yes

Year	A	B	C	D	E	F	G	H
1999–2000	0.82	-	0.80	-	0.82	-	0.80	-
2000–2001	0.76	-	0.79	-	0.74	-	0.77	-
2001–2002	0.73	-	0.78	-	0.74	-	0.78	-
2004–2005	0.69	-	0.77	-	0.70	-	0.78	-
2005–2006	0.74	-	0.77	-	0.72	-	0.78	-
2006–2007	0.78	-	0.79	-	0.78	-	0.79	-
2007–2008	0.74	0.75	0.78	0.79	0.74	0.75	0.78	0.79
2008–2009	0.57	0.62	0.69	0.72	0.58	0.62	0.70	0.73
2009–2010	0.79	0.79	0.81	0.80	0.79	0.80	0.81	0.81
2010–2011	0.74	0.75	0.77	0.78	0.75	0.76	0.78	0.79

But when this situation takes place, the shape of the simulation curve improves a lot (see Section 5.5 for an example).

Data from waste water treatments plants (WWTP) were also available for the Regge subcatchment in the period 2007–2011, but only on a monthly time scale. Therefor, all peaks (due to precipitation) are averaged out and can not help to improve the simulation of the discharge peaks. Nevertheless, these data were added to the original dataset, in WALRUS named as a surface water supply flux (f_{XS}). The results are showed in column B of Table 5.9. A small improvement can be observed.

In the end, WWTP data, adjusted ET_{pot} and the snow algorithm were combined in different ways and the parameter set was validated on this data. The results are visible in column D, F, G and H.

It can be concluded that the data with potential evapotranspiration corrected for land use is improving the simulation results the most. Adding WWTP data and using the snow module are on average also improving the results but to a lesser extent. Appendix D shows for each year the figures of the results of WALRUS Regge, using the original data (column A) and the combination of the snow algorithm, WWTP data (if available in that year) and corrected potential evapotranspiration (column G or H).

5.5 WALRUS Afwateringskanaal

Subcatchment Afwateringskanaal is probably the most difficult subcatchment to model correctly, since the water system is quite complex close to the outlet. Discharge was measured at the outlet of the subcatchment and at sluice Coevordersluis, which serves as inlet and outlet. It is known that the data from the Coevordersluis is very unreliable, but since a lot of water is passing through this sluice, it was investigated if including the data, could help to improve the results.

The calibration was executed on the hydrological year 2006–2007, first on the dataset with only discharge data from the outlet (e.g. no sluice included). After calibration, a parameter set was chosen (see Table 5.10) and validated on the other four hydrological years. Although the calibration lead to a Nash-Sutcliffe of 0.90, validation results were varying between 0.46 and 0.72. Figures of the results can be found in Appendix E.

Hereafter, the data from sluice Coevordersluis was added to the dataset (as a surface water supply flux) and a new calibration was performed. It seemed that parameters were not much deviating from the parameters found after the first calibration, so the same parameter set was chosen. The Nash-Sutcliffe of the calibration was found to be 0.91 and WALRUS also performs better on the validation years, see column B in Table 5.11. It must be noted that the observed discharge in the winter of 2008–2009 shows a really unnatural behavior. That is the reason why the Nash-Sutcliffe is consistently lower than the other hydrological years.

Data from waste water treatment plants (WWTP) in the subcatchment were available and added to the original dataset (column D in Table 5.11). The data was available on a daily time scale, so peaks in the WWTP data were clearly visible in the simulation (blue dotted line in the bottom panel of the standard WALRUS output figure). When comparing the Nash-Sutcliffe efficiencies of dataset A and D in the table, it can be concluded that the effect of the WWTP on the simulated discharge is on average not really visible.

The snow algorithm has also been applied in subcatchment Afwateringskanaal. To see the effects in terms of Nash-Sutcliffe, column C and E need to be compared. A longer colder period with precipitation was observed in the

Table 5.10: Overview of WALRUS model parameters, states and soil type found for subcatchment Afwateringskanaal.

c_{W}	c_{V}	c_{G}	c_{Q}	c_{S}	d_{G0}	c_{D}	a_{S}	st
325	25	37000000	65.0	3.0	1575	1850	0.01	sand

Table 5.11: Overview of the simulation results (in terms of Nash-Sutcliffe) of WALRUS Afwateringskanaal with different input datasets.

Dataset	A	B	C	D	E
Data Coevordersluis included	no	yes	yes	no	yes
WWTP data included	no	no	yes	yes	yes
Snow algorithm applied	no	no	no	no	yes
Year	**A**	**B**	**C**	**D**	**E**
2006–2007	0.90	0.91	0.89	0.88	0.89
2007–2008	0.72	0.87	0.86	0.69	0.86
2008–2009	0.46	0.61	0.59	0.50	0.60
2009–2010	0.71	0.82	0.81	0.73	0.81
2010–2011	0.58	0.81	0.82	0.65	0.87

winter of 2010–2011. The effects of the snow algorithm on the simulated discharge are clearly visible (see Figure 5.5). Initially, precipitation in the red square in the figure (top panel) is directly discharged by the model, leading to an overestimation of the simulated discharge. The observed discharge is delayed, due to the snow accumulation. When the snow melts, a bigger peak is observed than simulated, because WALRUS already discharged the melted snow, assuming it was rain. In the bottom panel of Figure 5.5, the snow algorithm has been applied. The discharge is now much better simulated, and the behavior of the recession curve is improved significantly, leading to an higher Nash-Sutcliffe efficiency. It is therefore recommended to implement the snow algorithm, when time series of temperature and global radiation are available, or can be predicted when using WALRUS to make discharge predictions.

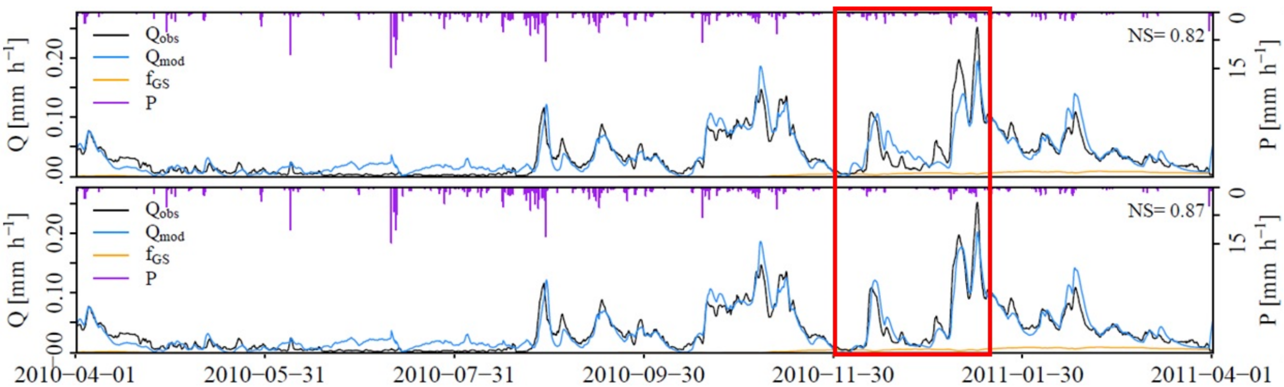


Figure 5.5: The effects of applying the snow algorithm in WALRUS on the simulated discharge. The top panel shows the WALRUS simulation of dataset C and the bottom panel shows the WALRUS simulation of dataset E, where the snow algorithm has been applied).

5.6 Season dependent parameter sets

The ten selected periods with a continuous positive or negative SPI value are presented in Table 5.12. Monte Carlo calibrations were applied on this ten periods and the best 20 out of 50000 parameter sets were evaluated. These parameters were plotted against the mean SPI of the calibration period. The results can be found in Figure 5.7.

It seems that there is a positive correlation between parameter c_W and the mean SPI. Wet conditions (positive SPI values) are leading to an higher c_W value, while for more dry conditions (negative SPI values) the c_W is decreasing. Parameter c_W is influencing the behavior of the wetness index W (value between 0 and 1), which is determining the fraction of rainfall that is going directly to quickflow reservoir. When parameter c_W increases, more water is send to the quickflow reservoir (comparing situations with the same storage deficit, see Figure 5.6). More quickflow is assumed under wet conditions, so the correlation between the mean SPI and parameter c_W is explainable.

A trend between the mean SPI and the other three investigated parameters (c_G, c_Q and c_S) is not clearly visible. One remarkable result is the relation between the mean SPI and the initial groundwater depth, which was also calibrated. Looking at the results in Figure 5.7e), it can be concluded (based on this results) that under more wet conditions (positive SPI), WALRUS sets the initial groundwater depth deeper, while shallower groundwater depths are expected.

It must be noted that (because of time limitations) this was an investigation of only ten periods. A better correlation between the parameters and the mean SPI can occur when more events are calibrated and analyzed.

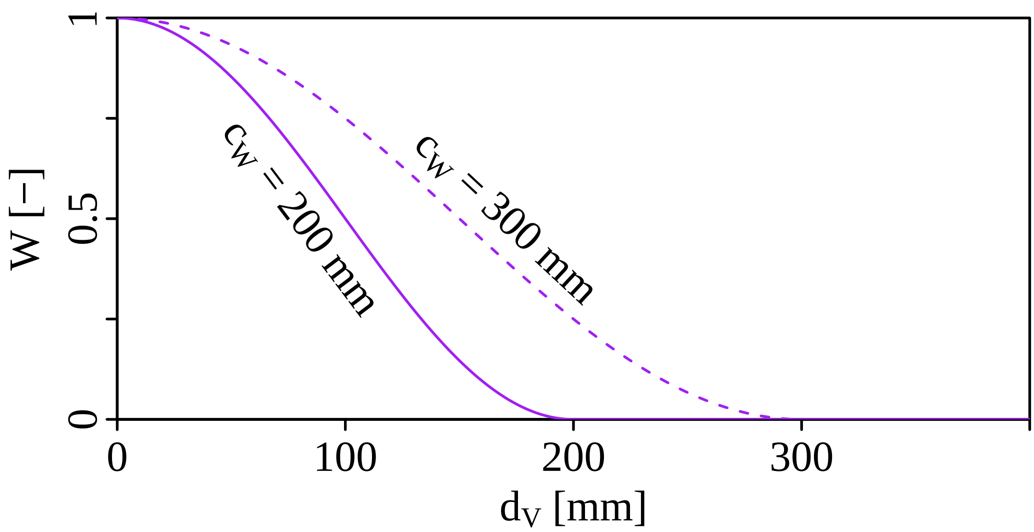
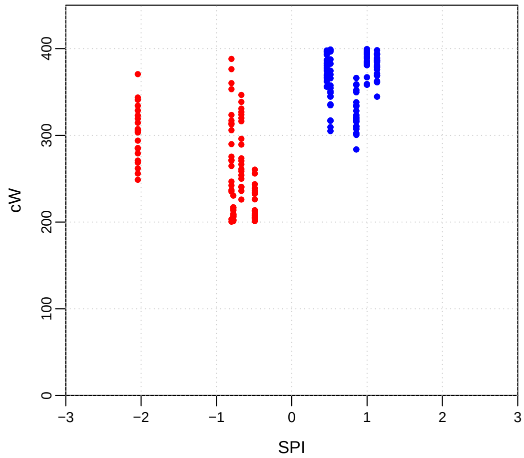


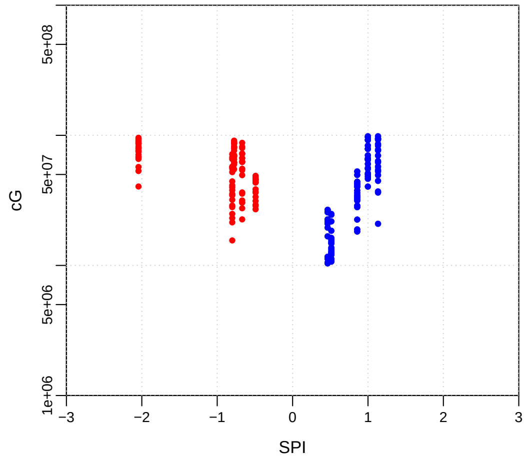
Figure 5.6: The relation between storage deficit d_V and the wetness index, influenced by parameter c_W.

Table 5.12: Selected periods with a positive SPI (Set P1–P5) or a negative SPI (Set N1–N5). Please note that besides the fact that this is the average SPI in the indicated periods, all SPI values were positive or negative during this period.

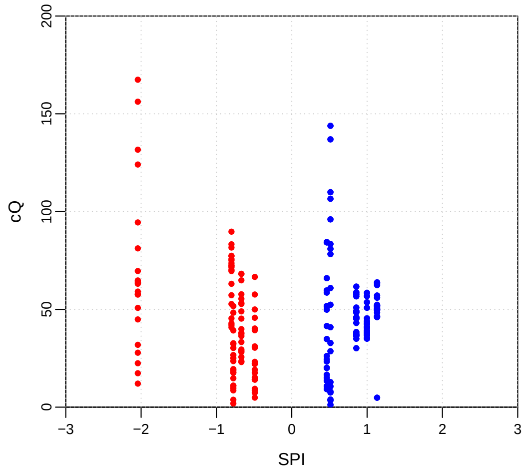
Set	Start	End	Days	SPI
P1	01-06-1999	01-08-1999	61	0.46
P2	07-12-1999	22-01-2000	46	1.00
P3	08-02-2000	06-04-2000	58	1.13
P4	13-05-2007	27-08-2007	106	0.86
P5	10-07-2008	24-08-2008	45	0.51
N1	15-10-1999	03-12-1999	49	−0.67
N2	07-04-2000	20-05-2000	43	−0.49
N3	01-04-2007	12-05-2007	41	−2.04
N4	19-04-2008	09-07-2008	81	−0.78
N5	11-12-2008	04-03-2009	83	−0.80



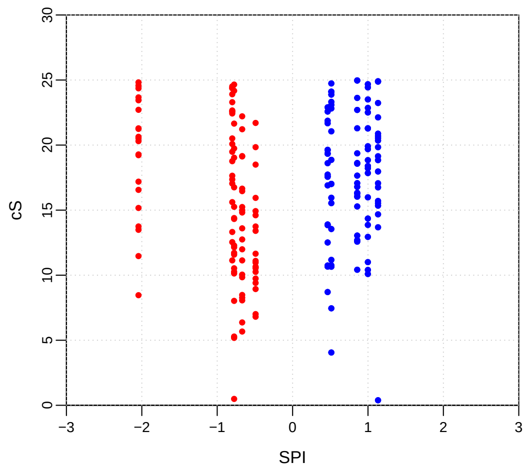
a) SPI plotted against c_W



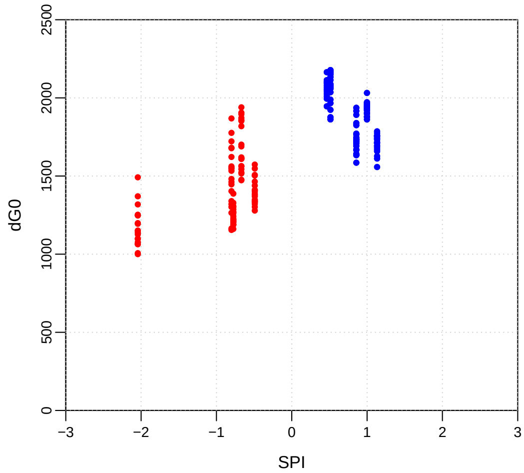
b) SPI plotted against c_G



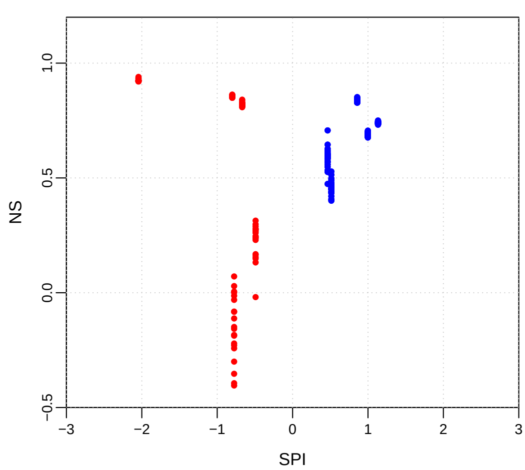
c) SPI plotted against c_Q



d) SPI plotted against c_S



e) SPI plotted against d_{G0}



f) SPI plotted against NS

Figure 5.7: Plots of the parameters founded after calibration of the ten periods with a continuous positive or negative SPI. The parameters are plotted in separate figures against the mean SPI of the calibration period.

6 | Discussion

Some points of discussion are presented in this chapter. The following aspects are discussed: comparison of the two models on a daily time resolution, the importance of good quality observations and parameter uncertainties.

Comparison of the two models

The comparison of the two models has been executed on a daily time resolution. Since the catchments are responding quite fast on precipitation events, it can be discussed if modeling these subcatchments with a daily time resolution is really effective. In the results of the comparison study, the simulated peak discharges of both models are often one day too early or too late. An example can be found in Figure 6.1. Even when the peaks are simulated well in terms of maximum discharge, a shift in this peak has a strong influences on the Nash-Sutcliffe efficiency. Despite the fact that hourly data was not directly available for the German catchments, it is likely that recession curves are smoother and that the timings of discharge peaks are better.

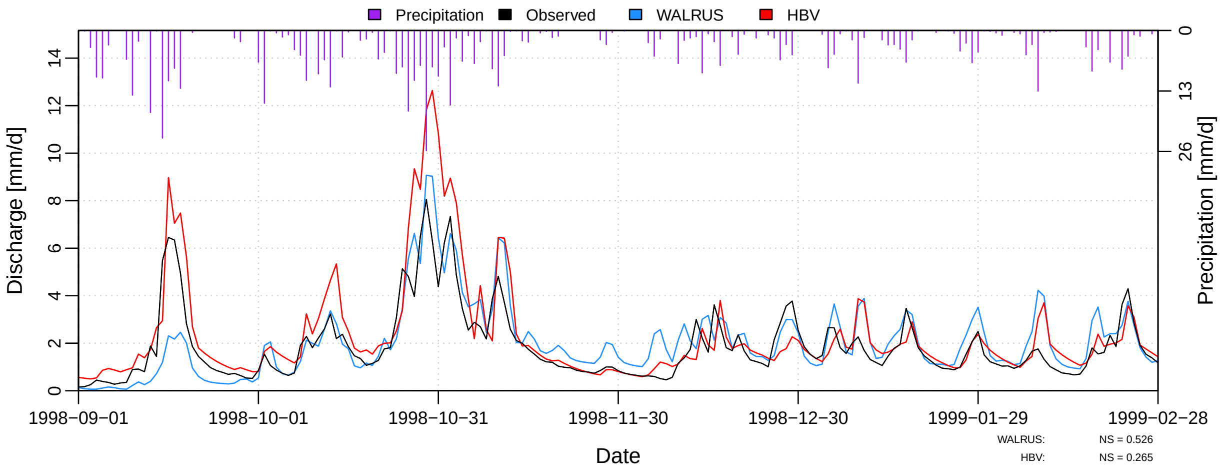
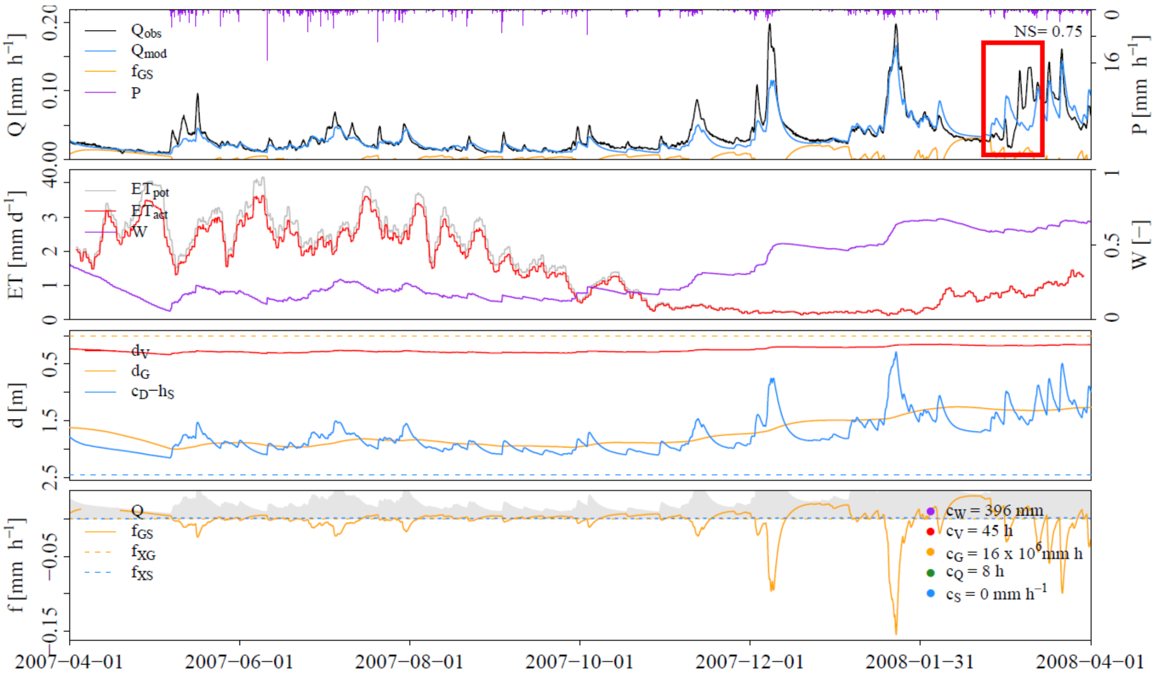


Figure 6.1: Effect of simulating discharge with a daily time resolution in relative fast responding catchments: timing of discharge peaks is often not accurate enough.

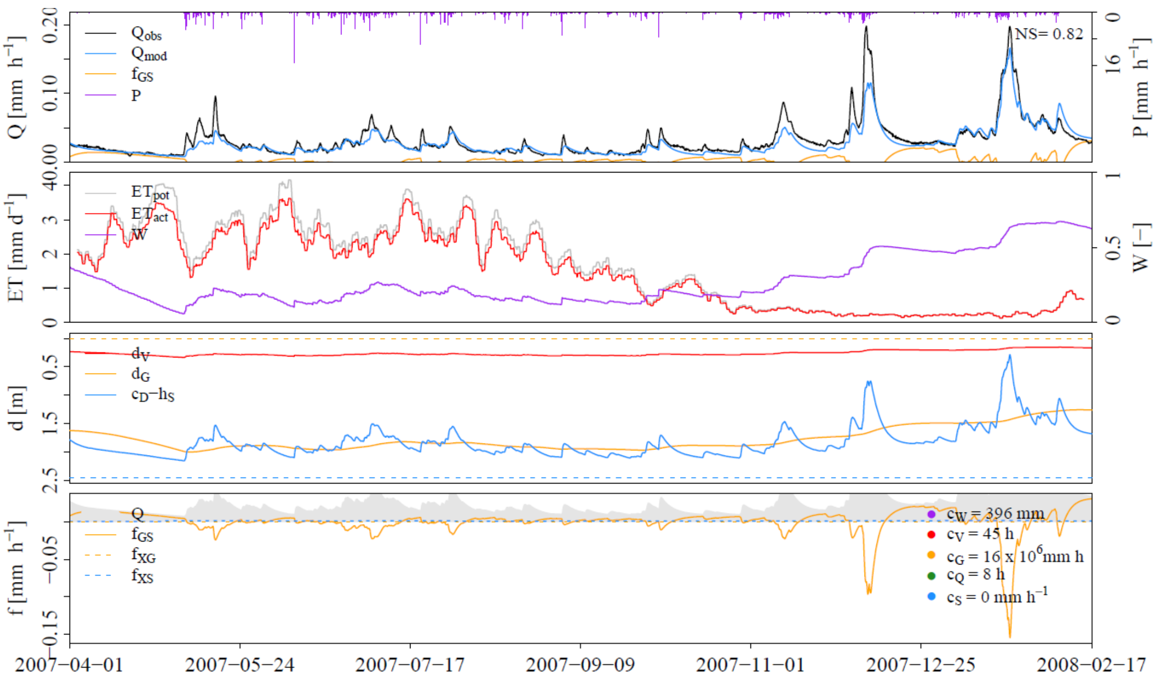
Importance of good quality observations for modeling hydrological processes

It is very important to have a set of good quality discharge observations when calibrating and validating a rainfall-runoff model like WALRUS. Gaps in time series of discharge are linearly interpolated by WALRUS, but this missing data can influence the Nash-Sutcliffe efficiency dramatically. Also errors in control systems of weirs can have a big influence on the model results. An example is given in Figure 6.2. In March 2008, an error occured in the control system of the weir where the discharge data of subcatchment Regge is measured. The weir was setting up the water level upstream, which led to a temporary decrease in observed discharge. After a short period, the weir was suddenly going down, which give the extreme peak discharge afterwards (see red box in Figure 6.2). While the observed discharge is measured correctly, WALRUS can not simulate this period correctly, since the behavior of the discharge is not natural. As a result, the Nash-Sutcliffe drops down and becomes 0.75 for the entire hydrological year. When simulating the same hydrological year but without the last period (starting from the location of the red box), the Nash-Sutcliffe increases to 0.82.

WALRUS is able to account for controlled water levels (summer and winter levels for instance). Therefor, an extra time series of the distance between the bottom of the channel and level of the weir ($h_{S,min}$) needs to be added to the dataset. In this way, unnatural fluctuations in the observed discharge could be tackled by WALRUS when simulating discharge, but this should be tested. This has not been done during this study, but could be investigated in next studies.



a Results of WALRUS Regge for the hydrological year 2007–2008, including the unnatural discharge observations due to errors in the control system of the weir (see red box).



b The same results as in the first figure, but now without the period with unnatural discharge behavior. The Nash-Sutcliffe efficiency is remarkably higher.

Figure 6.2: Simulation results of WALRUS Regge for the hydrological year 2007–2008.

Parameter uncertainties

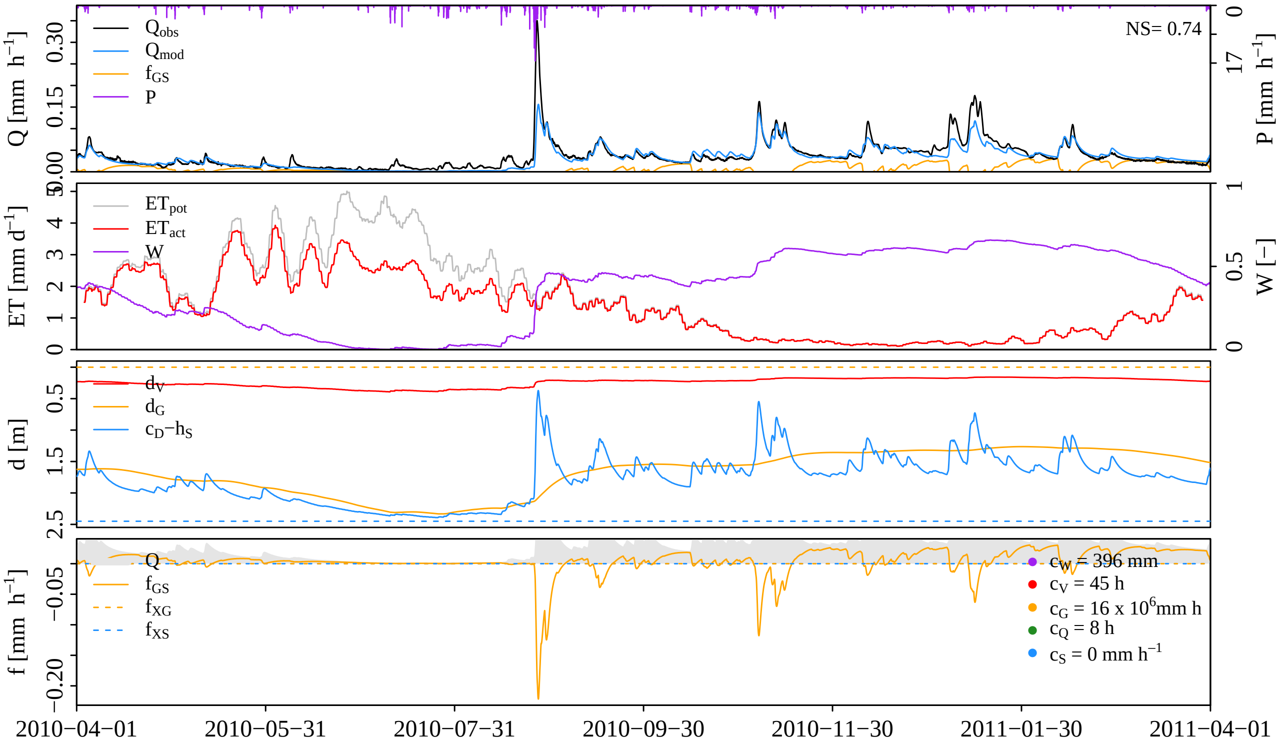
It is known that finding one optimal parameter set for a catchment is not trivial (Melsen et al., 2014) and that the same Nash-Sutcliffe efficiency can be reached by using two different sets of parameters (Brauer, 2014). The parameters of WALRUS Regge are calibrated on one hydrological year (1999–2000) and then validated on the other available hydrological years. Since the founded parameter set is the optimal one for the calibration year, it is logical that WALRUS performs less on the validation years.

Hydrological year 2010–2011 is well known in the eastern part of the Netherlands. At the end of August 2010, there was an extreme precipitation event with more than 120 mm of rainfall in less than 24 hours, with its center close to subcatchment Regge. More information and an analysis of the hydrological response of the catchment Hupsel (which is located close to the Regge subcatchment) can be read in Brauer et al. (2011).

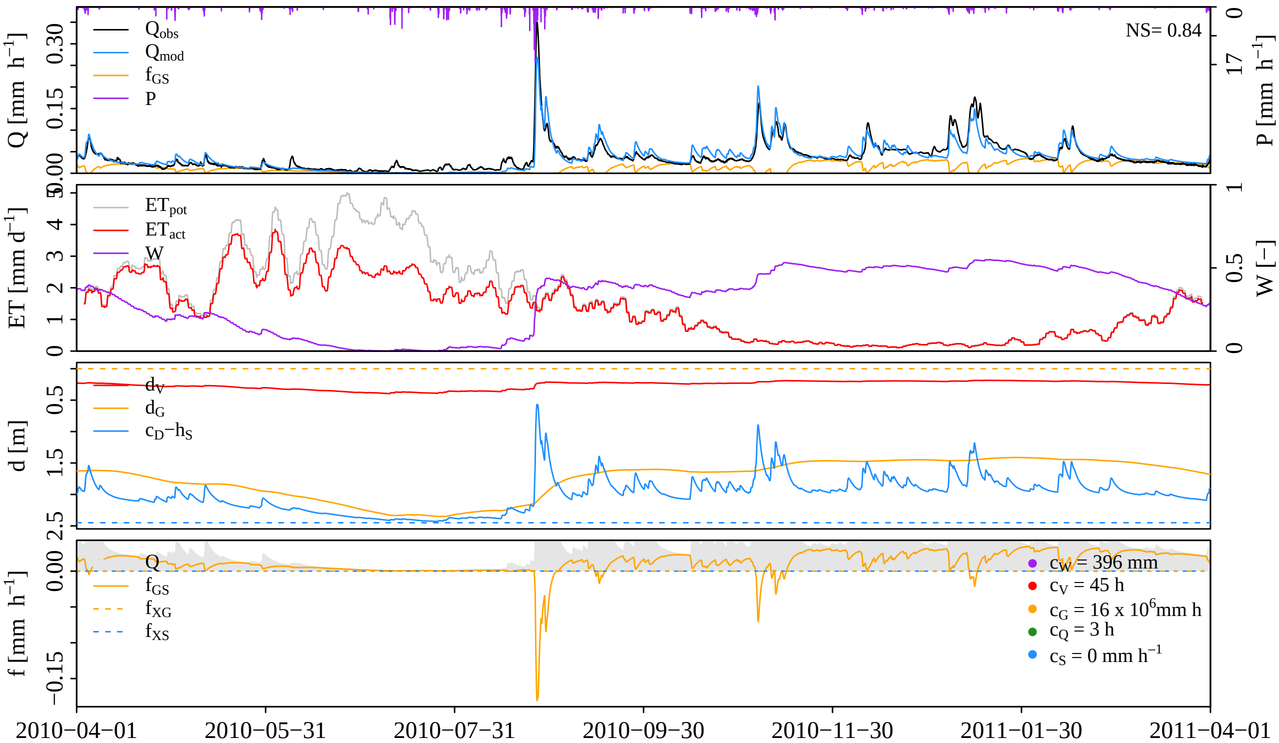
This extreme event can also be identified in the discharge observations of subcatchment Regge. As an experiment, this hydrological year was also calibrated. The validation of the parameter set from 1999–2000 and the calibration results can be found in Figure 6.3. The calibration on this year leads to better simulation results. The Nash-Sutcliffe efficiency increases from 0.74 to 0.84. The big discharge peak at the end of August 2010 is simulated better than after validating the chosen parameter set of the calibration of 1999–2010. This proofs that the results are highly depending on the chosen calibration period.

Table 5.9 shows the simulations results in terms of Nash-Sutcliffe of the chosen parameter under different conditions (evapotranspiration adapted for land use, snow algorithm applied, WWTP data used). It was found that dataset G was giving on average the highest Nash-Sutcliffe efficiencies (corrected evapotranspiration and snow algorithm applied). The new parameter set (founded after calibration of 2010–2011) is also validated on the other years with dataset G. Now it was found, that the Nash-Sutcliffe ranges from 0.47–0.83 with an average of 0.70. However this parameter set gives better results for hydrological year 2010–2011, WALRUS performs less when using this parameter set for the other hydrological years. It is necessary to find a strategy that can be used so that different parameter sets can be applied (depending on the current hydrological conditions), in order to get the best out of WALRUS.

As a first step, the Standardized Precipitation Index was used as an indicator to find a correlation between the hydrological conditions (dryness and wetness, expressed in terms of SPI) and the parameters of WALRUS. Because of time limitations only ten different events were analyzed. It seems that there is at least a correlation between parameter c_{W} and the SPI, but to prove that, more events should be studied.



a) Validation of the parameter set which was found after calibration of hydrological year 1999–2000.



b) Results of the calibration of hydrological year 2010–2011.

Figure 6.3: Simulation results of WALRUS Regge for the hydrological year 2010–2011.

7 | Conclusions & recommendations

Conclusions

Comparison of HBV and WALRUS

HBV models are currently implemented in the flood warning tool FEWS Vecht. It has been observed that those HBV models are not accurate enough during a first peak discharge after a longer dry period. The users of FEWS Vecht are looking for alternative rainfall-runoff models which are performing better, during summer and winter peak discharges. WALRUS is a possible alternative rainfall-runoff model, with less parameters that require calibration and a shorter computation time. A model comparison study has been executed. The performance of WALRUS in subcatchment Steinfurter Aa was remarkably better. The average Nash-Sutcliffe efficiency of the three validation periods was 0.62 for WALRUS compared to a Nash-Sutcliffe of 0.37 for HBV. Peak discharges are better simulated by WALRUS in this subcatchment. The calibration of WALRUS on data of subcatchment Afwateringskanaal led to a very good simulation of the peak discharges in the calibration period. The validation periods were a little bit less well simulated, but this is also caused by the fact that discharge observations were not accurate enough, since the discharge used by the HBV model consisted of the discharge at the outlet of the subcatchment as well as of discharge of a sluice (Coevordersluis), which can have negative and positive discharges. This cause some unnatural fluctuations in the observed discharge time series. Calibration of subcatchment Dinkel was leading to a high Nash-Sutcliffe (0.88) and a good simulation of the discharge peaks. After validating the used parameters, it was found that HBV was performing slightly better than WALRUS in this subcatchment. From the 10 investigated periods (3 calibration periods and 7 validation periods), WALRUS was performing better in 7 periods. HBV performed better in 3 out of the 10 periods (but only slightly better in 2 of them), so based on this model comparison study, it can be concluded that WALRUS performs (on average) better than the HBV model.

WALRUS subcatchments

After the comparison study, the models three subcatchments were further improved, without keeping in mind the assumptions of the HBV model. WALRUS Dinkel and WALRUS Steinfurter Aa were modeled with a daily time resolution (because of data availability). Both models performed well with average Nash-Sutcliffe efficiencies (based on ten hydrological years) of 0.71 for WALRUS Dinkel and 0.67 for WALRUS Steinfurter Aa. Both models can be further improved by using hourly observations of precipitation, evapotranspiration and discharge.

WALRUS Afwateringskanaal was developed using hourly data. During the comparison study, the observations of sluice Coevordersluis were summed with the observed discharge at the outlet of the subcatchment, leading to an unnatural behavior of the observed discharge. In the new situation, data from the sluice was added as an external surface water flux, instead of adding it to the observed discharge at the outlet. Also data from WWTP was added to the dataset as an external surface water flux and the effects of snow were investigated. It resulted in an average Nash-Sutcliffe of 0.81 (based on five hydrological years). Also this model can be improved by using more accurate observations (in this case of sluice Coevordersluis).

Subcatchment Regge is studied most detailed compared to the other subcatchments in this study, because of data availability. WALRUS was calibrated on a hourly time resolution. The average Nash-Sutcliffe for the original dataset was 0.74 (based on ten hydrological years). Data from waste water treatment plants (WWTP) were also used in this subcatchment, but because of the monthly time resolution of the data, no large improvement of the model results was observed. The snow algorithm was applied and led to slightly better results, depending on the amount of snowfall in the hydrological years that were investigated. The evapotranspiration was corrected for land use and that resulted in significant improvements of the simulations. After applying the WWTP data, snow algorithm and evapotranspiration corrections for land use, the average Nash-Sutcliffe increased to 0.78. It must be noted that some really high discharge peaks are not simulated accurate enough, although the timing of the peak is well done. Other parameter sets could help to solve this problem.

Season dependent parameter sets

A first step was made in finding a relation between the parameters of WALRUS and an certain index which indicates the hydrological circumstances in a catchment. If there is a correlation, such a index can be helpful in deciding when to use a parameter set that can simulate winter peak discharges or a parameter set that can better simulates a first peak discharge after a longer dry period (normally in summer). The Standardized Precipitation Index (SPI) was used as such an indicator. Ten periods with a continuously positive or negative SPI values were selected from the dataset of subcatchment Regge and calibrated separately. It was found that there is possibly a correlation between parameter c_{W} and the SPI. More research is necessary to confirm this result. Perhaps it also delivers a correlation between the other parameters and the SPI, a correlation that was not found in this small investigation.

Recommendations

Because of the results of WALRUS obtained in this (comparison) study and because of the relatively short computation time (due to the presence of less parameters), it is recommended to implement WALRUS into FEWS Vecht. WALRUS performed on average slightly better than HBV, but that was based on a few selected periods. Running WALRUS parallel to HBV in FEWS Vecht for a longer period could give a more clear conclusion on which model performs better in certain conditions (dry/wet). The WALRUS models can also be improved by using different parameter sets, depending on the season, but this needs to be further investigated first. During the comparison study, WALRUS was calibrated on winter peaks. This resulted in other parameter sets than for the calibration of WALRUS on complete hydrological years, which was done after the comparison study. It is also interesting to see how WALRUS simulates the extreme peak discharge in August 2010 and compare the results to the HBV results, also for the subcatchments in Germany. Because of time limitations this was not done during this study. Another option is to calibrate WALRUS on winter peaks and validate the parameter set on the extreme event in August 2010. Although the effects of routing are not investigated in this study, it could be interesting to see if it improves the simulations of discharge and water levels in the streams of a catchment.

Some other general recommendations for next studies that make use of WALRUS:

- The correction of the potential evapotranspiration data on the land use in the catchment. It was found that WALRUS simulations improve when using this corrected evapotranspiration data. Recent land use maps are necessary and also good estimations of crop factors for different land uses.
- The snow algorithm in WALRUS. It has been observed that simulations improves by using this algorithm. It will not always directly lead to a higher Nash-Sutcliffe efficiency, that is depending on the length of the snow accumulation period.
- An algorithm for using the WWTP data can be developed, so that this flux can also be added to WALRUS in areas where no measurements of WWTP effluents are available. A correlation between precipitation and WWTP effluent needs to be found, taking into account the surface of urban areas and the average amount of sewage water from households. Maybe it is possible to implement a special reservoir in WALRUS for this special "quick" flow route.

Bibliography

Bergström, S., Forsman, A., 1973. Development of a conceptual deterministic rainfall-runoff model. Nordic Hydrology 4, 147–170.

Bergström, S., Singh, V., et al., 1995. The HBV model. Computer models of watershed hydrology, 443–476.

Brauer, C., 2014. Modelling rainfall-runoff processes in lowland catchments. Ph.D. thesis.

Brauer, C. C., Teuling, A. J., Overeem, A., van der Velde, Y., Hazenberg, P., Warmerdam, P. M. M., Uijlenhoet, R., 2011. Anatomy of extraordinary rainfall and flash flood in a Dutch lowland catchment. Hydrology and Earth System Sciences 15 (6), 1991–2005.

Brauer, C. C., Teuling, A. J., Torfs, P. J. J. F., Uijlenhoet, R., 2014a. The Wageningen Lowland Runoff Simulator (WALRUS): a lumped rainfall-runoff model for catchments with shallow groundwater. Geoscientific Model Development Discussions 7, 2313–2332.

Brauer, C. C., Torfs, P. J. J. F., Teuling, A. J., Uijlenhoet, R., 2014b. The Wageningen Lowland Runoff Simulator (WALRUS): application to the Hupsel Brook catchment and Cabauw polder. Hydrology and Earth System Sciences Discussions 18, 4007–4028.

Feddes, R., 1987. Crop factors in relation to Makkink's reference crop evapotranspiration. Vol. Proceedings and Informations 39. Comm. Hydrol. Research TNO, The Hague, pp. 33–45.

Hiemstra, P., Sluiter, R., 2011. Interpolation of Makkink evaporation in the Netherlands. Tech. rep., KNMI.

HKV, July 2012. Neerslag-afvoermodellen voor de Overijsselsche Vecht, pr2324.10.

Kirchner, J. W., 2006. Getting the right answers for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. Water Resources Research 42.

Kloosterman, P., 2012. A comparison of the performance of lumped hydrological models in modelling a flash flood in the Hupsel Brook catchment. Msc Thesis, Wageningen University.

KNMI, last visited on: 14 May 2015. Klimatologie.
URL `http://www.knmi.nl/klimatologie/`

Loos, R., 2015. Making WALRUS applicable for large catchments: a case study in the Reusel catchment. Msc Thesis, Wageningen University.

Makkink, G., 1957. Testing the Penman formula by means of lysimeters. J. Inst. Water Eng 11, 277–288.

McKee, T. B., Doesken, N. J., Kleist, J., et al., January 1993. The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology. American Meteorological Society Boston, MA, USA, pp. 179–183.

Melsen, L. A., Teuling, A. J., van Berkum, S. W., Torfs, P. J. J. F., Uijlenhoet, R., 2014. Catchments as simple dynamical systems: A case study on methods and data requirements for parameter identification. Water Resources Research 50 (7), 5577–5596.

Moré, J., 1977. Levenberg–Marquardt algorithm: implementation and theory.

Nash, J., Sutcliffe, J., 1970. River flow forecasting through conceptual models part I: A discussion of principles. Journal of Hydrology 10, 282–290.

Seibert, J., 2000. Multi-criteria calibration of a conceptual runoff model using a genetic algorithm. Hydrology and Earth System Sciences Discussions 4 (2), 215–224.

Vansteenkiste, T., Tavakoli, M., Van Steenbergen, N., De Smedt, F., Batelaan, O., Pereira, F., Willems, P., 2014. Intercomparison of five lumped and distributed models for catchment runoff and extreme flow simulation. Journal of Hydrology 511, 335–349.

Wendt, D., 2015. Snow hydrology in the Netherlands (developing snowmelt algorithms for dutch regional water management modules). Msc Internship report, Wageningen University.

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

A | Results comparison HBV and WALRUS

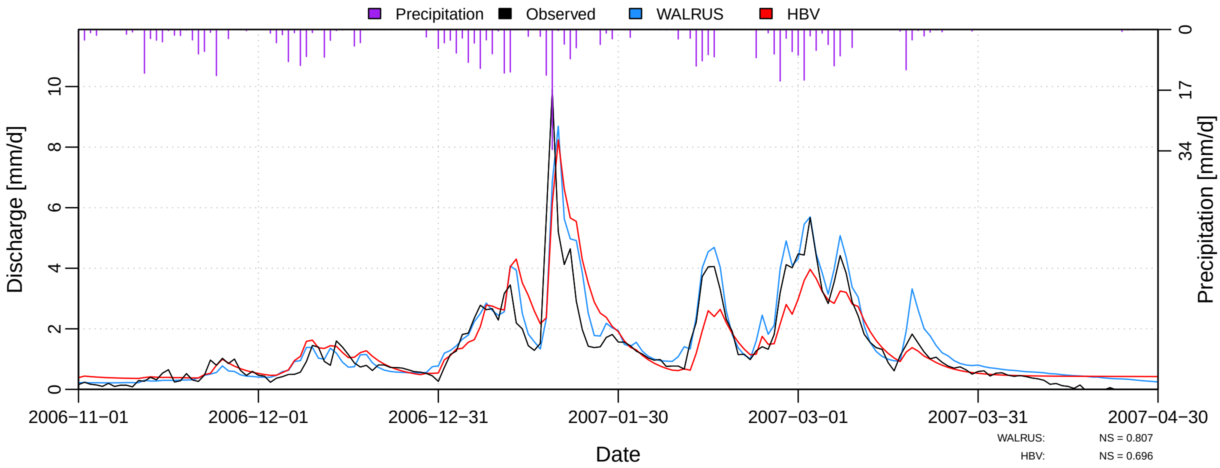


Figure A.1: Results of WALRUS and the HBV model for subcatchment Afwateringskanaal for the calibration period.

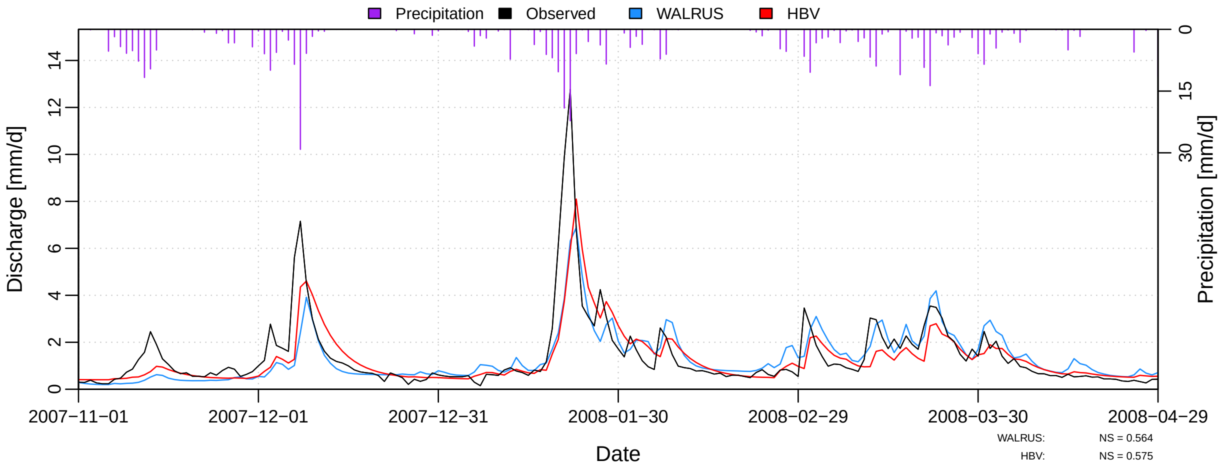


Figure A.2: Results of WALRUS and the HBV model for subcatchment Afwateringskanaal for validation period 1.

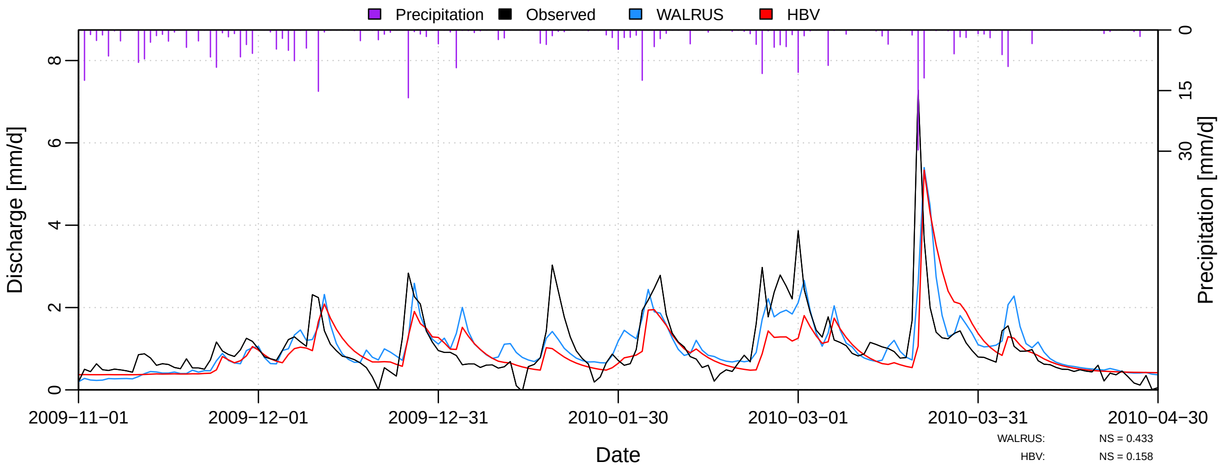


Figure A.3: Results of WALRUS and the HBV model for subcatchment Afwateringskanaal for validation period 2.

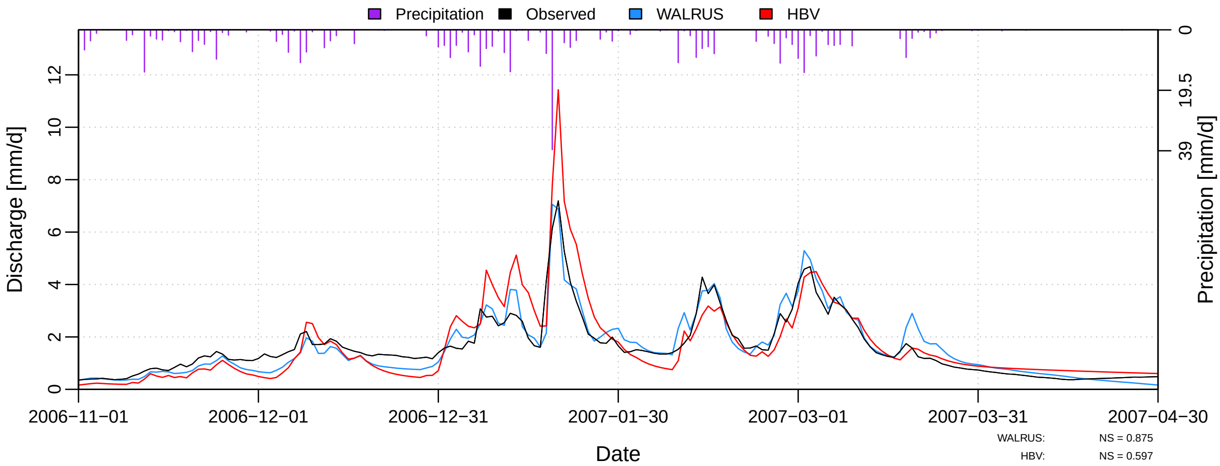


Figure A.4: Results of WALRUS and the HBV model for subcatchment Dinkel for the calibration period.

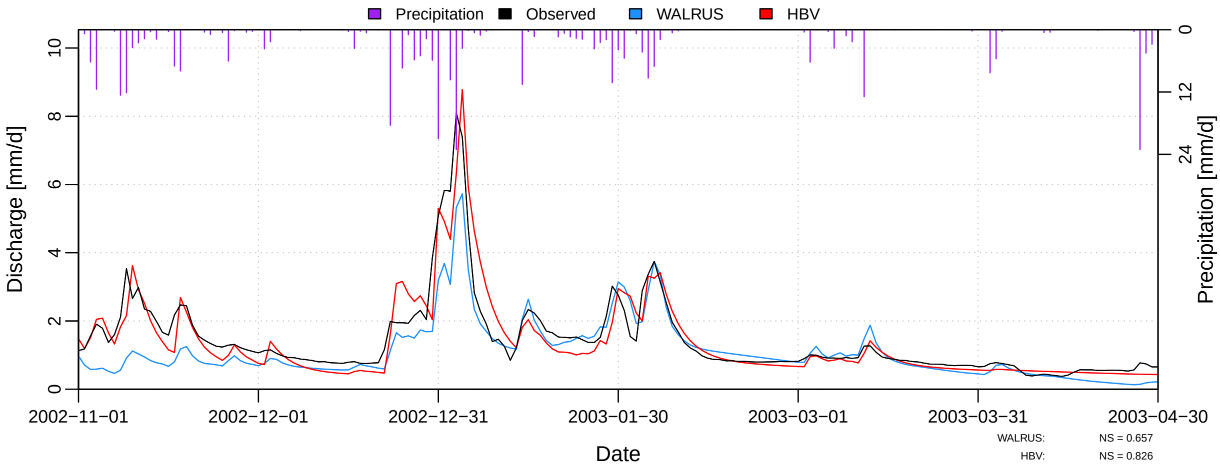


Figure A.5: Results of WALRUS and the HBV model for subcatchment Dinkel for validation period 1.

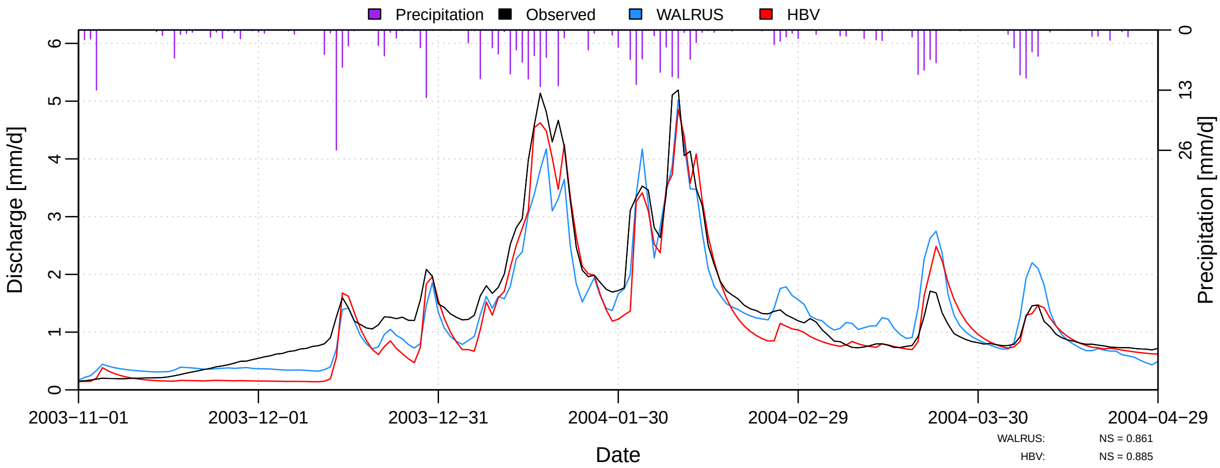


Figure A.6: Results of WALRUS and the HBV model for subcatchment Dinkel for validation period 2.

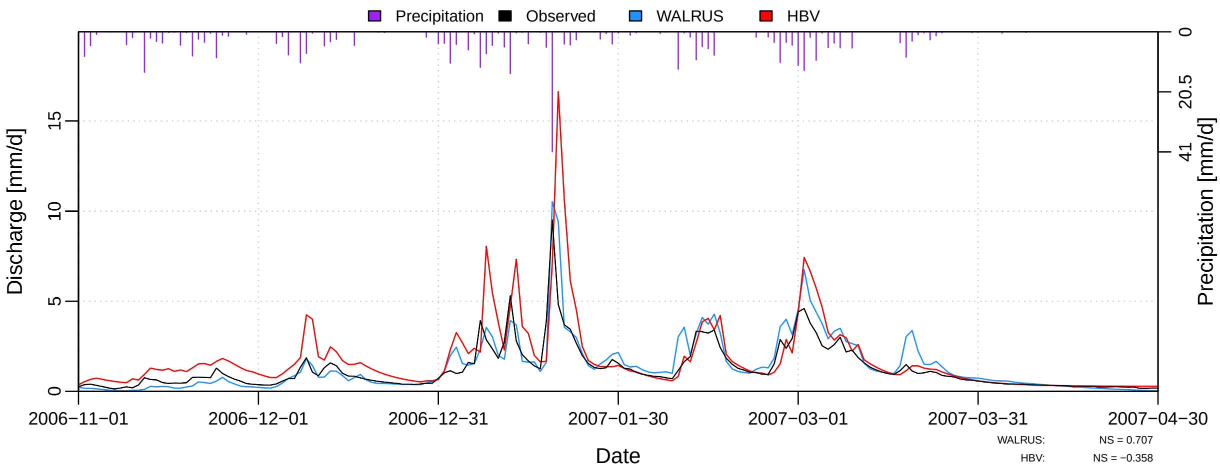


Figure A.7: Results of WALRUS and the HBV model for subcatchment Steinfurter Aa for the calibration period.

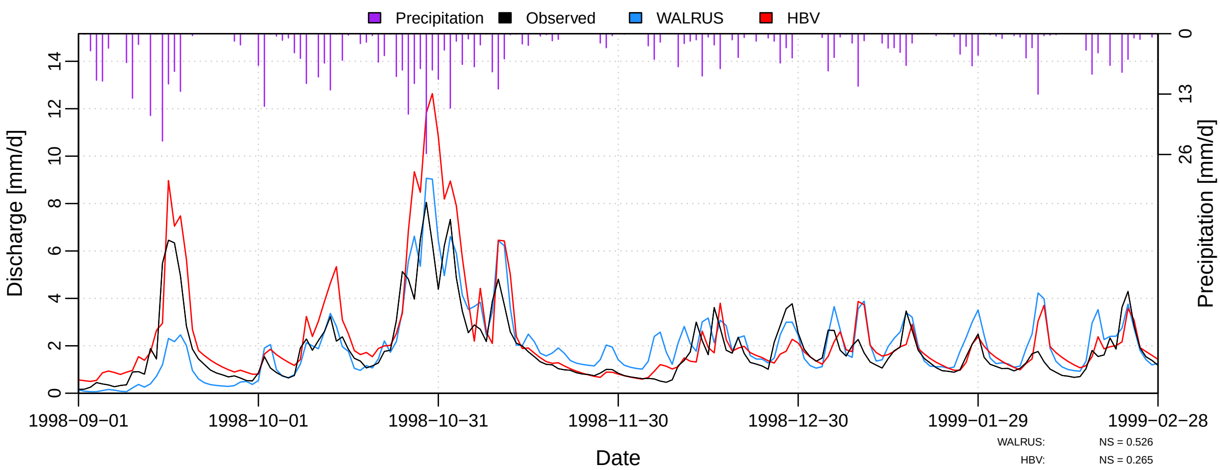


Figure A.8: Results of WALRUS and the HBV model for subcatchment Steinfurter Aa for validation period 1.

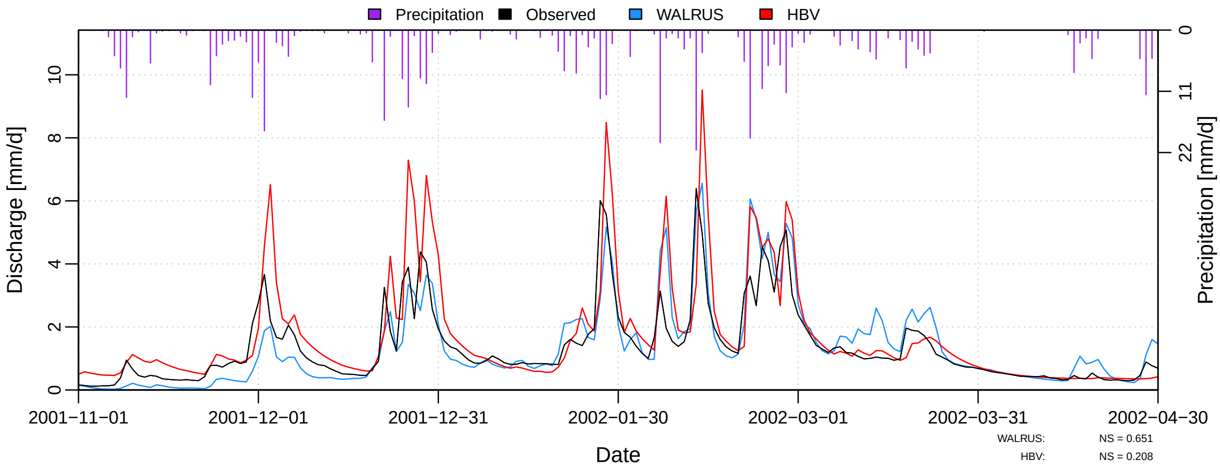


Figure A.9: Results of WALRUS and the HBV model for subcatchment Steinfurter Aa for validation period 2.

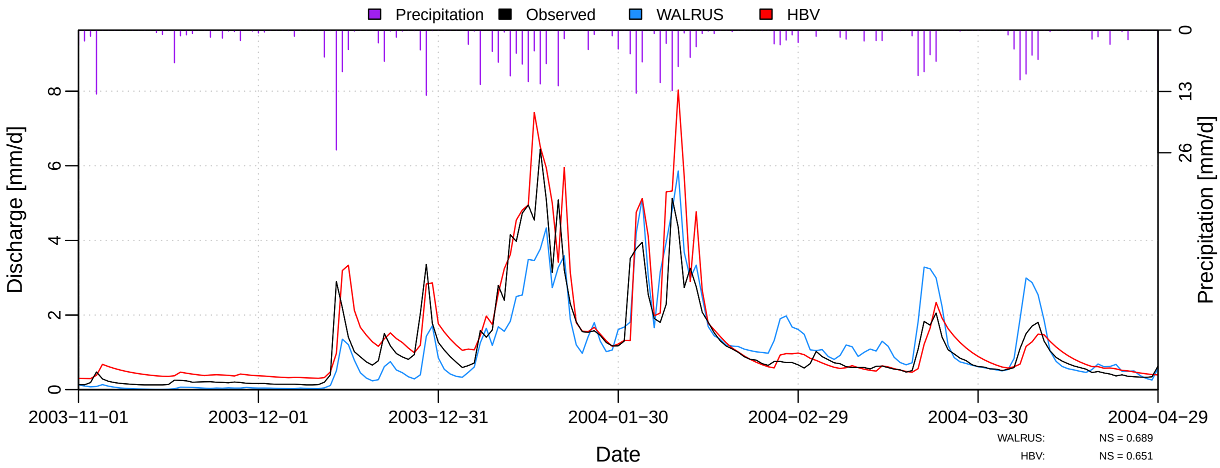


Figure A.10: Results of WALRUS and the HBV model for subcatchment Steinfurter Aa for validation period 3.

B | Simulations WALRUS Dinkel

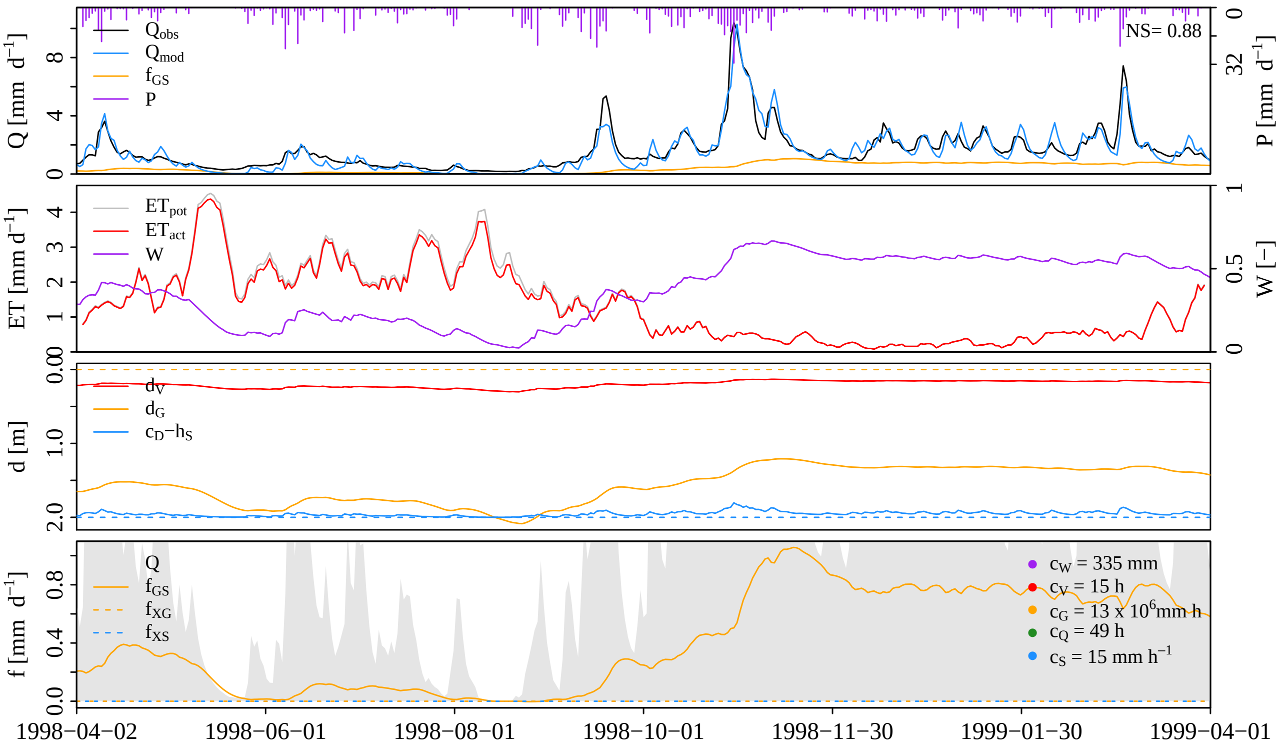


Figure B.1: Simulation result of WALRUS Dinkel for the hydrological year 1998–1999.

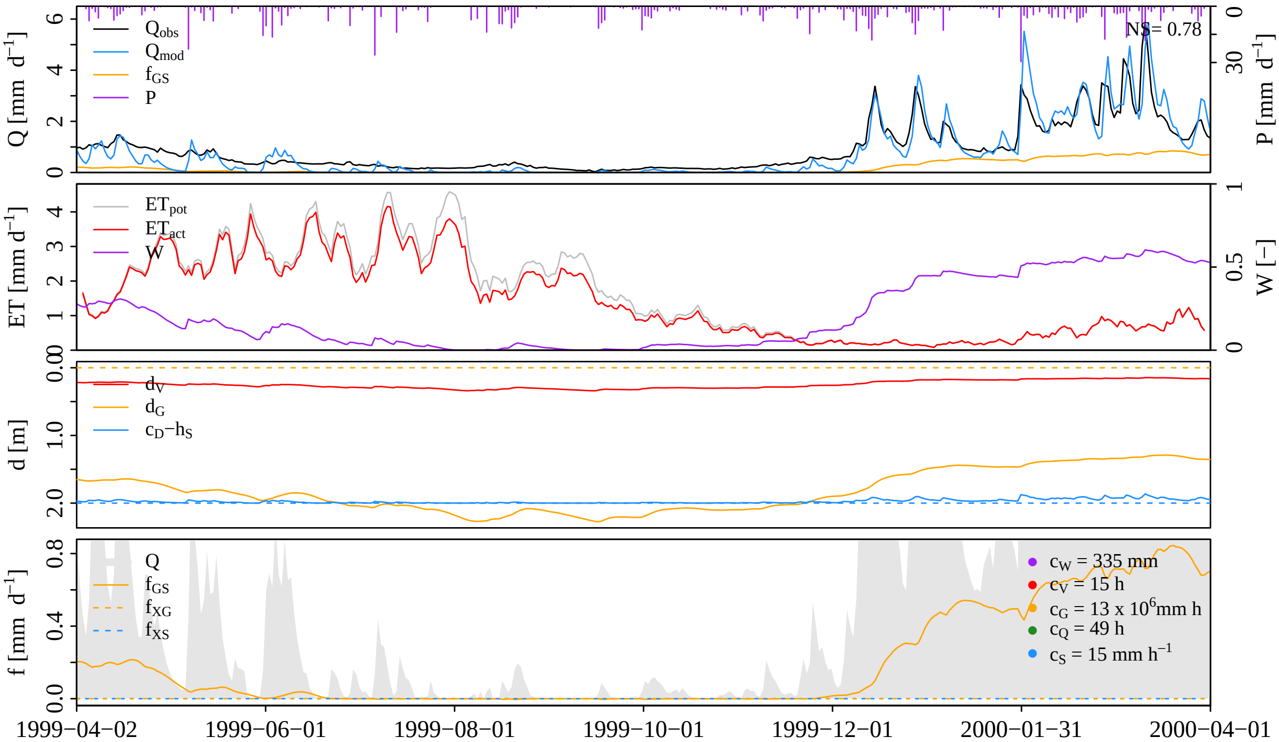


Figure B.2: Simulation result of WALRUS Dinkel for the hydrological year 1999–2000.

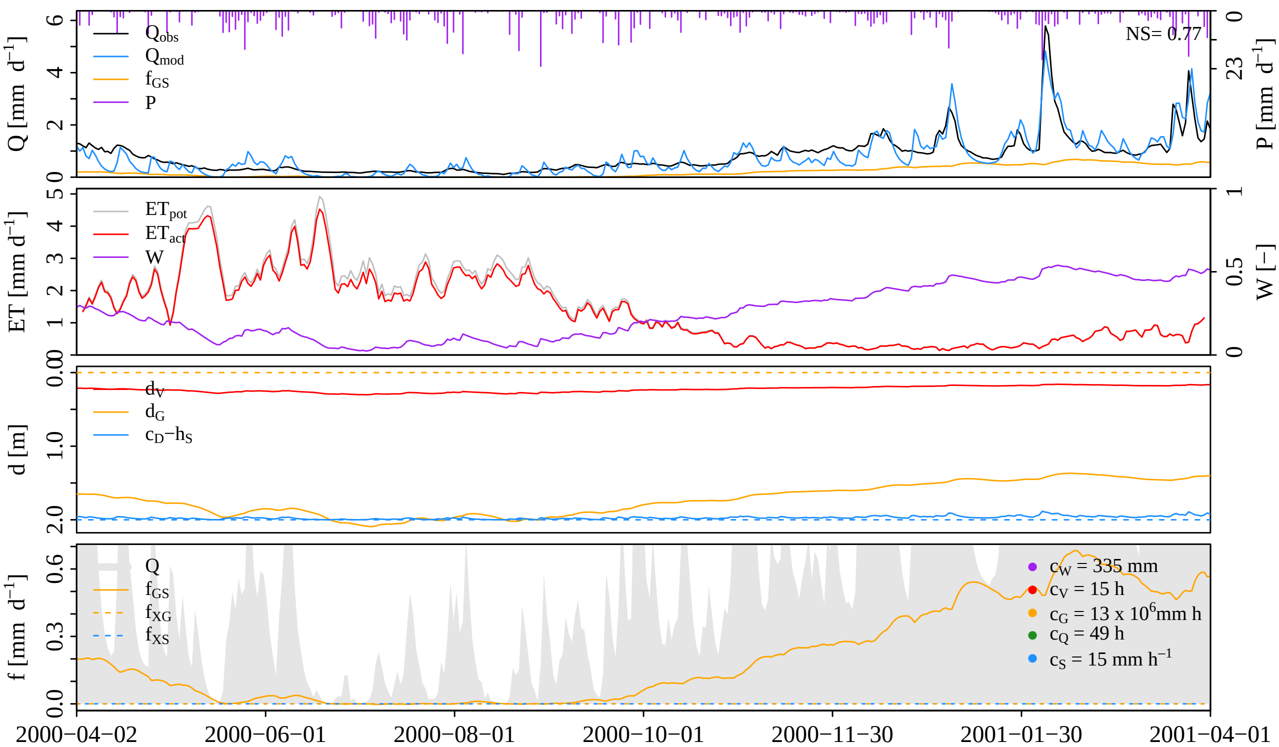


Figure B.3: Simulation result of WALRUS Dinkel for the hydrological year 2000–2001.

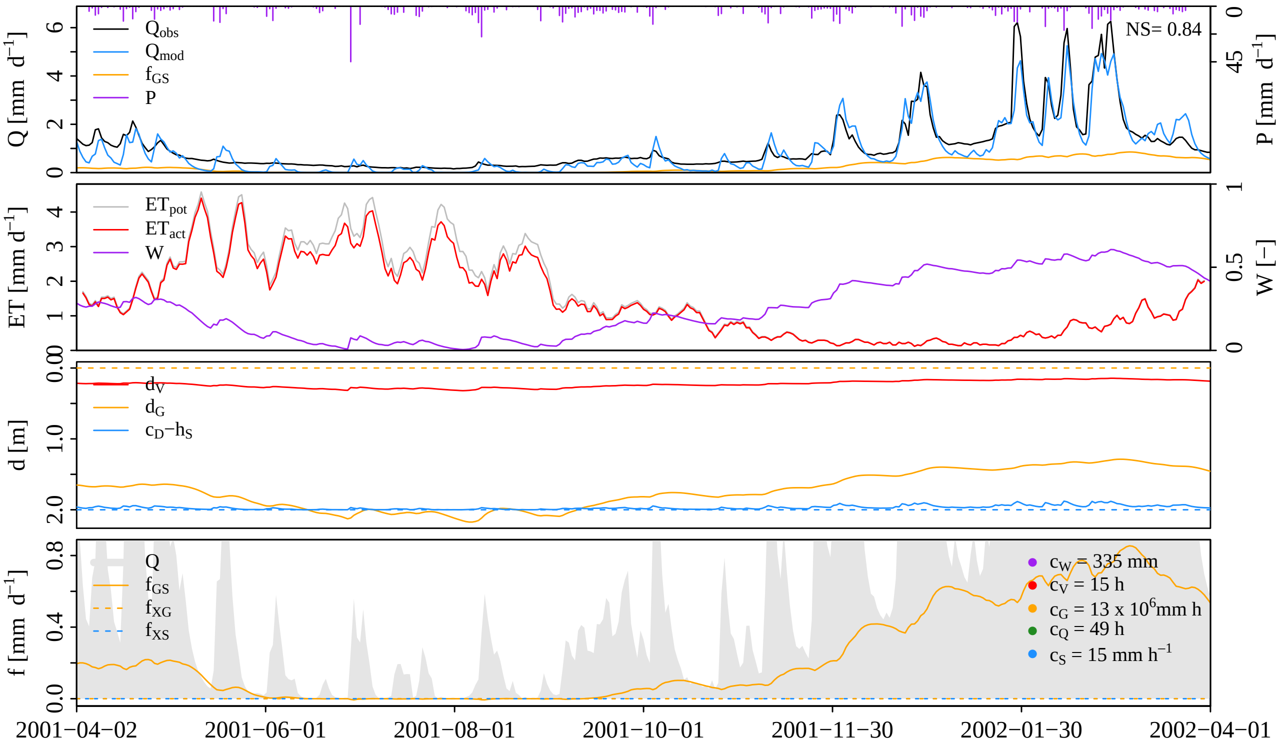


Figure B.4: Simulation result of WALRUS Dinkel for the hydrological year 2001–2002.

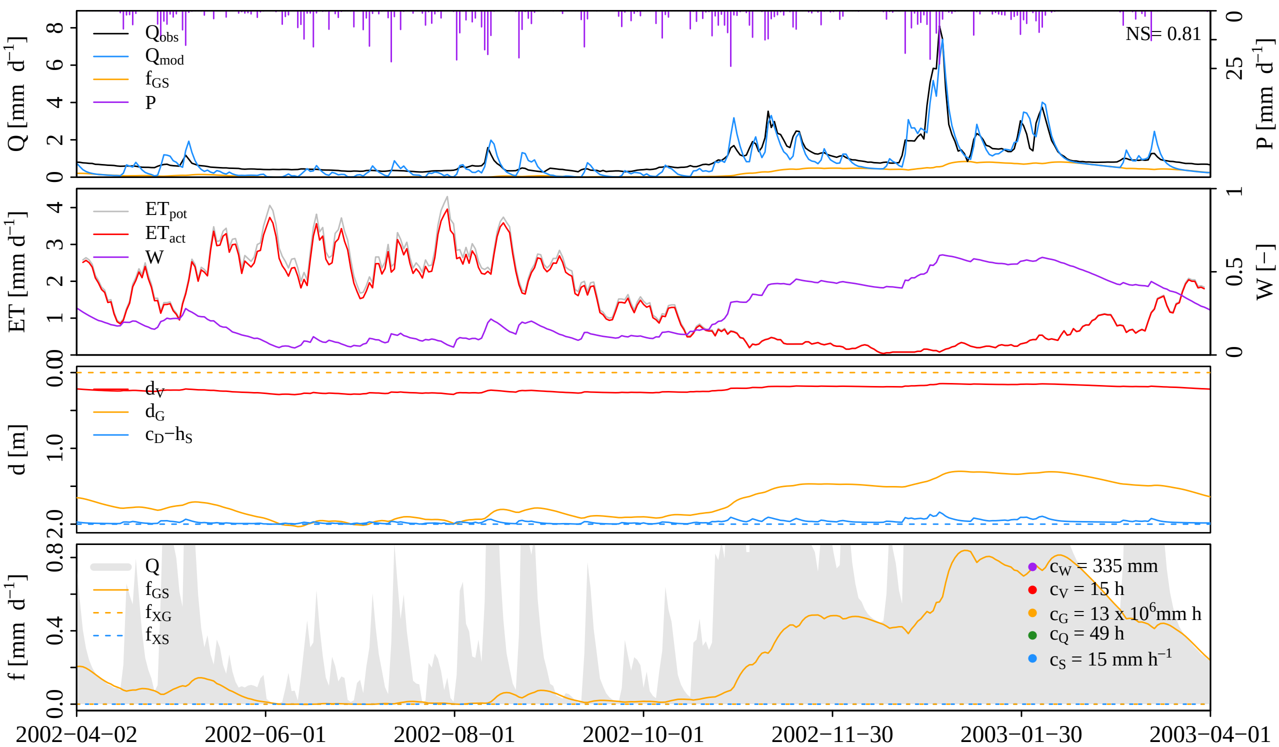


Figure B.5: Simulation result of WALRUS Dinkel for the hydrological year 2002–2003.

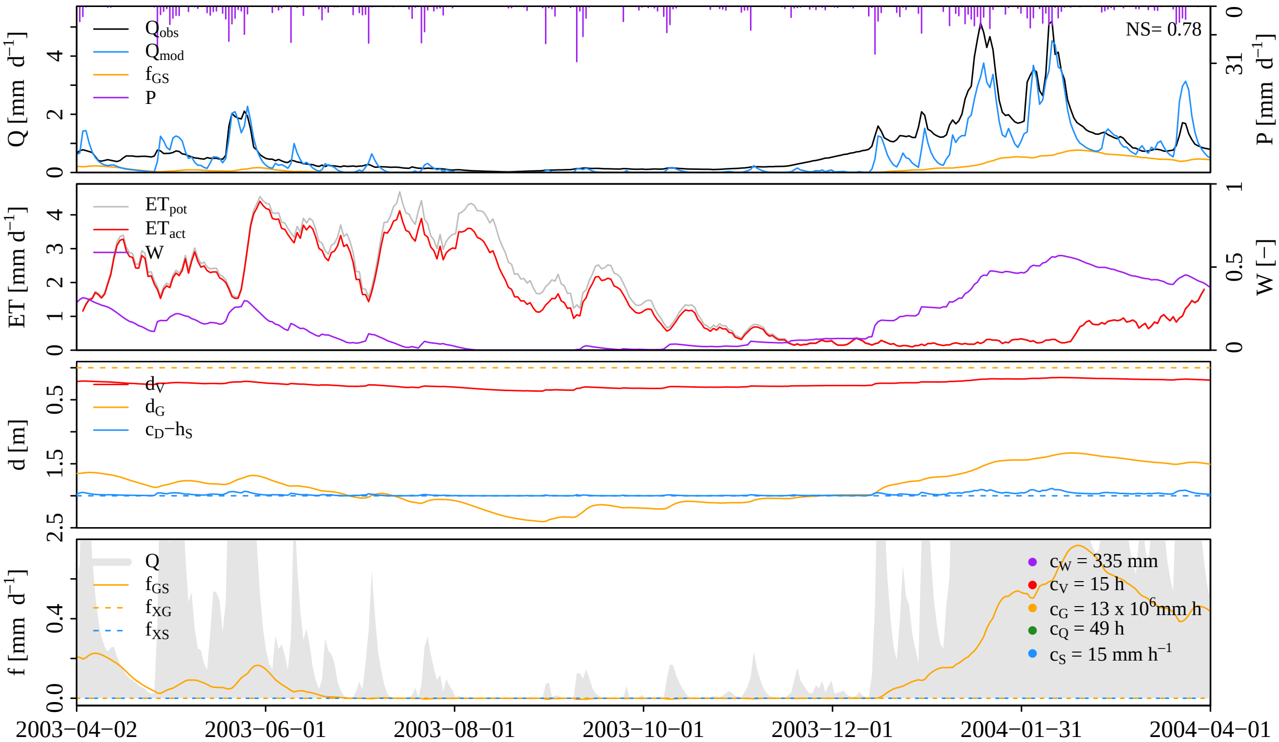


Figure B.6: Simulation result of WALRUS Dinkel for the hydrological year 2003–2004.

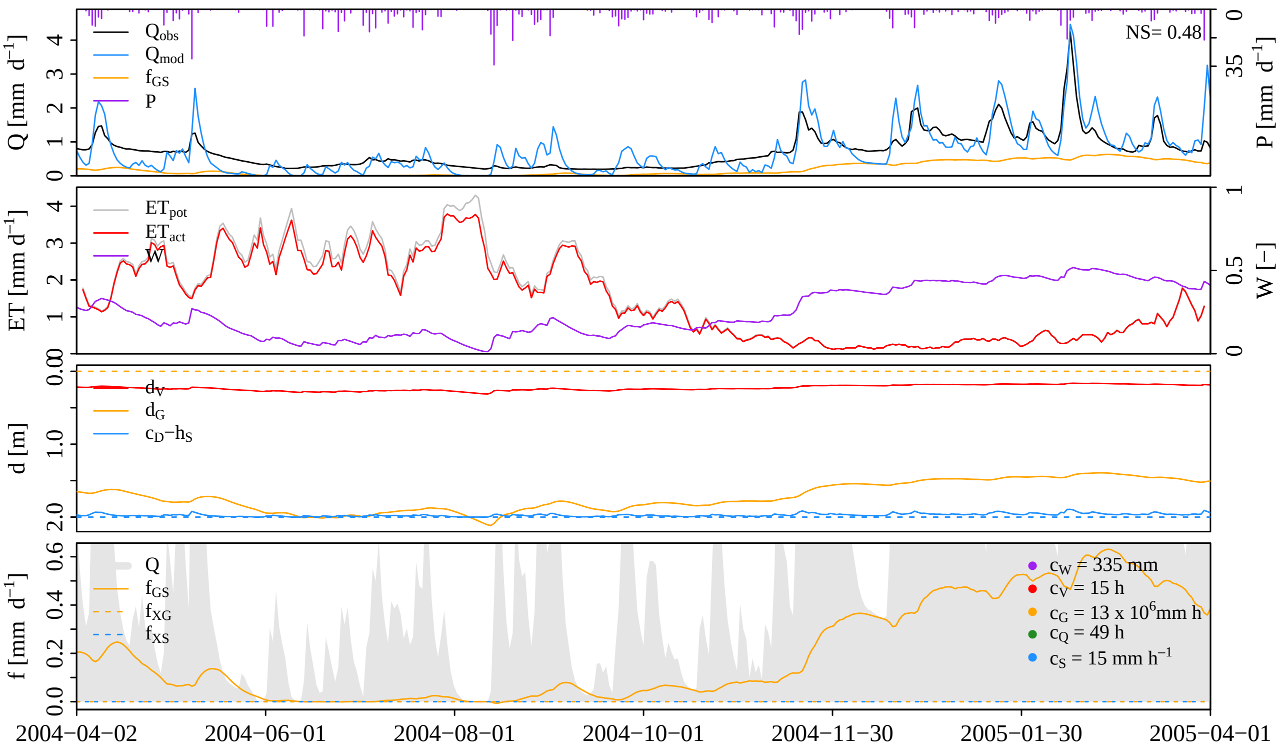


Figure B.7: Simulation result of WALRUS Dinkel for the hydrological year 2004–2005.

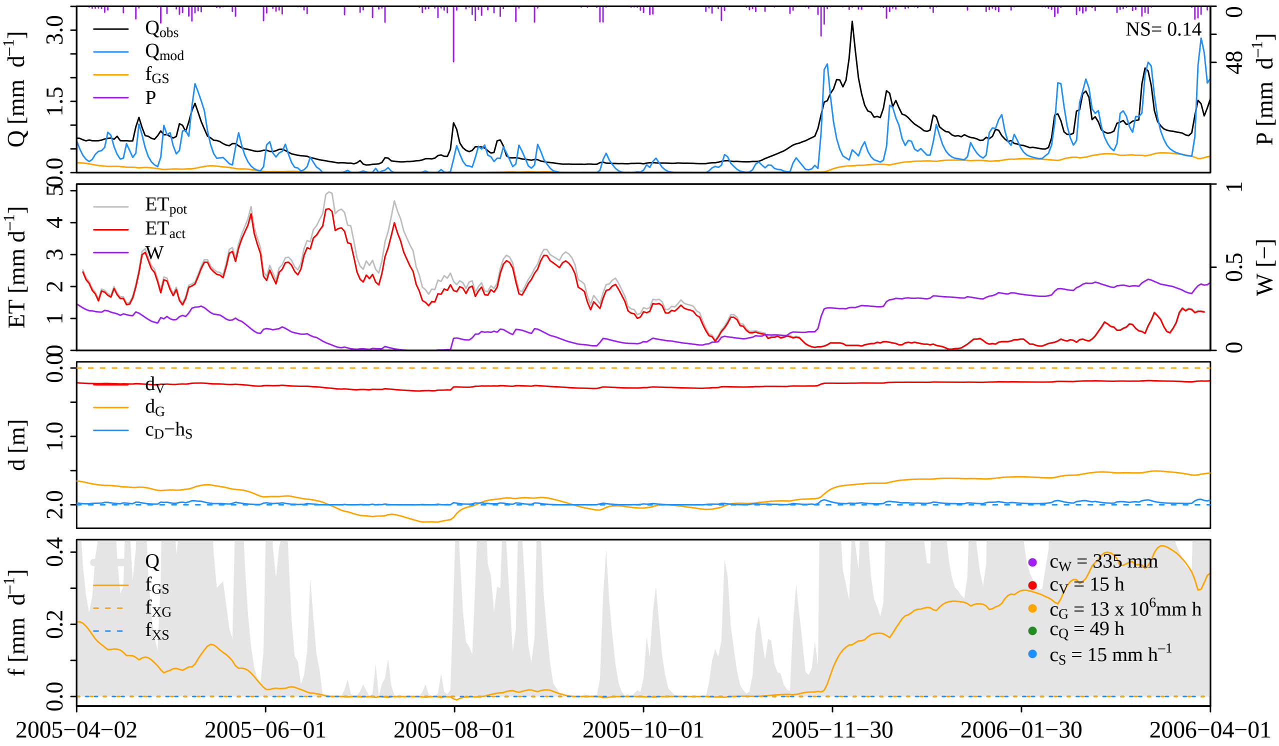


Figure B.8: Simulation result of WALRUS Dinkel for the hydrological year 2005–2006.

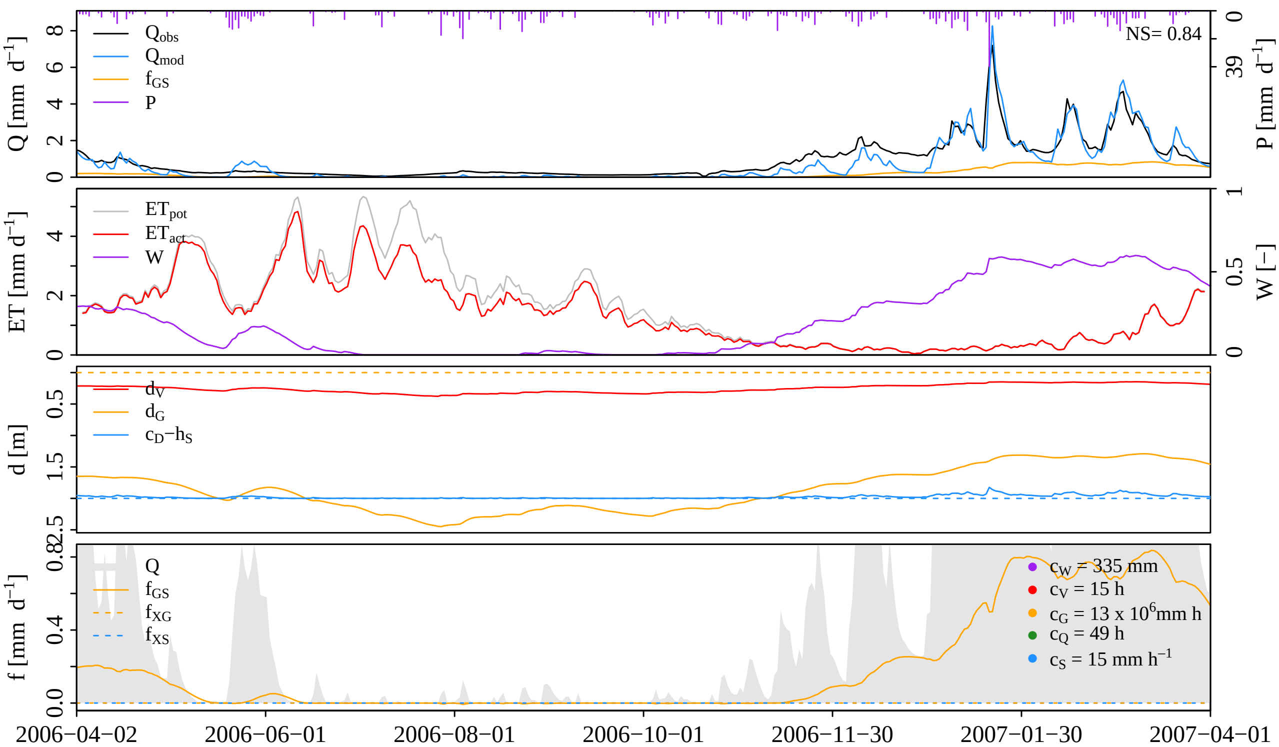


Figure B.9: Simulation result of WALRUS Dinkel for the hydrological year 2006–2007.

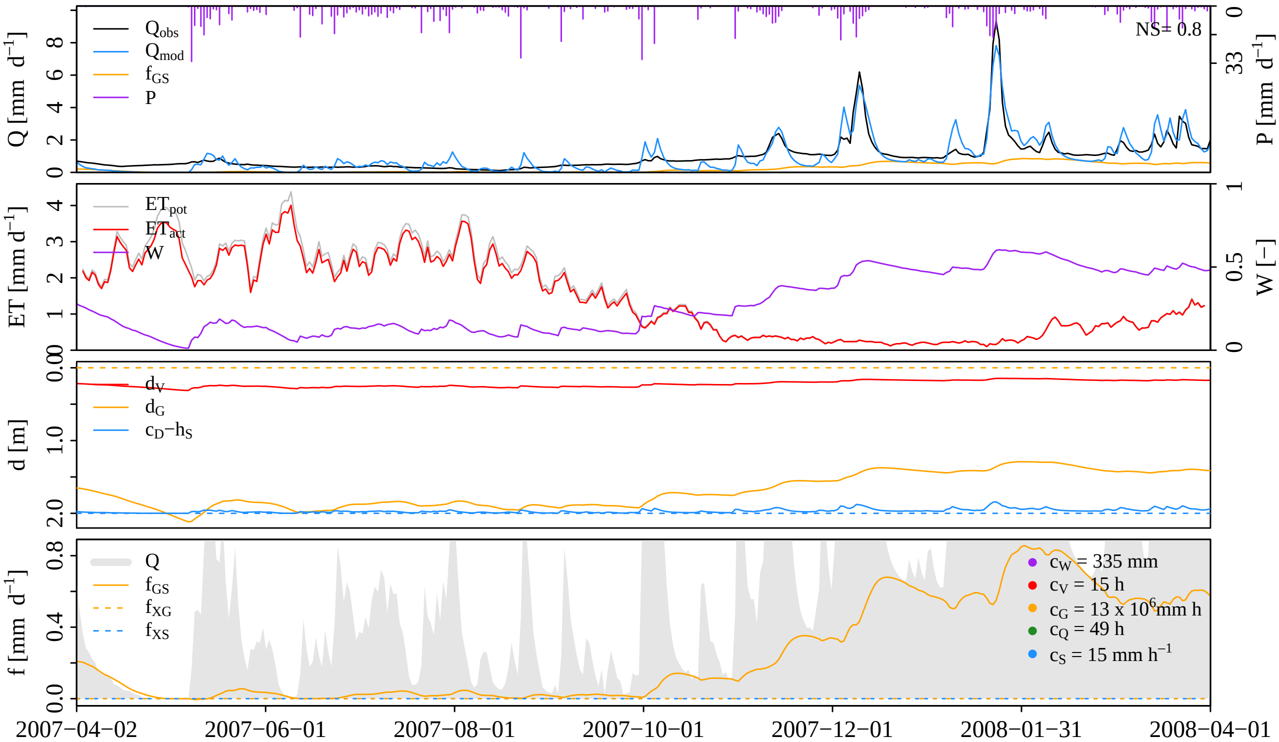


Figure B.10: Simulation result of WALRUS Dinkel for the hydrological year 2007–2008.

C | Simulations WALRUS Steinfurter Aa

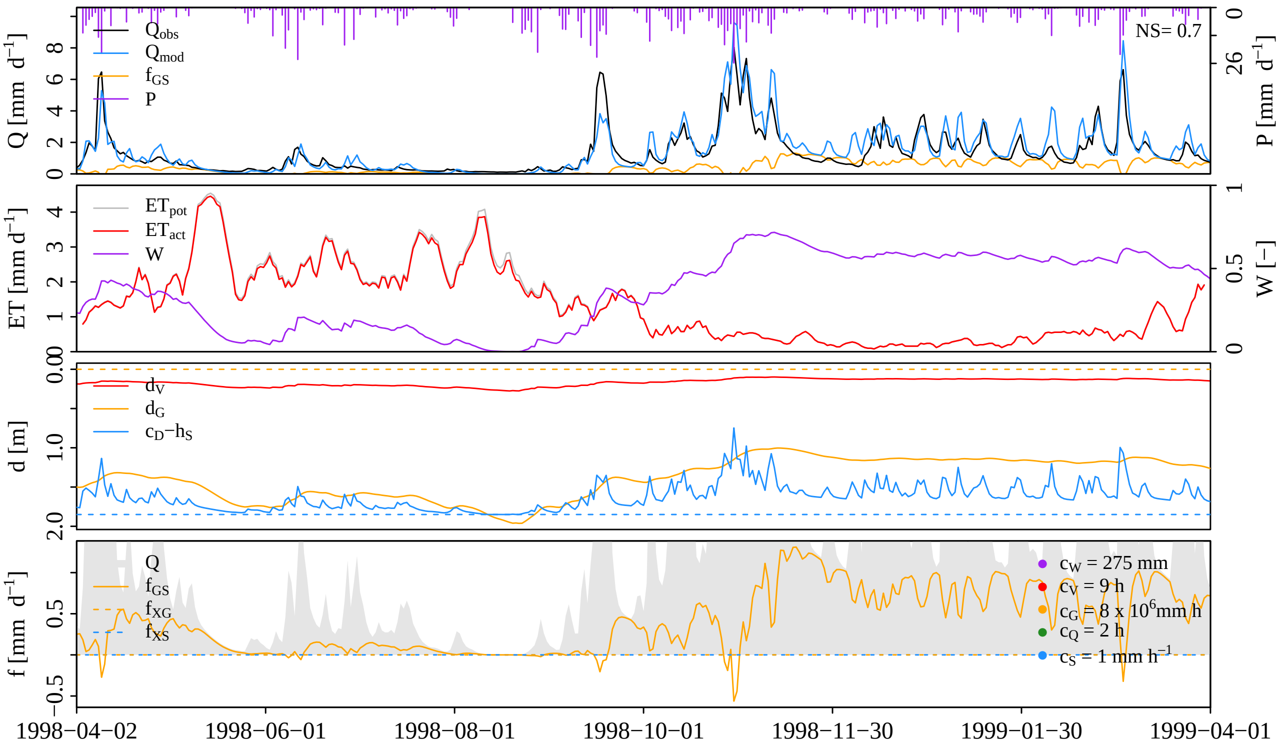


Figure C.1: Simulation result of WALRUS Steinfurter Aa for the hydrological year 1998–1999.

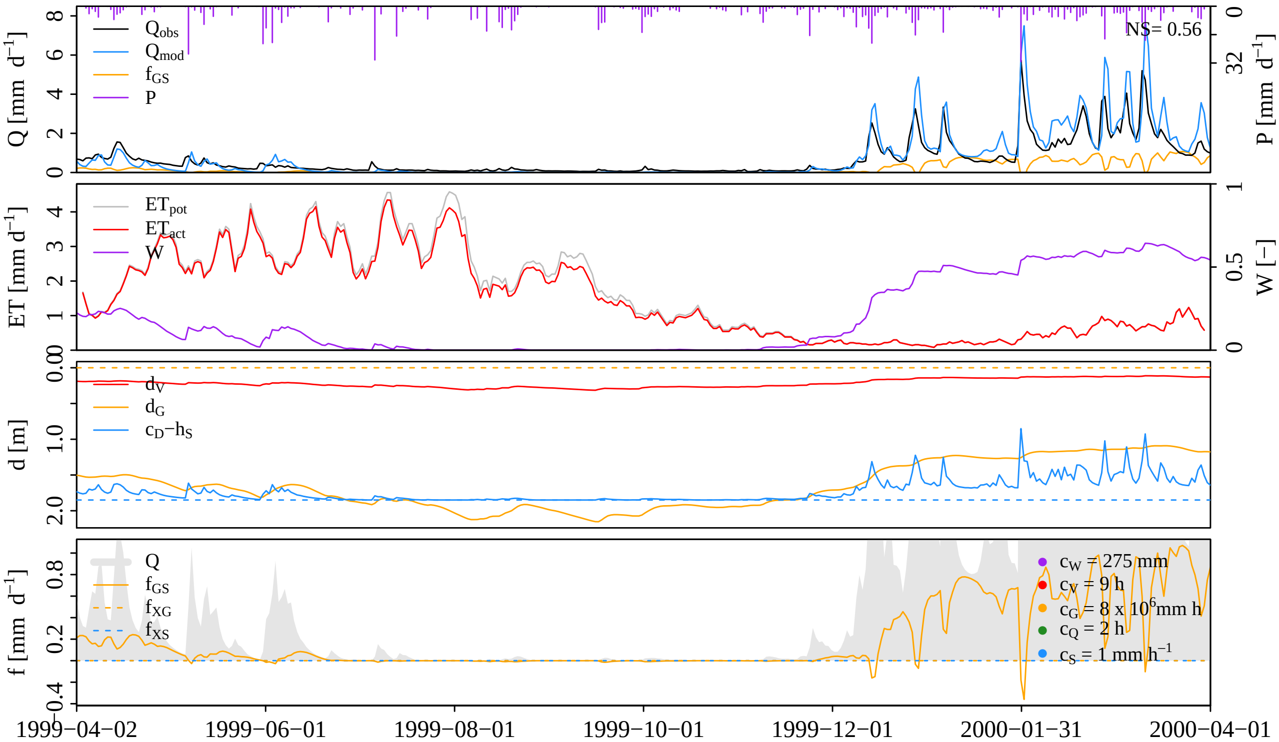


Figure C.2: Simulation result of WALRUS Steinfurter Aa for the hydrological year 1999–2000.

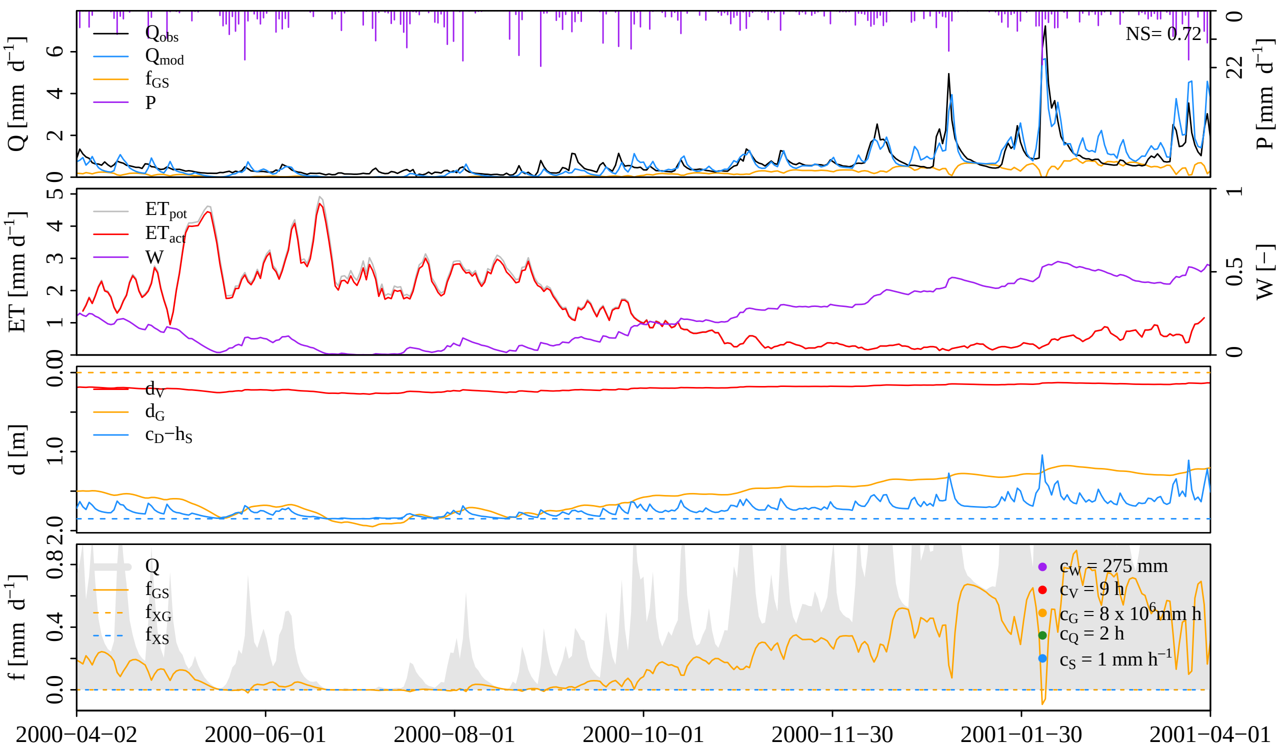


Figure C.3: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2000–2001.

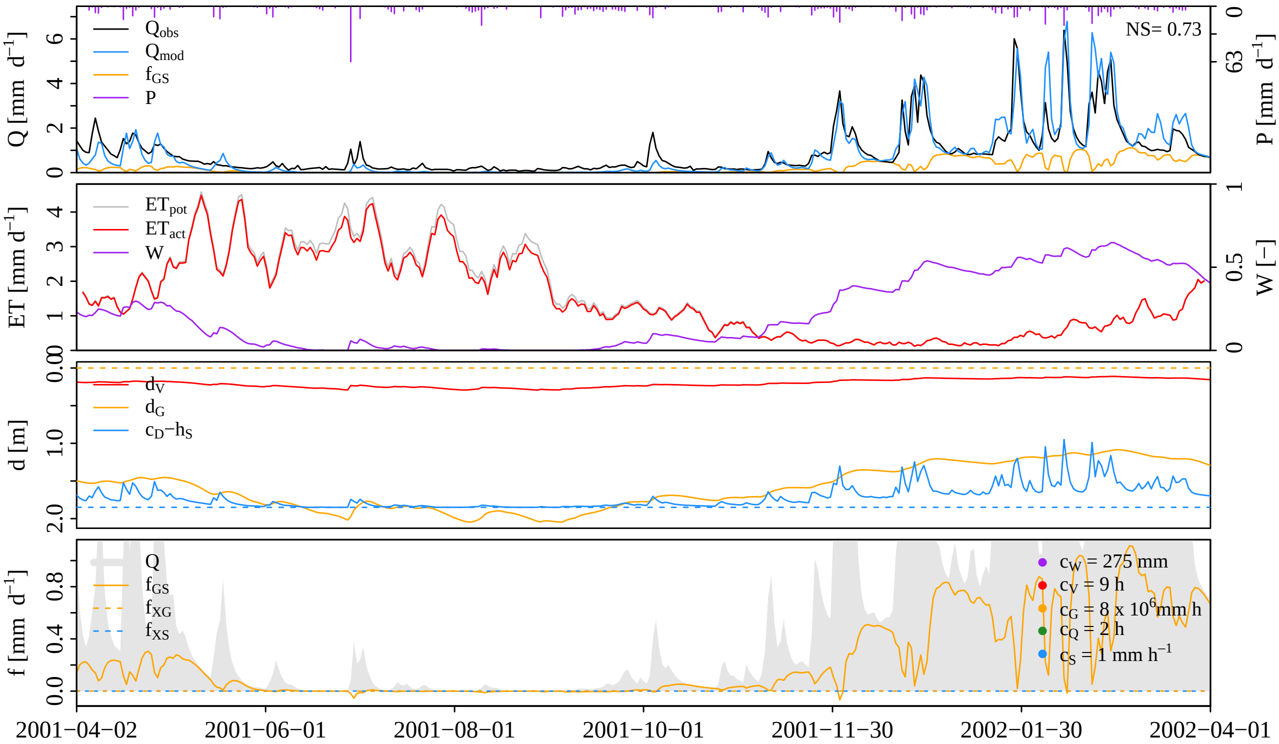


Figure C.4: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2001–2002.

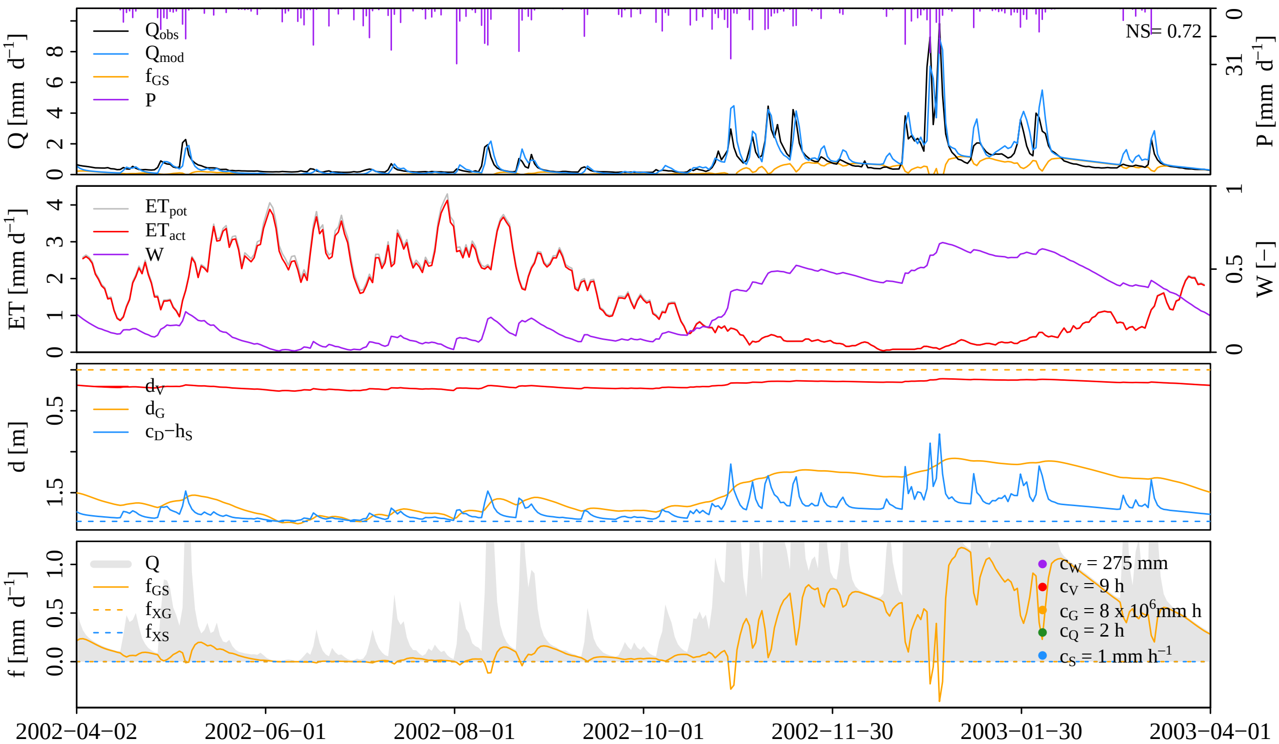


Figure C.5: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2002–2003.

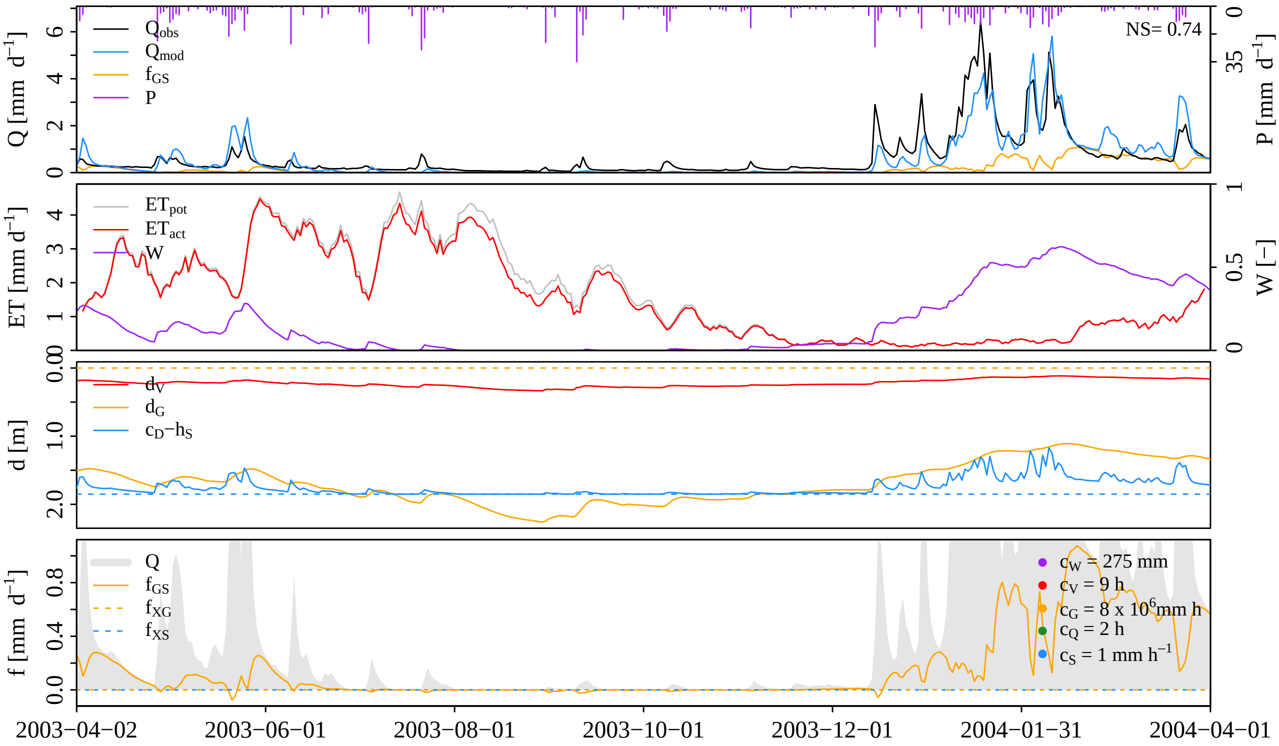


Figure C.6: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2003–2004.

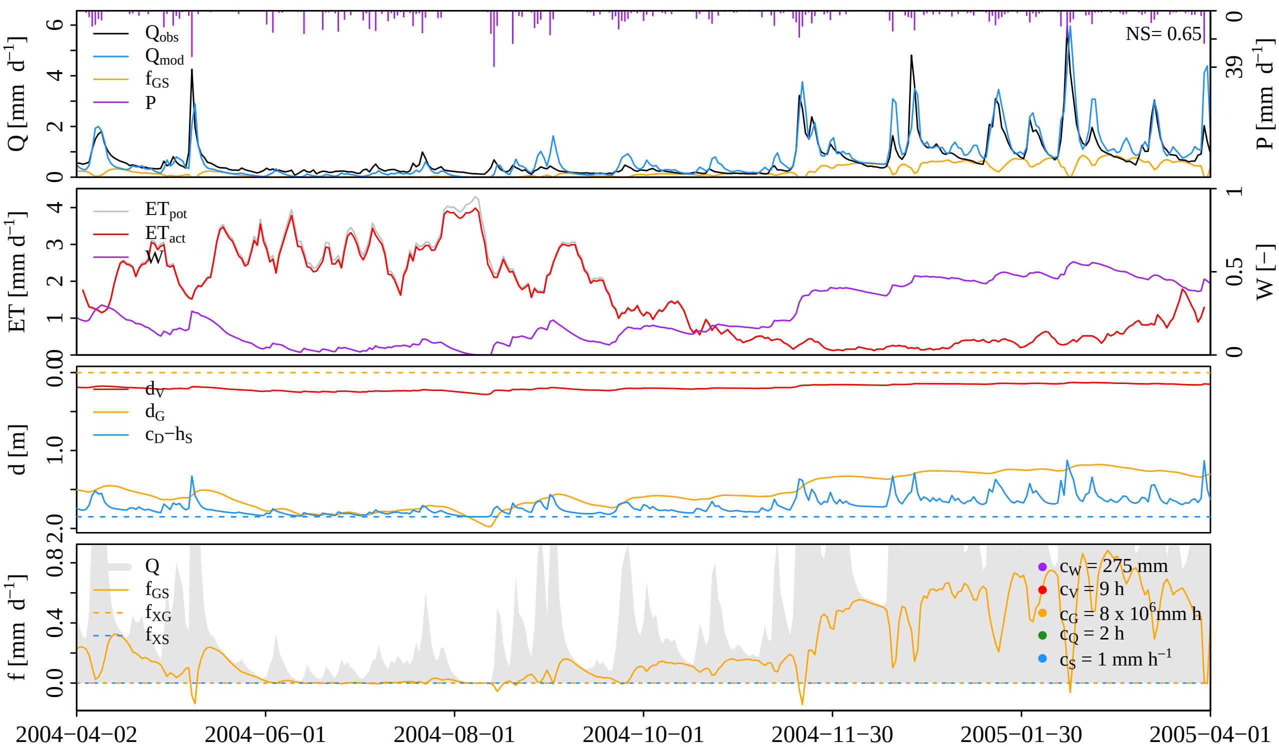


Figure C.7: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2004–2005.

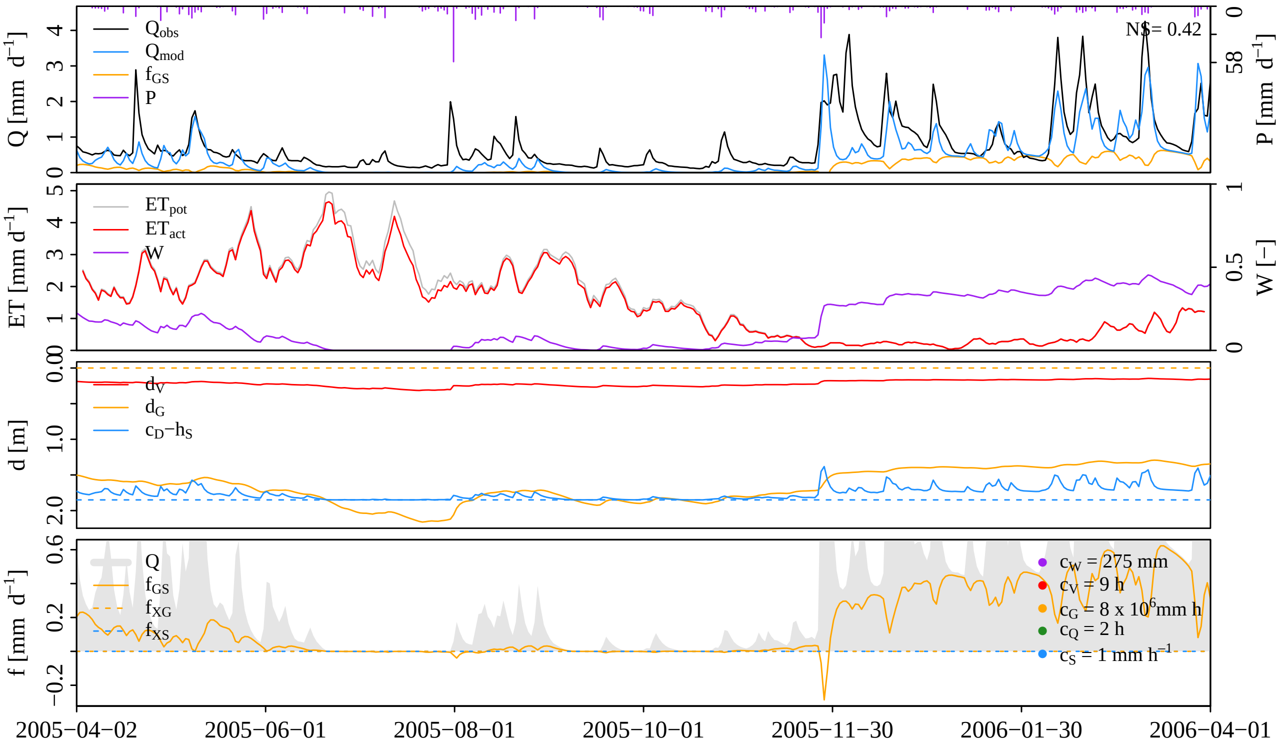


Figure C.8: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2005–2006.

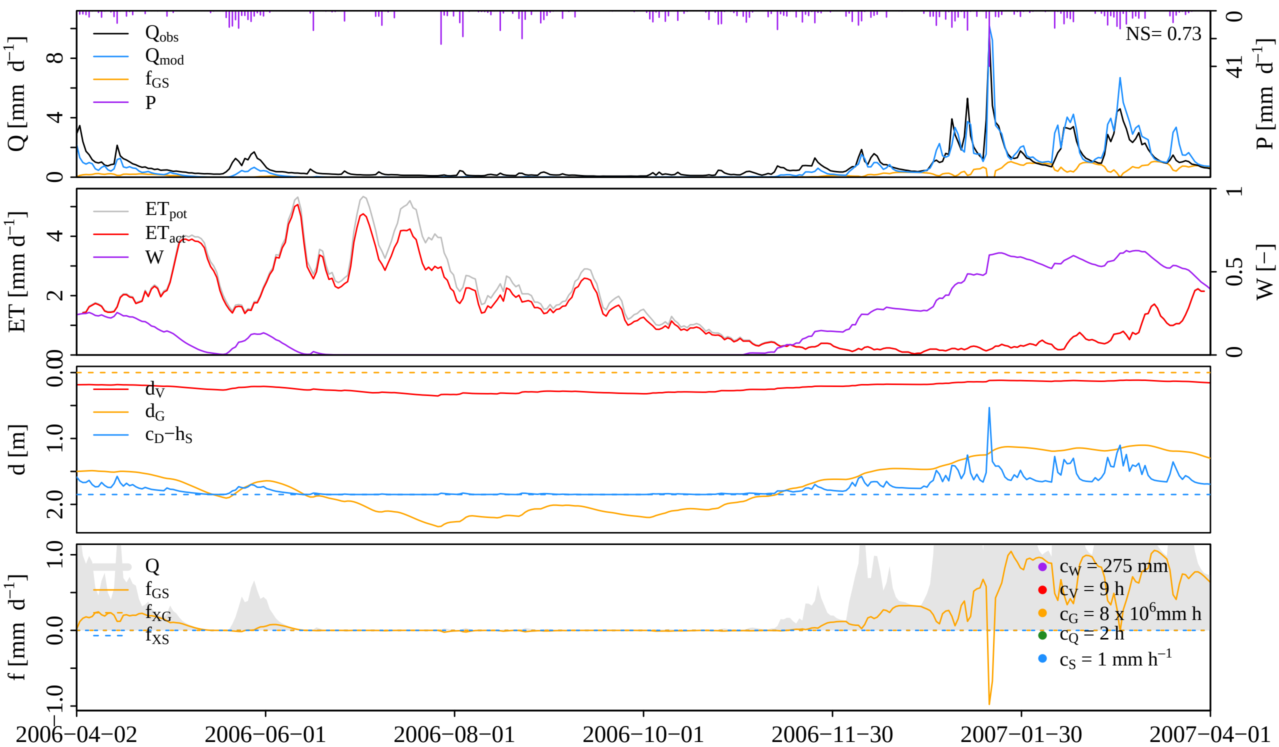


Figure C.9: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2006–2007.

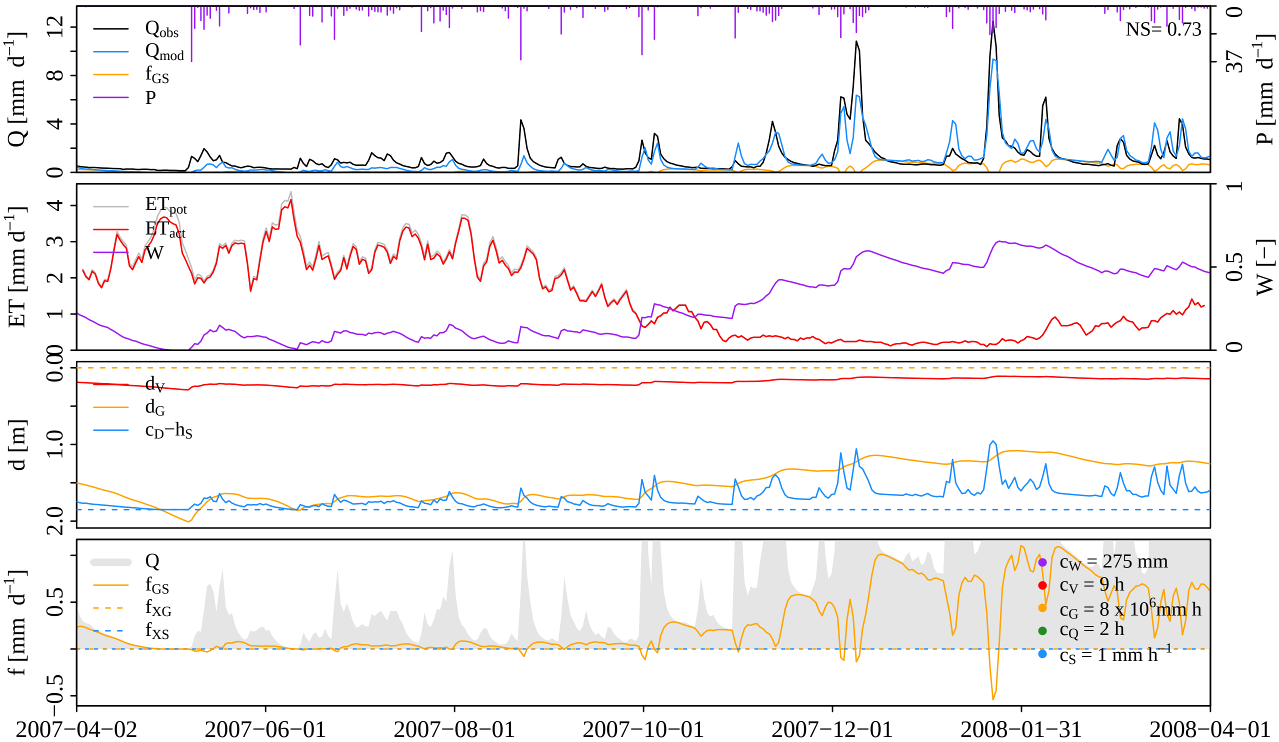


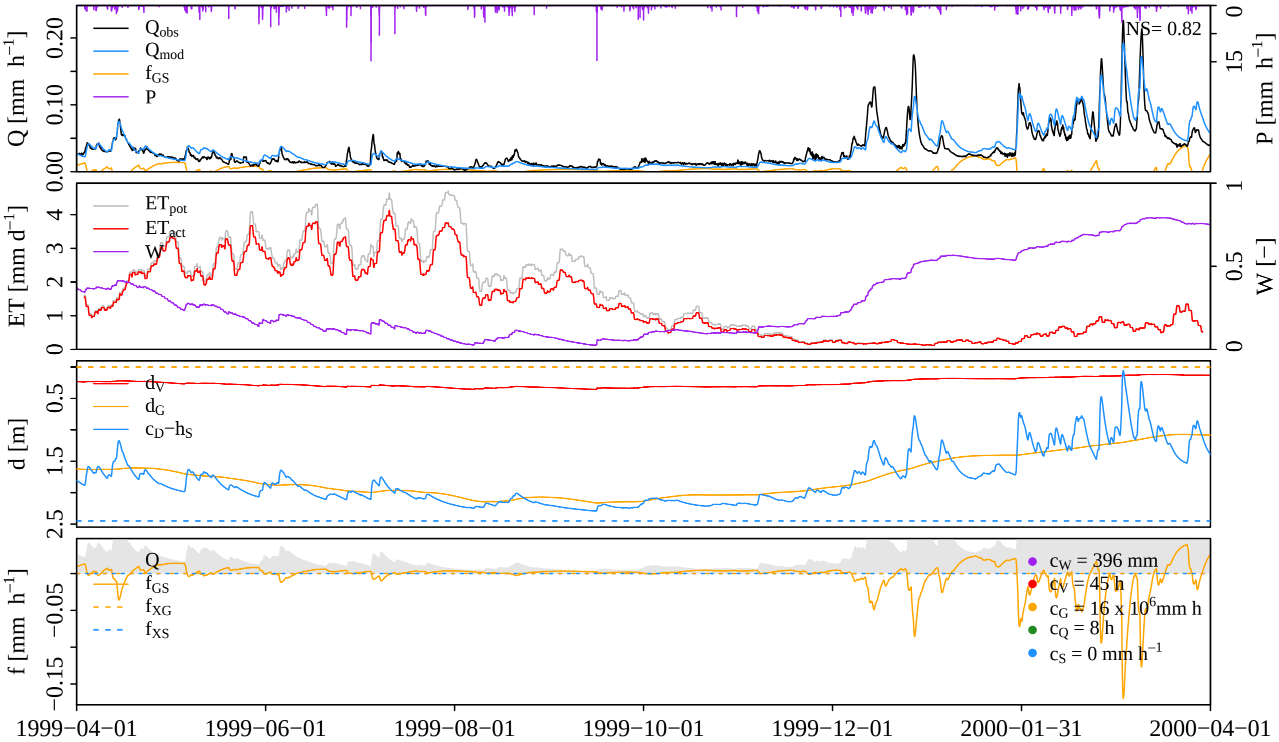
Figure C.10: Simulation result of WALRUS Steinfurter Aa for the hydrological year 2007–2008.

D | Simulations WALRUS Regge

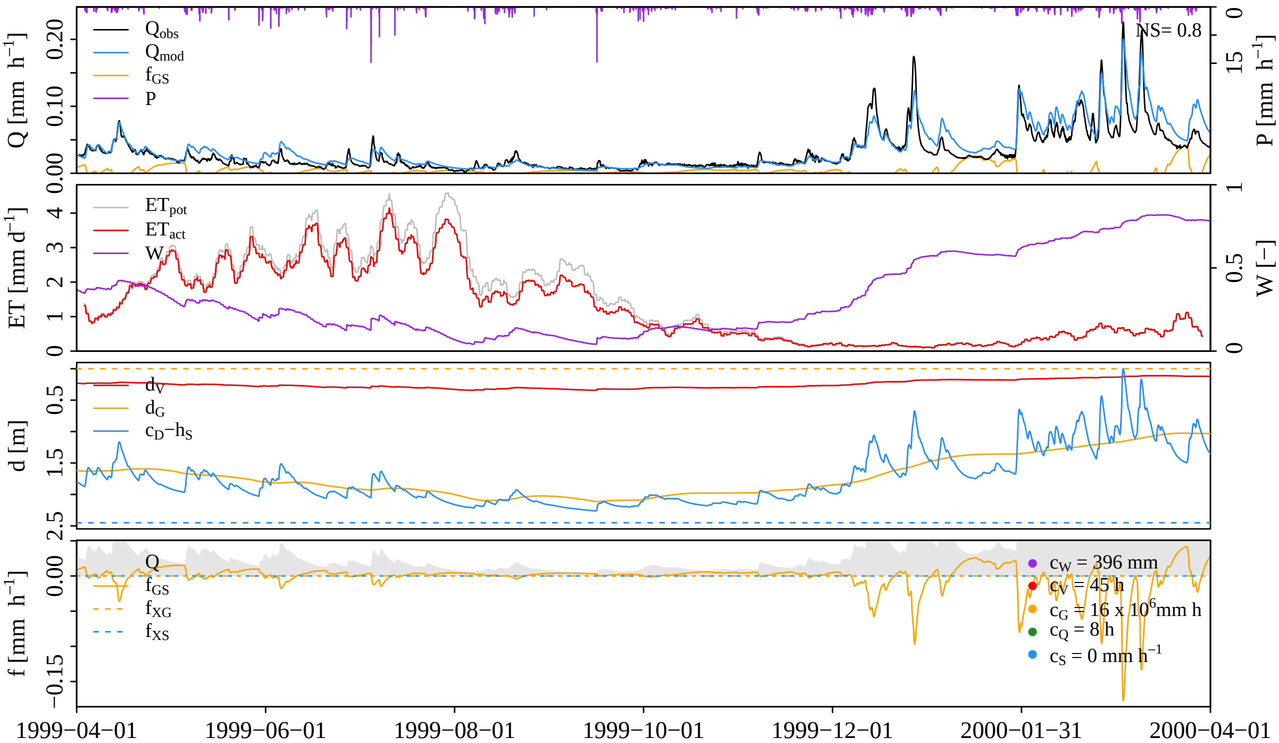
This appendix gives the simulation results of WALRUS Regge, by using dataset A and G or H, depending on the availability of WWTP data (see Table D.1).

Table D.1: Overview of the simulations of WALRUS Regge with different input datasets.

Data set	A	B	C	D	E	F	G	H
WWTP data included	no	yes	no	yes	no	yes	no	yes
ET_{pot} corrected for land use	no	no	yes	yes	no	no	yes	yes
Snow algorithm applied	no	no	no	no	yes	yes	yes	yes

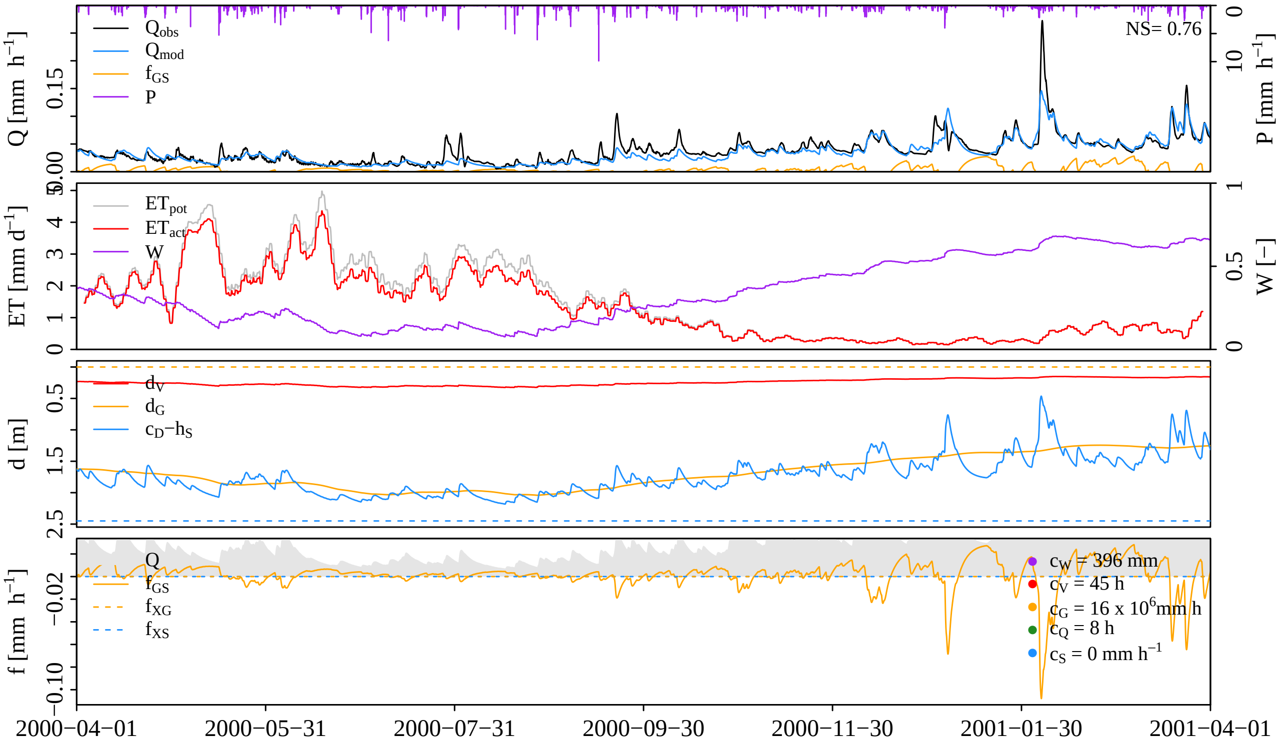


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

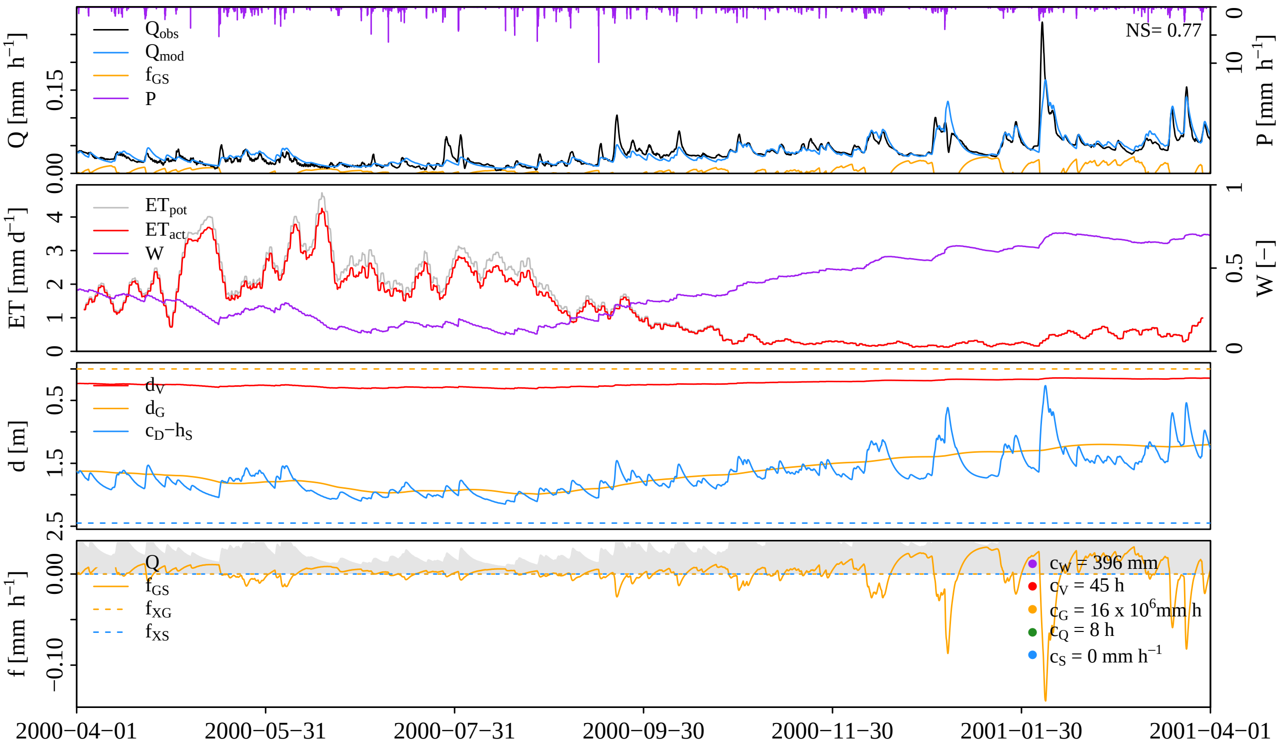


b Dataset G: No WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.1: Simulation results of WALRUS Regge for the hydrological year 1999–2000.

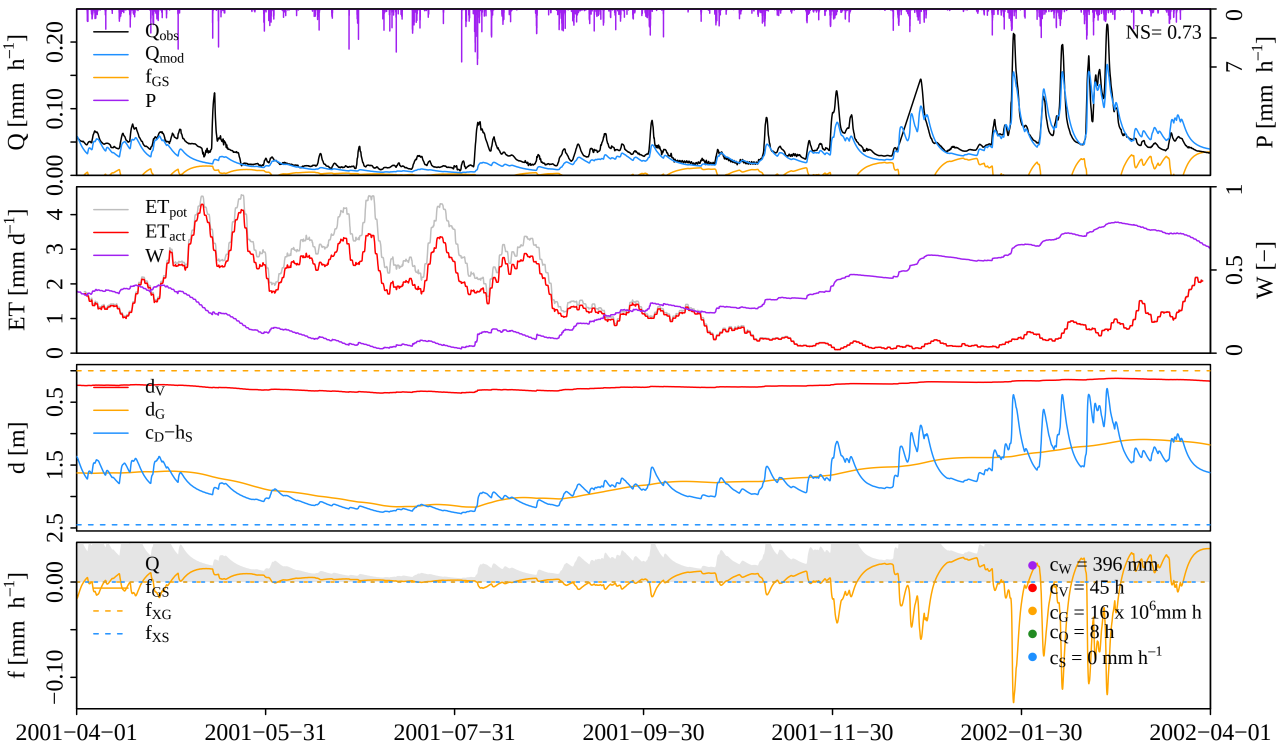


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

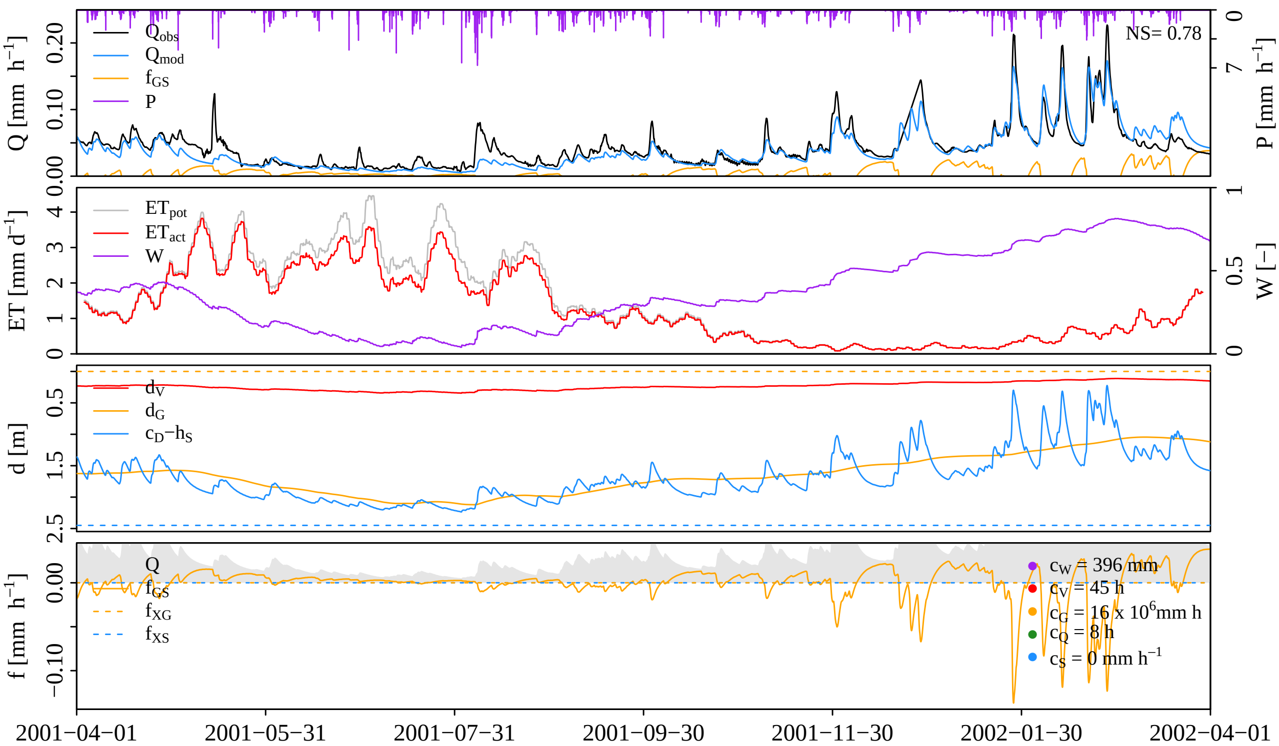


b Dataset G: No WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.2: Simulation results of WALRUS Regge for the hydrological year 2000–2001.

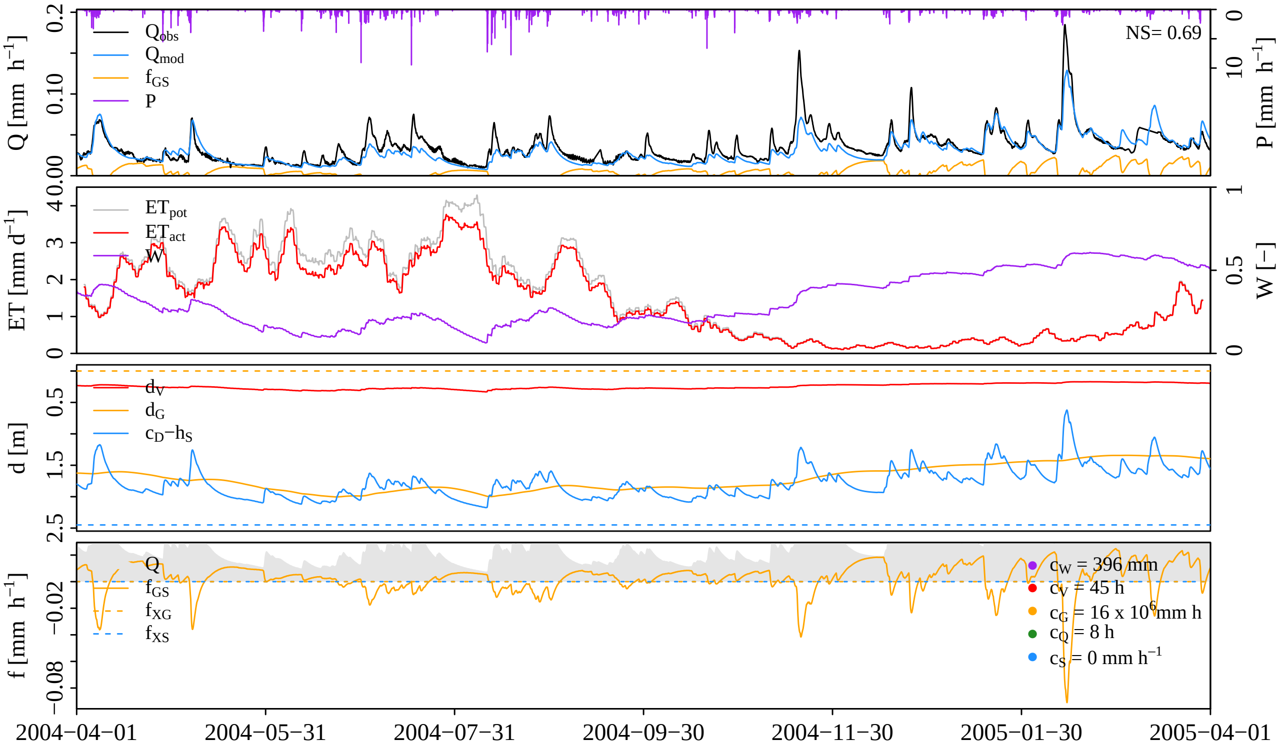


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

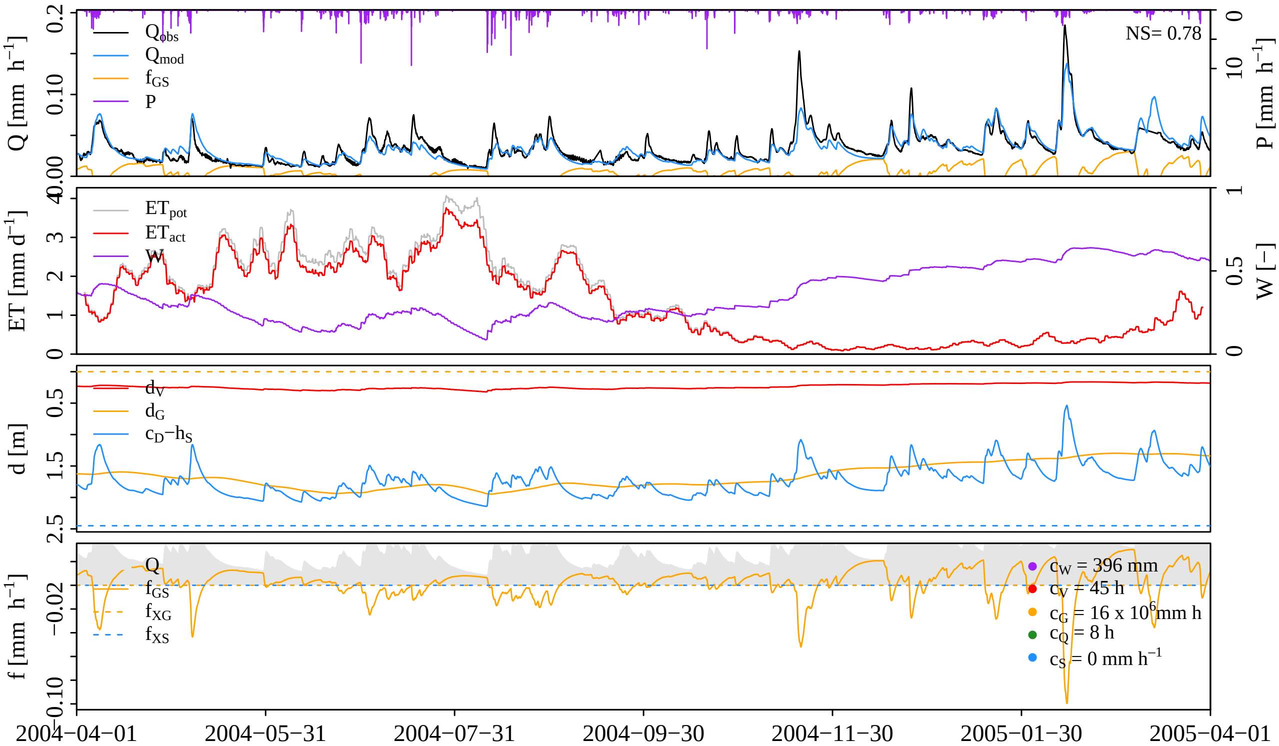


b Dataset G: No WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.3: Simulation results of WALRUS Regge for the hydrological year 2001–2002.

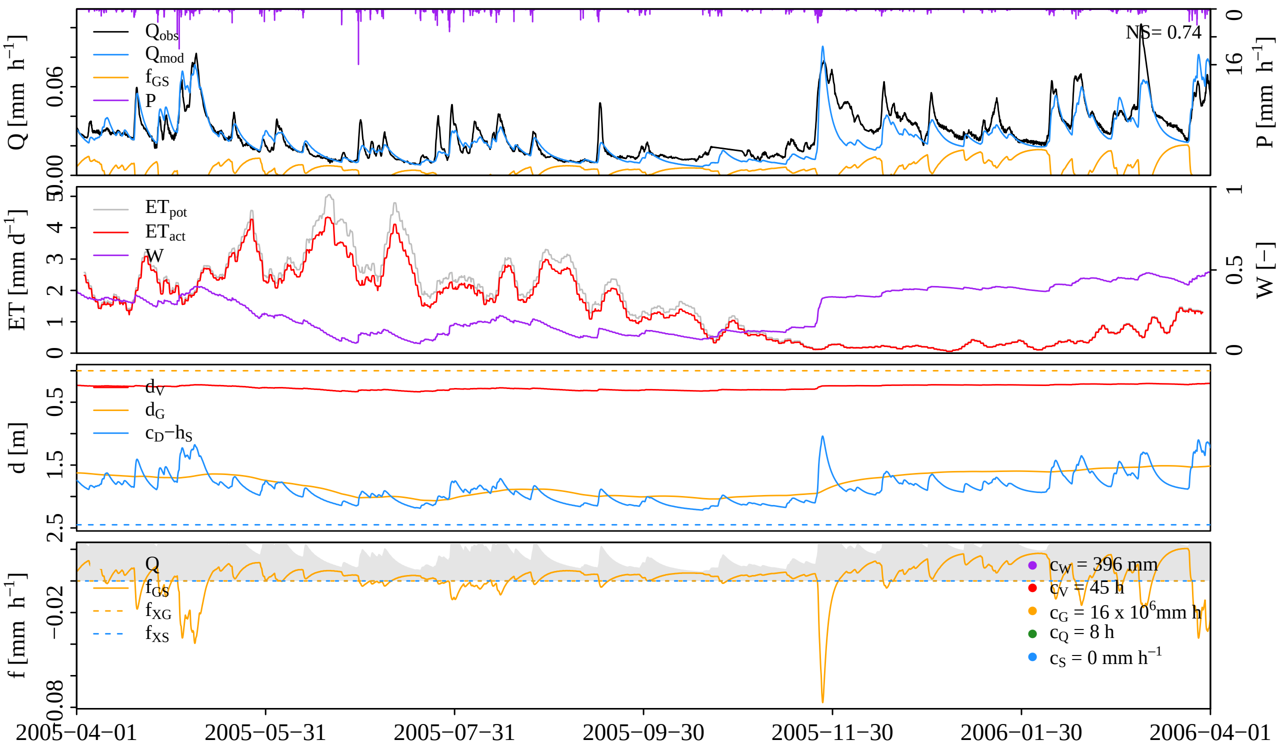


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

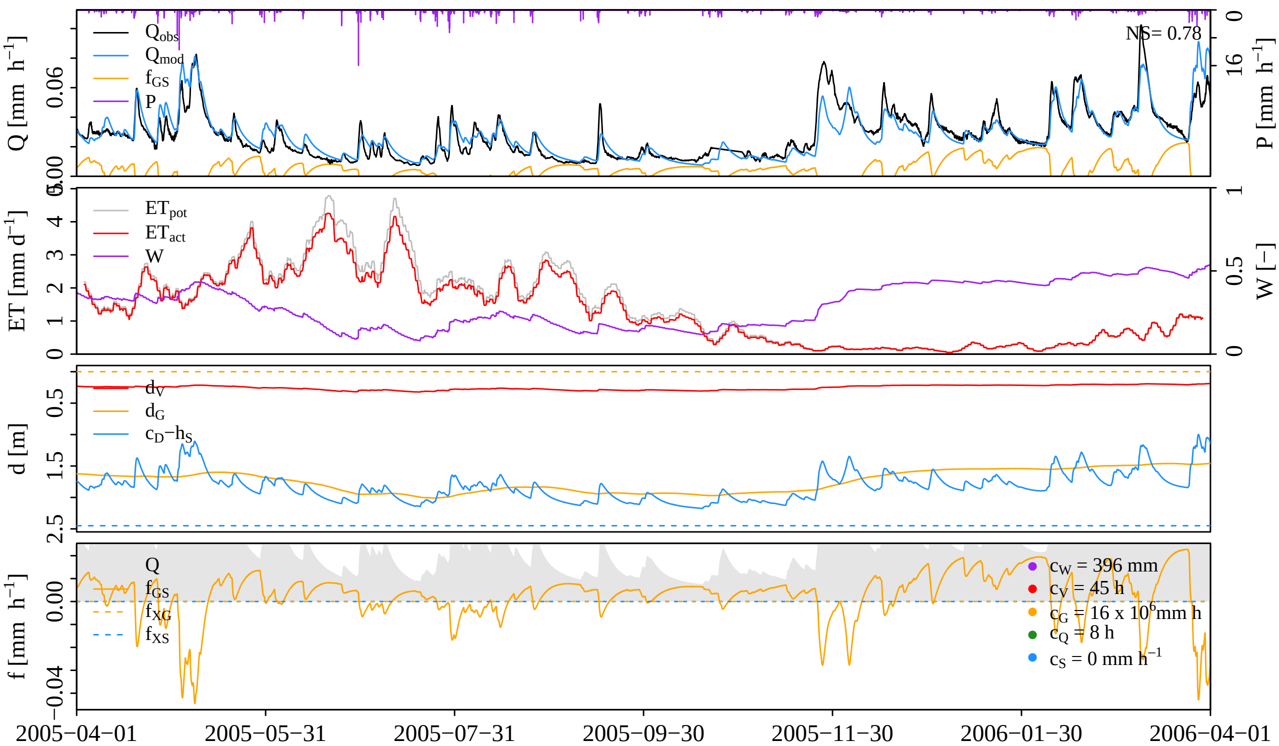


b Dataset G: No WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.4: Simulation results of WALRUS Regge for the hydrological year 2004–2005.

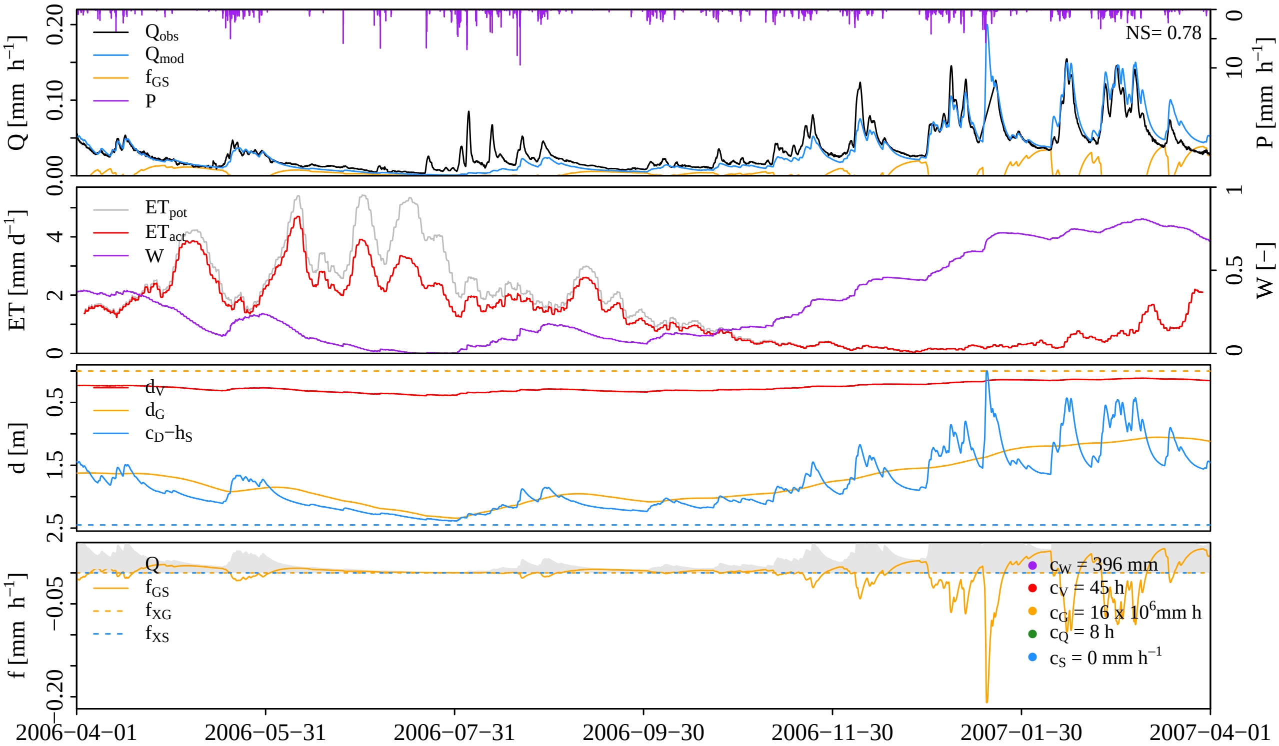


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

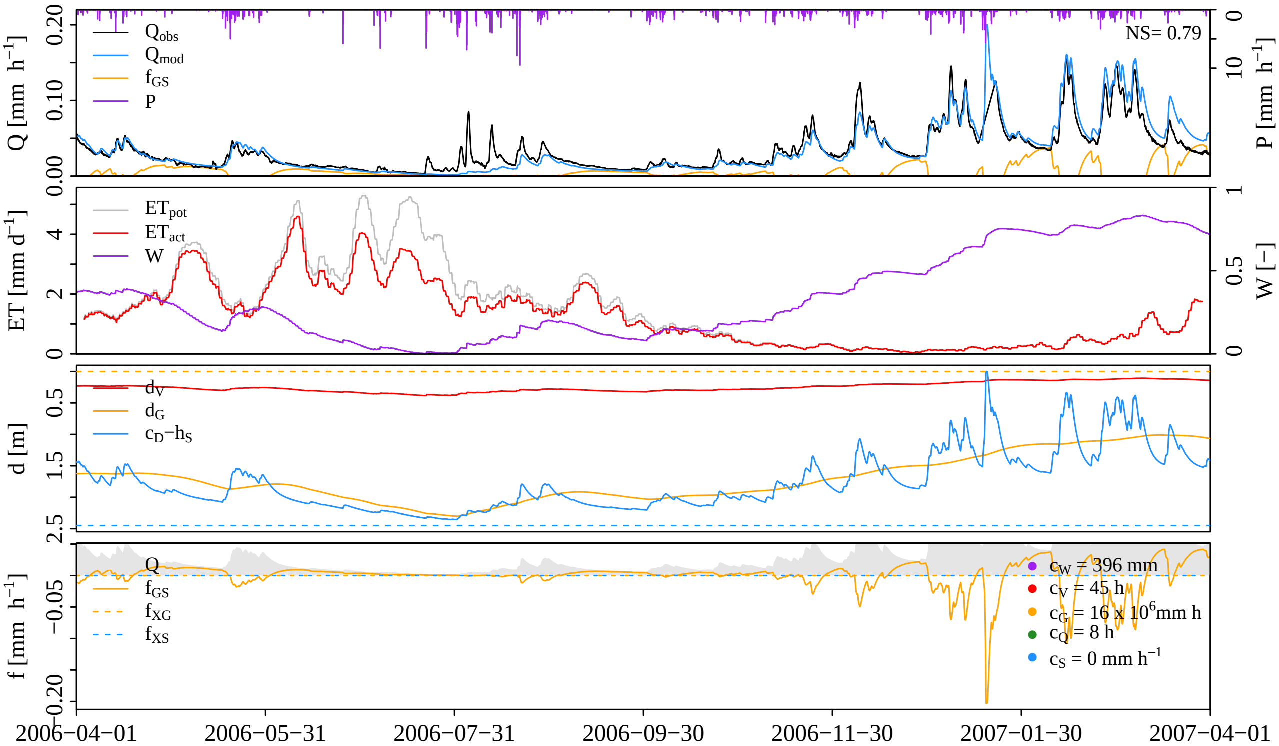


b Dataset G: No WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.5: Simulation results of WALRUS Regge for the hydrological year 2005–2006.

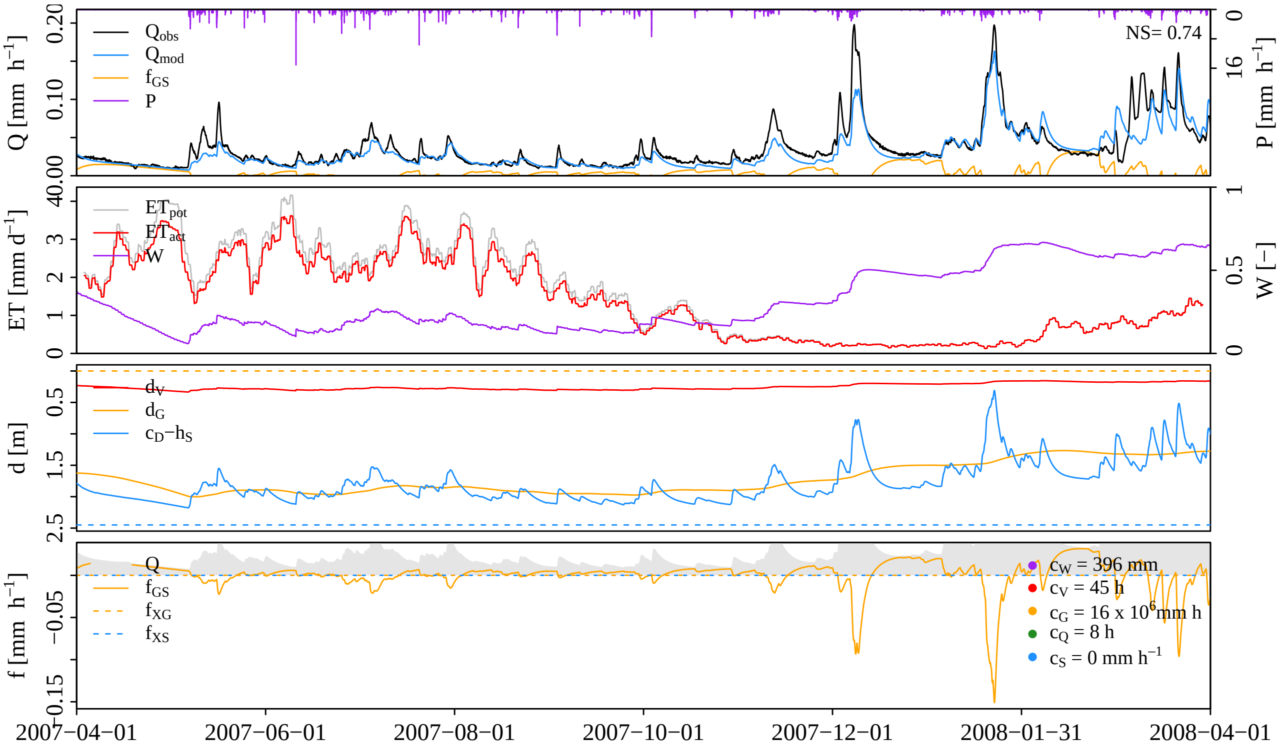


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

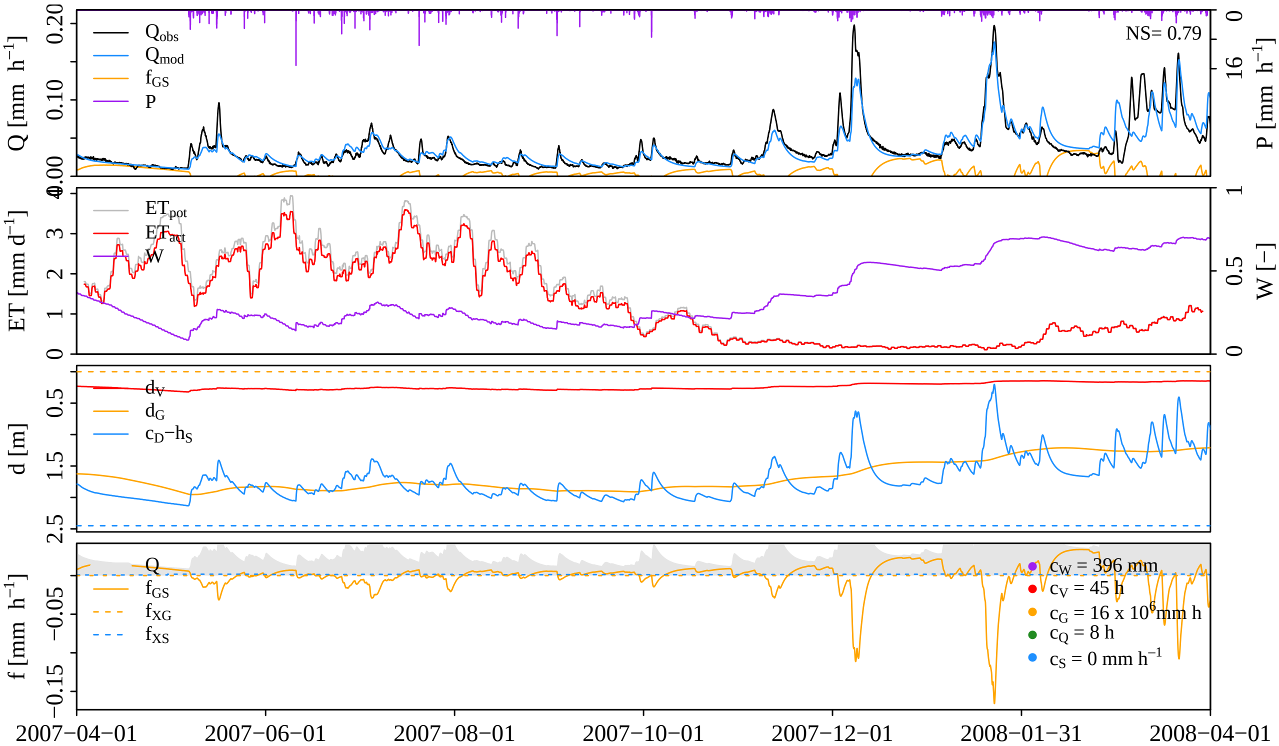


b Dataset G: No WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.6: Simulation results of WALRUS Regge for the hydrological year 2006–2007.

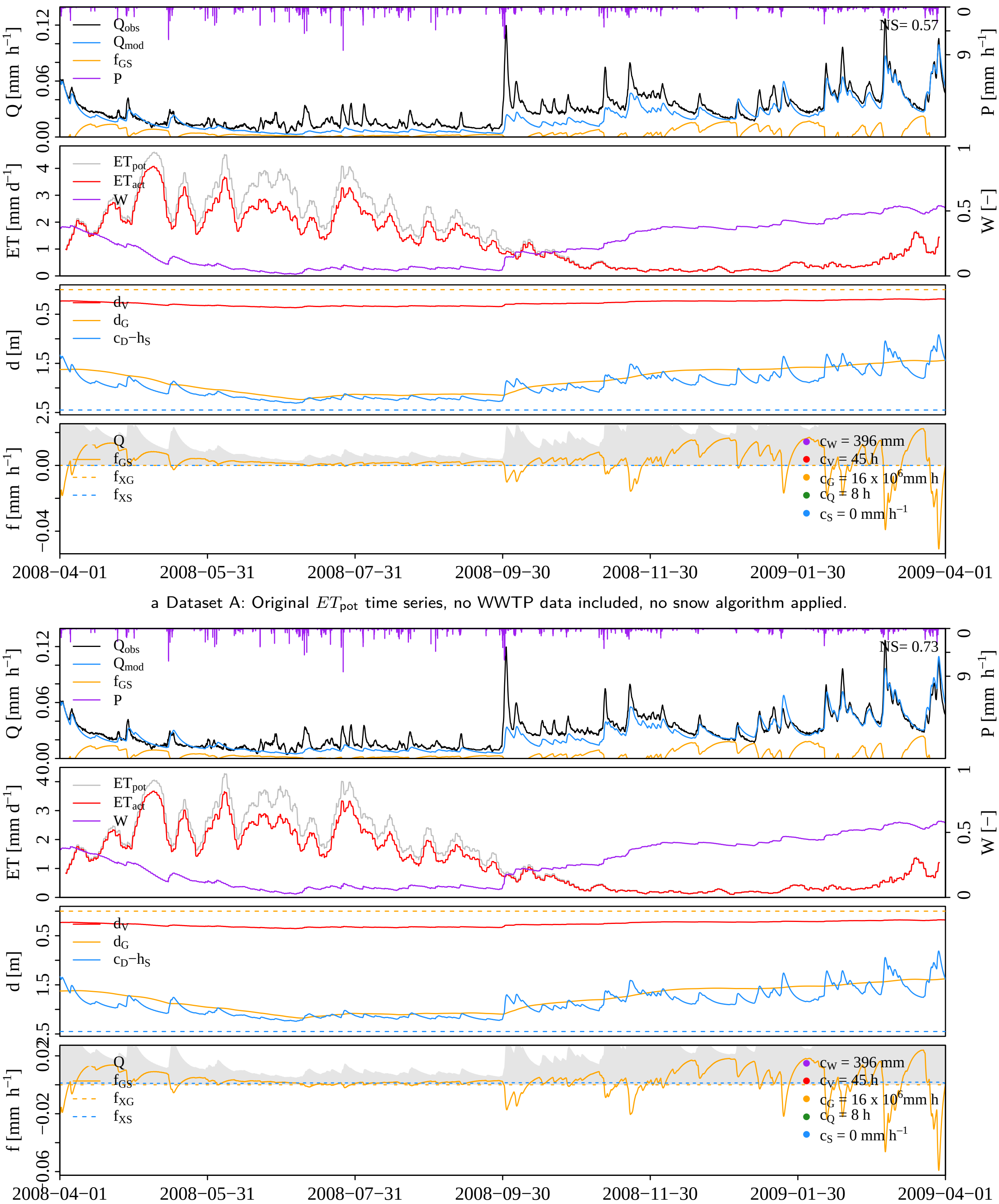


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.



b Dataset H: WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

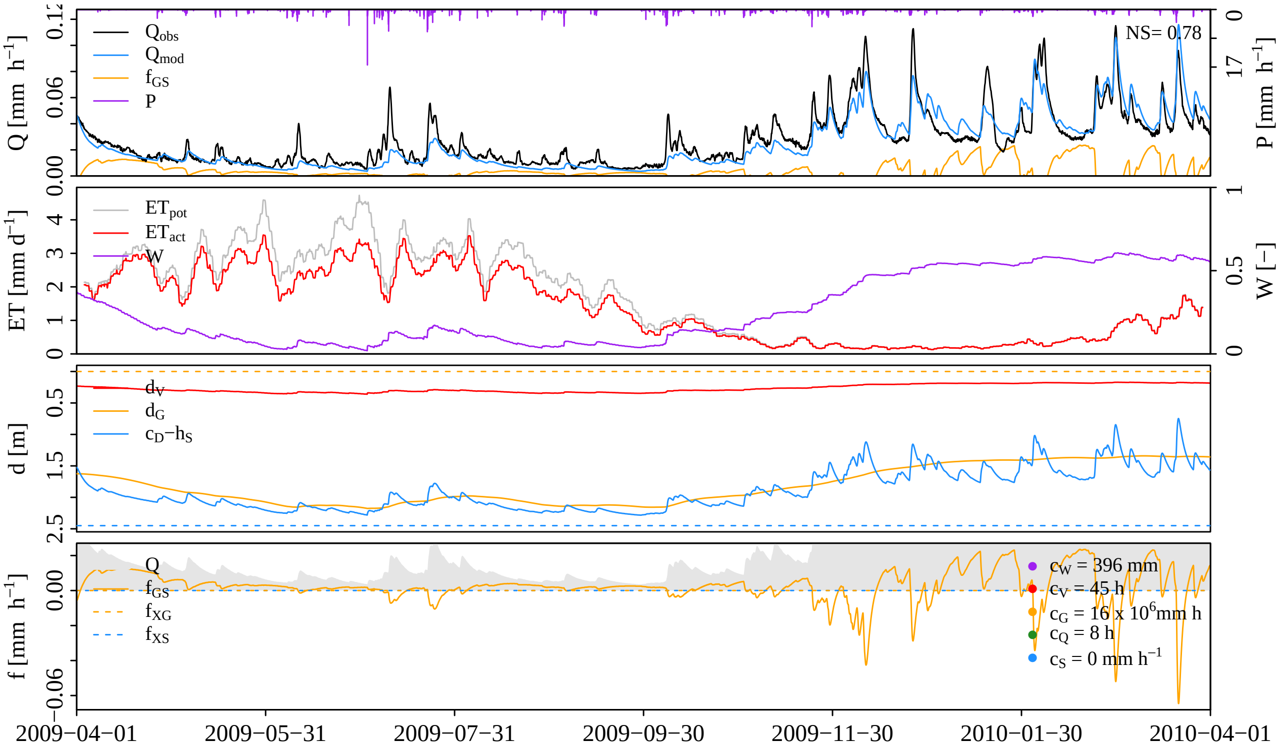
Figure D.7: Simulation results of WALRUS Regge for the hydrological year 2007–2008.



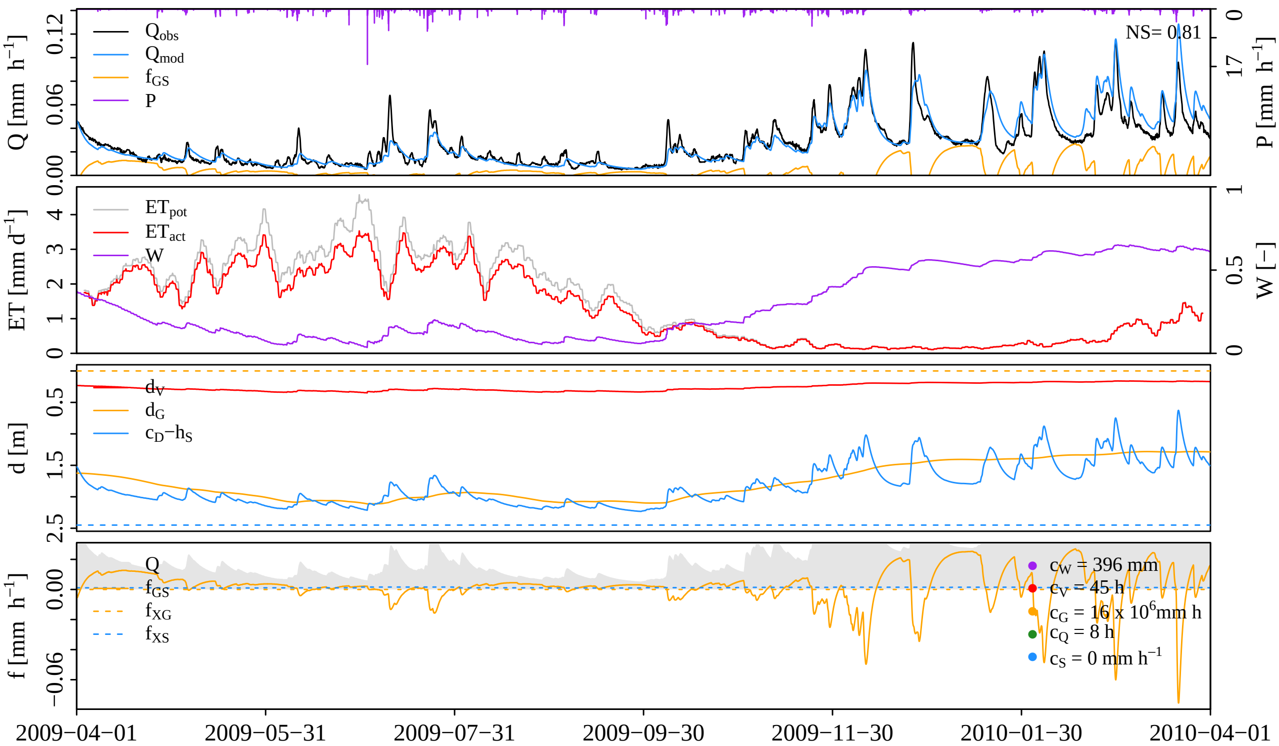
a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

b Dataset H: WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.8: Simulation results of WALRUS Regge for the hydrological year 2008–2009.

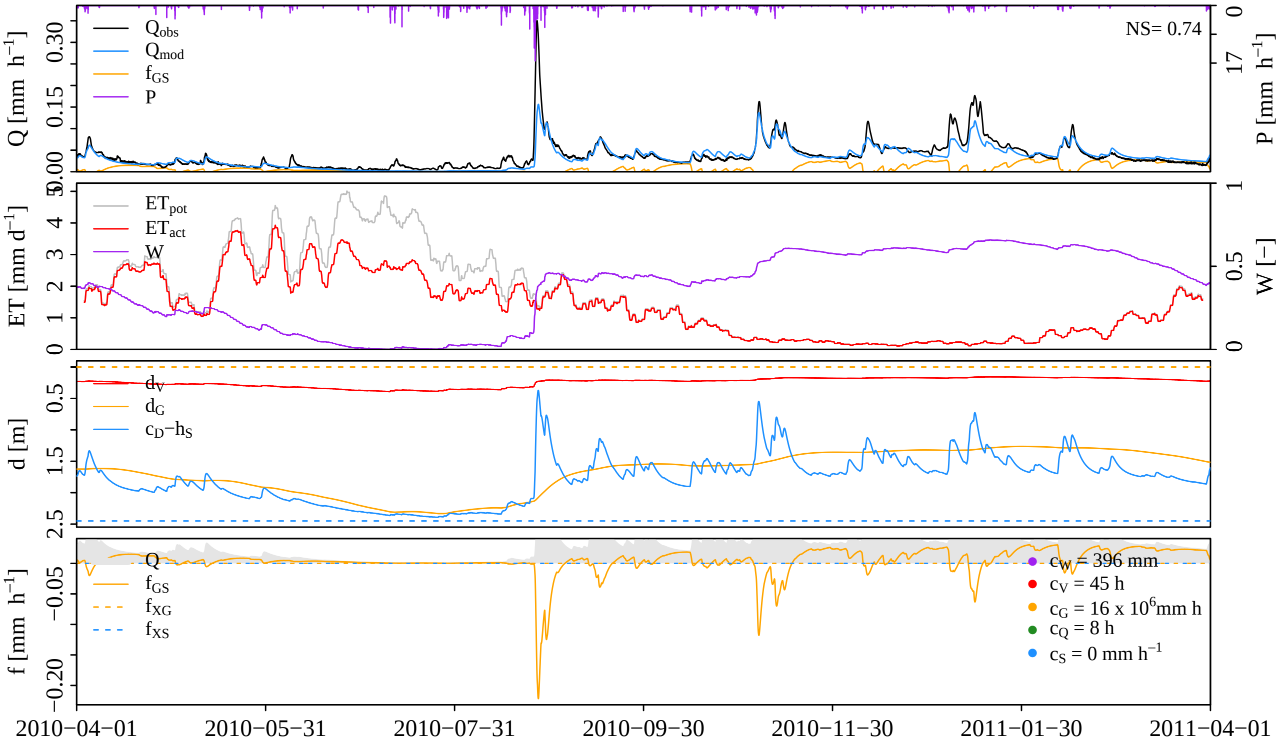


a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.

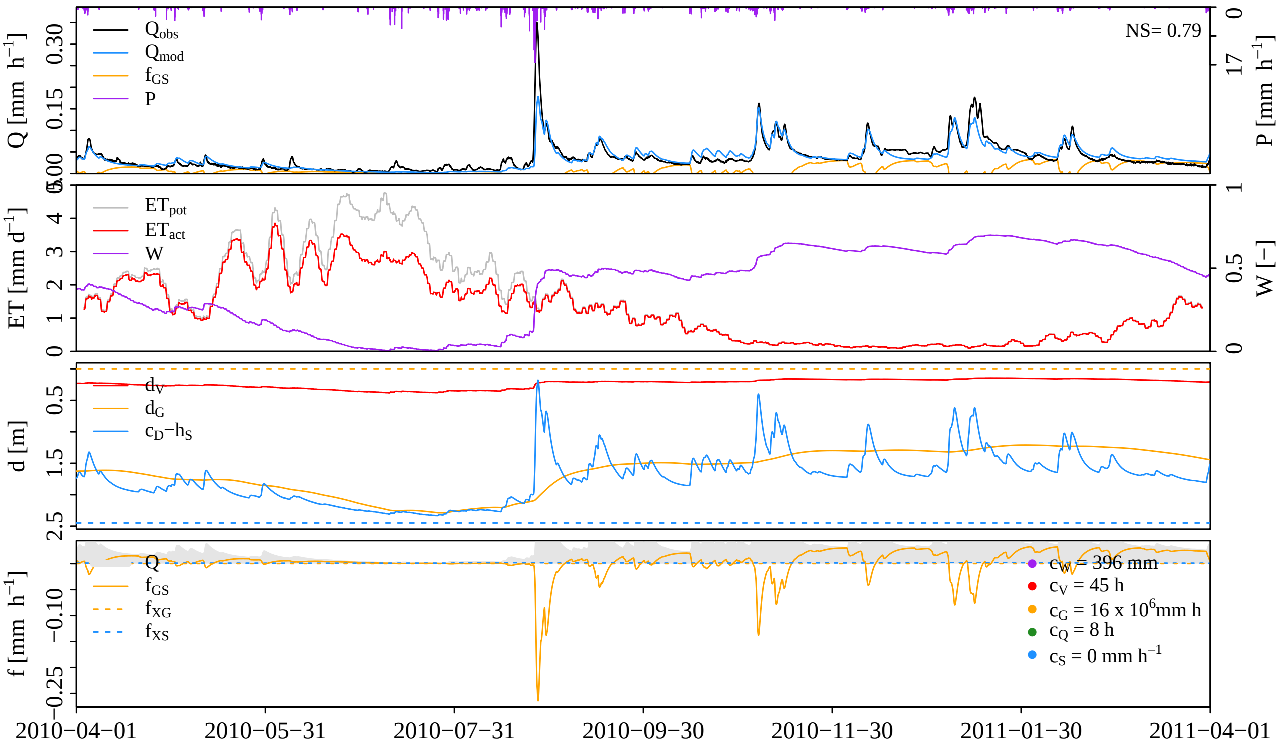


b Dataset H: WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.9: Simulation results of WALRUS Regge for the hydrological year 2009–2010.



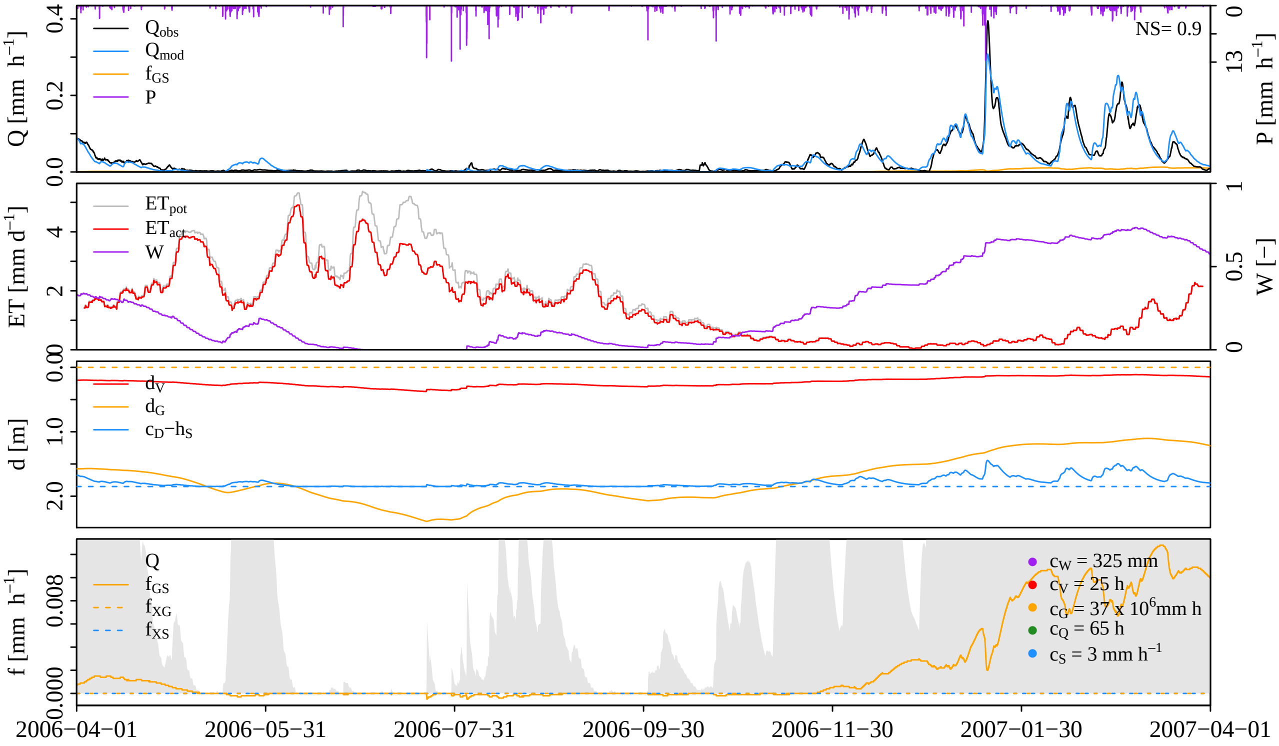
a Dataset A: Original ET_{pot} time series, no WWTP data included, no snow algorithm applied.



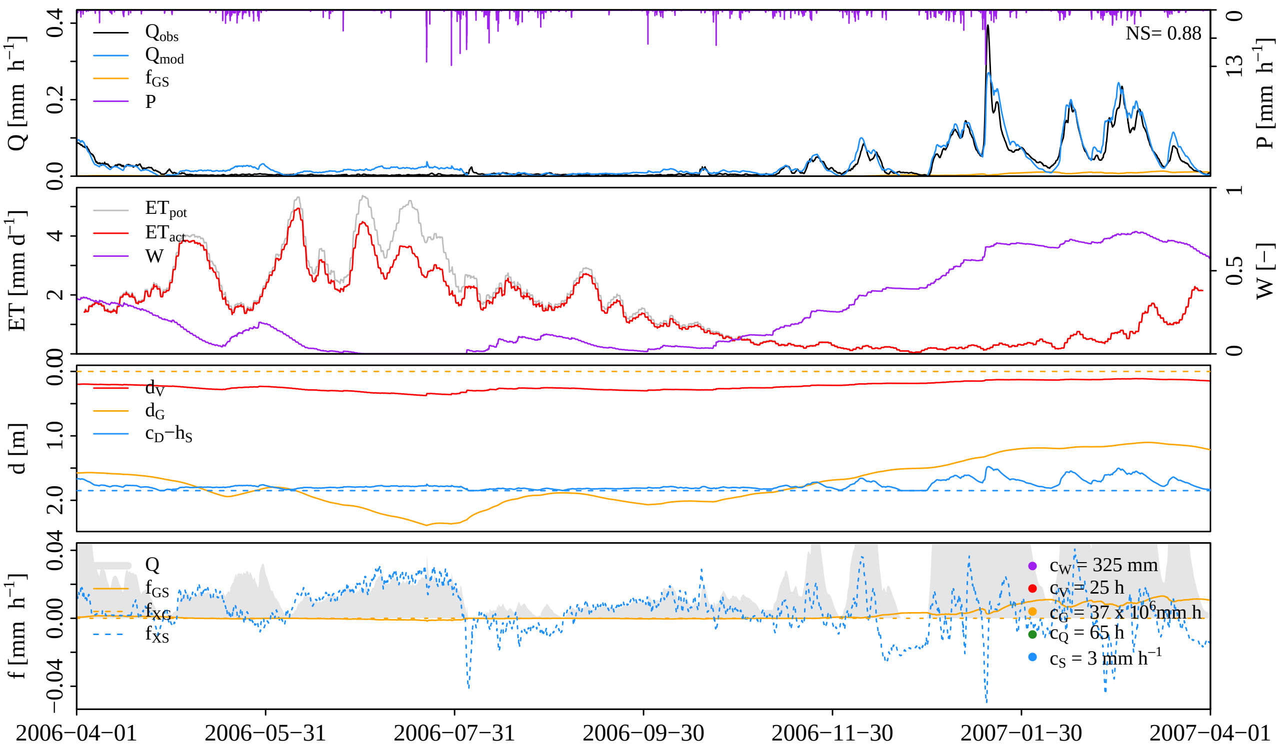
b Dataset H: WWTP data included, ET_{pot} time series corrected for land use and the snow algorithm has been applied.

Figure D.10: Simulation results of WALRUS Regge for the hydrological year 2010–2011.

E | Simulations WALRUS Afwateringskanaal

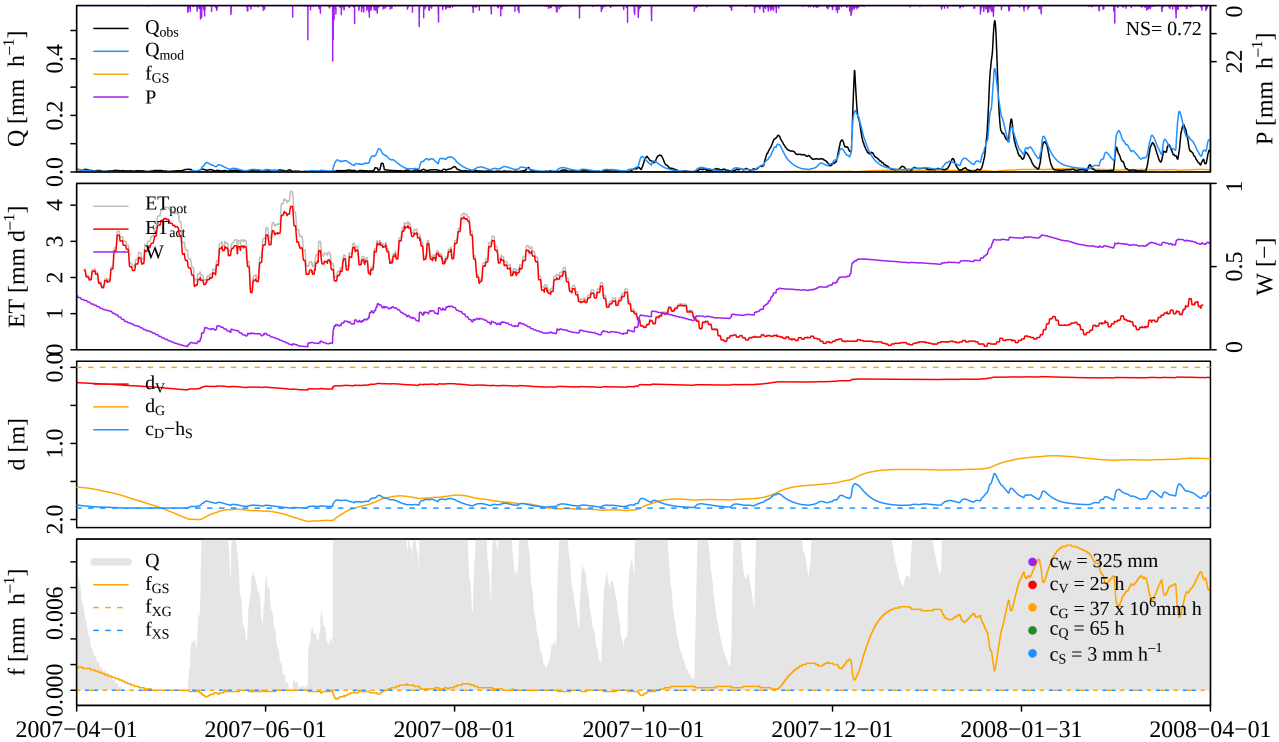


a Dataset A: Data Coevordersluis and WWTP are not included, no snow algorithm is applied.

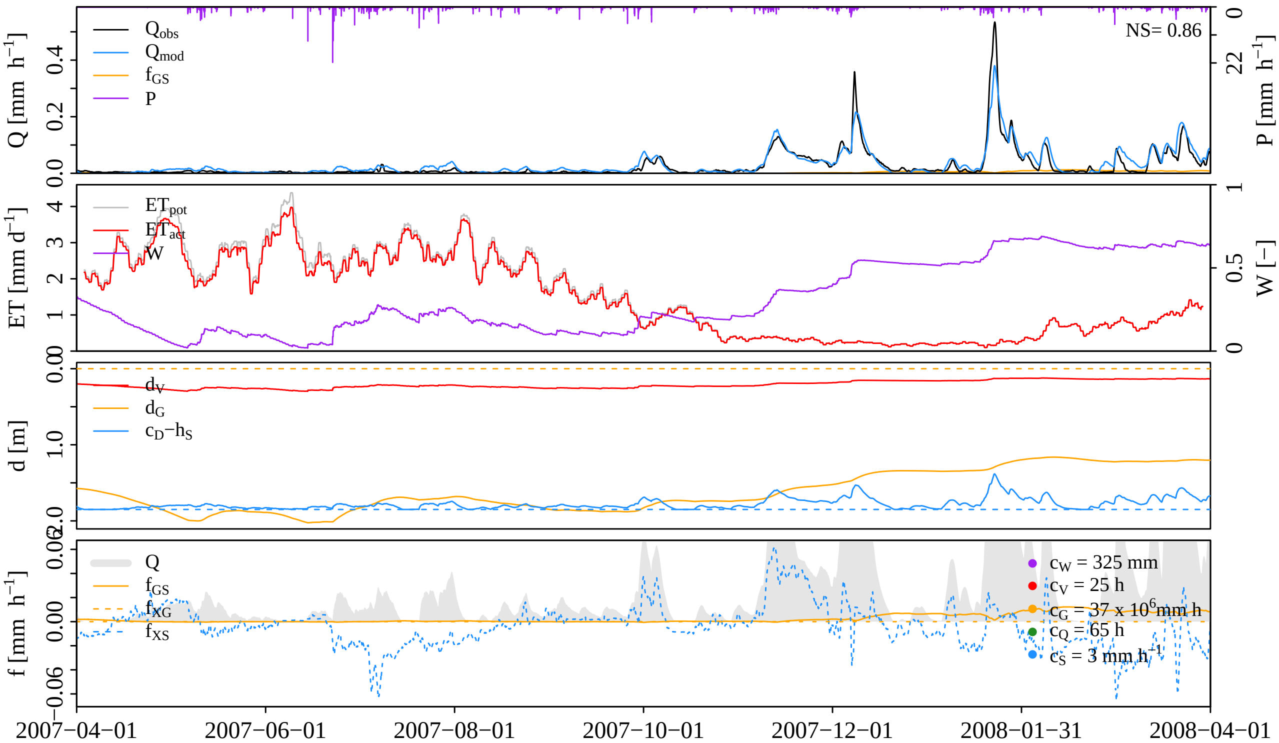


b Dataset E: Data Coevordersluis and WWTP are included, the snow algorithm has been applied.

Figure E.1: Simulation results of WALRUS Afwateringskanaal for the hydrological year 2006–2007.

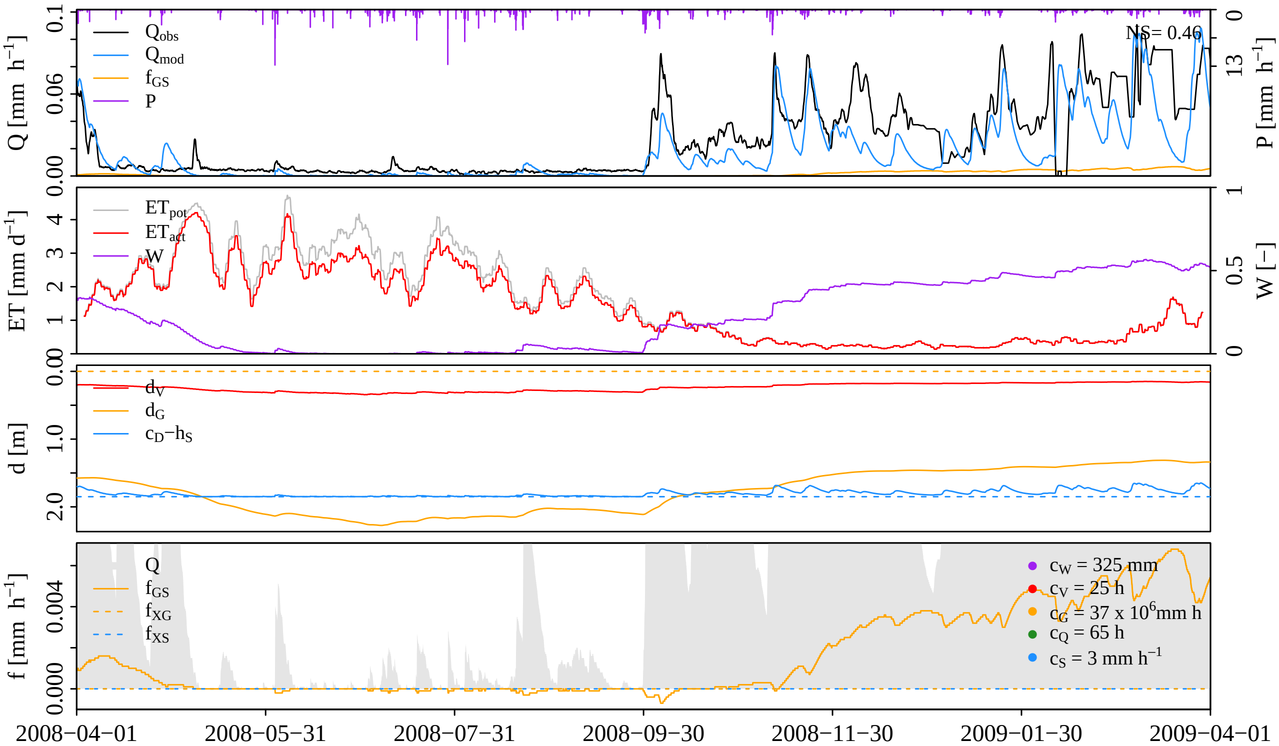


a Dataset A: Data Coevordersluis and WWTP are not included, no snow algorithm is applied.

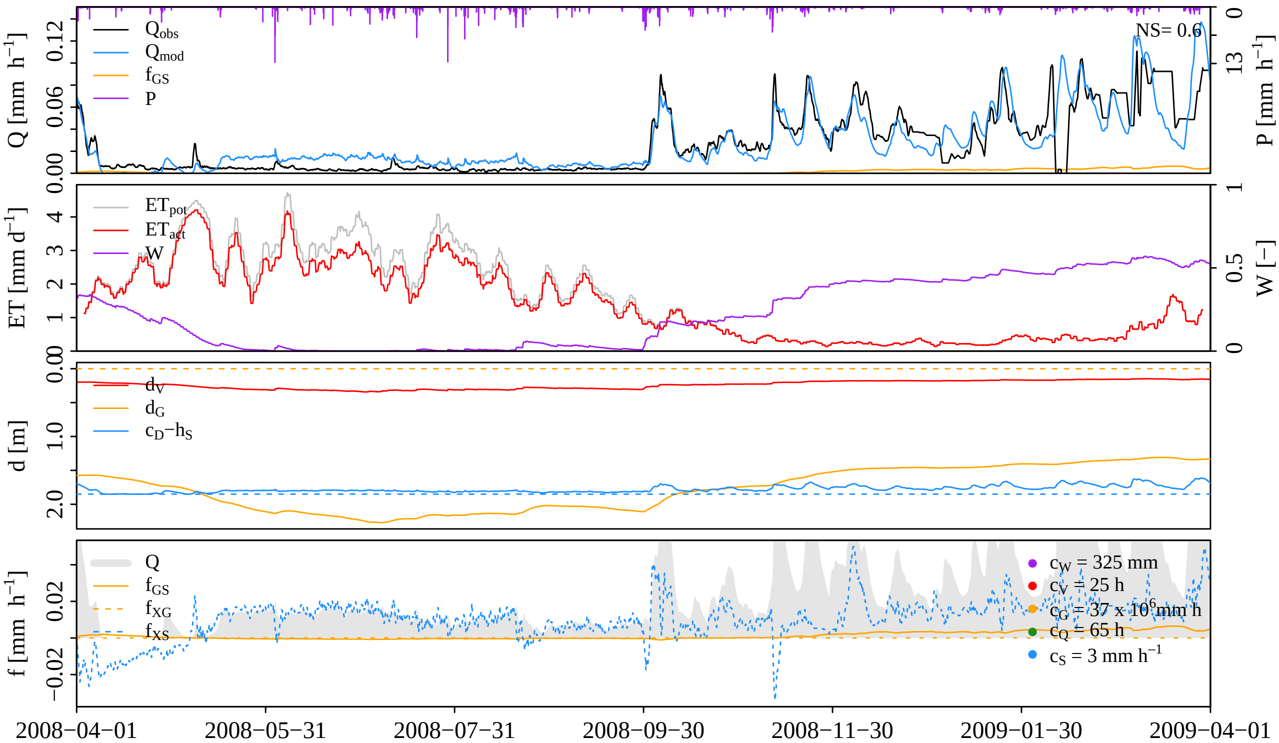


b Dataset E: Data Coevordersluis and WWTP are included, the snow algorithm has been applied.

Figure E.2: Simulation results of WALRUS Afwateringskanaal for the hydrological year 2007–2008.

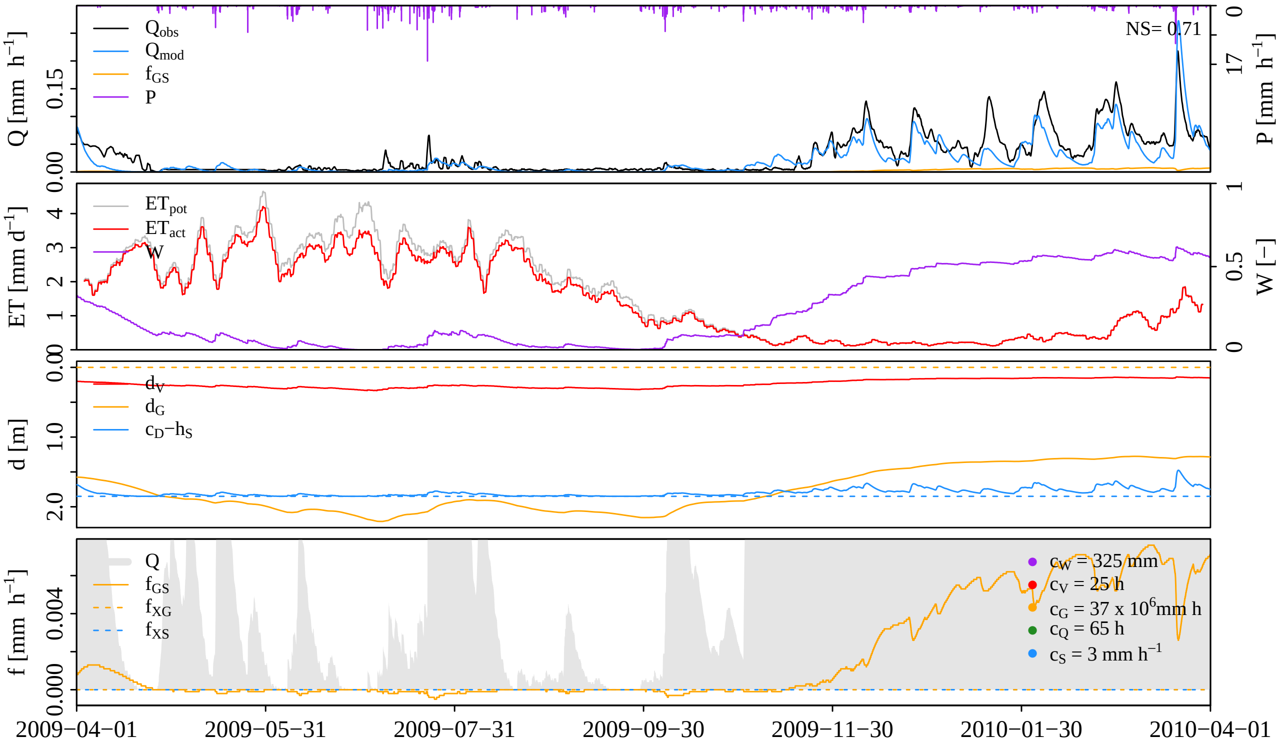


a Dataset A: Data Coevordersluis and WWTP are not included, no snow algorithm is applied.

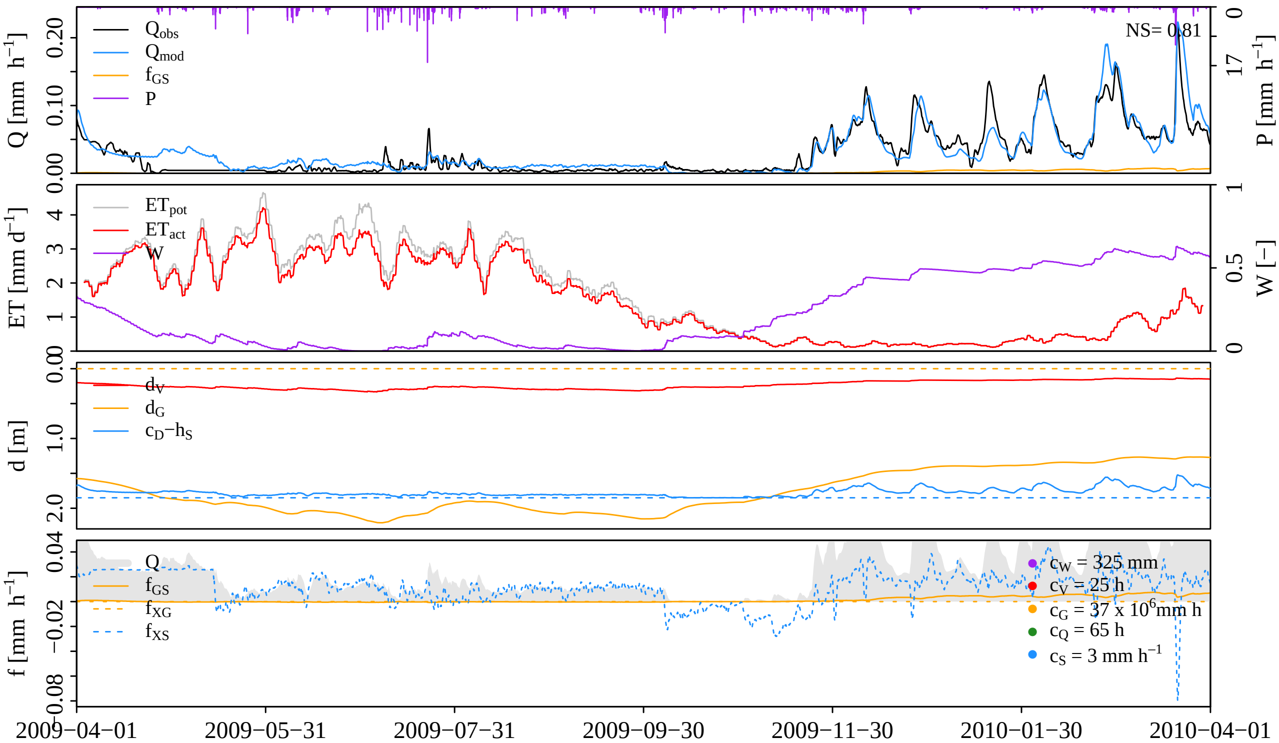


b Dataset E: Data Coevordersluis and WWTP are included, the snow algorithm has been applied.

Figure E.3: Simulation results of WALRUS Afwateringskanaal for the hydrological year 2008–2009.

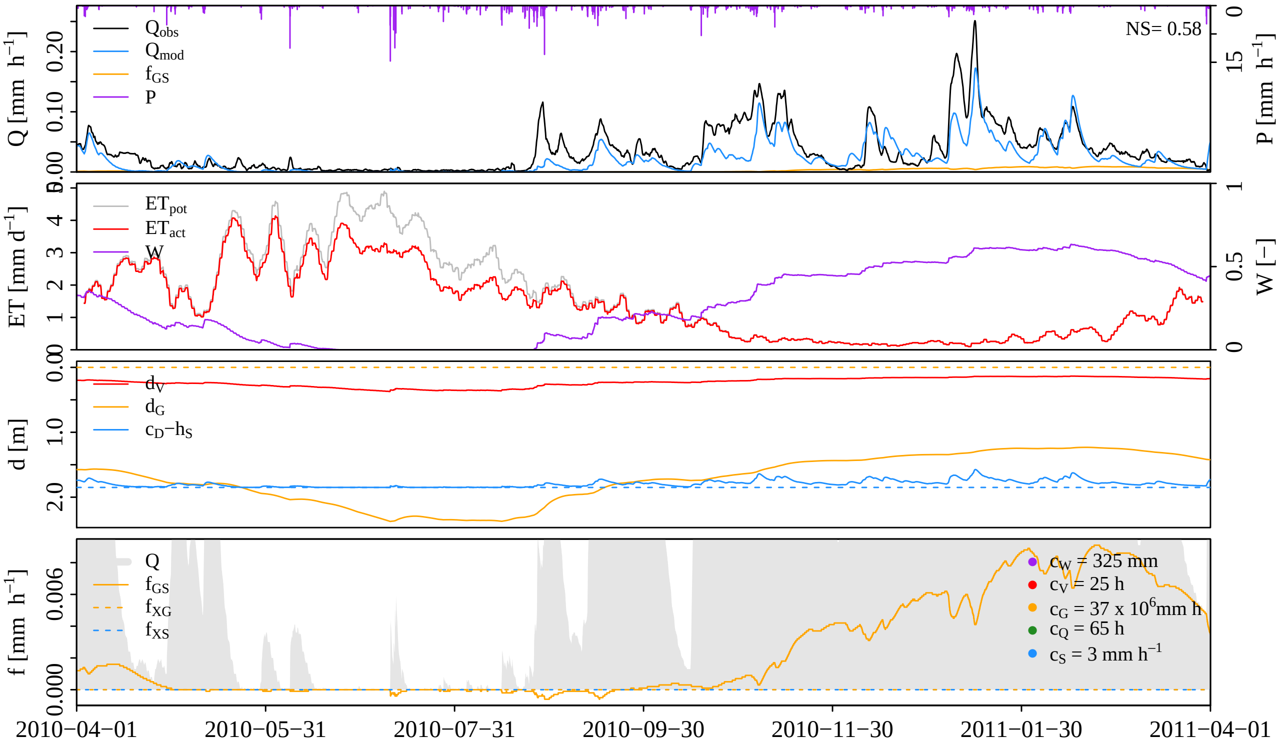


a Dataset A: Data Coevordersluis and WWTP are not included, no snow algorithm is applied.

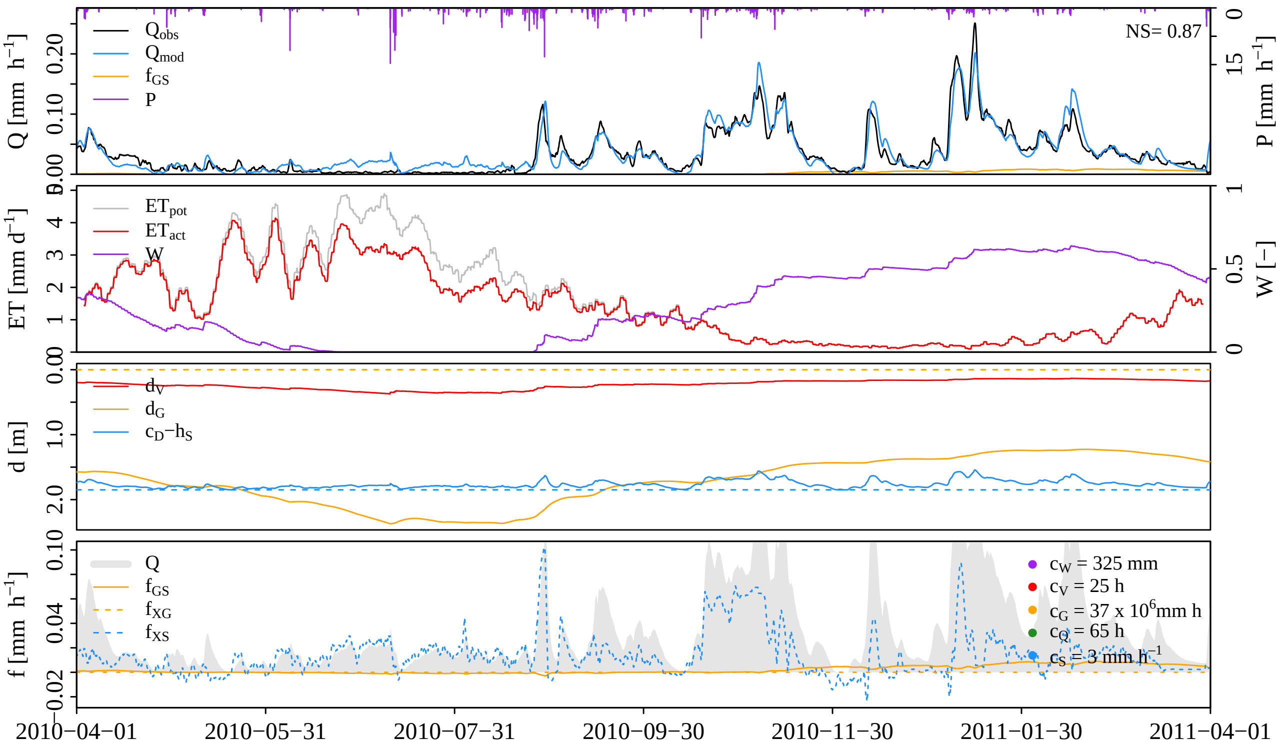


b Dataset E: Data Coevordersluis and WWTP are included, the snow algorithm has been applied.

Figure E.4: Simulation results of WALRUS Afwateringskanaal for the hydrological year 2009–2010.



a Dataset A: Data Coevordersluis and WWTP are not included, no snow algorithm is applied.



b Dataset E: Data Coevordersluis and WWTP are included, the snow algorithm has been applied.

Figure E.5: Simulation results of WALRUS Afwateringskanaal for the hydrological year 2010–2011.

F | Crop factors Regge

Table F.1: Crop factors of different land uses in the period April–September, based on the crop factor table from Feddes (1987). Crop factors in the other months of the year are equal to the crop factor of bare soil, while other crop factors (mixed/deciduous/coniferous forest and water) are equal to the crop factor of that land use in September. For urban areas, a reduction factor of 0.5 has been assumed, since no crop factors were available.

	January	February	March	April	May	June	July	August	September	October	November	December
Potatoes	0.50	0.50	0.50	0.50	0.70	1.13	1.13	1.10	0.57	0.50	0.50	0.50
Bulb/tuber crops	0.50	0.50	0.50	0.50	0.57	0.93	1.20	1.20	1.20	0.50	0.50	0.50
Mixed forest	1.08	1.08	1.08	1.17	1.17	1.17	1.17	1.08	1.08	1.08	1.08	1.08
Cereals	0.50	0.50	0.50	0.80	1.00	1.20	0.90	0.53	0.50	0.50	0.50	0.50
Grass	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.90	1.00	1.00	1.00
Bare soil	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Deciduous forest	0.96	0.96	0.96	1.04	1.04	1.04	1.04	0.96	0.96	0.96	0.96	0.96
Maize	0.50	0.50	0.50	0.50	0.67	1.03	1.27	1.20	1.20	0.50	0.50	0.50
Coniferous forest	1.20	1.20	1.20	1.30	1.30	1.30	1.30	1.20	1.20	1.20	1.20	1.20
Sugar beets	0.50	0.50	0.50	0.50	0.50	0.93	1.13	1.17	1.13	0.50	0.50	0.50
Water	1.17	1.17	1.17	1.30	1.30	1.31	1.27	1.19	1.17	1.17	1.17	1.17
Other crops	0.50	0.50	0.50	0.58	0.72	0.86	1.01	0.95	0.85	0.50	0.50	0.50
Urban area	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Table F.2: Table of the crop factor multiplied by the percentages of that land use in the Regge subcatchment. The bottom line shows the average crop factor per month. The reference evapotranspiration time series are multiplied by the factor belonging to each month in order to obtain the potential evapotranspiration, taking land use into account.

	January	February	March	April	May	June	July	August	September	October	November	December
Potatoes	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Bulb/tuber crops	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mixed forest	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Cereals	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Grass	0.49	0.49	0.49	0.49	0.49	0.49	0.49	0.48	0.44	0.49	0.49	0.49
Bare soil	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Deciduous forest	0.05	0.05	0.05	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05
Maize	0.08	0.08	0.08	0.08	0.11	0.16	0.20	0.19	0.19	0.08	0.08	0.08
Coniferous forest	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.08	0.08	0.08	0.08	0.08
Sugar beets	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Water	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Other crops	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Urban area	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	0.83	0.83	0.83	0.85	0.88	0.95	0.98	0.94	0.90	0.83	0.83	0.83