M.E. Groot Zwaaftink

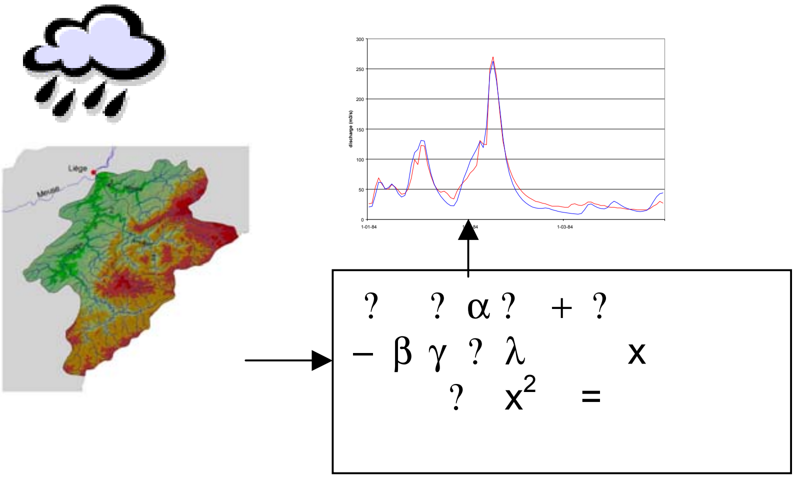
Hydrological Modelling of the Ourthe

A Comparison of Rainfall-Runoff Models

Supervisors:
P.J.J.F. Torfs (WU)
P.M.M. Warmerdam (WU)
M. de Wit (RIZA)

Master's thesis
August 2003

RIZA Werkdocument
2003.125X



WAGENINGEN UNIVERSITY
ENVIRONMENTAL SCIENCES

Ministerie van Verkeer en Waterstaat
Directoraat-Generaal Rijkswaterstaat

Rijksinstituut voor Integraal Zoeterwaterbeheer en Afvalwaterbehandeling (RIZA)

Hydrological Modelling of the Ourthe

A Comparison of Rainfall-Runoff Models

Author:	Mirjam Groot Zwaaftink	
Supervisors:	Drs. P.J.J.F. Torfs	Wageningen University
	Ir. P.M.M. Warmerdam	Wageningen University
	Dr M. de Wit	RIZA
Subject code:	K150-706	study weight: 17 weeks
RIZA werkdocument:	2003.125X	

WAGENINGEN UNIVERSITY
ENVIRONMENTAL SCIENCES

Ministerie van Verkeer en
Waterstaat
Directoraat-Generaal
Rijkswaterstaat

Rijksinstituut voor Integraal
Zoeterwaterbeheer en
Afvalwaterbehandeling
(RIZA)

Preface

This report is the result of my student thesis research in hydrology for a period of 4 months at the River Department of the Institute for Inland Water Management and Waste Water Treatment (RIZA) in Arnhem, a subdivision of the Dutch Ministry of Transport, Public Works and Water Management. This study was organised in cooperation with the sub-department of Water Resources of Wageningen University.

This diploma thesis would not be what it is now without the help of numerous people. First of all I would like to thank Marcel de Wit (RIZA), who made it possible for me to do my thesis at RIZA, gave lots of advices and questions were always welcome.
Also, thanks to Piet Warmerdam and Paul Torfs for arranging an opportunity to do my thesis at RIZA, their supervising, their interest in the research, their advice and reading this report.

Mirjam Groot Zwaaftink
August 2003, Arnhem

Table of contents

Summary

The floods of 1993 and 1995 where a cause for improvement of high flow forecasting for the river Meuse. For this purpose the HBV model from the Swedish Meteorological and Hydrological Institute (SMHI) was selected from a range of other models. Some studies about the spatial and temporal scales that should be used are already done for the HBV model by RIZA. The main objective of this research is the complexity of the HBV model, to give better insight in the advantages of applying the HBV model to the Meuse catchment. The complexity of a model is formed by the processes in the model. To determine the effect of some of the processes, used in the HBV model, the HBV model is being compared with a simpler conceptual model in this study for the Ourthe catchment. The “simple” model is being build up step by step with processes, following a strategy from a very simple to a relatively complex model.

There is started with a very simple model, a constant runoff model in which the discharge is a constant function. This model is seen as the reference model. The second model is a linear rainfall-runoff model in which a linear function is added to the model, creating a discharge as function of the precipitation. The second step is the addition of a linear reservoir, creating a linear rainfall-runoff model with one reservoir. The addition of a second reservoir follows in the third step. The process of the evapotranspiration in the catchment is added to the model in two ways. The first way is in a second run for each model, with effective precipitation, which is a function of an evapotranspiration coefficient (averaged over the total calibration period) and the potential evapotranspiration, as input. The second way of adding an evaporation function is in a fourth step in the row of the “simple” models, called a linear-rainfall-runoff model with two reservoirs and evapotranspiration. In this last model, the effective precipitation, based on a monthly averaged difference between measured discharge and precipitation over the total calibration period, is used as input.

The results of the simulations with the “simple” models show the improvement of the model for each process addition. There can be concluded that the addition of a linear function improves the model results a lot, followed by the addition of a linear reservoir, causing a better result as well. There can also be concluded that the addition of an evapotranspiration function is essential for the simulation of rainfall-runoff processes. Including a second reservoir slightly improve the results of the model.

A small research about possible differences between input data used in studies before (Booij, 2002 and Wal, 2001) and the input data used in this study (Wójcik and Buishand (2001)) is also done. There can be concluded that differences exist between these data. For this reason, a new calibration of the HBV model had to be done for the Ourthe catchment, to compare the results of the “simple” models with the result of the HBV model.

The results of the HBV model, after calibration, are very good with an efficiency coefficient of 0.86 for the calibration and 0.91 for the validation and even better than the results for the simulations of the Ourthe catchment done by Booij (2002). The result of the HBV model is also much better than the results of the simulations with the “simple” models.

From the results of all simulations can be concluded that each process added in the row of “simple” models is necessary to give a good result. The HBV model gives a better result than the best “simple” model. It can be concluded that some more processes, used in the HBV model have to be added to the “simple” model to give a result that is at least as best as the HBV model. These processes could be a third reservoir, representing the soil-moisture process and/or a transformation routine.

Chapter 1 Introduction

The floods of 1993 and 1995 caused a lot of damage in the basin countries and regions of the river Meuse and its tributaries. This gave rise to a Flood Action Plan Meuse (WHM, 1998). The aim of this plan is the reduction of risk of floodings and there are two ways formulated in the plan to achieve this aim:

1. Reduction of high water levels
2. Reducing the vulnerability for floods

To achieve the second purpose, a better rainfall-runoff model of the river Meuse is being developed to get more accurate forecasts of high flows. Obviously a good representation of the rainfall-runoff processes is necessary for flood forecasting and the determination of design discharges.

RIZA, the Institute for Inland Water Management and Waste Water Treatment (RIZA), a subdivision of the Dutch Ministry of Transport, Public Works and Water Management is, within the Netherlands, responsible for the development of rainfall-runoff models for the Rhine and the Meuse. Their work on these models is especially about a rainfall-runoff model for operational forecasting and defining the design discharge for these rivers. The design discharge is the maximum discharge, which, in theory, should be exceeded on average once every 1250 years. This discharge has been derived from statistical analyses of time series of peak discharges. Since the available time series, used for the prediction of the design discharge, are relatively short compared to the required mean recurrence period of 1250 years, and may also be non-homogeneous, the estimated design discharge is subject to large uncertainties. In order to reduce these uncertainties, a new methodology is being developed, consisting of a stochastic precipitation generator, developed by the Royal Dutch Meteorological Institute (KNMI) and a hydrological model (Parmet et al, 1999) to construct long series of discharges which are then subjected to statistical analysis.
For this purpose the HBV model from the Swedish Meteorological and Hydrological Institute (SMHI) was selected from a range of other models (Passchier, 1996). During the last few years RIZA did some studies on the feasibility of the HBV model for use of short term and long term simulations. Especially about the spatial and temporal scales that should be used, taking into account factors like uncertainties, availability of data and feasibility for the model user.

Velner (2000) performed a study about the temporal scale for simulation of high discharge events. In this study HBV was applied with a time step of 1 hour, 6 hours and 1 day to the Ourthe, a tributary of the Meuse. From this study could be concluded that a time step of 6 hours is appropriate for predictions of extreme events in the river Ourthe.

Booij (2002) determined an appropriate model scale for the assessment of the impact of climate change on river flooding in the Meuse basin. The definition of appropriate is in this context: “a right balance between uncertainties of inputs, parameters, and process descriptions resulting in an output uncertainty acceptable for the model user and feasible in view of data availability and computational possibilities”. Statistics of precipitation, temperature, evapotranspiration and catchments characteristics were analysed for an appropriate scale for each feature and integrated into one appropriate model scale. From this research there can be concluded that a spatial model resolution of 10 km is appropriate.

Van der Wal (2001) concluded that with the available data, better model results of the HBV model can not be achieved by dividing the Meuse basin from 15 into 118 sub basins. The best results, that can be obtained with the data is already reached with the HBV-15 model, which is the appropriate spatial resolution for the Meuse basin, Booij (2002) concluded from his research.

De Bruijn (2000) performed a study in which the HBV model was applied to the catchments of the Ambleve, Vesdre, Lesse and Meuse till Chooz with good results.

This research will focus on the complexity of the HBV model to give better insight in the advantages of applying the HBV model to the Meuse catchment.

The aim of the research

All the processes described in the model form the complexity of a model. To determine the effect of each process description in a model on the simulation of the discharge in a model, a strategy can be formed: a model can be cut into pieces or being build up in different stages of complexity, starting with a very simple model to a relative complex model at the end.

Which strategy is chosen, building up or cutting into pieces, depends on the investigator. The construction of the HBV model is done following the strategy of going from a simple to a complex model, building up step by step. Bergström (1991) gave the following reason for this:

"Going from a complex to simpler model structures requires an open mind, because it is frustrating to have to abandon seemingly elegant concepts and theories. It is normally much more stimulating, from an academic point of view, to show significant improvement of the model performance by increasing complexity."

If the result of the model simulation improves significantly with addition of a new process description the addition made sense, if the result doesn't improve the quality of the addition in the model, the model structure cannot be valued. There should always be remembered, "*good model performance does not guarantee that we have described the system correctly"* (Bergstrom, 1991).

This research will focus on the value of using the HBV model compared to simpler conceptual models, being built up step by step.

The aim of the research is to see if a simple model, which looks like a part of the HBV model, gives already almost the same result as the HBV model for the Ourthe catchment. From this, the following research question can be formulated:

1. Does the relatively complex conceptual model HBV give a better result than a simple conceptual model?

The "simple" models will also be conceptual like the HBV model.

Together with these research question, some sub-questions can be formulated:

2. How much does every addition of a new process description to the model improve the results and is it worth making this addition?

3. What are the most relevant processes for the simulation of the rainfall-runoff processes in the catchment?

The data of the study of Wójcik and Buishand (2001) will be used in this study. These data were also used in a study before by van der Wal (2002) as input for the HBV model. The parameters of the HBV model were not changed in this study from the parameters used in the earlier studies by Booij (2002) and van der Wal (2001), in which other input data were used. Another research question can be formulated from this:

4. Are there any differences between the input data used in the studies before for the Ourthe catchment (Booij (2002), van der Wal (2001)) and the data of Wójcik and Buishand (2001)?

If there are differences between the input data used in the studies of Booij (2002) and van der Wal (2001), and the data of Wójcik and Buishand (2001), a new calibration of the parameters in the HBV model with the data of Wójcik and Buishand (2001) should be done, formulating another question for this research:

5. What are the results of the HBV model obtained with the meteorological data of Wójcik and Buishand (2001) with or without a new calibration of the parameters?

Delimitation

The simulations will be done for the catchment of the Ourthe, upstream of Tabreux, a sub-catchment of the Ourthe catchment, which is a subbasin of the Meuse basin, with Tabreux as gauging station for the measured discharge. The Ourthe is used as a casestudy for the development of the rainfall runoff generator for the Meuse. The simulation will be done for the years 1970-1996, with the years 1970-1984 as calibration period and 1985-1996 as validation period for the different models. A time step of one day will be used. Since the discharge data is only available for this time step.

Plan of the research and report structure

To give an answer to the questions of this research some simple models will be build up step by step and the input data used in the studies of Booij (2002) and van der Wal (2001) and the data of Wójcik and Buishand (2001) will be compared. If differences exist between the input data, the HBV model will be calibrated for the Ourthe catchment, otherwise the results of the study of van der Wal (2002) with the HBV model will be compared with the results of the simpler models.

“Simple” models

There will be started with a very simple model, a constant runoff model in which the discharge is a constant function. This model can be seen as the reference model. The second model will be a linear rainfall-runoff model in which a linear function is added to the model, creating a discharge as function of the precipitation. The second step is the addition of a linear reservoir, creating a linear rainfall-runoff model with one reservoir. In this model is the discharge a function of the precipitation, and a function of the outflow of the reservoir, in which a storage of a part of the precipitation is taking place. The addition of a second reservoir will follow in the third step, creating a linear rainfall-runoff model with two reservoirs. All these models don’t have any process for the computation of the evapotranspiration in the catchment, but this process is quite important in the process from precipitation to discharge and is added to the models in the following two ways:

1. For each rainfall-runoff model, two model runs are done, with different input data. The first run is done with the observed precipitation, the second run is done with a kind of precipitation taking the evapotranspiration into account, called the effective precipitation in this research and is computed with the potential evapotranspiration data and an averaged evapotranspiration coefficient over the total calibration period. An explanation of how this effective precipitation is computed exactly will be given in this study.
2. In addition to the linear-rainfall-runoff model with two reservoirs, a linear rainfall-runoff model with two reservoirs and evapotranspiration is used, in which the difference between the precipitation and discharge over a certain period is seen as the evapotranspiration. This evapotranspiration is computed as a mean daily value per month over the total calibration period. The explanation of the computation of the evapotranspiration will be given in the model description.

The first solution is done for every model and the second solution is seen as a fourth step of the simple models, in which the data of the potential evapotranspiration are not used. These two different ways of adding the evapotranspiration process to the models are also compared in this research.

To evaluate the influence of peak discharges on the results computed with the model, two other simulations are done for both models with reservoirs, with precipitation and effective precipitation as input. In these model simulations, the measured discharges with a discharge exceeding a threshold of 2 mm/d (“peaks”) are emphasized.

Report structure

This report is organised according to the steps taken in this research. First a description of the area will be given (chapter 2), followed by a description of the input data (chapter 3), in which the input data of Booij (2002) and van der Wal (2001) and the data of Wójcik and Buishand (2001) will be compared and the computation of the effective precipitation is also explained. In chapter 4 the “simple” models will be described. Chapter 5 shows the results of the simulation with the simple models. A description of the HBV model and the results will follow in chapter 6. A summary and comparison of the results is given in chapter 7 and the conclusions and recommendations will be at the end of this report (chapter 8).

Chapter 2 Description of the Meuse and the Ourthe basin

2.1 The Meuse Basin

The basin of the river Meuse has a total area of 33.000 km^2 and is mainly fed by precipitation. The basin covers parts of France, Belgium, Luxembourg, the Netherlands and a relatively small part of Germany. It's length from the source in France, at an altitude of 400 m a.s.l. (above sea level), to the mouth, is about 875 km (Berger, 1992).

Since the river can be regarded as an almost purely rain fed river, high annual and seasonal variations in discharges and water levels are caused. The Meuse responds strongly and fast to variations in precipitation, due to the physical characteristics of the catchment.

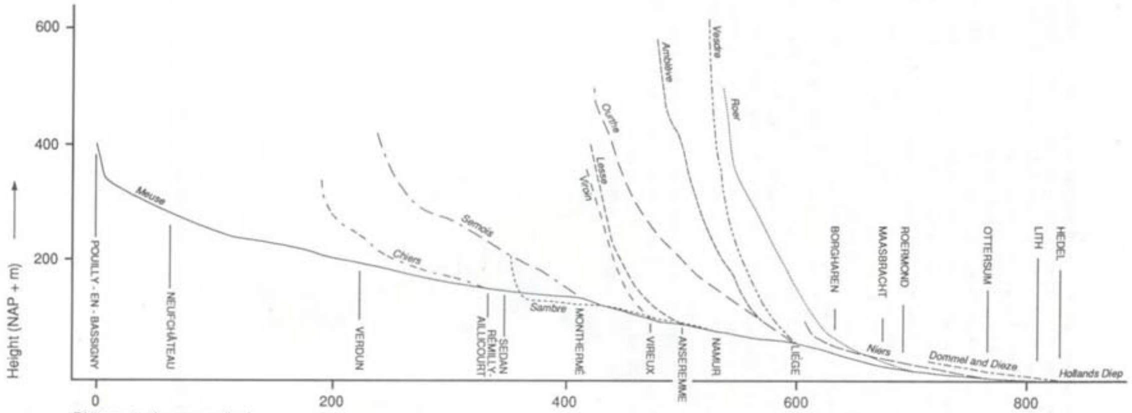


Figure 2.1 Longitudinal profiles of the Meuse and its tributaries (source Berger, 1992)

Figure 2.1 shows that especially the tributaries Ourthe, Vesdre, Amblève and Lesse of the Meuse, which are situated in the Ardennes, have steep slopes and an altitude of 600 m a.s.l. The soil in these areas consists mostly of hard impermeable rock, resulting in a small storage capacity, a narrow river and a large slope. The poor permeability, the steep slopes, the narrow beds and the large amounts of rainfall in the Ardenne area contribute to a fast responding discharge to precipitation. During low flows the contribution of this region of the Meuse basin is small, due to its low storage capacity. During flood waves, the contribution of the Ardenne area to the discharge is large (Berger, 1992).

In the next section the characteristics of the Ourthe catchment, the catchment used in this study, will be described. A complete description of the river Meuse and its tributaries is given by Berger (1992).

2.2 The Ourthe Basin

The Ourthe covers an area of 3,626 km^2 and is the largest tributary of the river Meuse. During floods, the discharge rates are relatively high. The Ourthe is a fast rising river, which makes this river, through its hydrological behaviour and location (close to the Dutch border) the most important Meuse tributary for flood risks in the Netherlands. It is therefore important to forecast discharges of the Ourthe.

The Ourthe catchment can be divided into three sub-catchments, the Ourthe, the Amblève and the Vesdre catchment, see figures 2.2, 2.3 and table 2.1. In the Ourthe sub-catchment the river consists of two branches in its upper course: The Ourthe Occidentale and the Ourthe Orientale. Its total length is approximately 175 km.

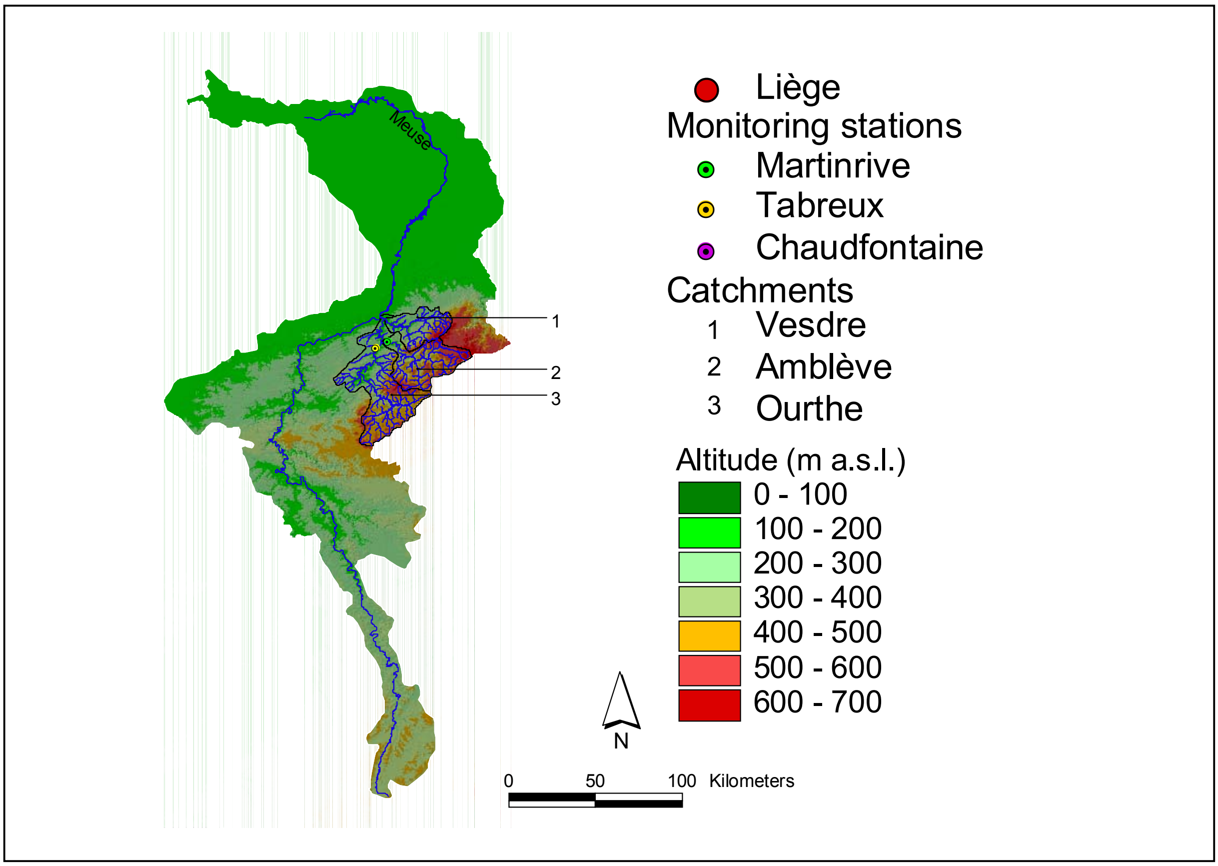


Figure 2.2 The Meuse basin and the Catchments Vesdre, Amblève and Ourthe (source: Wit et al, 2002)

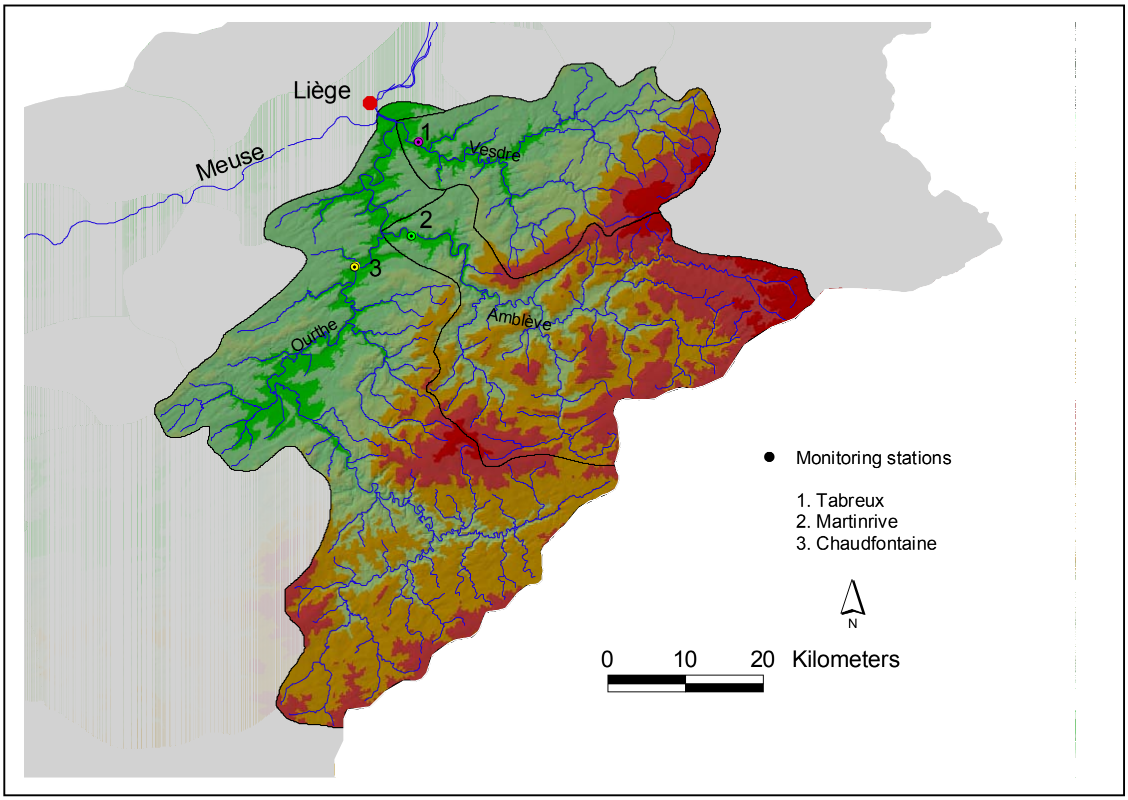


Figure 2.3 The location of the sub-catchments and the different gauging stations for the sub-catchments (source: Wit et al, 2002)

Table 2.1 (sub)-catchments of the Ourthe and their size

Catchment	**Size (km^2)**
Total catchment of the Ourthe	3626
Ourthe at Tabreux	1597
Amblève at Martinrive	1044
Vesdre at Chaudfontaine	677
Remaining area	**308**

This study is limited to the sub-catchment of the Ourthe, upstream from Tabreux. A description of this sub-catchment in the Ardennes will follow in the next section.

2.2.1 The Ourthe upstream from Tabreux

The Ourthe consists of two branches. The Ourthe Occidentale springs at +500 m a.s.l. and the Ourthe Orientale springs at 520 m a.s.l. After the confluence in the Nisramont reservoir, the Ourthe continues as one river. Up to Tabreux many small tributaries drain into the Ourthe. The catchment covers an area of 1597 km^2 and the highest point is at 658 m a.s.l. The region has a mountainous character. Up to Tabreux the average gradient amounts 3.7 10^{-3}. Thirty percent is covered with forests, of which 70% consists of deciduous forests. The reservoir at Nisramont has a capacity of 3 10^6 m^3 and its purpose is the supply of drinking water and the generation of electricity. (Berger, 1992)
In the next sections, some of the characteristics of the catchment will be described.

2.2.1.1 Geology and soils

From a geological point of view the catchment of the Ourthe can be splitted into two parts. These are the relatively flat limestone and shale area in the northwestern part of the Marche-en-famenne and the larger sandstone area in the southern part (Figure 2.4). Both branches of the Ourthe have their source in a sandstone area (Dijksma et al,-).

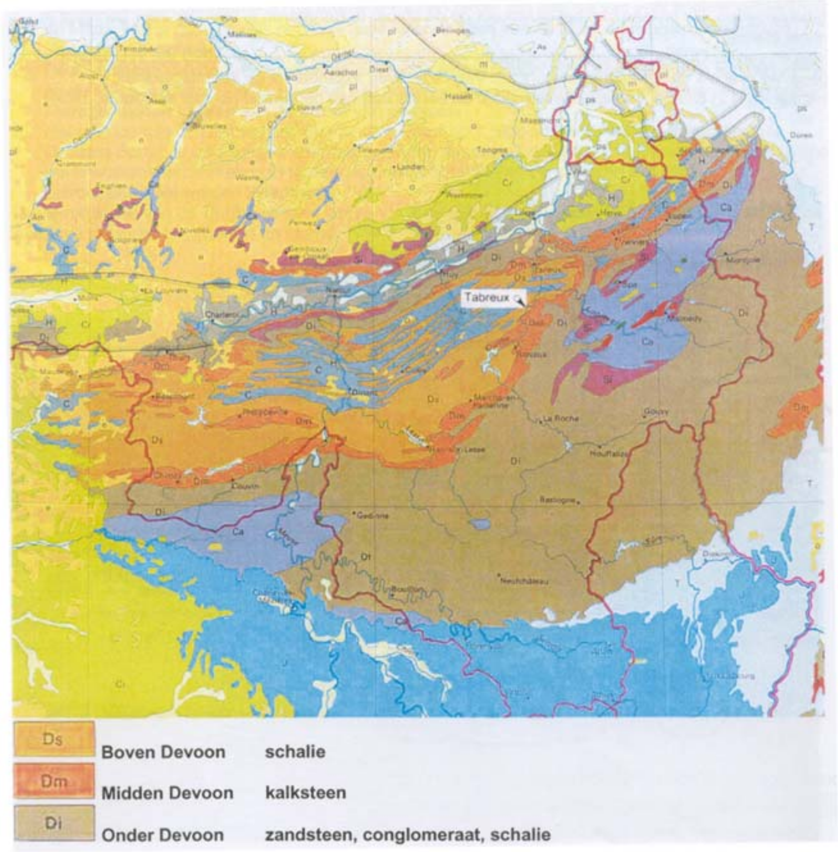


Figure 2.4 Geology of the Ourthe catchment (source: Tilmont et al., 1984)

The soils in the area are strongly related to the geology (figure 2.5). In the southern parts the stony loam and slate stones dominate. In the northern part, where the underground exists of lime stones, limestone soils and some loam and sandy loam soils can be found.

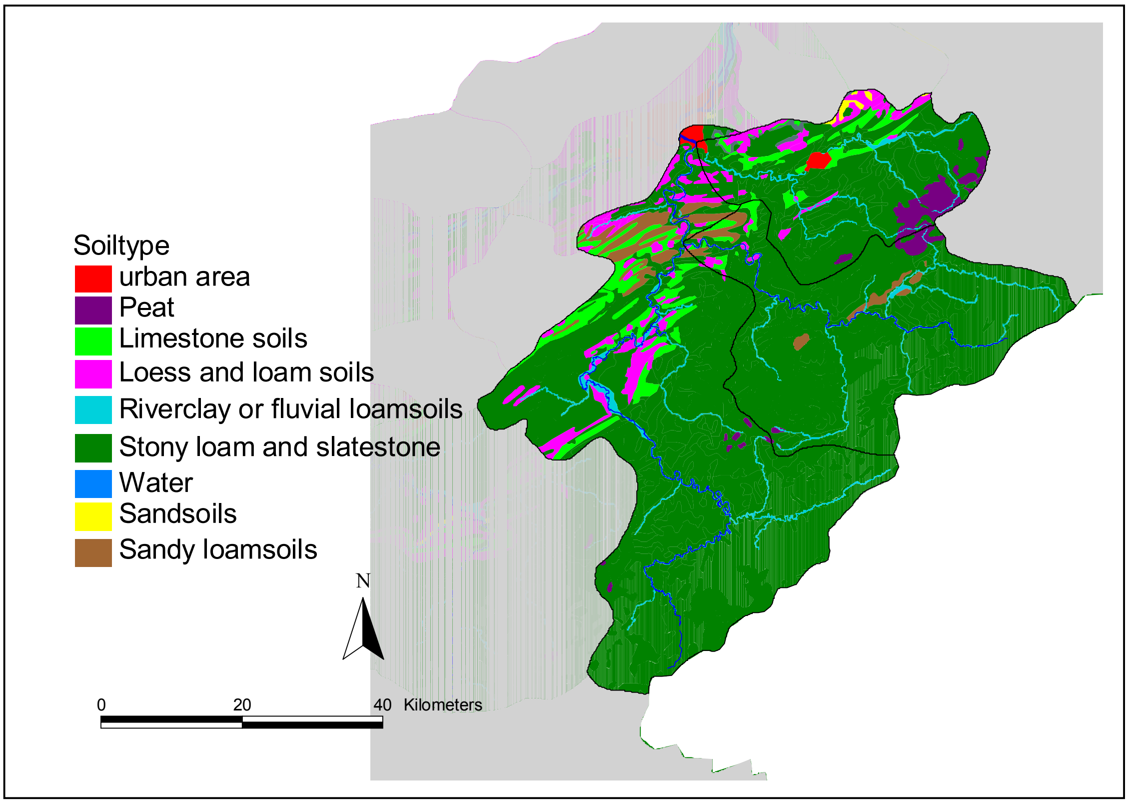


Figure 2.5 The soils in the catchment of the Ourthe (source: Wit et al, 2002)

2.2.1.2 Landuse

The landuse in this area is mainly depending on the steepness of the slopes. At the very steep slopes forests can be found, while at the less steep slopes, agriculture with areas of natural vegetation and pastures (figure 2.6).

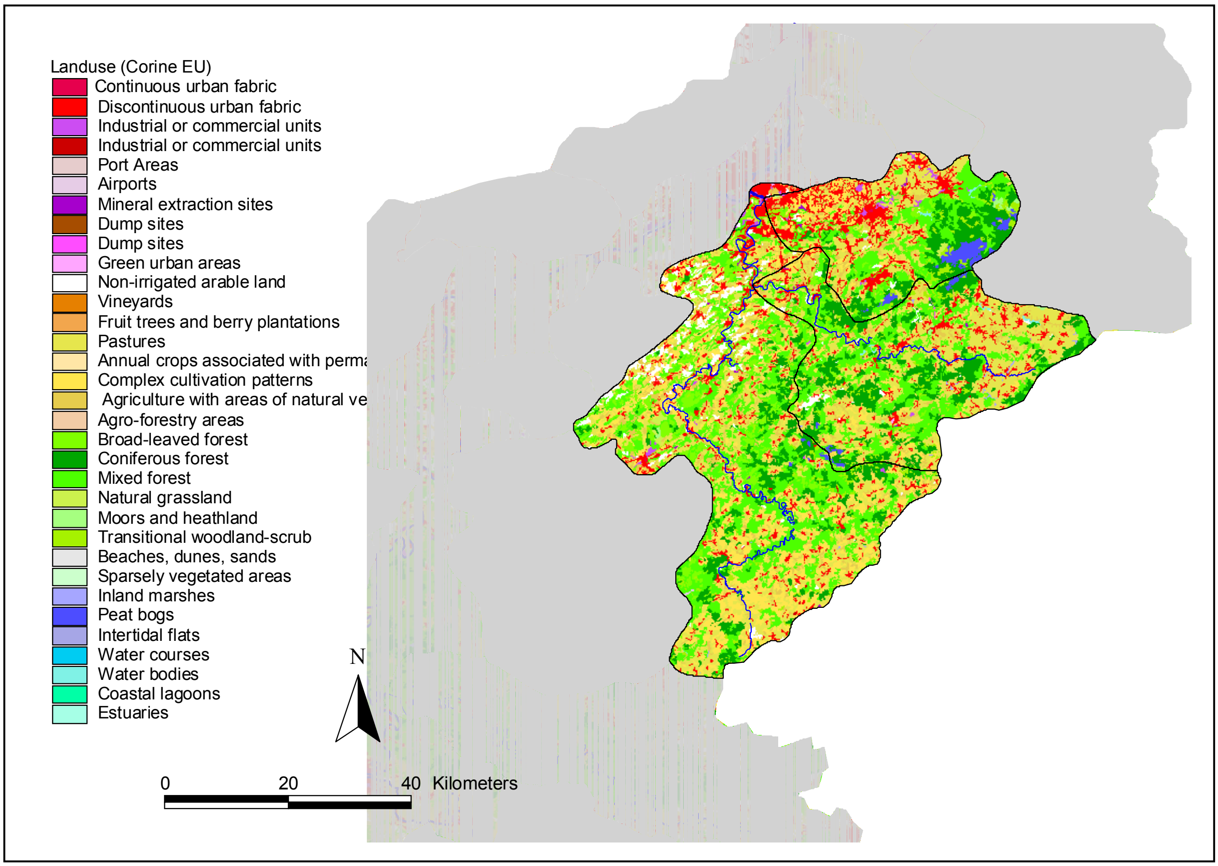


Figure 2.6 Landuse in the catchment of the Ourthe (source: Wit et al, 2002)

2.2.1.3 Precipitation

The mean annual areal precipitation in the catchment of the Ourthe is 969 mm (Berger, 1992). There is a clear correlation between the altitude and the precipitation. In the lower parts the annual precipitation is approximately 900 mm, in the higher parts of the catchment of the Ourthe upstream from Tabreux approximately 1100 mm. The distribution of the annual precipitation over the months for the catchments of the Ourthe, Amblève and Vesdre are shown in figure 2.7. Summer and winter months are relatively wet, while April is the driest month of the year.

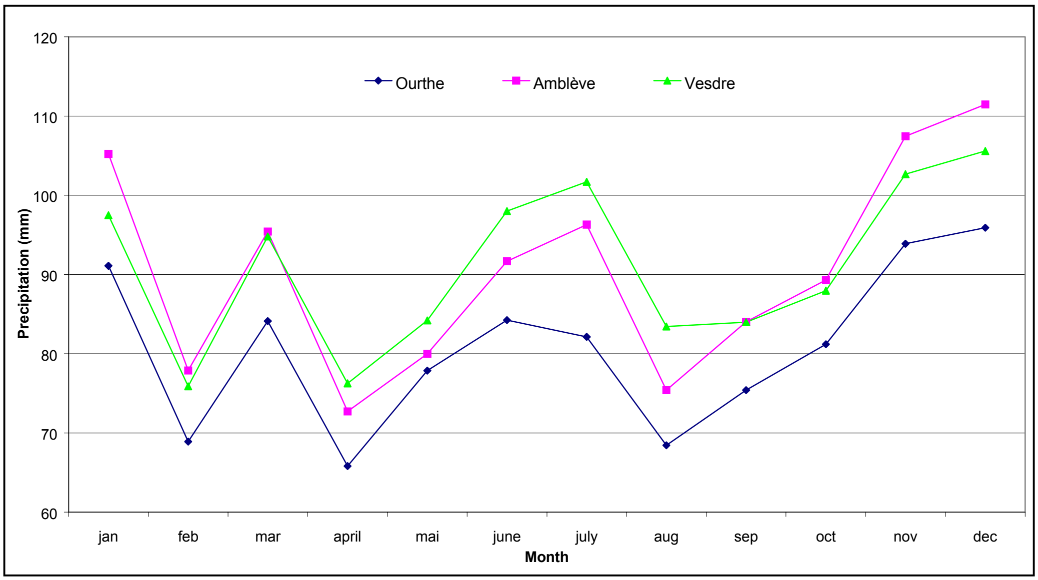


Figure 2.7 Monthly averaged precipitation sum for the Ourthe, Amblève and Vesdre for the years 1970-1996 of the data of Wójcik and Buishand (2001)

2.2.1.4 Discharge

The discharge gauging station for the catchment, used in this study, is located at Tabreux (see figure 2.3). The mean annual discharge of the Ourthe at Tabreux is 22 m^3/s. During winter the discharge rates are much higher than during summer and ranges from about $44 m^3/s$ in January to 5 m^3/s in August. This variation in rates is due to the influence of the evaporation, which is of course highly related to the temperature, see figure 2.8. As a consequence discharges are high in winter and low in summer.

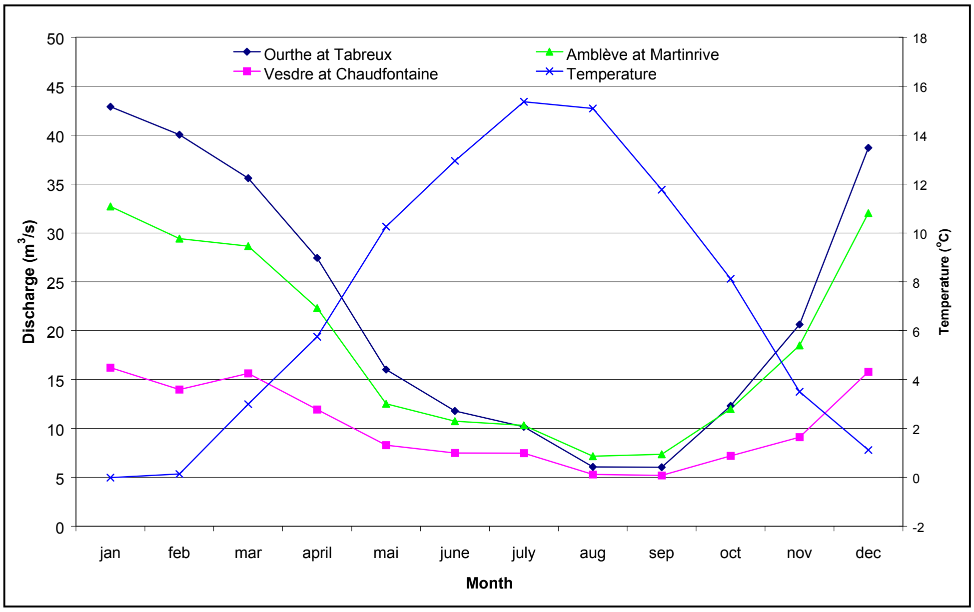


Figure 2.8 Monthly averaged discharges of the Ourthe, Amblève and Vesdre and monthly averaged temperature for the area for the years 1970-1996

Chapter 3 Input data

To run all the models, two kinds of input data are required for the catchment. These input data are the meteorological data and the hydrological data. This chapter describes how these data are edited, so that they can be applied in the models as input. The comparison of the input data used in the studies of Booij (2002) and van der Wal (2001) and the data of Wójcik and Buishand (2001) can also be found in this chapter (section 3.3), even as the explanation of the computation of the effective precipitation (section 3.4).

The precipitation, potential evapotranspiration and discharge data are given in millimetres for the total area.

3.1 Hydrological data

To compare the performances of the hydrological models, efficiency coefficients are calculated and compared. For the calculation of these coefficients, the measured discharges are needed. These data have been provided by the Ministere Wallon d'Equipement et des Transport (MET) of Belgium. The mean discharge at Tabreux for the total period (1970-1996) is 1.2 mm/d

The modelling is done on a daily basis, since the discharge data are only available as daily means for the total period (1970-1996). For some flood events also hourly data are available, but since this study is about the total period, these data are not used in the models.

3.2 Meteorological data

The meteorological data, used as input for the models are delivered by the KNMI (Royal Dutch Meteorological Institute, Wójcik and Buishand (2001)). The mean precipitation for each year is 969 mm, the mean temperature is 7.3 ^{o}C and the mean potential evapotranspiration is 587 mm/year. The precipitation and evaporation data are used as input for the "simple" models and the HBV model. The temperature data is only used in the HBV model, for the simulation of snowfall and snowmelt, which is neglected in the "simple" models.

The areal computed data of the KNMI (Wójcik and Buishand, 2001) is on a 6 hourly basis, but the modelling is done on a daily basis, so daily sums have to be computed. In the study of the KNMI by Wójcik and Buishand (2001) is explained that daily rainfall at climatological stations in Belgium has always been recorded at 8:00 national time. But it is not clear, if, for instance, a value in the data of the KNMI is at the time 6:00, if this is at the time 6:00 in the morning or at 14:00, which is 6 hours after 8:00 (the time at which daily rainfall is always recorded in Belgium). To find out at what time the 6 hourly data, delivered by the KNMI, are, a small study was done. For this study the assumption was made that the daily discharge values are mean discharges, computed over a period from midnight to midnight the next day.

6-hourly data, at what time are they?
For some peak events, also hourly precipitation data from some meteorological stations are available, delivered by MET. With these data this difference in time can be cleared. The peak events of December 1993-January 1994 and January 1993 for the station Ortho (M61280015) were chosen from the data. The station Ortho is situated close to the confluence of the Ourthe Occidentale and Ourthe Orientale.

Figure 3.1 shows a plot of both data of the peak event of December 1993-January 1994, in which the time of the data of the KNMI is the same as the time of the day. So, if there is mentioned for the 6-hourly KNMI data the time 18:00 this will be the sum of the precipitation from the time 14:00 till 18:00 for the hourly precipitation, since the KNMI data is on a 6 hourly basis.

The next figure shows a plot for December 1993-January 1994 in which the time of the KNMI data is shifted 6 hours from 8:00 on. This means that if in the KNMI data stands the time 18:00 this will be 2:00 at daytime (the following day), 12:00 will be 20:00 at day time, 6:00 will be 14:00 at day time and 0:00 will be 8:00 at day time.

Comparing these two figures there can be concluded that in the second figure, with shifted data, a better fit of the trend line can be found. An interval between the data exists, since the hourly data are hourly data from a meteorological station and not for the total catchment. In appendix A the plots for the peak event in January 1993 for the meteorological station Ortho and the KNMI data are displayed.

From these figures can be concluded that a shift of the KNMI data is needed, to compare the results of the model with the discharge data on a daily basis, if the assumption that the discharge data are mean discharges, computed over a period from midnight to midnight the next day, is correct.

The KNMI data are only on a 6 hourly basis, starting at 8:00, so a shift in data cannot be made to a day from 0:00 till 0:00. For this research is chosen to use meteorological data with a shift from 2:00 till 2:00. This means that daily sums from 18:00 (the day before, which is 2:00 in real time on the day) till 18:00 (on the day, which is 2:00 in real time on the following day)) are computed from the KNMI data and used as input for the models. Daily precipitation sums, with this shift, are computed as the precipitation data. For the temperature, daily means are calculated. No shift is done for the evapotranspiration data, since these data are already divided over 6 hour periods from total daily values.

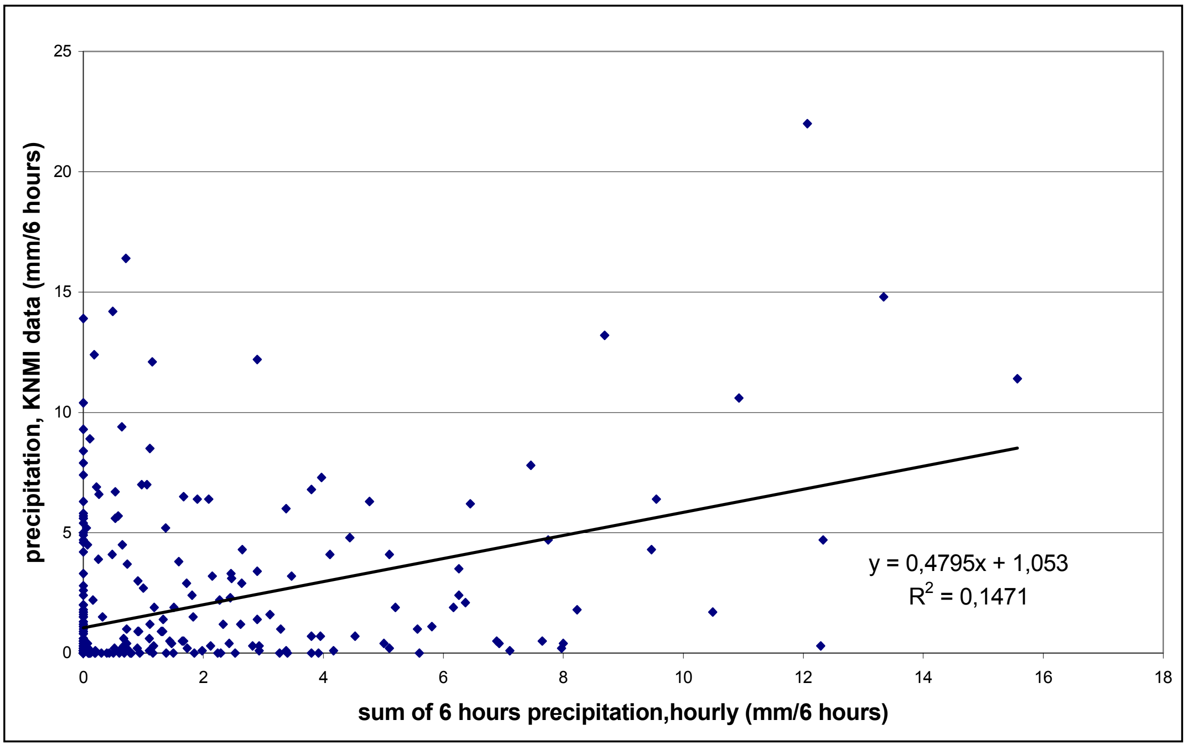


Figure 3.1 Precipitation (mm/6 hours) of the KNMI data and 6 hour sums of hourly precipitation data of the station Ortho (M61280015), for which the time 6:00 is set to 6:00 in real time

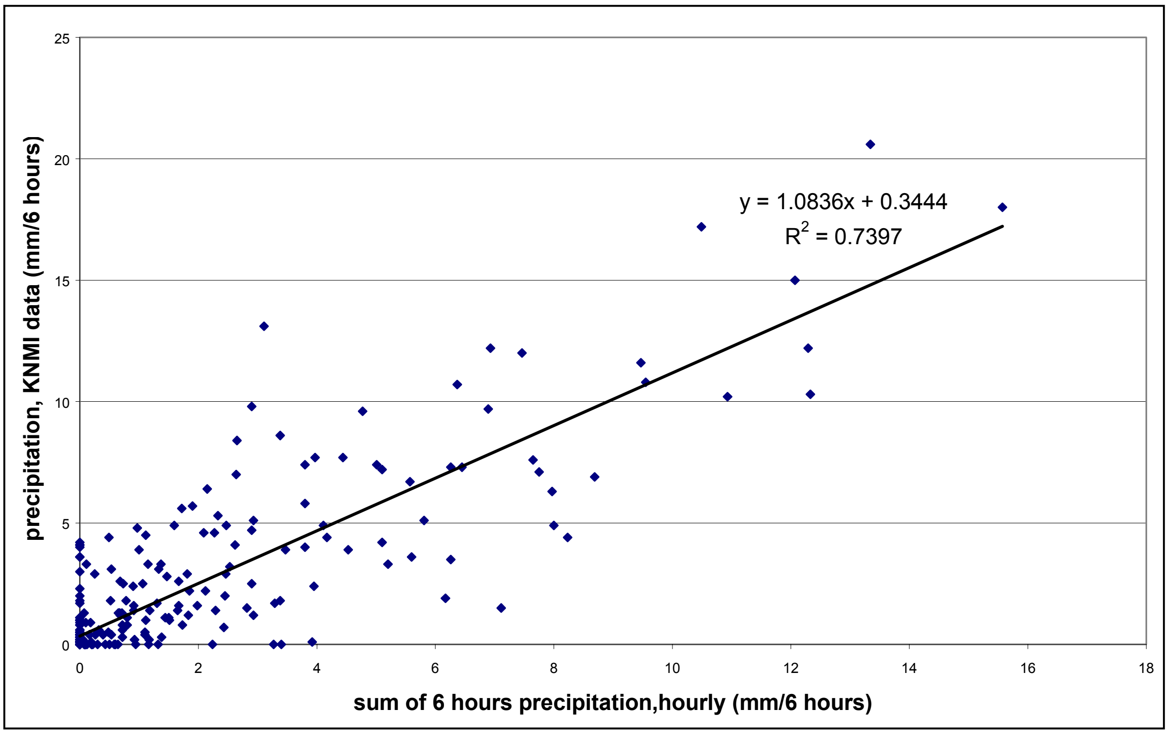


Figure 3.2 Precipitation (mm/6 hours) of the KNMI data and 6 hour sums of hourly precipitation data of the station Ortho (M61280015), for which the time 6:00 is set to 14:00 in real time, 12:00 is 20:00 in real time, 18:00 is 2:00 in real time and 0:00 is 8:00 in real time

3.3 Comparison of the input data of the KNMI and the data used in other studies

To see if differences exist between the meteorological data, delivered by the KNMI and the data used in the study's before for the Meuse catchment with the HBV model by Booij (2002) and Wal (2001), these data are compared.

Figure 3.3 shows a plot of the daily precipitation data of the KNMI, with the shift of 6 hours, and the precipitation data used before in the model studies for the Ourthe catchment for the calibration and validation period (1970-1996). The next figure shows a plot with the potential evapotranspiration data and the third figure a plot of the temperature data (shifted for the KNMI data).

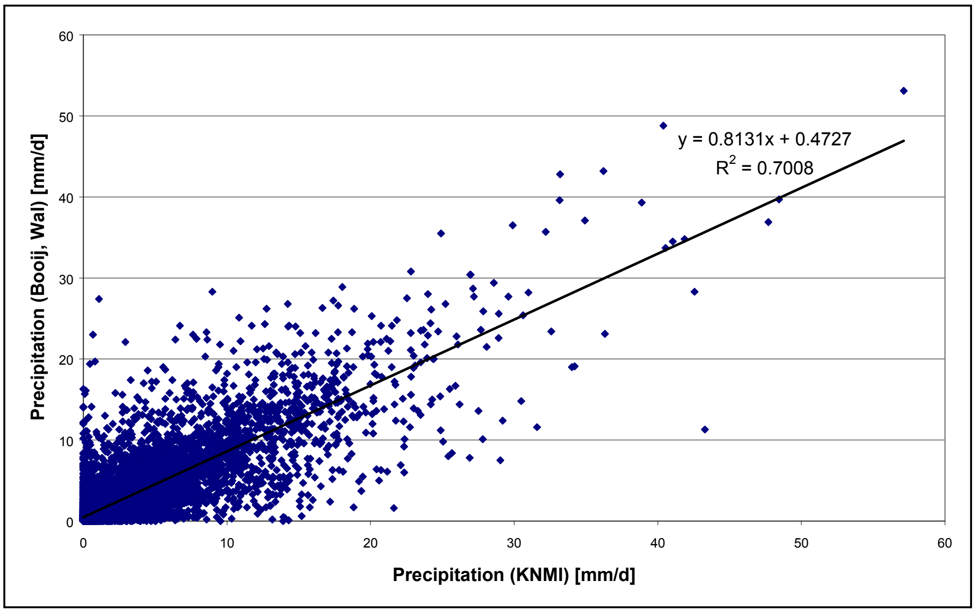


Figure 3.3 The precipitation data from the KNMI and the precipitation data used in studies before by Booij (2002) and Wal (2001) (1970-1996).

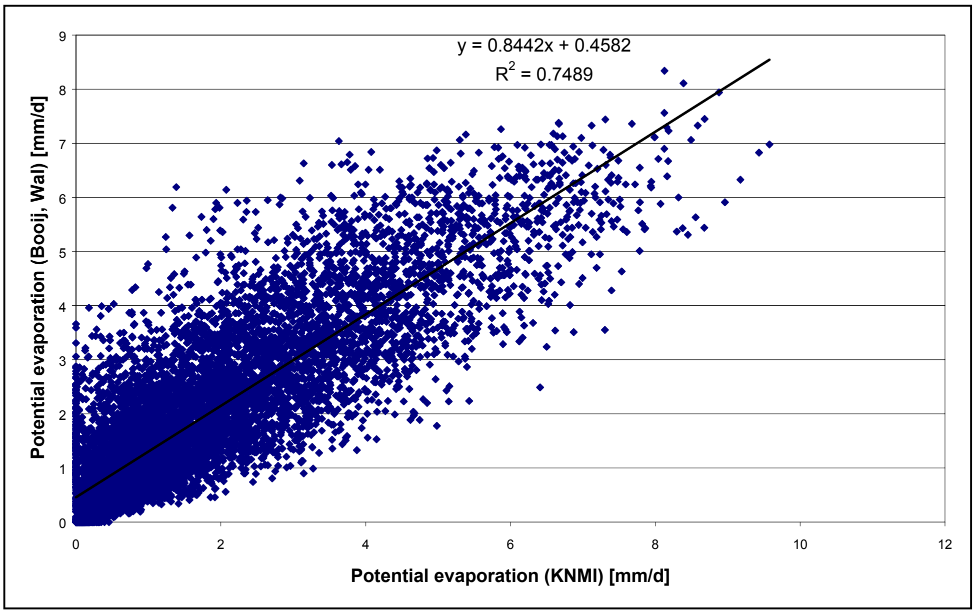


Figure 3.4 The potential evapotranspiration data from the KNMI and the potential evapotranspiration data used in studies before by Booij (2002) and Wal (2001) (1970-1996).

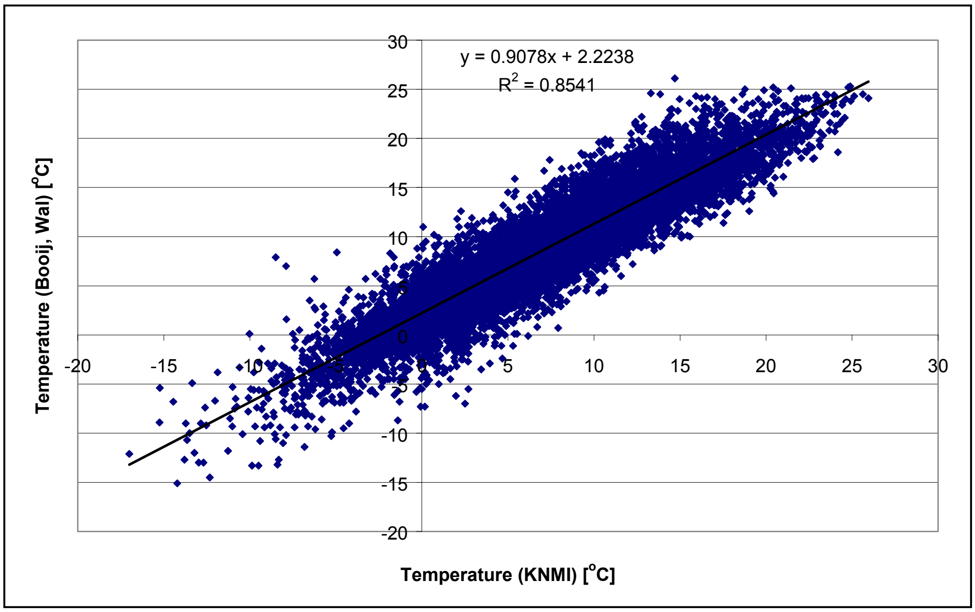


Figure 3.5 The temperature data from the KNMI and the temperature data used in studies before by Booij (2002) and Wal (2001) (1970-1996).

It can be concluded that there are differences between the input data. For the precipitation and evapotranspiration are the systematic differences small, but for the temperature data, a systematic difference of 2.2 °C can be found, as the equation of the trend lines show. The explanation for this systematic difference is the area of research. In the model studies of Booij (2002) and Wal (2001) a temperature for the total catchment of the Meuse river was used, since these studies are about the total catchment. The temperature from the KNMI data is specifically computed for the catchment of the Ourthe, inclusively the Amblève and Vesdre catchment. So these temperature data cannot be compared. The differences in precipitation data are random differences. A possible explanation is the amount of meteorological stations used for the calculation of the precipitation.

Since differences exist between the input data used in the studies of Booij (2002) and van der Wal (2001) and the KNMI data, a new calibration of the parameters in the HBV model with the KNMI data as input has to be done.

Another point of attention is, that it is not known what kind of time periods the meteorological data, used in the studies of Booij (2002) and van der Wal (2001) are based on. It could be that these daily values are also not from midnight to midnight, but from 8:00 to 8:00, like the KNMI data or a total different time period is even possible. Comparing the KNMI data, without a shift with the input data used in the studies, delivers the graphs, shown in figure 3.6 and 3.7. Since the potential evapotranspiration of the KNMI data was not shifted, the plot of the evapotranspiration will be the same as figure 3.4.

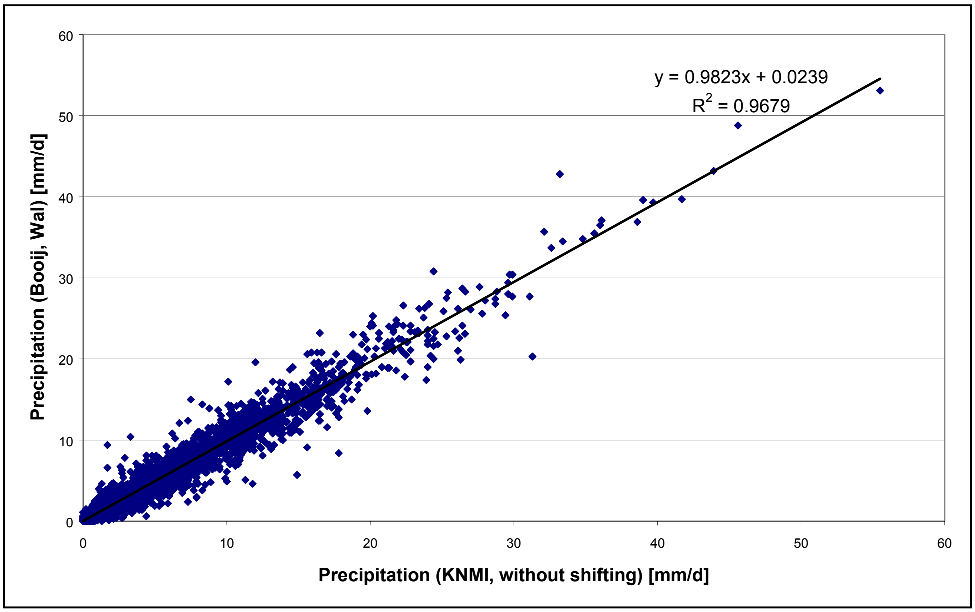


Figure 3.6 The precipitation data from the KNMI, without the shift of 8 hours, and the precipitation data used in studies before by Booij (2002) and Wal (2001) (1970-1996).

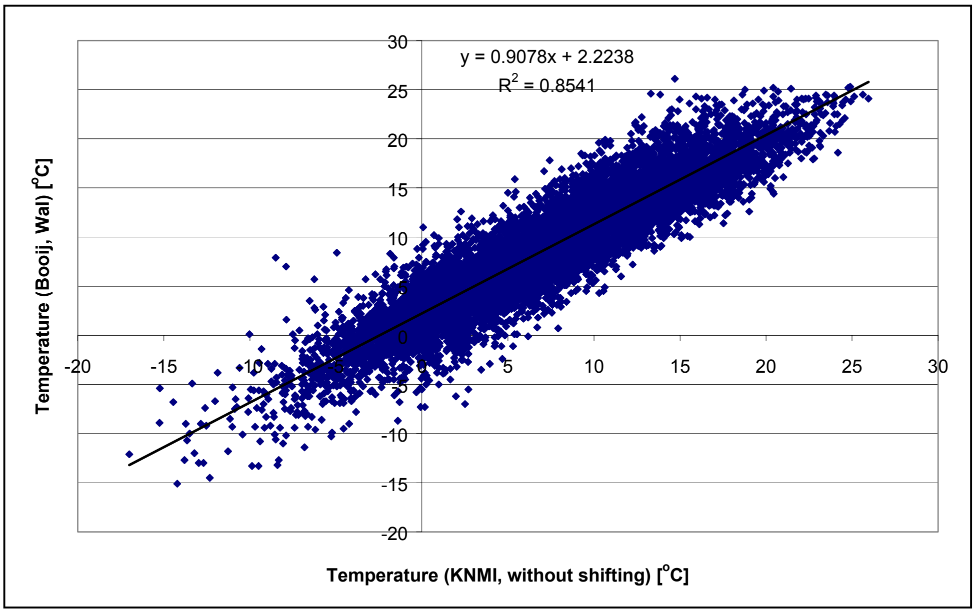


Figure 3.7 The temperature data from the KNMI, without the shift of 8 hours, and the temperature data used in studies before by Booij (2002) and Wal (2001) (1970-1996).

The trend line in figure 3.6 has a direction coefficient (0.9823). This is closer to the value one than the direction coefficient of the trend line in figure 3.3, 0.8131. The systematic difference is smaller for the not shifted data (0.0239, figure 3.6) than the shifted data (0.4727, figure 3.3). These differences can also be found for the temperature data The systematic difference between the temperature data from the KNMI and the data used in earlier studies, is very large again, 1.9 °C.

A possible conclusion from figures 3.6 and 3.7 can be that the data used in the studies before are also from 8:00 to 8:00 the next day, as for the KNMI data. But, no information on the time period of these data could be found. However it should be noticed that the interval is not known, if these data are used. For this research, the KNMI data of Wójcik an Buishand are used.

3.4 Effective precipitation

In this research several runs of the rainfall runoff models are done, in which the effective precipitation is used instead of the observed precipitation as input for the model. The effective precipitation is a kind of precipitation in which the evapotranspiration is taken into account.

The effective precipitation is calculated with the following equations over the total calibration period:

$$Peff(t) = P(t) - \varphi \cdot E_{pot}(t) \tag{3-1}$$

$$\varphi = \frac{\sum_{i=1}^{n} P - \sum_{i=1}^{n} Q_m}{\sum_{i=1}^{n} E_{pot}} \tag{3-2}$$

in which:

φ	Evapotranspiration coefficient
P	Precipitation
n	Number of days in the calibration period
Q_m	Measured discharge
E_{pot}	Potential evapotranspiration
$Peff$	Effective precipitation

The evapotranspiration coefficient represents the relation between the total actual evapotranspiration and the total potential evapotranspiration for the total calibration period. Introducing this coefficient, multiplied with the potential evapotranspiration, results into a seasonal fluctuation per year for the precipitation data. This can be seen in figure 3.8.

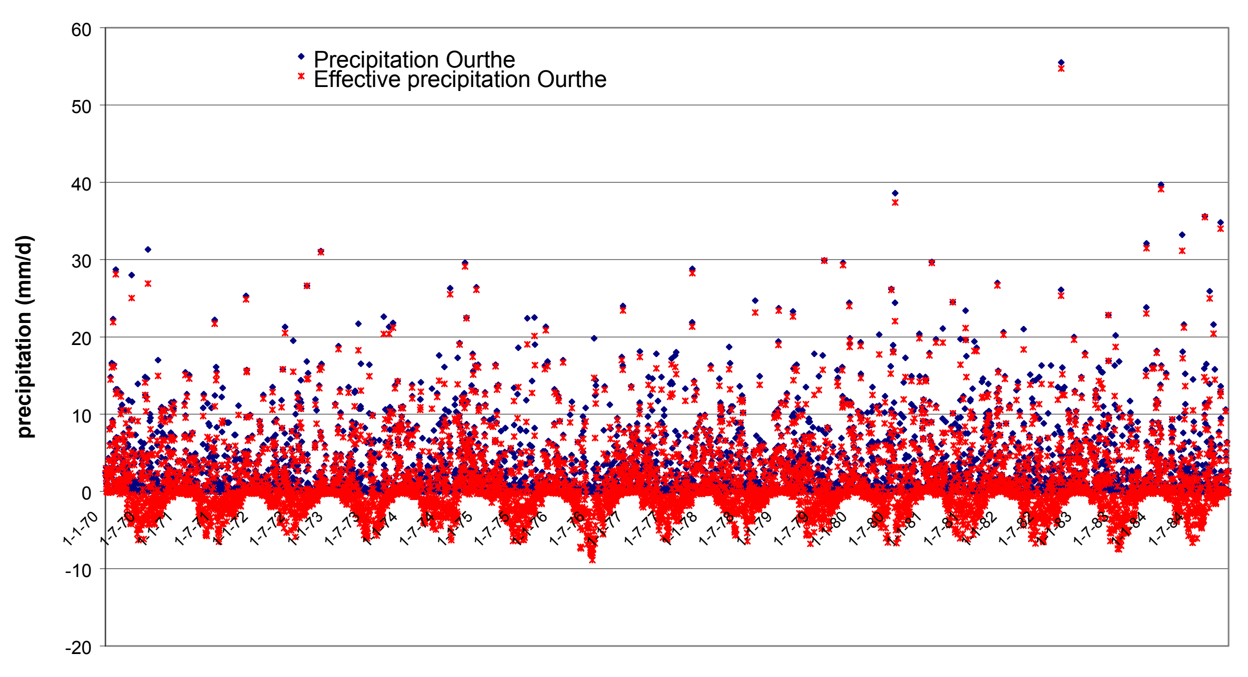


Figure 3.8 The precipitation and effective precipitation for the Ourthe catchment for the calibration period (1970-1984).

Chapter 4 Rainfall-runoff models

4.1 Introduction

Already for decades, mathematical models have become general accepted tools in hydrology. The models are nowadays used for many reasons:

- To solve a large span of problems in hydrology and water resources
- To extrapolate our knowledge of the hydrological system to extreme events
- Attempting to model long-term effects of manmade changes of the environment

There are many kinds of hydrological models and several ways to classify them. In this study, a classification by the degree of causality (Torfs (2000)) is used.

1. *Empirical/statistical models:* Only statistics are used to construct relations that form the model. These models are not constructed to give an insight in the physical causalities of the reality (black box models) and are mainly used for forecasting.
2. *Physical models:* These models are based on physical laws, like Newton's law, preservation of mass etc, representing the natural processes. This approach results in models that can be used for many kinds of research. The values of parameters and variables are physically related and can mostly be measured directly in nature.
3. *Conceptual models:* These models concentrate on the base of the hydrological system: mass balances. Many details are neglected. Generally parameters cannot be found directly through measurements. The strength of these models can be found in their limited data demand in comparison with physically based models. Many rainfall-runoff models are conceptual.

The last two groups of models can be subdivided again into two groups according to their spatial discretization:

1. *Lumped models:* In these models, all the spatial variability is being neglected. The catchment is seen as a whole. Variables and parameters represent averages.
2. *Distributed models:* In these models, the spatial variability is represented by dividing the space into grid cells or sub-catchments.

All kind of models, mixing the classifications above, exists, like semi-distributed models or physically based models with a conceptual focus.

What kind of model is being used in a research depends on the data available and its application.
It cannot be stated that physically based models should always be preferred to conceptual models. However, physically based models are often thought to be more reliable, because of their more realistic representation of the catchment processes. Since all three kinds of models have their advantages and disadvantages its better not to focus on what kind of model to be used, but on which processes should be incorporated and how to represent these processes formulated in the model.

As described in chapter 1, in this study, a simple model will be build out towards the HBV model. In the next section, descriptions of the "simple" rainfall-runoff model approaches which have been built for this study will be given. The model calculations are done in excel, except for the HBV model. Also the calibration and validation are being discussed in this chapter in section 4.3. In chapter 6 the description of the HBV model follows, together with the results.

4.2 The Simple model approaches

The so called “simple” model approaches, will be described in the next sections. They can be classified as lumped conceptual models. However, the models have increasing complexity and number of parameters. For all models is a simulation with precipitation and a simulation with effective precipitation as input done.

All the equations will be formulated discrete in time.

4.2.1 Constant runoff model

In this very simple “model”, the discharge is supposed to be constant.

$$Q(t) = a \tag{4-1}$$

$Q(t)$	Discharge at time t [mm/d]
a	Constant value (mm/d)

The mean discharge of the calibration period will be used as the constant value (both for the calibration and validation period) and can be seen as the starting point or reference model for the other “simple” models.

4.2.2 Linear rainfall-runoff model

In this model is the discharge computed as a linear function of the amount of precipitation during a time period (T) of x+1 days.

$$Q(t) = \alpha + \beta \cdot \left[\frac{P(t) + P(t-1) + \ldots + P(t-x)}{x+1} \right] \tag{4-2}$$

$Q(t)$	Discharge at time t [mm/d]
$P(t)$	Precipitation [mm/d]
α, β	Parameters [-]

If the effective precipitation is used as input for this model, instead of the total precipitation, the following restriction is needed:

if $\alpha + \beta \cdot \left[\frac{Peff(t) + Peff(t-1) + \ldots + Peff(t-x)}{x+1} \right] < 0$; $Q(t) = a$ (4-3)

if $\alpha + \beta \cdot \left[\frac{Peff(t) + Peff(t-1) + \ldots + Peff(t-x)}{x+1} \right] > 0$;

$$Q(t) = \alpha + \beta \cdot \left[\frac{Peff(t) + Peff(t-1) + \ldots + Peff(t-x)}{x+1} \right]$$

$Peff$ Effective precipitation (mm/d)

4.2.3 Non-linear rainfall-runoff model

This model uses a non-linear function for the calculation of the discharge of the following form:

$$Q(t) = \alpha + \beta \cdot \left[\frac{P(t) + P(t-1) + ... + P(t-x)}{x+1} \right] + e^{-\lambda \left[\frac{P(t)+P(t-1)+...+P(t-x)}{x+1} \right]} \qquad (4\text{-}4)$$

$P(t)$ Precipitation during time t [mm/d]

α, β, λ Parameters [-]

4.2.4 Linear rainfall runoff model, with one reservoir

In this model, the discharge is not only a direct linear function of the precipitation in the same period, but also of the outflow of a linear reservoir fed by rainfall. Such a linear reservoir can be thought as representing for instance an aquifer generating baseflow. The discharge is computed using the following equation:

$$Q(t) = \alpha + \beta \cdot P(t) + R_{out}(t) \qquad (4\text{-}5)$$

$R_{out}(t)$	Discharge from the reservoir, during time t [mm/d]
α, β	Parameters [-]
t	period of time [days]

A short explanation of the linear reservoir will be given in the next section, followed by an overview of the restrictions needed in this model.

Linear reservoir

A linear reservoir is based on the mass balance. Figure 4.1 shows a schematic view of a linear reservoir.

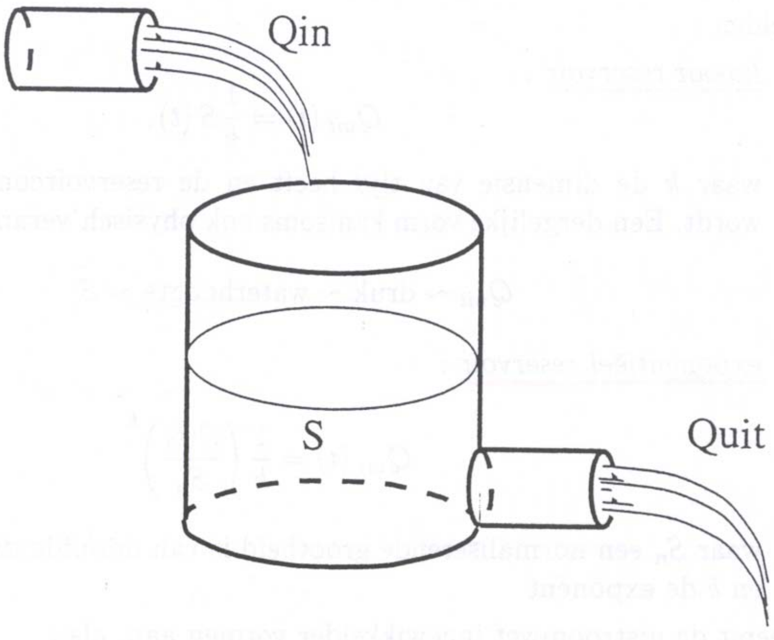


Figure 4.1 Linear reservoir (source: Torfs, 2000)

The mass balance for the reservoir can be formulated as:

$$\frac{dS}{dt}(t) = R_{in}(t) - R_{out}(t) \tag{4-6}$$

$$S(t) = S(t-1) + R_{in}(t) - R_{out}(t) \tag{4-7}$$

$S(t)$	Content of the reservoir at time t [mm]
$S(t-1)$	Content of the reservoir at the end of the period of time before [mm]
$R_{in}(t)$	Inflow of the reservoir during the period of time t [mm/d]
$R_{out}(t)$	Outflow of the reservoir during the period of time t [mm/d]
t	period of time [days]

To solve equation 4-7 a second equation is needed, since S and R_{out} are both unknown. For a linear reservoir, this second equation is given by:

$$R_{out}(t) = \frac{1}{k} \cdot S(t-1) \tag{4-8}$$

k	Reservoir coefficient [days]

A high reservoir coefficient means that the reservoir has a small opening. This small opening causes a very slow outflow of the reservoir.

The inflow of the reservoir can be described with the following equation:

$$R_{in}(t) = \gamma \cdot P(t) \tag{4-9}$$

γ	Parameter [-]

If the inflow is zero, the outflow of the reservoir will be given by the following equation:

$$R_{out}(t + t_0) = R_{out}(t_0) \cdot e^{-\frac{t}{k}} \tag{4-10}$$

Restrictions
In order to keep all computed discharges positive, some restrictions are needed, as given by the following algorithm:

```
if $\alpha + \beta \cdot Peff(t) + R_{out}(t) \geq 0$ ; $Q(t) = \alpha + \beta \cdot Peff(t) + R_{out}(t)$        (4-11)
if $\alpha + \beta \cdot Peff(t) + R_{out}(t) < 0$ ;
        if $\frac{1}{k} \cdot S(t-1) \geq 0$ ; $Q(t) = R_{out}(t) = \underset{1}{\frac{1}{\,}} \cdot S(t-1)$
        if $\frac{1}{k} \cdot S(t-1) < 0$ ;
                if $R_{out}(t) + \alpha \geq 0$; $Q(t) = R_{out}(t) + \alpha = \frac{1}{k} \cdot S(t-1) + \alpha$
                if $R_{out}(t) + \alpha < 0$; $Q(t) = 0$
```

For a positive content of the reservoir the following restriction is implemented:

$$\begin{aligned}&\text{if } S(t-1)+R_{in}(t)-R_{out}(t)\geq 0\,;\; S(t)=S(t-1)+R_{in}(t)-R_{out}(t) \\ &\text{if } S(t-1)+R_{in}(t)-R_{out}(t)<0\,;\; S(t)=0\end{aligned} \tag{4-12}$$

If the effective precipitation ($P(t)=Peff(t)$) is used as input for the model, another restriction is needed in the model for the calculation of the inflow of the reservoir:

$$\begin{aligned}&\text{if } Peff(t)\geq 0\,;\; R_{in}(t)=\gamma\cdot Peff(t) \\ &\text{if } Peff(t)<0\,;\; R_{in}(t)=0\end{aligned} \tag{4-13}$$

4.2.5 Linear rainfall runoff model, with two reservoirs

The linear rainfall runoff model with two reservoirs is almost the same as the model described in section 4.2.4. The only difference is that a second linear reservoir is added parallel to the other reservoir. One may think of the first reservoir describing the fast runoff, the second reservoir the baseflow. The following equation describes the model:

$$Q(t)=\alpha+\beta\cdot P(t)+R_{1,out}(t)+R_{2,out}(t) \tag{4-14}$$

$R_{1,out}(t)$	Discharge from reservoir 1 during time t
$R_{2,out}(t)$	Discharge from reservoir 2 during time t

Linear reservoirs

The equations of the linear reservoir, as described in section 4.2.4.1 are used for both reservoirs and can be written as:

$$S_i(t)=S_i(t-1)+R_{i,in}(t)-R_{i,out}(t) \tag{4-15}$$

$$R_{i.out}(t)=\frac{1}{k_i}\cdot S_i(t-1) \tag{4-16}$$

i	The number of the reservoir, in this study reservoir 1 or reservoir 2
$S_i(t-1)$	Reservoir content of reservoir i, at the end of the period of time before (the day before, in this study) (mm)
k_i	Reservoir coefficient of reservoir i (days)

The inflow of the reservoirs during time t can be described as:

$$R_{1,in}(t)=\gamma\cdot P(t) \tag{4-17}$$

for reservoir 1, respectively as:

$$R_{2,in}(t)=\delta\cdot P(t) \tag{4-18}$$

for reservoir 2, in which γ and δ are parameters

Restrictions

Again, to keep important hydrological variables positive, some restrictions are implemented.

For the calculation of the discharge:

$$\text{if } \alpha + \beta \cdot Peff(t) + R_{1,out}(t) + R_{2,out}(t) \geq 0 \;;\; Q(t) = \alpha + \beta \cdot P(t) + R_{1,out}(t) + R_{2,out}(t) \tag{4-19}$$

$$\begin{aligned}
&\text{if } \alpha + \beta \cdot Peff(t) + R_{1,out}(t) + R_{2,out}(t) < 0 \;; \\
&\qquad \text{if } R_{1,out}(t) + R_{2,out}(t) \geq 0 \,; Q(t) = R_{1,out}(t) + R_{2,out}(t) = \frac{1}{k_1} \cdot S_1(t-1) + \frac{1}{k_2} \cdot S_2(t-1) \\
&\qquad\qquad \text{if } R_{1,out}(t) + R_{2,out}(t) < 0 \,; \\
&\qquad\qquad\qquad \text{if } R_{1,out}(t) + R_{2,out}(t) + \alpha \geq 0 \,; \\
&\qquad\qquad\qquad\quad Q(t) = R_{1,out}(t) + R_{2,out}(t) + \alpha = \frac{1}{k_1} \cdot S_1(t-1) + \frac{1}{k_2} \cdot S_2(t-1) + \alpha \\
&\qquad\qquad\qquad \text{if } R_{1,out}(t) + R_{2,out}(t) + \alpha < 0 \,;\; Q(t) = 0
\end{aligned}$$

For the positive reservoir content:

$$\text{if } S_i(t-1) + R_{i,in}(t) - R_{i,out}(t) \geq 0 \,;\; S_i(t) = S_i(t-1) + R_{i,in}(t) - R_{i,out}(t) \tag{4-20}$$

$$\text{if } S_i(t-1) + R_{i,in}(t) - R_{i,out}(t) < 0 \;;\; S_i(t) = 0$$

If the effective precipitation is used as an input for the model, the following restrictions are used:

$$\text{if } Peff(t) \geq 0 \,;\; R_{i,in}(t) = Peff(t) \tag{4-21}$$

$$\text{if } Peff(t) < 0 \,;\; R_{i,in}(t) = 0$$

4.2.6 Linear rainfall-runoff model with two reservoirs and evapotranspiration

In this model an evapotranspiration calculation is added, resulting in a calculated effective precipitation.

Here, different from the effective precipitation described in section 3.4, values for actual evaporation are monthly averaged instead for each year.

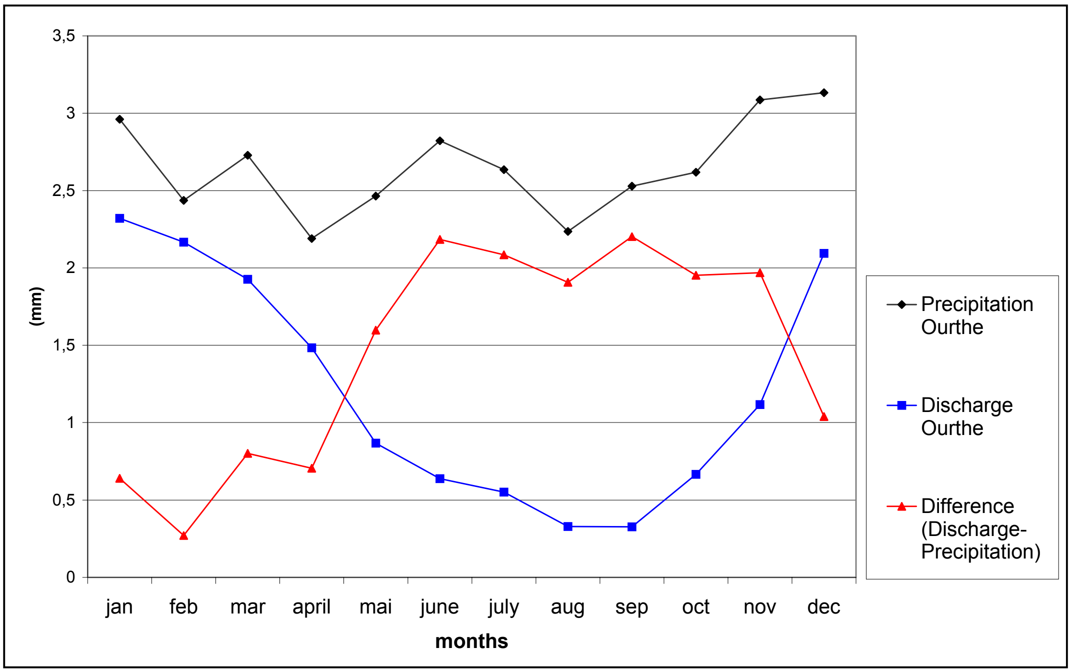


Figure 4.2 The mean daily precipitation, mean daily discharge and difference between mean daily precipitation and mean daily discharge per month for the Ourthe (1970-1996).

As can be seen from figure 4.2, the difference between the mean daily precipitation and mean daily discharge, averaged for each month, mainly caused by evapotranspiration, is not the same for each month. The temperature has a large influence on this process. Figure 4.2 shows a larger difference for the months June till November than for the months in winter and spring (December-Mai).

The following equations are used (a concrete example of a calculation follows):

$$\overline{E_{act}}(m) = \overline{P}(m) - \overline{Q}(m) \tag{4-22}$$

m	Month
$\overline{E_{act}}(m)$	Mean daily actual evapotranspiration per month m (mm/d)
$\overline{P}(m)$	Mean daily precipitation per month m (mm/d)
$\overline{Q}(m)$	Mean daily discharge per month m (mm/d)

In this study these values are computed over the calculation period.

With equation 4-34 a mean daily actual evapotranspiration per month is calculated.

In the first run, the effective precipitation for each day, will be calculated, with the following equation:

$$Peffm(t) = P(t) - \overline{E_{act}}(m(t)) \tag{4-23}$$

in which:

$Peffm(t)$	Effective precipitation at time t calculated with the mean daily actual evapotranspiration for month m at time t (mm/d)
$\overline{E_{act}}(m(t))$	Mean daily actual evapotranspiration for month m in which time t is (mm/d)

In this run equation 4-14 of the linear rainfall-runoff model with two reservoirs will be used with all restrictions, with $Peffm(t)$ instead of $P(t)$.

As an example for the calculation of $Peffm(t)$, the effective precipitation used as input for the model for the 17th January in a certain year will be calculated.

17th January

The month in which this date falls is January so m =January and equation 4-23 can be written as:

$$Peffm(17\,jan) = P(17\,jan) - \overline{E_{act}}(jan)$$

$P(17\,jan)$ means the precipitation fallen at the 17th of January, for example 2 mm.

For the calculation of $\overline{E_{act}}(jan)$, the mean daily actual evapotranspiration of the month January has to be calculated with equation 4-22 :

$$\overline{E_{act}}(jan) = \overline{P}(jan) - \overline{Q}(jan)$$

$\overline{P}(jan)$ is calculated with the sum of all the precipitation values for each day in the month January over several years and dividing this sum by the amount of total days in the month January multiplied with the amount of years. In this study, the calibration period (1970-1984) counts 15 years, so the sum of all the precipitation data of the month January is calculated (1285.2mm) and divided by 15x31=465 days. This delivers a value of 2.764 mm/d for $\overline{P}(jan)$.

The same calculation is done for the discharge. The total sum of the discharges of the month January is: 874.2 mm.

$\overline{Q}(jan)$ =1.880 mm/d.

$\overline{E_{act}}(jan) = 2.764 - 1.880 = 0.884$ mm/d

The effective precipitation on the 17th of January can now be calculated:

$Peffm(17\,jan) = P(17\,jan) - \overline{E_{act}}(jan) = 2 - 0.884 = 1.116$ mm

In the second run, more based on the effective precipitation, as used before in the other models, the following equations are used:

$$Peffm(t) = P(t) - \varphi(m(t)) \cdot E_{pot}(t) \tag{4-24}$$

$$\varphi(m(t)) = \frac{\overline{E_{act}}(m(t))}{\overline{E_{pot}}(m(t))} = \frac{\overline{P}(m(t)) - \overline{Q}(m(t))}{\overline{E_{pot}}(m(t))} \tag{4-25}$$

$\overline{E_{pot}}(m(t))$ Mean daily potential evapotranspiration for month m in which time t is (mm/d)

$\varphi(m(t))$ Mean monthly evapotranspiration coefficient for month m in which time t is (-)

In this run, the effective precipitation $Peffm(t)$ will be used in the equations and restrictions of the linear rainfall-runoff model with two reservoirs instead of the $Peff(t)$ and $P(t)$.

The calculation for the 17th January, used as example, can be found in the next box.

17th January

The equation for the computation of the effective precipitation at the 17th January with the second run is:

$$Peffm(17jan) = P(17jan) - \varphi(jan(17jan)) \cdot E_{pot}(17jan)$$

in which:

$$\varphi(jan(17jan)) = \frac{\overline{E_{act}}(jan(17jan))}{\overline{E_{pot}}(jan(17jan))} = \frac{\overline{P}(jan(17jan)) - \overline{Q}(jan(17jan))}{\overline{E_{pot}}(jan(17jan))}$$

$\overline{E_{act}}(jan(17jan))$ is already calculated and has a value of 0.884 mm/d. The $\overline{E_{pot}}(jan(17jan))$ is calculated in the same way as for the precipitation and discharge before.

The total sum of the potential evapotranspiration for the month January for the total calibration period is 96.4mm. Dividing this by the total amount of days (465), delivers a $\overline{E_{pot}}(jan) = 0.2051$.

The evapotranspiration coefficient can now be calculated:

$$\varphi(m(t)) = \frac{\overline{E_{act}}(m(t))}{\overline{E_{pot}}(m(t))} = \frac{0.884}{0.2051} = 4.3099$$

If the potential evapotranspiration at the 17th January is, for instance, 0.3mm, the effective precipitation for the 17th of January is:

$Peffm(17jan) = 2 - 4.3099 \cdot 0.3 = 0.7880$

4.3 Model calibration and validation

To asses the parameters for each model, a calibration was performed. Calibration can be defined as: "the process whereby some parameters of the model are adjusted to make the model output match the observations" (Bergström, 1991).
Three criteria of goodness of fit are used:

- Nash-Sutcliffe efficiency coefficient R^2 (Nash and Sutcliffe, 1970):

$$R^2 = \left(1 - \frac{\sum_{i=1}^{n} (Q_{s,i} - Q_{m,i})}{\sum_{i=1}^{n} (Q_{m,i} - \overline{Q}_m)} \right) \tag{4-26}$$

- Relative difference in total discharge RD_Q:

$$RD_Q = \frac{\sum_{i=1}^{n} \left(Q_{s,i} - Q_{m,i} \right)}{\sum_{i=1}^{n} Q_{m,i}} \cdot 100\% \tag{4-27}$$

- Visual inspection of the hydrograph

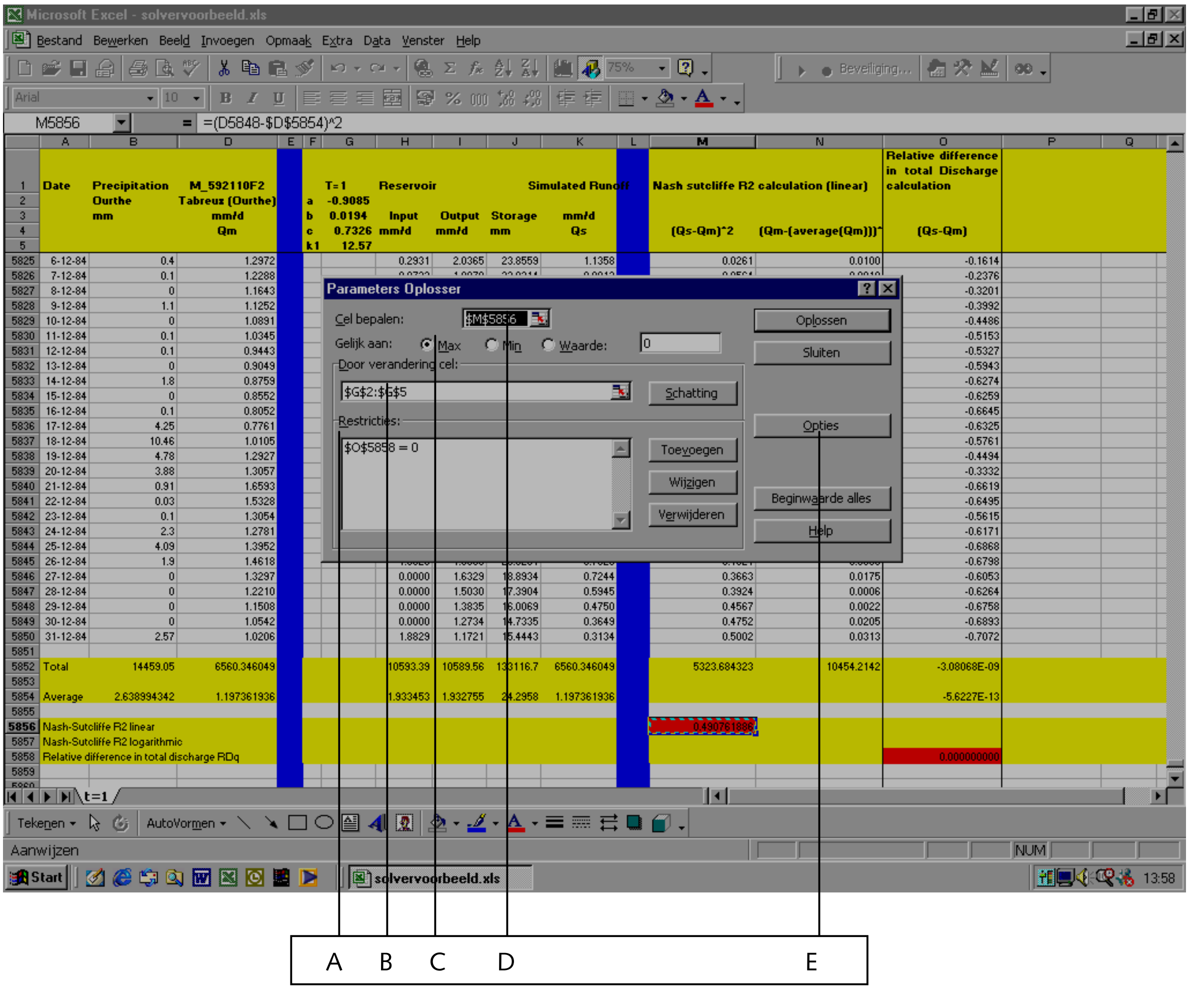
Where Q expresses the discharge, with s indicates simulation, m measured, i is the time step and n the total number of time steps.
The value of the efficiency coefficient R^2 can range from minus infinity to 1. A negative value indicates that the model produces worse than using the mean observed value, an efficiency of 1 indicates that the model results are exactly equal to the observations.

Although less objective, also the visual inspection of the hydrograph can play an important role in the calibration process. The hydrograph can show for example the correspondence between peaks, if there is enough baseflow, if the timing of the peak events is correct and whether the recession is satisfactory.

For the "peak" simulations, in which the measured discharges with a discharge exceeding a threshold of 2 mm/d ("peaks") are emphasized, the Nash-sutcliffe calibration criterium is used twice. An extra Nash-Sutcliffe efficiency, in which the values for the efficiency coefficient count twice for a measured discharge, higher than 2 mm/d, is computed. In the optimalisation is tried to find the highest value for this efficiency computation. After achieving this, the Nash-Sutcliffe efficiency was calculated, following the original method with these parameters.

The calibration procedure for all the models, except for the HBV model, is done with the "solver function"-tool in Microsoft Excel. This function uses the Generalized Reduced Gradient (GRG2) non linearity optimalization code and can be found under the "extra" menu of Excel.
A short description of this tool follows.

Figure 4.3 shows the menu of the solver function. D is the place where the cell for the calculation can be selected. At C a selection is possible for the type of problem: a maximum, a minimum or a certain value. At B the cells which are allowed to change (representing parameters to be fitted) can be selected and at A extra restrictions can be selected.



M5856 = =(D5848-$D$5854)^2

	A	B	D	F	G	H	I	J	K	M	N	O
1	Date	Precipitation	M_592110F2		T=1	Reservoir			Simulated Runoff	Nash sutcliffe R2 calculation (linear)		Relative difference in total Discharge calculation
2		Ourthe	Tabreux (Ourthe)	a	-0.9085							
3		mm	mm/d	b	0.0194	Input	Output	Storage	mm/d			
4			Qm	c	0.7326	mm/d	mm/d	mm	Qs	(Qs-Qm)^2	(Qm-(average(Qm)))^	(Qs-Qm)
5				k1	12.57							
5825	6-12-84	0.4	1.2972			0.2931	2.0365	23.8559	1.1358	0.0261	0.0100	-0.1614
5826	7-12-84	0.1	1.2288									-0.2376
5827	8-12-84	0	1.1643									-0.3201
5828	9-12-84	1.1	1.1252									-0.3992
5829	10-12-84	0	1.0891									-0.4486
5830	11-12-84	0.1	1.0345									-0.5153
5831	12-12-84	0.1	0.9443									-0.5327
5832	13-12-84	0	0.9049									-0.5943
5833	14-12-84	1.8	0.8759									-0.6274
5834	15-12-84	0	0.8552									-0.6259
5835	16-12-84	0.1	0.8052									-0.6645
5836	17-12-84	4.25	0.7761									-0.6325
5837	18-12-84	10.46	1.0105									-0.5761
5838	19-12-84	4.78	1.2927									-0.4494
5839	20-12-84	3.88	1.3057									-0.3332
5840	21-12-84	0.91	1.6593									-0.6619
5841	22-12-84	0.03	1.5328									-0.6495
5842	23-12-84	0.1	1.3054									-0.5615
5843	24-12-84	2.3	1.2781									-0.6171
5844	25-12-84	4.09	1.3952									-0.6868
5845	26-12-84	1.9	1.4618									-0.6798
5846	27-12-84	0	1.3297			0.0000	1.6329	18.8934	0.7244	0.3663	0.0175	-0.6053
5847	28-12-84	0	1.2210			0.0000	1.5030	17.3904	0.5945	0.3924	0.0006	-0.6264
5848	29-12-84	0	1.1508			0.0000	1.3835	16.0069	0.4750	0.4567	0.0022	-0.6758
5849	30-12-84	0	1.0542			0.0000	1.2734	14.7335	0.3649	0.4752	0.0205	-0.6893
5850	31-12-84	2.57	1.0206			1.8829	1.1721	15.4443	0.3134	0.5002	0.0313	-0.7072
5851												
5852	Total	14459.05	6560.346049			10593.39	10589.56	133116.7	6560.346049	5323.684323	10454.2142	-3.08068E-09
5853												
5854	Average	2.638994342	1.197361936			1.933453	1.932755	24.2958	1.197361936			-5.6227E-13
5855												
5856	Nash-Sutcliffe R2 linear									0.490761886		
5857	Nash-Sutcliffe R2 logarithmic											
5858	Relative difference in total discharge RDq											0.000000000
5859												

Parameters Oplosser

Cel bepalen: $M$5856

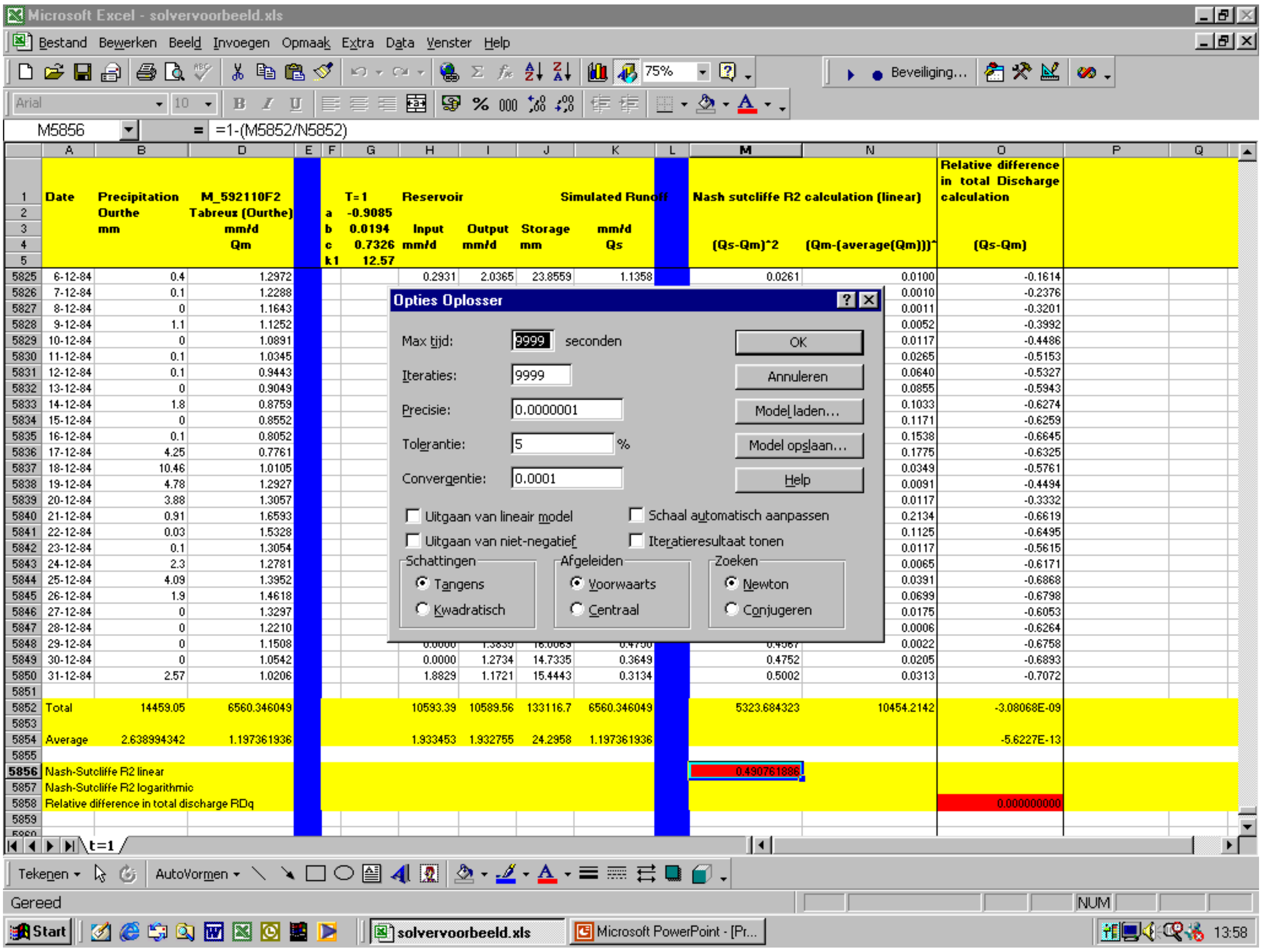
Gelijk aan: ● Max ○ Min ○ Waarde: 0

Door verandering cel: $G$2:$G$5

Restricties: $O$5858 = 0

Figure 4.3 The solver function in Microsoft Excel

For the models of this study there was always the restriction that the value of relative difference in total discharge (RDq) had to be close to 0. The problem formulated was to maximize the value for R^2 by changing the parameters $\alpha,\beta,\gamma,\delta,k_1,k_2$ (depending on the used model). At E more options for the solver function can be adjusted. By clicking on this function the screen as in figure 4.4 appears.



M5856 = =1-(M5852/N5852)

T=1
a -0.9085
b 0.0194
c 0.7326
k1 12.57

	Date	Precipitation Ourthe mm	M_592110F2 Tabreux (Ourthe) mm/d Qm	Reservoir Input mm/d	Output mm/d	Storage mm	Simulated Runoff mm/d Qs	Nash sutcliffe R2 calculation (linear) (Qs-Qm)^2	(Qm-(average(Qm)))^	Relative difference in total Discharge calculation (Qs-Qm)
5825	6-12-84	0.4	1.2972	0.2931	2.0365	23.8559	1.1358	0.0261	0.0100	-0.1614
5826	7-12-84	0.1	1.2288						0.0010	-0.2376
5827	8-12-84	0	1.1643						0.0011	-0.3201
5828	9-12-84	1.1	1.1252						0.0052	-0.3992
5829	10-12-84	0	1.0891						0.0117	-0.4486
5830	11-12-84	0.1	1.0345						0.0265	-0.5153
5831	12-12-84	0.1	0.9443						0.0640	-0.5327
5832	13-12-84	0	0.9049						0.0855	-0.5943
5833	14-12-84	1.8	0.8759						0.1033	-0.6274
5834	15-12-84	0	0.8552						0.1171	-0.6259
5835	16-12-84	0.1	0.8052						0.1538	-0.6645
5836	17-12-84	4.25	0.7761						0.1775	-0.6325
5837	18-12-84	10.46	1.0105						0.0349	-0.5761
5838	19-12-84	4.78	1.2927						0.0091	-0.4494
5839	20-12-84	3.88	1.3057						0.0117	-0.3332
5840	21-12-84	0.91	1.6593						0.2134	-0.6619
5841	22-12-84	0.03	1.5328						0.1125	-0.6495
5842	23-12-84	0.1	1.3054						0.0117	-0.5615
5843	24-12-84	2.3	1.2781						0.0065	-0.6171
5844	25-12-84	4.09	1.3952						0.0391	-0.6868
5845	26-12-84	1.9	1.4618						0.0699	-0.6798
5846	27-12-84	0	1.3297						0.0175	-0.6053
5847	28-12-84	0	1.2210						0.0006	-0.6264
5848	29-12-84	0	1.1508						0.0022	-0.6758
5849	30-12-84	0	1.0542	0.0000	1.2734	14.7335	0.3649	0.4752	0.0205	-0.6893
5850	31-12-84	2.57	1.0206	1.8829	1.1721	15.4443	0.3134	0.5002	0.0313	-0.7072
5851										
5852	Total	14459.05	6560.346049	10593.39	10589.56	133116.7	6560.346049	5323.684323	10454.2142	-3.08068E-09
5853										
5854	Average	2.638994342	1.197361936	1.933453	1.932755	24.2958	1.197361936			-5.6227E-13
5855										
5856	Nash-Sutcliffe R2 linear							0.490761886		
5857	Nash-Sutcliffe R2 logarithmic									
5858	Relative difference in total discharge RDq									0.000000000
5859										

Opties Oplosser

Max tijd: 9999 seconden
Iteraties: 9999
Precisie: 0.0000001
Tolerantie: 5 %
Convergentie: 0.0001

☐ Uitgaan van lineair model
☐ Schaal automatisch aanpassen
☐ Uitgaan van niet-negatief
☐ Iteratieresultaat tonen

Schattingen
● Tangens
○ Kwadratisch

Afgeleiden
● Voorwaarts
○ Centraal

Zoeken
● Newton
○ Conjugeren

Figure 4.4 The options of the solver function in Microsoft excel

In the first field a value for the maximum time in seconds as limit for the solving time can be given. The second field is the maximum number of iterations. The third field contains the desired size of precision (the smaller the value, the better the precision). In the last field the convergence criterion can be filled in. This is the relative change in the last five iterations before a solution is given. If the convergence is small, the changes between the results of the last five iterations have to be small.

Model validation

To test the calibrated model an independent period is chosen to check the model performance by simulation of a new period. This period is called the validation period and the process the validation.

If the model performance for this independent period is significantly lower than it was for the calibration period, there is a strong indication of overparameterization. This means that the model may have too many degrees of freedom for the information contained in the observed records. This leaves the modeller with two options, model simplification or improvement of the control data base (Bergström, 1991).

Chapter 5 Model application and results

In this chapter the results of all the simulations of the “simple” models will be shown and discussed. As explained in chapter 1 there are two time periods used in this research, the calibration period, from 1970 to 1984 and the validation period, from 1985 to 1996. The results will be shown for each model. In chapter 7, a summary and interpretation of all results can be found.

5.1 Constant runoff model

The constant runoff model is a very simple model, in which the discharge is supposed to be constant ($Q(t)=a$). As value for the constant discharge, the average discharge of the calibration period is taken for the calibration and the validation period. The precipitation in the catchment is not taken into account in this model.

5.1.1 Calibration period

The mean discharge for the Ourthe at Tabreux for the calibration period is 1.197 mm/d. With the equation of the model:

$$Q(t)=a \tag{4-1}$$

in which:

$Q(t)$	Discharge at time t (mm/d)
a	Constant value (mm/d)

The constant a has the value of the average discharge for the calibration period (1970-1984), so the simulated discharge is 1.197 mm/d at each time t.

Figure 5.1 shows the hydrograph of the measured and the constant mean discharge for the calibration period.

The measured discharge shows some very dry years. Especially the year 1977, which had a very long dry period during summer. Also some extreme events can be seen in the measured discharge, like the event in February 1984, with a maximum of 14.6 mm/d.

Since the simulated discharge is constant, no peaks and low flows are simulated. Using the average discharge as the constant value of this model, means that the efficiency coefficient (R^2) and the relative difference in total discharge (RD_Q) both have a value of zero, since these calibration criteria are based on the average measured discharge.

5.1.2 Validation period

For the validation period (1985-1996) the simulated discharge, the constant a has the same value, a=1.197 mm/d.

Figure 5.2 shows the hydrographs of the measured and simulated discharge for the validation period.

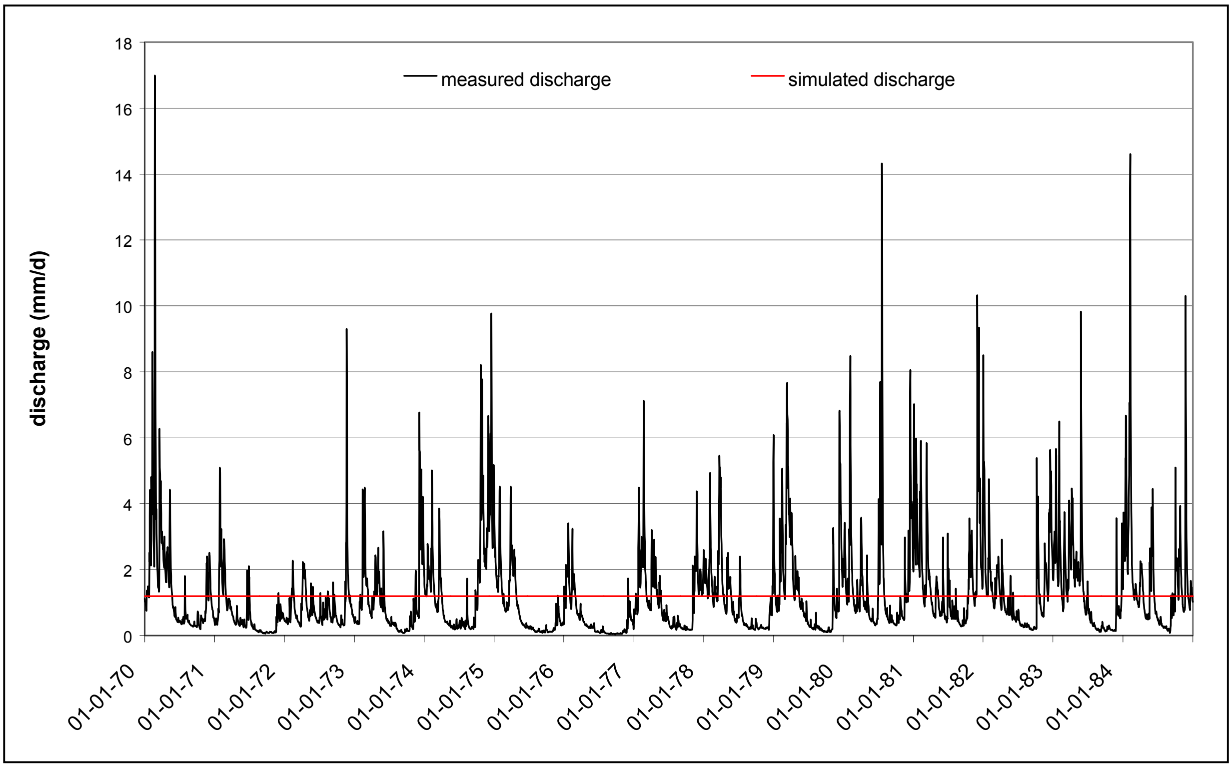


Figure 5.1 Hydrograph of the measured and simulated discharge with the constant runoff model for the calibration period

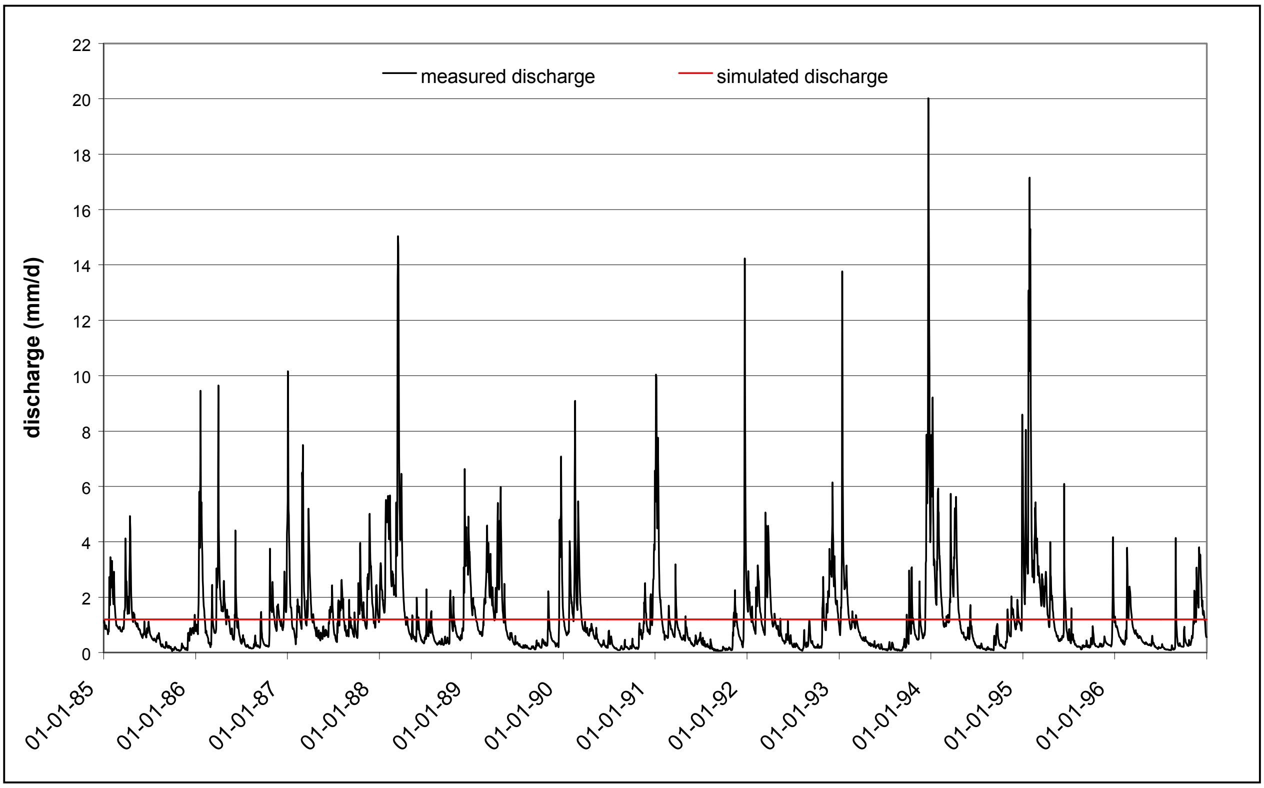


Figure 5.2 Hydrograph of the measured and simulated discharge with the constant runoff model for the validation period

The values of the efficiency (R^2) and relative difference (RD_Q) criteria are shown in table 5.1. The constant runoff model shows negative values for both calibration criteria. A negative efficiency means that the model produces worse than using the mean measured value of the discharge. The reason for this is that in this model the constant simulated discharge is the mean discharge of the calibration period. The mean discharge for the calibration period is 1.197 mm/d, for the validation period 1.209 mm/d. Because of this difference in mean discharges, a negative efficiency coefficient and a negative relative difference can be expected.

Table 5.1 R^2 and RD_Q for the simulation with the constant runoff model

	Calibration (1970-1984)	Validation (1985-1996)
R^2 (-)	0	-5.4E-05
RDq (%)	0	-0.99

5.2 Linear rainfall-runoff model

In the linear rainfall-runoff model the simulated discharge is a linear function of the mean precipitation, fallen during a period of T=1+x days (see section 4.2.2 for the description of the model). The size of the time period (T=1+x) is chosen as 1 to 15 days. This means for instance, if (1+x) has the value 15, the discharge, calculated for a certain day, is a function of the mean precipitation fallen during the 14 days before this certain day and at the day for which the discharge is calculated. Besides a run of the model with precipitation as input, also a run with the effective precipitation as input is done.

5.2.1 Calibration period

An optimalisation process for this model was done with the solver technique, available in Microsoft excel (see section 4.4 for more explanation of this technique) for the calibration. The values of the parameters, as result of the optimalisation, can be found in Appendix C.

Figure 5.3 shows the hydrograph of the years 1970-1972 of the simulated and measured discharge.

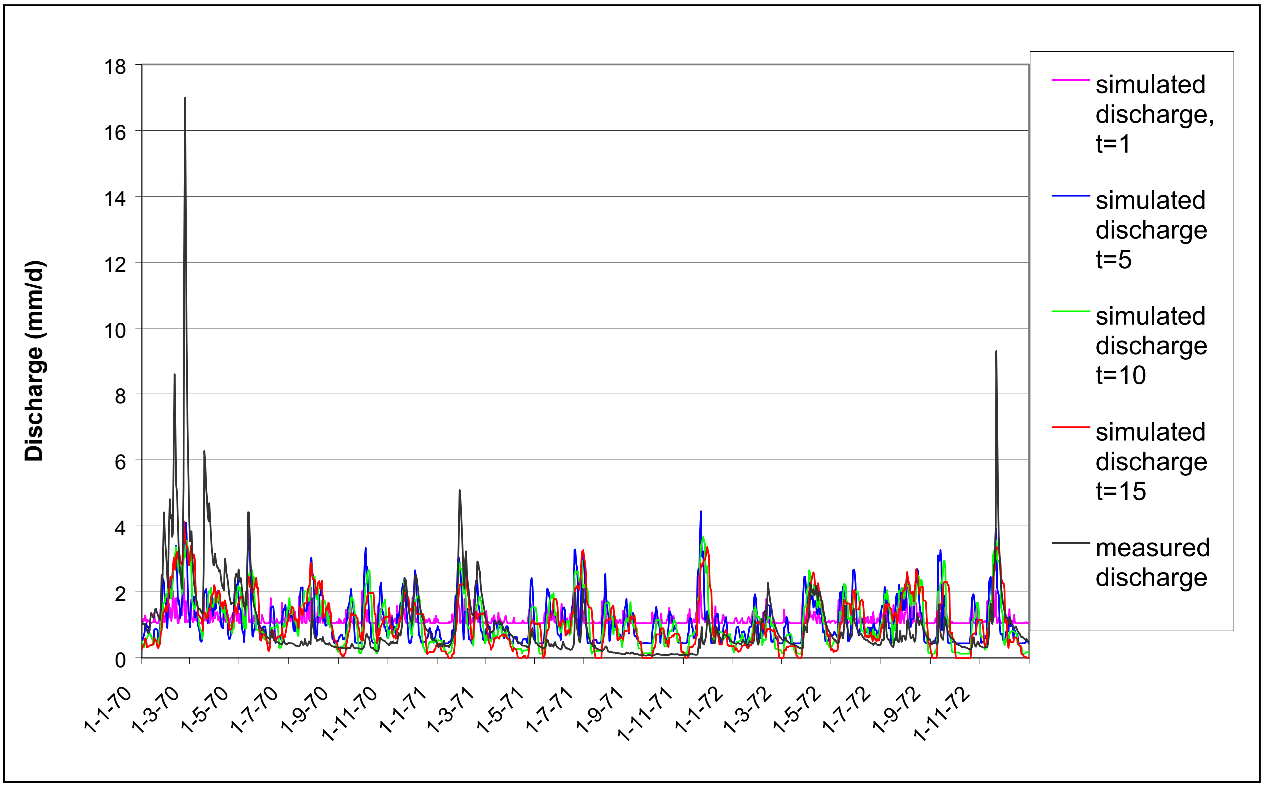


Figure 5.3 Hydrograph of the measured and simulated discharge with the linear rainfall runoff model for the years 1970-1972.

From figure 5.3 it can be concluded that when the precipitation is averaged over a longer period, the more the difference between the simulated and measured hydrograph decreases. This is also presented in figure 5.4, in which the efficiency values are plotted against the number of days, over which the precipitation is averaged. The explanation is, that if the precipitation is averaged over a number of days, the precipitation observed at a certain day is divided over these several days. This means that if there is a peak event in precipitation on a certain day, out of ten (for example), the volume of precipitation of this peak is smoothed out over these ten days. This is like in nature, the precipitation at a certain day doesn’t flow into the river at once, but only a part flows into the river during that day and will partly be stored into the soil. Figure 5.4 shows that the difference of the efficiency is small with increasing number of days exceeding 10 days. The maximum value of R^2 for this model with precipitation as input is 0.3688 for T=15 days.

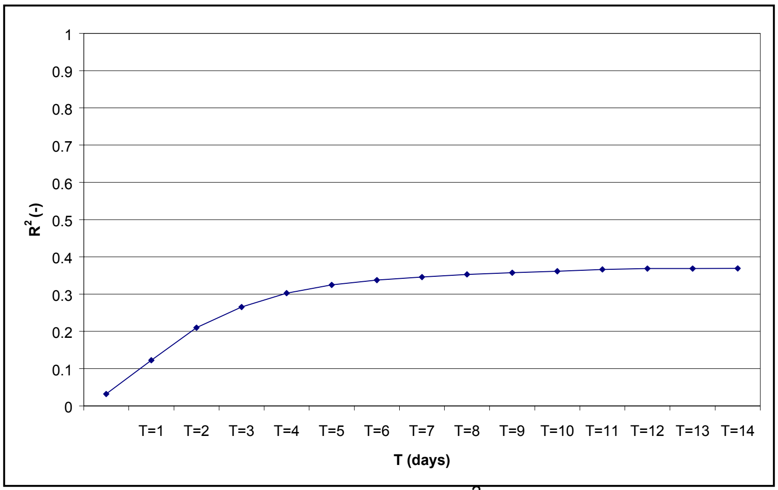


Figure 5.4 The efficiency values R^2, for the calibration period with the linear rainfall-runoff model, against the number of days over which the precipitation is averaged.

Effective precipitation

A run of this model with the effective precipitation as input for the model is also done. The effective precipitation is calculated with an evapotranspiration coefficient and the precipitation, as described in section 3.4. The effective precipitation is the precipitation without the amount of precipitation that evaporates. In figure 5.5 some of the hydrographs of the model simulation for the calibration period with the effective precipitation as input, are shown.

If the effective precipitation is used as input for the model, the discharge can turn negative, as shown in figure 5.5. The reason for the negative discharge is the effective precipitation, which can be negative if the evapotranspiration is higher than the precipitation. Due to this negative effective precipitation, the calculated discharge can be negative, depending on the values of the parameters α and β. To solve the problem of the negative discharges, which are not possible in nature, restrictions as shown in equation 4-3 are added to the model (see section 4.2.2).

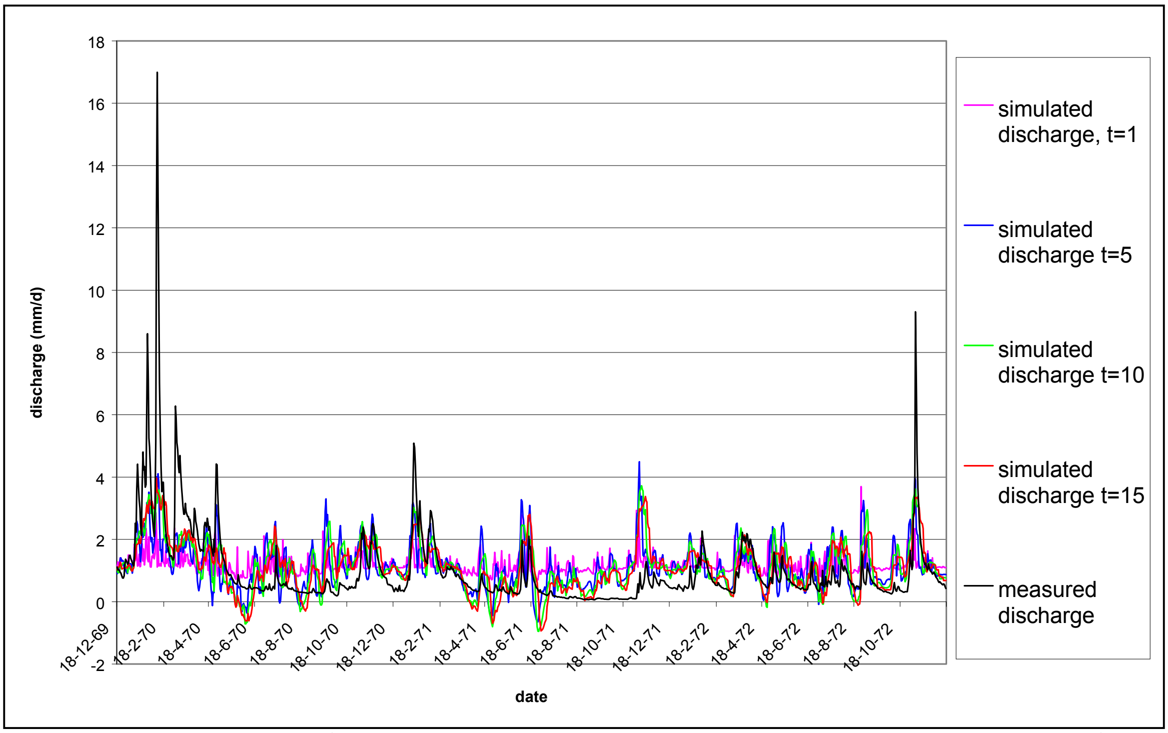


Figure 5.5 Hydrograph of the measured and simulated discharge with the linear rainfall-runoff model for the years 1970-1972 with the effective precipitation as input

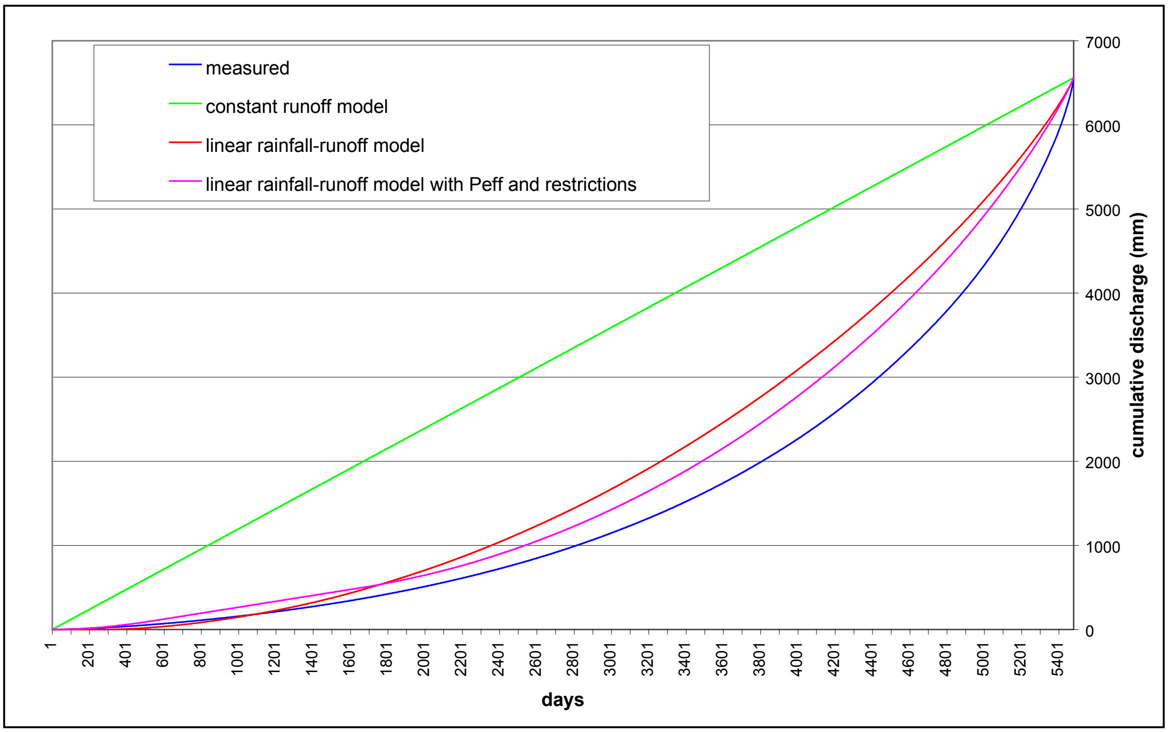


Figure 5.6 Cumulative discharge from low discharge values to high discharge values for the constant runoff model and the linear rainfall-runoff model.

From figure 5.6 it can be concluded that the linear rainfall runoff model gives a better simulation of the discharges than the constant runoff model, since the shape of the graphs of the model runs with the linear rainfall-runoff model are more similar to the graph of the measured discharge. The lower discharges are overestimated, as shown in figure 5.5 and 5.6, the higher discharges are underestimated.

5.2.2 Validation period

For the validation of the model, the same values for the parameters α and β are used as in the calibration. The values of the parameters can be found in appendix C for each period of x days. Figure 5.7 shows the results for the efficiency coefficient R^2 for the calibration and the validation period for the linear rainfall-runoff model with precipitation or effective precipitation as input.

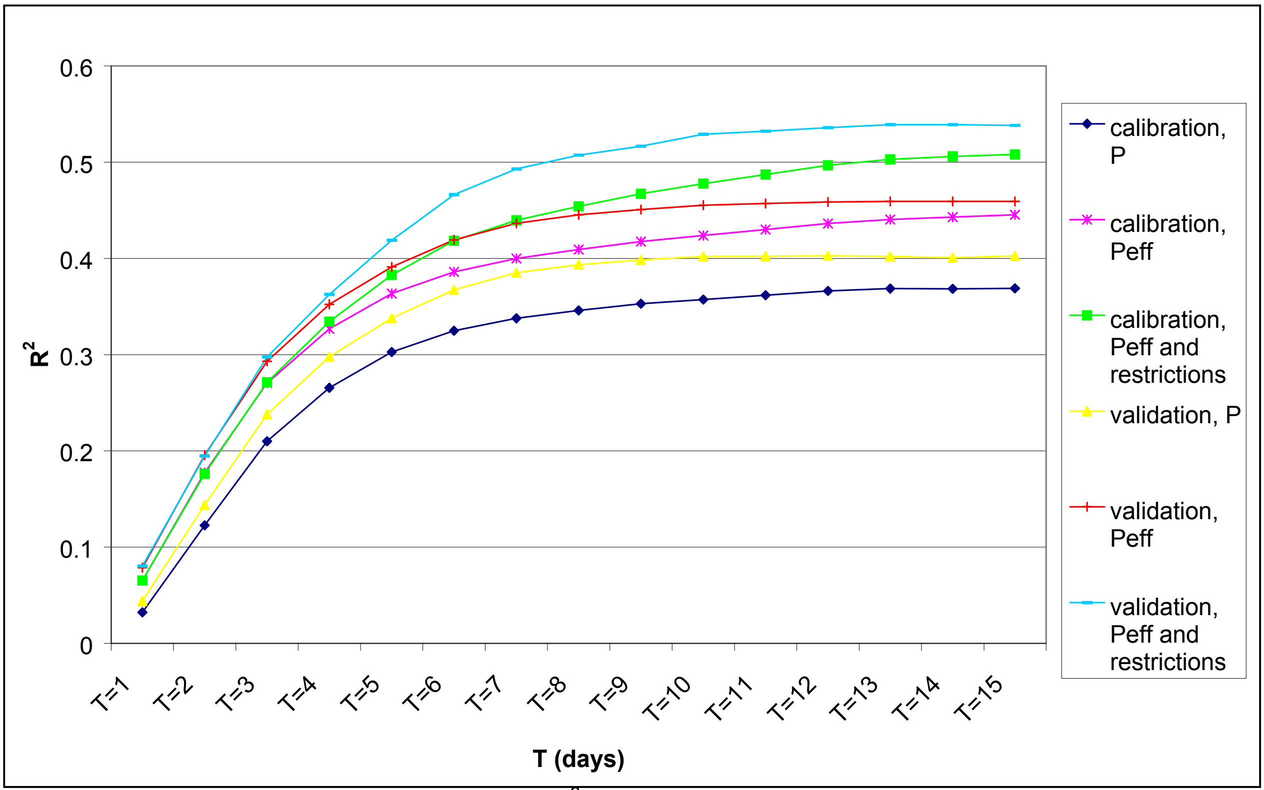


Figure 5.7 The efficiency coefficients R^2, following the Nash-Sutcliffe method, for the calibration and validation period with the linear rainfall-runoff model against the amount of days over which the precipitation is averaged for different model runs.

The efficiency coefficients are all higher for the validation than for the calibration period. The highest value for the efficiency coefficient R^2 is 0.54 for the validation of the linear rainfall-runoff model with effective precipitation and restrictions for a time period of T=15 days. Table 5.2 shows the values of the efficiency coefficients (R^2) and the values of the relative differences in total discharge (RDq) for the different runs of the model for the calibration and validation period at T=15. In appendix C the values for the other time periods can be found.

Table 5.2 shows that the percentages of relative differences in total discharge have a higher absolute value for the validation period, than for the calibration period and are negative for the simulation with effective precipitation as input.

Table 5.2 The efficiency coefficients (R^2) and relative differences in total discharge (RDq) for the different model runs for the calibration and validation period at T=15

	R^2 (-)		**RDq (%)**	
T=15	**Calibration**	**Validation**	**Calibration**	**Validation**
Linear rainfall-runoff model, P	0.37	0.40	0.00	0.13
Linear rainfall-runoff model Peff and restrictions	0.51	0.54	0.00	-0.69

5.3 Non-linear rainfall-runoff model

The non-linear rainfall-runoff model (section 4.2.3) presents a non-linear function for the calculation of the discharge and is used in this research to give a short overview of some of the features of the solver function in Microsoft Excel and how this function operates. It is not used as a model in the row of simple models towards the HBV model, since a good hydrological interpretation is not possible for this model.

The difference with the linear rainfall-runoff model is the last term of the equation. This term makes the equation non-linear. As input for the precipitation, again the precipitation, averaged over the last 14 days (x=14) and the day for which the discharge is computed (T=15) is used as input for the model. If the solver is used in this model for the optimalisation process, several solutions are given, depending on the value of the starting value of the parameters. Table 5.3 shows these values. For all five cases (A-E) the solver is used in the same way as in the other models: Try to find the parameters for the maximum value for R^2 if RDq~0. It can be concluded that with different values of λ even the same values for R^2 can be derived (see C, D and E).

In the solver function in Microsoft Excel, the Generalized Reduced Gradient (GRG2) non-linearity optimalisation code is used. From the results in table 5.3 it can be concluded that local maxima can be found for the model, using the solver technique, and their final values depend on the starting value of the parameter. This is also indicated in the function description in Microsoft Excel: a non-linear optimalisation can have local minima and maxima and it is best to give the parameters starting values around the value expected for the parameters. To find the right starting values for the parameters is quite difficult, since the parameters α, β and λ do not have a distinct meaning from a hydrological point of view. For this reason, the other models, constructed in this study use only linear equations.

Table 5.3 Parameter values and efficiency criteria and relative differences for several runs of the non-linear rainfall-runoff model.

	Parameter	Starting value	Final value	R^2	RDq
A	α (mm)	0.0000	-0.84	0.39	0.00
	β (–)	0.0000	0.12		
	λ (–)	0.0000	-0.19		
B	α (mm)	1.0000	-0.65	0.39	0.00
	β (–)	1.0000	0.60		
	λ (–)	1.0000	0.75		
C	α (mm)	100.0000	-0.09	0.37	0.00
	β (–)	100.0000	0.49		
	λ (–)	100.0000	100.00		
D	α (mm)	100.0000	-0.09	0.37	0.00
	β (–)	100.0000	0.49		
	λ (–)	500.0000	500.00		
E	α (mm)	500.0000	-0.09	0.37	0.00
	β (–)	500.0000	0.49		
	λ (–)	500.0000	499.83		

Considering the efficiencies this non-linear model doesn't show any improvement in simulation as compared to the previous linear models.

5.4 Linear rainfall-runoff model with one reservoir

The linear rainfall-runoff model with one reservoir is a combination of the linear rainfall-runoff model, of which the results were shown in section 5.2, and a linear reservoir (see section 4.2.4 for a description). A linear reservoir can be considered as representing for instance, an aquifer generating baseflow. The fastness of the outflow of a reservoir is simulated with a reservoir coefficient. The higher this coefficient, the longer the precipitation is stored and the longer it takes before the precipitation flows out of the system (Bos, 2001). The usage of a linear reservoir allows to simulate the storage of water in a catchment and expresses the memory of the system. In appendix D, a description is given of how the reservoir coefficients are derived in this study. Two reservoir coefficients are found, with the averaged values of 12.66 days (fast reservoir) and 70.47 days (slow reservoir). These will be used as the starting values for the optimalisation with the Solver function in Microsoft Excel for this model and the other model with two reservoirs, described in section 5.5.

To prevent the simulation of the model for the computation of negative discharges, that can occur since the reservoir doesn't have a minimum storage, restrictions are added to the model, to give the reservoir a minimum storage. These restrictions are described in section 4.2.4.

5.4.1 Calibration period

To calibrate the linear rainfall-runoff model with one reservoir, two runs were done with different starting values of the reservoir coefficient. The values of the efficiency coefficient using a starting value for the reservoir coefficient of 12.66 were much higher, so there was decided that this value was used as starting value. To start the calibration period (1970-1984) with a reservoir that is already used and has a value at the beginning of the calibration period, the data of the year 1969 were used.

Appendix B gives an overview of the way this model is build in Microsoft Excel. The linear rainfall-runoff model with one reservoir is used as an example for the description of the formats of the models in this appendix.

The final run for the calibration of the model showed the following values for the parameters, calibration criteria R^2 and RDq with precipitation as input (see table 5.4):

Table 5.4 The values of the parameters, efficiency coefficient and relative difference of the total discharge for the calibration of the linear rainfall-runoff model with one reservoir.

α (mm)	-0.9085
β (–)	0.0193
γ (–)	0.7326
k1 (d)	12.5702
R^2 (-)	0.49
RDq (%)	0.00

Comparing the efficiency with the efficiency of the linear rainfall-runoff model without a reservoir, it appears that using a reservoir produces higher efficiencies.

The calibrated value of the reservoir coefficient (k_1) differs not much from that derived out of the recession curves (12.66 days). Figure 5.8 shows the effect of adding a reservoir to the linear model. The simulated discharge in the recession periods fit better to the measured discharge than the simulated discharge of the model without a reservoir. A plot of the simulated discharge and measured discharge is shown in figure 5.9. The value R^2 used in this figure is a fit of the trend line and not the Nash Sutcliffe R^2, used as calibration criterium in this study.

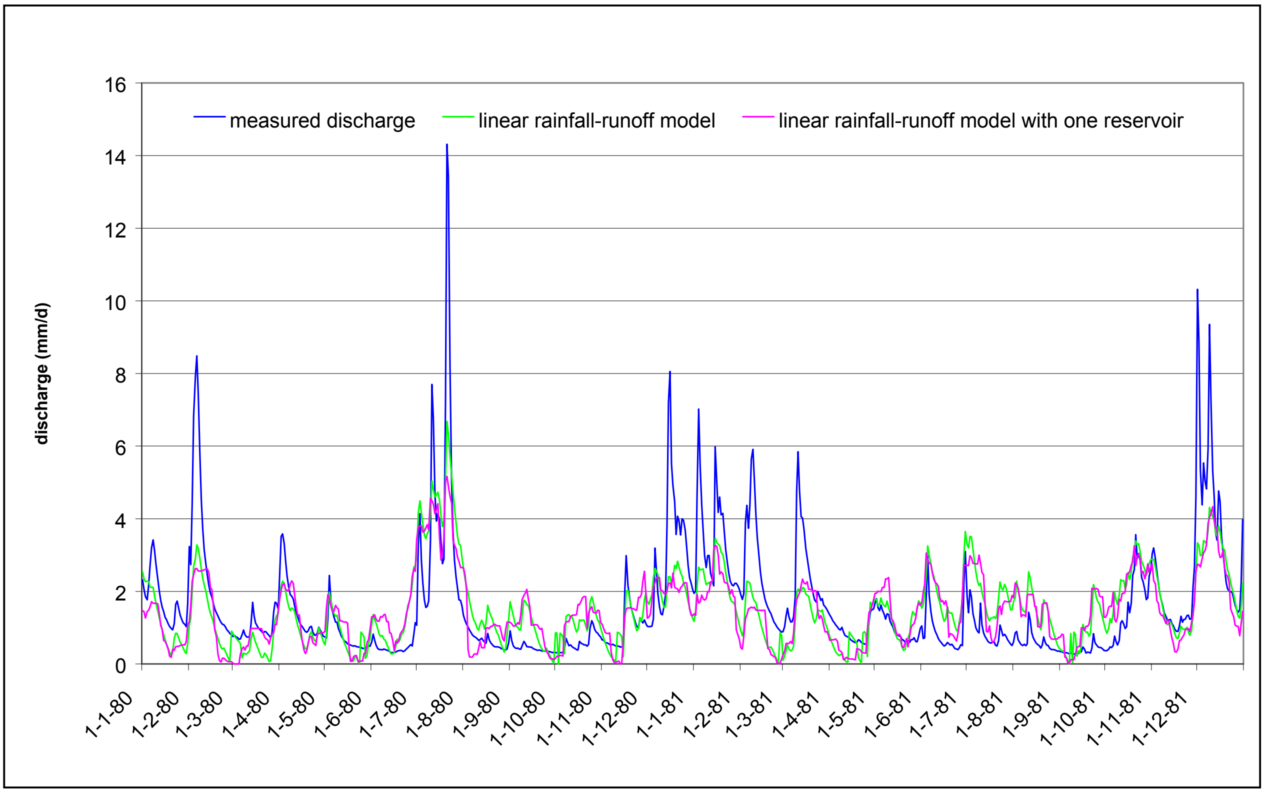


Figure 5.8 Hydrograph of the measured and simulated discharge with the linear rainfall-runoff models with and without a reservoir for the years 1980 and 1981

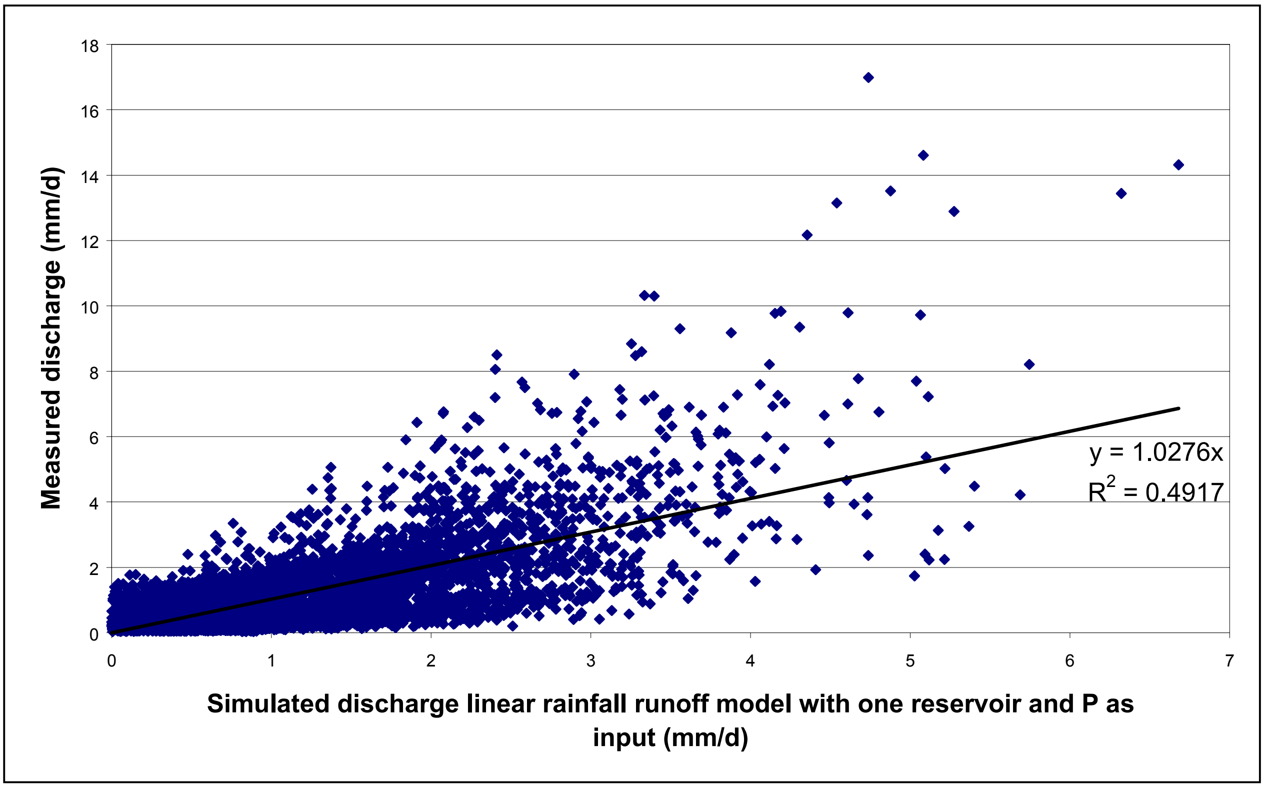


Figure 5.9 The simulated discharge plotted against the measured discharge for the calibration period.

Effective precipitation

If the effective precipitation is used as input for the model instead of “normal” precipitation, better results are obtained for the model with the added linear reservoir. The R^2 of Nash and Sutcliffe has a value of 0.5872 for this model run.

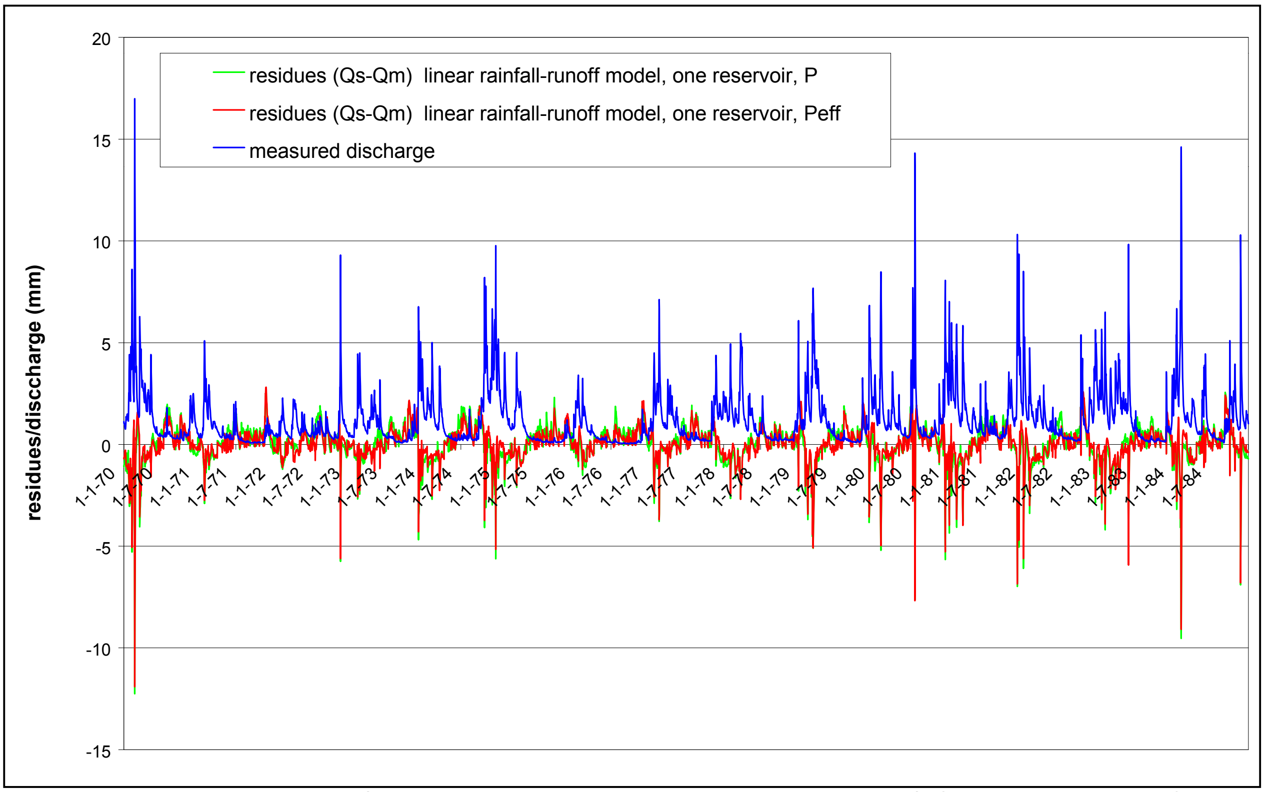


Figure 5.10 The residues (simulated discharge-measured discharge) for the linear rainfall-runoff model with one reservoir with precipitation and effective precipitation as input for the calibration period.

Figure 5.10 shows the differences between simulated and measured discharge of the model runs using effective precipitation (red) and precipitation (green) as input and the measured discharge. It can be concluded that if this model computation is done with the effective precipitation, the differences between the measured and simulated discharge are smaller especially for the peak events and for low discharges, as is shown in figure 5.10.

The next figure, figure 5.11, shows again a plot of the simulated discharge with the effective precipitation as input for the simulation and the measured discharge. Comparing this figure to figure 5.9, it can be concluded that the simulation with the effective precipitation is better, since the fit of the trend line (R^2) is 0.1 higher for the model simulation with effective precipitation as input and the coefficients of the trend line are nearly the same.
Figure 5.12 is a plot of the differences between measured and simulated discharges (Peff) against the measured discharges. From this plot it can be concluded that the higher the measured discharge, the greater the difference between simulated and measured discharge for this model. In the case of a high measured discharge value, the computed discharge is too low. Figure 5.13 shows a plot of the measured discharge against the relative differences between simulated and measured discharge. Also this figure shows, that if the measured discharge value is high, the relative difference (simulated discharge-measured discharge, divided by the measured discharge) is higher than for small measured discharges values.

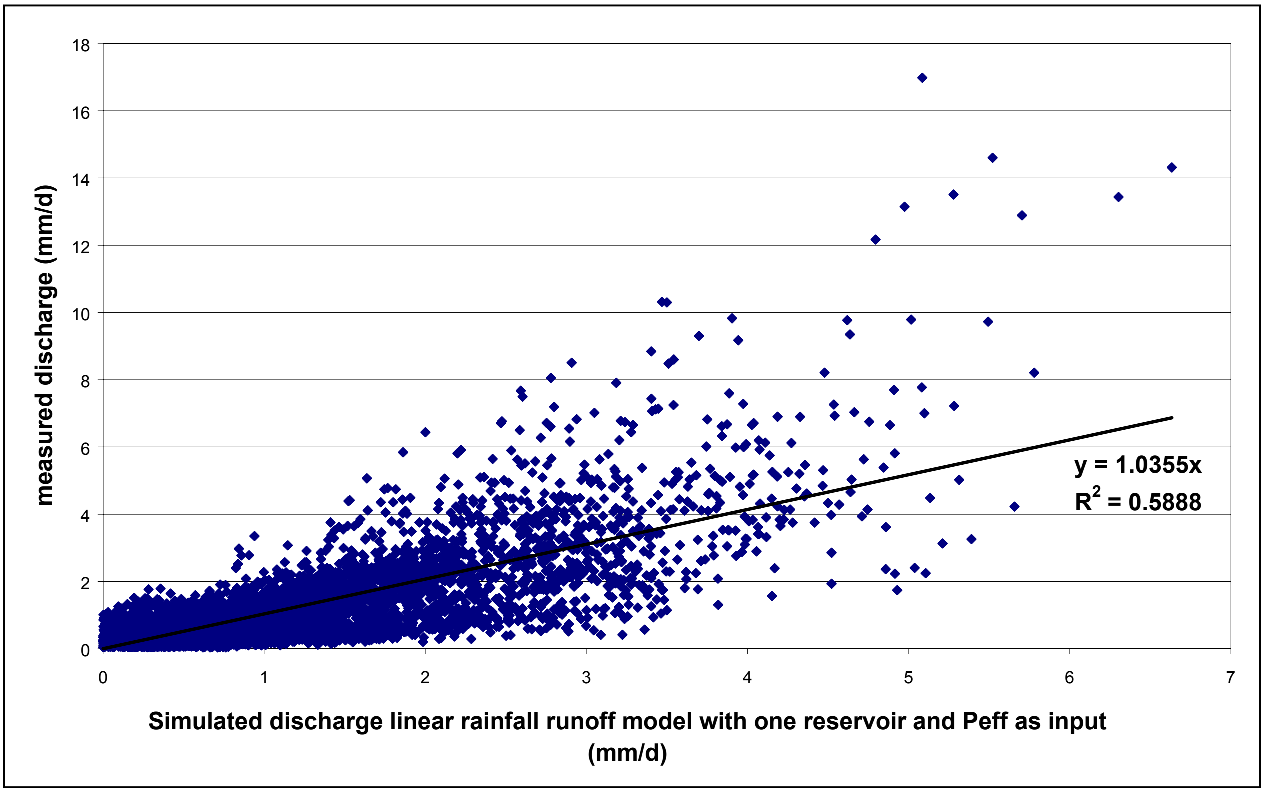


Figure 5.11 The simulated discharge plotted against the measured discharge for the calibration period

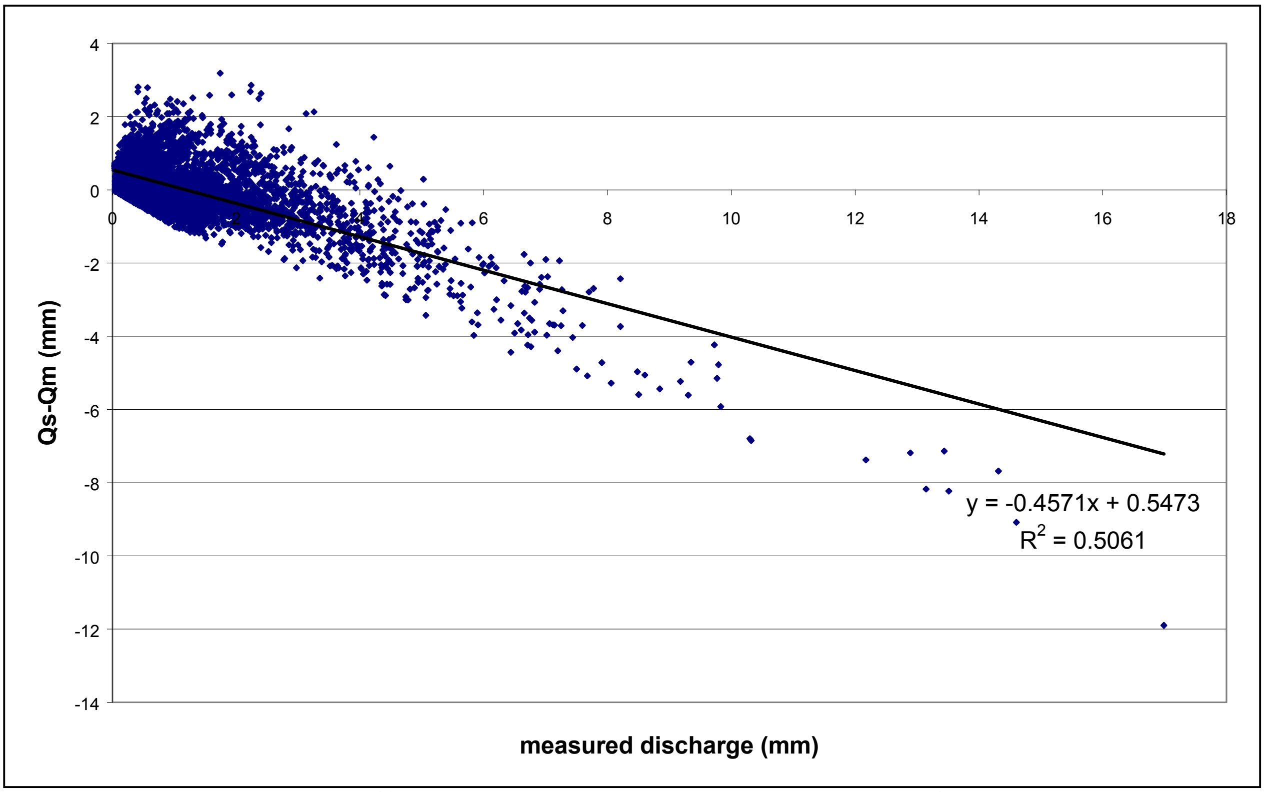


Figure 5.12 The residues (Simulated discharge-measured discharge) plotted against the measured discharge for the calibration period

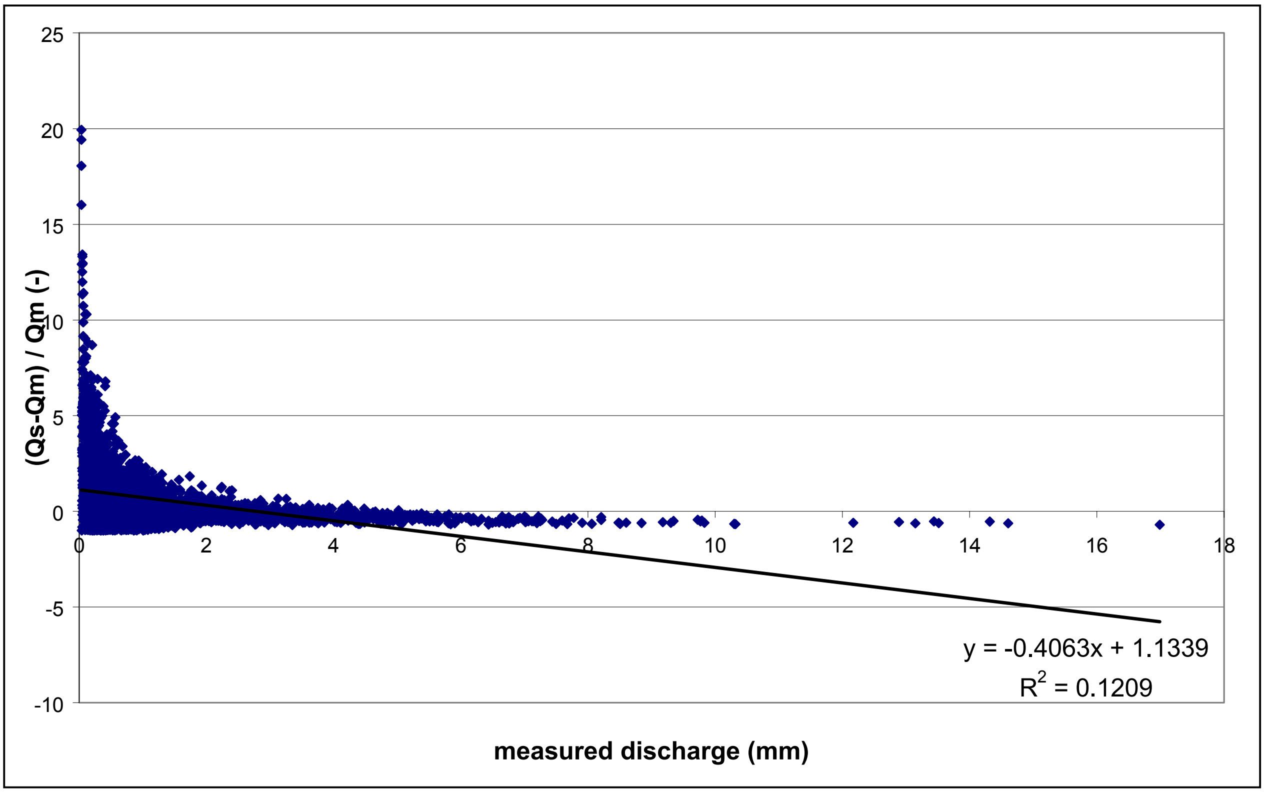


Figure 5.13 The relative residues (Simulated discharge-measured discharge, divided by the measured discharge) plotted against the measured discharge for the calibration period

Because of the difference between measured and simulated discharge, which is higher for peak events, two other simulations are done with the linear rainfall-runoff model with one reservoir, for precipitation and effective precipitation as input to evaluate the influence of the peak discharges on the results computed with the model.

Peak discharges

In these model simulations, the measured discharges with a discharge exceeding a threshold of 2 mm/d ("peaks") are emphasized. This is done by calculating an extra Nash-Sutcliffe efficiency, in which the values for the efficiency coefficient count twice for a measured discharge, higher than 2 mm/d. In the optimalisation is tried to find the highest value for this efficiency computation. After achieving this, the Nash-Sutcliffe efficiency was calculated, following the original method with these parameters.

The results of these simulations are shown in table 5.5.

Table 5.5 The values of the parameters, efficiency coefficients and relative differences for the different runs of the calibration of the linear rainfall-runoff model with one reservoir.

	Linear rainfall-runoff model with one reservoir			
	P	**P, peak**	**Peff**	**Peff, peak**
α (mm)	-0.9085	-1.0018	-0.7698	-0.7763
β (–)	0.0194	0.0158	0.0236	0.0273
γ (–)	0.7326	0.7398	0.8488	0.8320
k1 (d)	12.5702	9.7271	14.9724	11.9559
R^2 (-)	0.49	0.49	0.59	0.58
RDq (%)	0.00	0.00	0.00	0.00

There are not very remarkable changes in the model results. The most remarkable change is the change in the values of the reservoir coefficients in the models with extra attention to the peaks. Both have lower values for both simulations, with a difference of about 3 days. A reason for this can be found in the recession curves of peaks. If the measured discharge is higher than 2 mm/d, it's influence is higher for the value of R^2 in this model run, so the parameters will be more chosen for these "peaks" in the optimalisation process. The recession curves of these higher "peaks" are different from the mean recession curves and will have a steeper slope, which causes lower values for the reservoir coefficients.

Figure 5.14 shows the cumulative discharge from low discharge values to high discharge values for some of the other model simulations and the simulation with linear rainfall-runoff model with one reservoir and considering the days exceeding 2 mm/d discharge. The simulated discharge of the model with one reservoir is closer to the measured discharge at the higher discharges, and the model without a reservoir is closer to the measured discharge for the lower discharges. The difference between the "peak" model run and the "normal" model run with one reservoir, can also be found in the higher discharges, where the simulated discharge, with "peaks", is closer to the measured discharges.

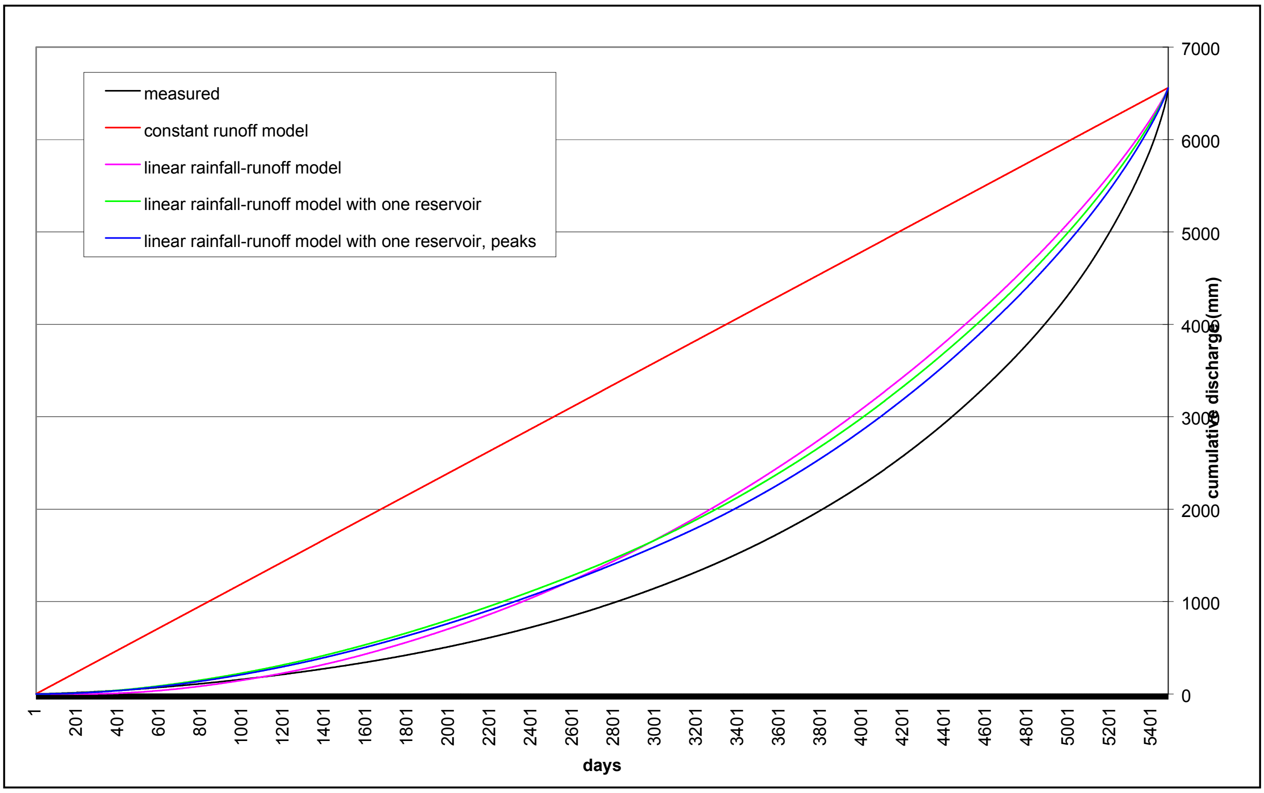


Figure 5.14 Cumulative discharge from low discharge values to high discharge values for the constant runoff model, the linear rainfall-runoff model, the linear rainfall-runoff model with one reservoir and the linear rainfall-runoff with one reservoir with extra underlined the peaks above 2 mm. All model runs have precipitation as input.

5.4.2 Validation period

All the parameter values, as derived in the calibration, are used for the validation. The following results are achieved:

Table 5.6 The values of the parameters, efficiency coefficients and relative differences for the different runs of the validation of the linear rainfall-runoff model with one reservoir.

	Linear rainfall-runoff model with one reservoir			
	P	P, peak	Peff	Peff, peak
α (mm)	-0.9085	-1.0018	-0.7698	-0.7763
β (–)	0.0194	0.0158	0.0236	0.0273
γ (–)	0.7326	0.7398	0.8488	0.8320
k1 (d)	12.5702	9.7271	14.9724	11.9559
R^2 (-)	0.52	0.54	0.61	0.63
RDq (%)	1.40	1.57	1.57	1.71

From table 5.6 can be seen that the RDq are all quite small, smaller than 2%. The table also shows that the RDq values for the model runs with the effective precipitation as input are not negative, what would not be expected after the model run of the linear rainfall-runoff model without a reservoir and effective precipitation as input. The explanation is, that the differences between the measured and simulated discharges (because of the added reservoir, with its restrictions) are smaller and the sum of these differences is positive.

Remarkable are the differences of the efficiency between the two “peak” models runs and “normal” model runs. These are higher for the model runs of the validation, in which the discharges above 2 mm/d are emphasized than for the validation of the “normal” model runs.

5.5 Linear rainfall-runoff model with two reservoirs

In this model, a second linear reservoir has been added. A description of this model can be found in section 4.2.5. As described in appendix D, two reservoir coefficients were calculated by hand, as an indication of their start values for the start of the model optimalisation. In this model, both reservoir coefficients were used as starting values. During the process of optimalisation had to be concluded that, although the model is linear, the solver technique of Microsoft Excel doesn’t work properly anymore including 6 parameters and all the restrictions. The consequence is that the optimalisation process for this model was done by hand, by changing the reservoir coefficients and then optimize the model with the solver function for the other parameters. This process makes it difficult to find the best fit.

5.5.1 Calibration period

After the optimalisation of the model by hand, the values of the parameters, as displayed in table 5.7, were found. The reservoir coefficients have values of 9.5 days and 64 days. These values are a bit lower than calculated by hand (12.7 and 70.5). Comparing the results of this model with the results of the linear rainfall-runoff model with one reservoir (table 5.6), there can be concluded that adding a second reservoir does not improve the model results much. Figure 5.15 shows the hydrograph of the simulated and measured discharge for the total calibration period and figure 5.16 shows the hydrograph for the year 1974 in more detail for the measured and simulated discharge of the models with one and two reservoirs. Only very small differences between the simulated discharge of the model with one reservoir and the simulated discharge of the model with two reservoirs can be seen.

Table 5.7 The values of the parameters, efficiency coefficient and relative difference for the calibration of the linear rainfall-runoff model with two reservoirs.

Parameter	Value
α (mm)	-0.98021
β (–)	0.0150
γ (–)	0.5305
δ (–)	0.2442
k1 (d)	9.4921
k2 (d)	63.9985
R^2 (-)	0.50
RDq (%)	0.00

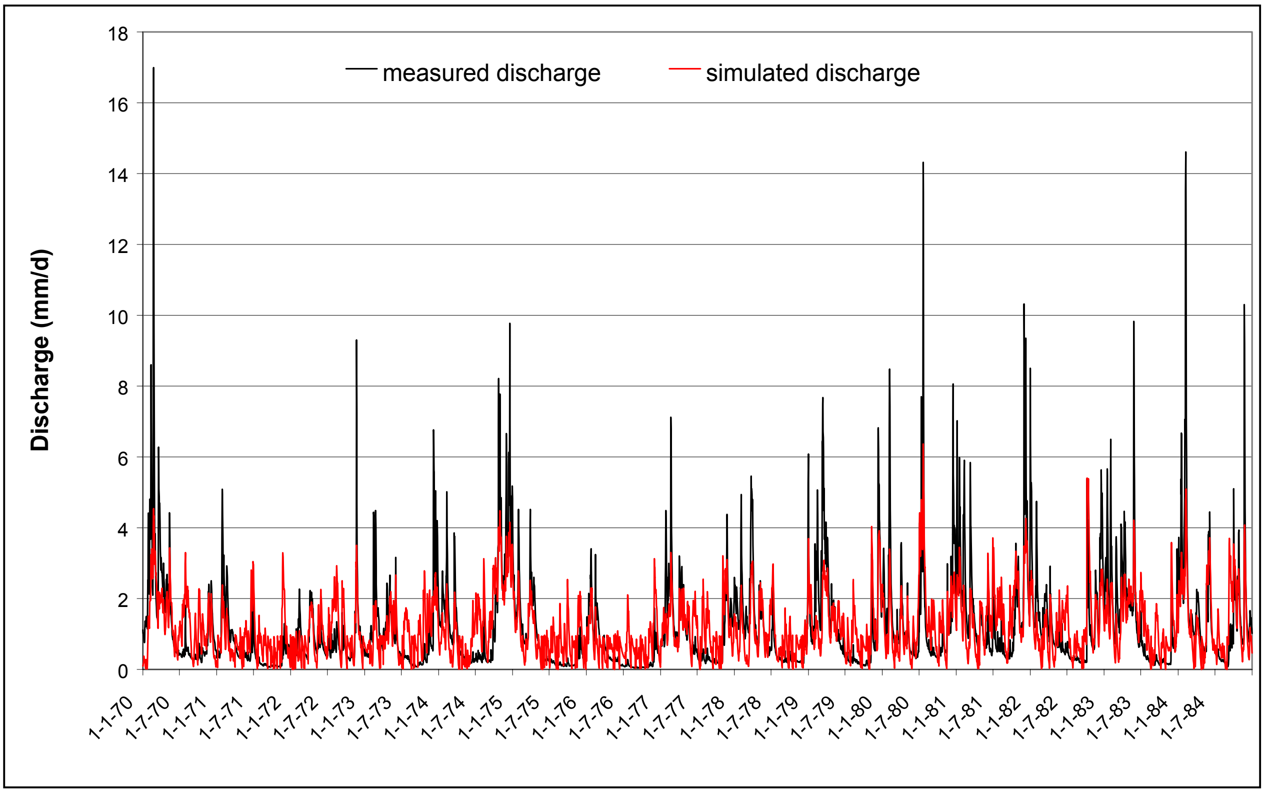


Figure 5.15 Hydrograph of the measured and simulated discharge with the linear rainfall runoff model with two reservoirs for the years 1970-1984

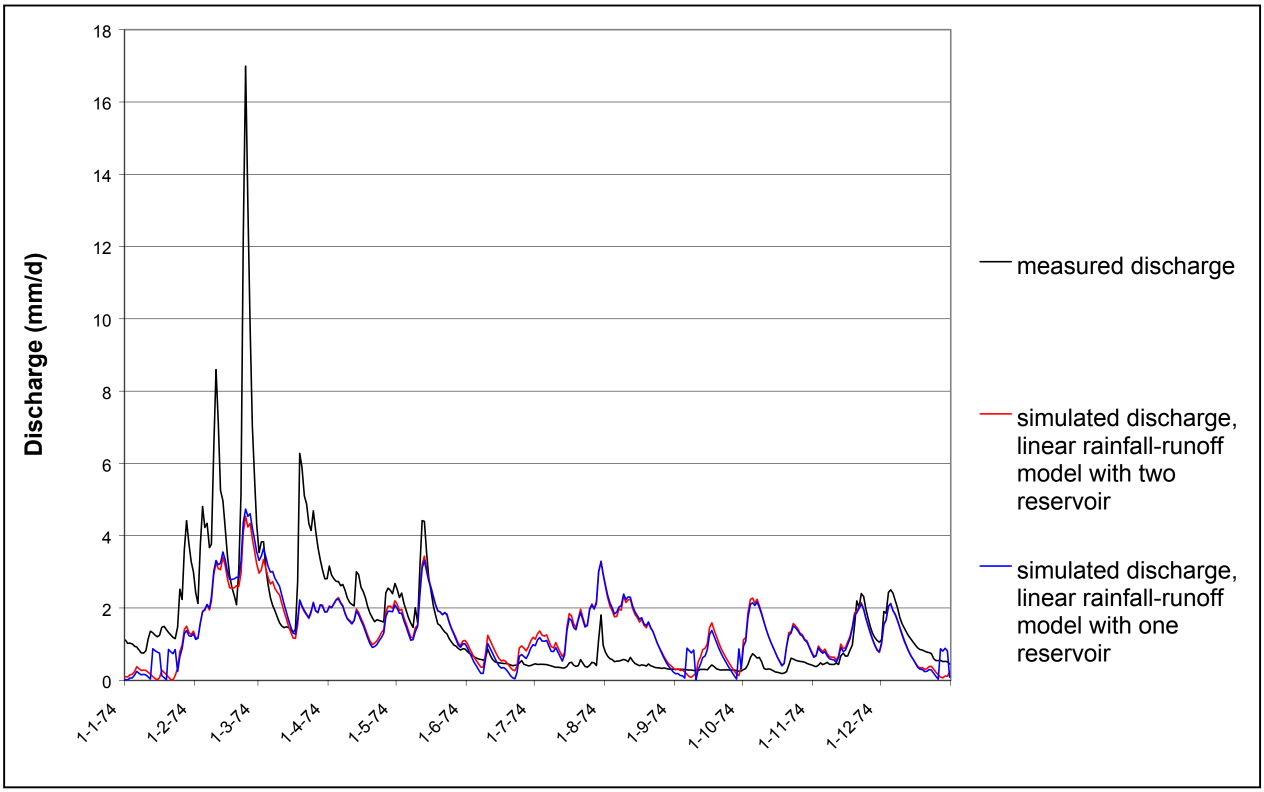


Figure 5.16 Hydrograph of the measured and simulated discharge with the linear rainfall runoff model with two reservoirs and one reservoir for the year 1974

Effective precipitation, peak discharges

For this model, also a run with the effective precipitation and two runs with precipitation or effective precipitation as input using the threshold of 2 mm/d are also done.

Table 5.8 shows the results of all these runs for the calibration period. The results of the model runs with effective precipitation are also better for this model than the results with precipitation as input.

The results for the “peak” model runs with have to be less than the results for the “normal” model runs, since in the runs with the “normal” model there has been tried to reach the maximum optimalisation of the model. Table 5.8 shows that this is correct.

Table 5.8 also shows, that the reservoir coefficients are smaller for the model runs with the “peaks”, than for the other two (“normal”) model runs, as already seen in the results of the simulations with the linear rainfall-runoff model with one reservoir.

Table 5.8 The values of the parameters, efficiency coefficients and relative differences for the different runs of the calibration of the linear rainfall-runoff model with two reservoirs.

	Linear rainfall-runoff model with two reservoirs			
	P	P, peak	Peff	Peff, peak
α, (mm)	-0.9802	-1.1324	-0.7858	-0.8360
β (–)	0.0150	0.0215	0.0306	0.0302
γ (–)	0.5305	0.5263	0.4628	0.3968
δ (–)	0.2442	0.2690	0.4104	0.4751
k1 (d)	9.4921	7.4898	8.0045	6.9740
k2 (d)	63.9985	56.9976	49.9987	47.9985
R^2 (-)	0.50	0.49	0.61	0.61
RDq (%)	0.00	0.00	0.00	0.00

Figure 5.17 shows the measured discharge and the simulated discharges, calculated with the models with one reservoir and two reservoirs, using the effective precipitation as input. The influence of the reservoirs on the simulated discharges can be observed very well in this figure. Many small peaks are followed by a recession in the simulation. The slope of these recessions is a result of the reservoir coefficients of the models. The reservoir coefficient of the model with one reservoir has a value of 15 days, the values of the reservoir coefficients of the model with two reservoirs are 8 and 50 days. This difference should result into a difference of the shape of the recession curves, which can be seen in figure 5.17. The slopes of the recession curves of the simulated discharge with the linear rainfall-runoff model with one reservoir are smoother than the slopes of the recession curves of the simulated discharge with the model with two reservoirs. The opposite is found for the shorter recession curves.

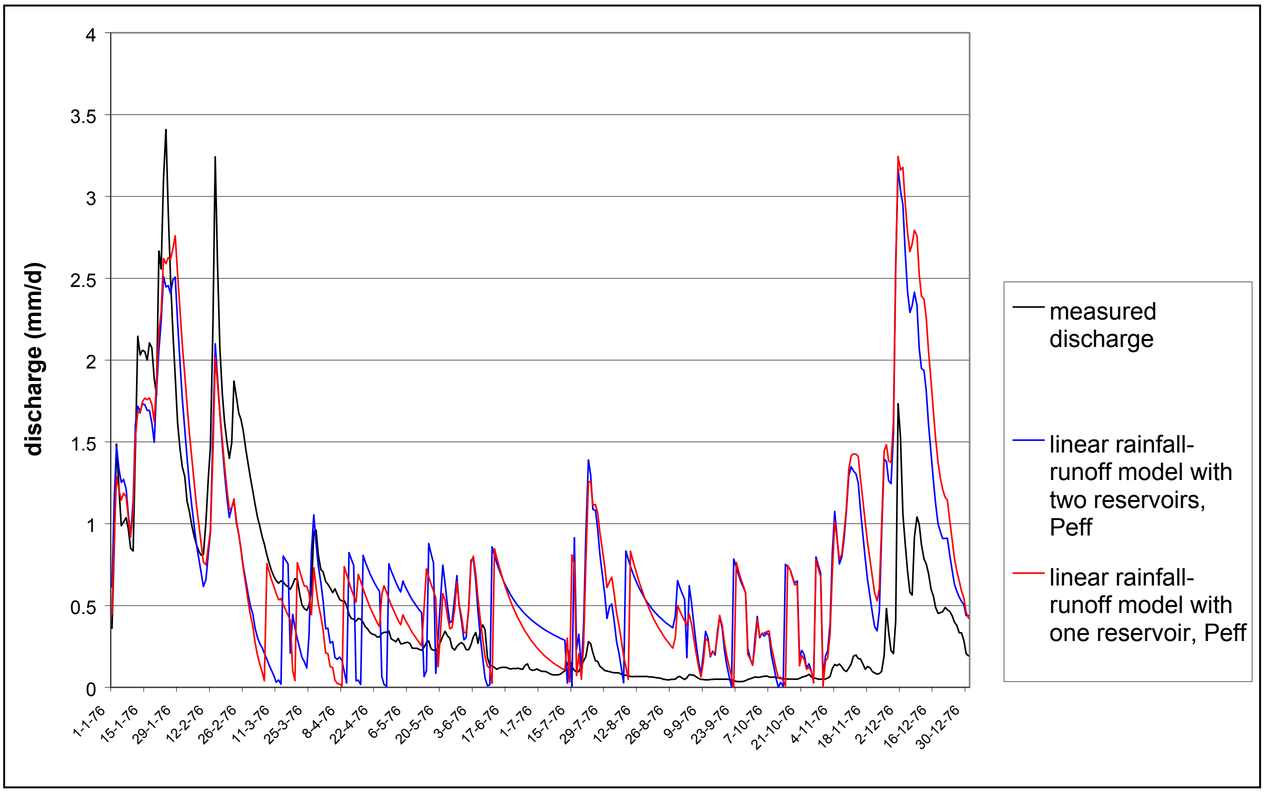


Figure 5.17 Hydrograph of the measured and simulated discharges with the linear rainfall-runoff models with one reservoir and two reservoirs for the year 1976

5.5.2 Validation period

A validation of all four runs with this model is also done. The results are displayed in table 5.9. Comparing these results for the validation period with the results for the validation of the linear rainfall-runoff model with one reservoir (table 5.6), the differences between the two models are negligible. The values of the relative differences in total discharge are not very significant, with a maximum of 3%.

Figure 5.18 shows the cumulative discharge of the model runs for the linear rainfall-runoff model with two reservoirs with effective precipitation as input for the “normal” run and the “peak” run, both for the validation. The same runs for the model with one reservoir are also shown in this figure. Both models show that the run with emphasized peaks fits better to the measured discharges. For the calibration period, the values of the efficiency coefficients are lower for the runs with emphasized peaks.

The efficiency coefficients for the runs with effective precipitation as input are also higher than for the runs with precipitation as input.

Table 5.9 The values of the parameters, efficiency coefficients and relative differences for the different runs of the validation of the linear rainfall-runoff model with two reservoirs.

	Linear rainfall-runoff model with two reservoirs			
	P	P, peak	Peff	Peff, peak
α (mm)	-0.9802	-1.1324	-0.7858	-0.8360
β (–)	0.0150	0.0215	0.0306	0.0302
γ (–)	0.5305	0.5263	0.4628	0.3968
δ (–)	0.2442	0.2690	0.4104	0.4751
k1 (d)	9.4921	7.4898	8.0045	6.9740
k2 (d)	63.9985	56.9976	49.9987	47.9985
R^2 (-)	0.52	0.54	0.62	0.64
RDq (%)	1.48	2.85	1.73	2.01

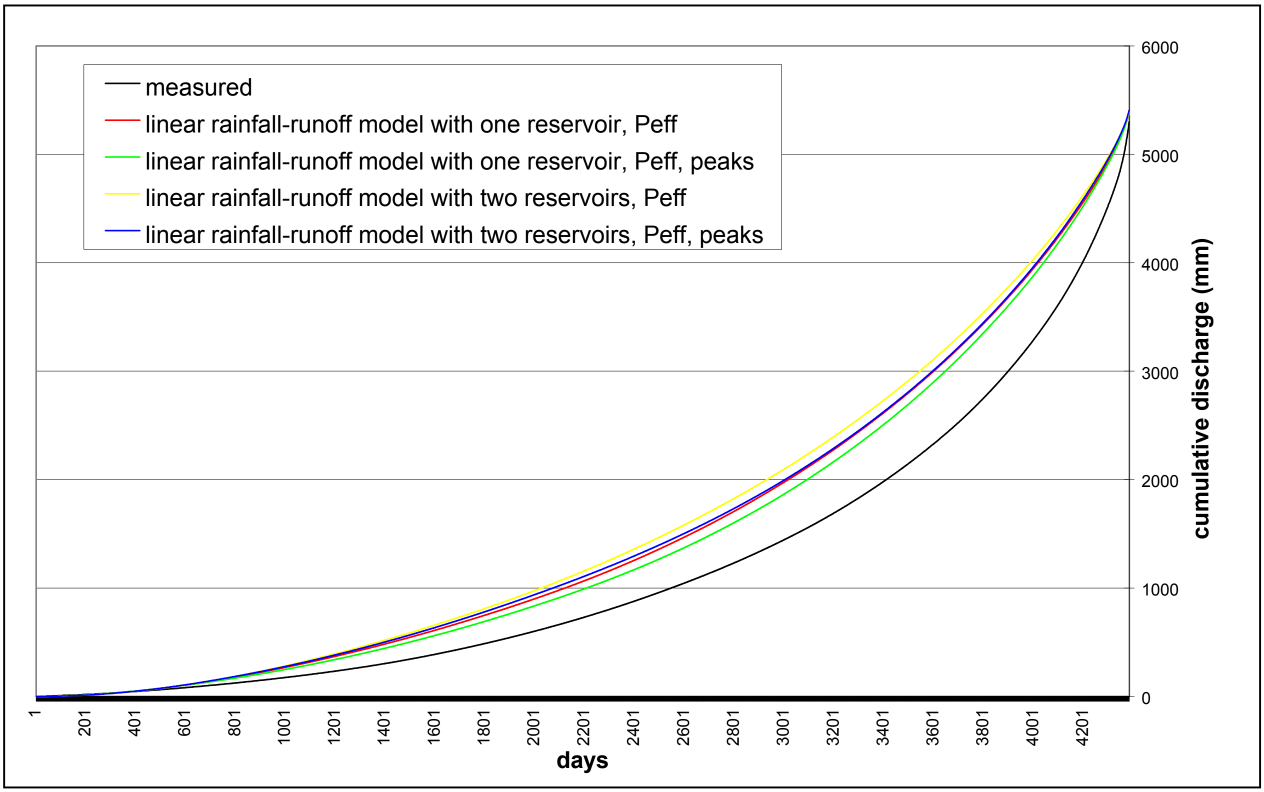


Figure 5.18 Cumulative discharge from low discharge values to high discharge values for the linear rainfall-runoff model with one reservoir and the linear rainfall-runoff model with two reservoirs with the effective precipitation as input

5.6 Linear rainfall-runoff model with two reservoirs and evapotranspiration

This model is a combination of the linear rainfall-runoff model with two reservoirs and a function for the evapotranspiration. This model is used to see if there is a difference in the results for a different way of adding the evapotranspiration process to the model. As described in section 4.2.6, a sort of effective precipitation is used in this model, based on a mean daily actual evapotranspiration per month [mm/d].
Two runs are done with this model, as explained in section 4.2.6. In this section (4.2.6) is also an example for the calculation of the effective precipitation given.

5.6.1 Calibration period

Figure 5.19 shows the values of the mean daily actual evapotranspiration per month [mm/d]. These values are averaged over the total calibration period. The values for the months January, February, March, April and December are low, the other values are between 1.5 and 2.5 mm/d. The month February has even a negative mean daily actual evapotranspiration of 0.01 mm/d. From this figure it can be concluded that especially during summer and autumn a lot of actual evapotranspiration takes place.

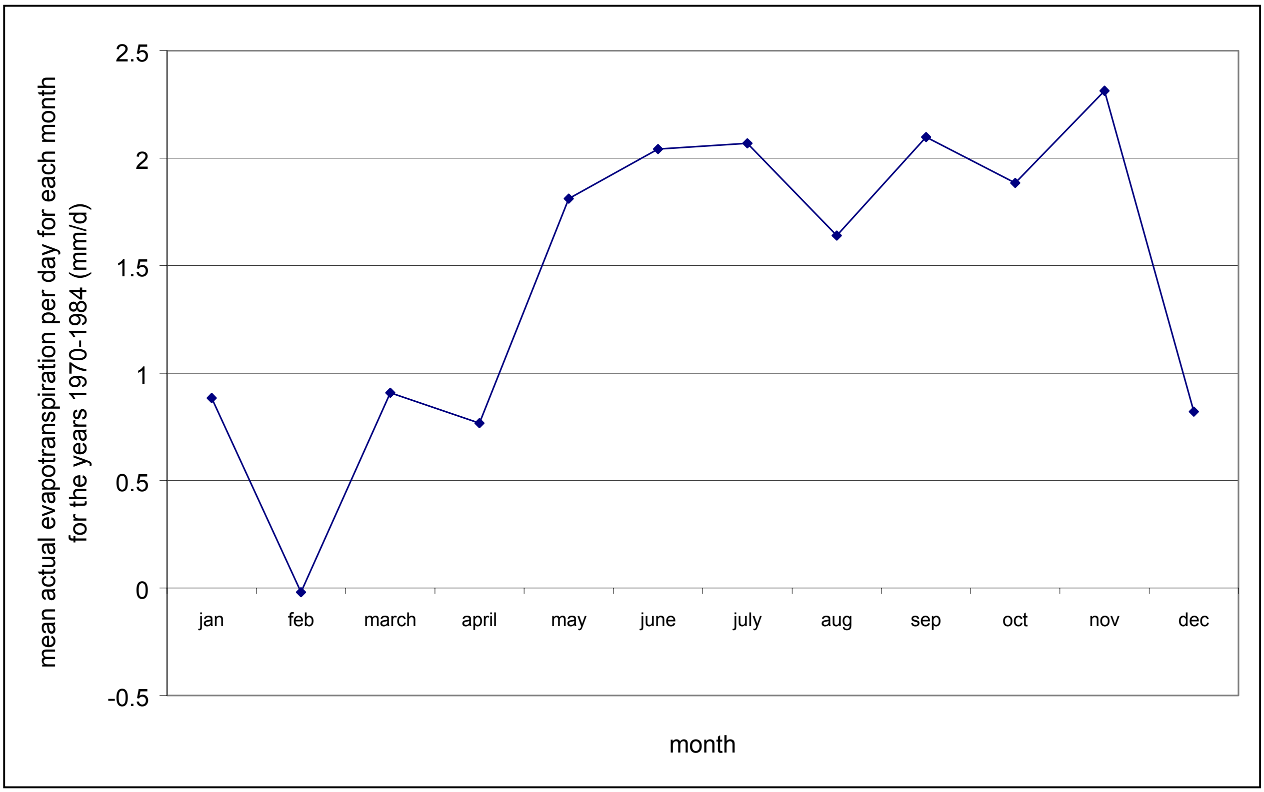


Figure 5.19 The mean daily actual evapotranspiration per month for the calibration period

The optimalisation of the model was done, following the same method as before for the linear rainfall-runoff model with two reservoirs, and delivers an efficiency coefficient of 0.61.

The second run, done with this model is more like the runs before with the effective precipitation. For this run, only a monthly evapotranspiration coefficient is used, instead of a yearly evapotranspiration coefficient, based on the total calibration period. For a description of the model see section 4.2.6.

Table 5.10 shows the results of both simulation runs. It can be seen that the value for the efficiency coefficient for the second run is not very high. If this value is compared with the value of the efficiency coefficient of the simulation with the model with two reservoirs and effective precipitation used as input, the difference is even larger. The only difference between these two simulations is the kind of evapotranspiration coefficient used in the model. In this run, the evapotranspiration coefficients have monthly averaged values, in the run with the model with two reservoirs and effective precipitation, as input is the evapotranspiration coefficient on averaged bases for the total year.

Table 5.10 The values of the parameters, efficiency coefficients and relative differences for the two runs with the linear rainfall-runoff model with two reservoirs and evapotranspiration.

	Linear rainfall-runoff model with two reservoirs and evapotranspiration	
	P	Peff
α (mm)	-0.8634	-0.8474
β (–)	0.0295	0.0291
γ (–)	0.4525	0.5161
δ (–)	0.5187	0.4145
k1 (d)	8.0023	7.0380
k2 (d)	49.9969	47.9974
R^2 (-)	0.6129	0.5610
RDq (%)	0.0000	0.0000

Figure 5.20 shows the hydrograph of both runs with this model and the measured discharge.

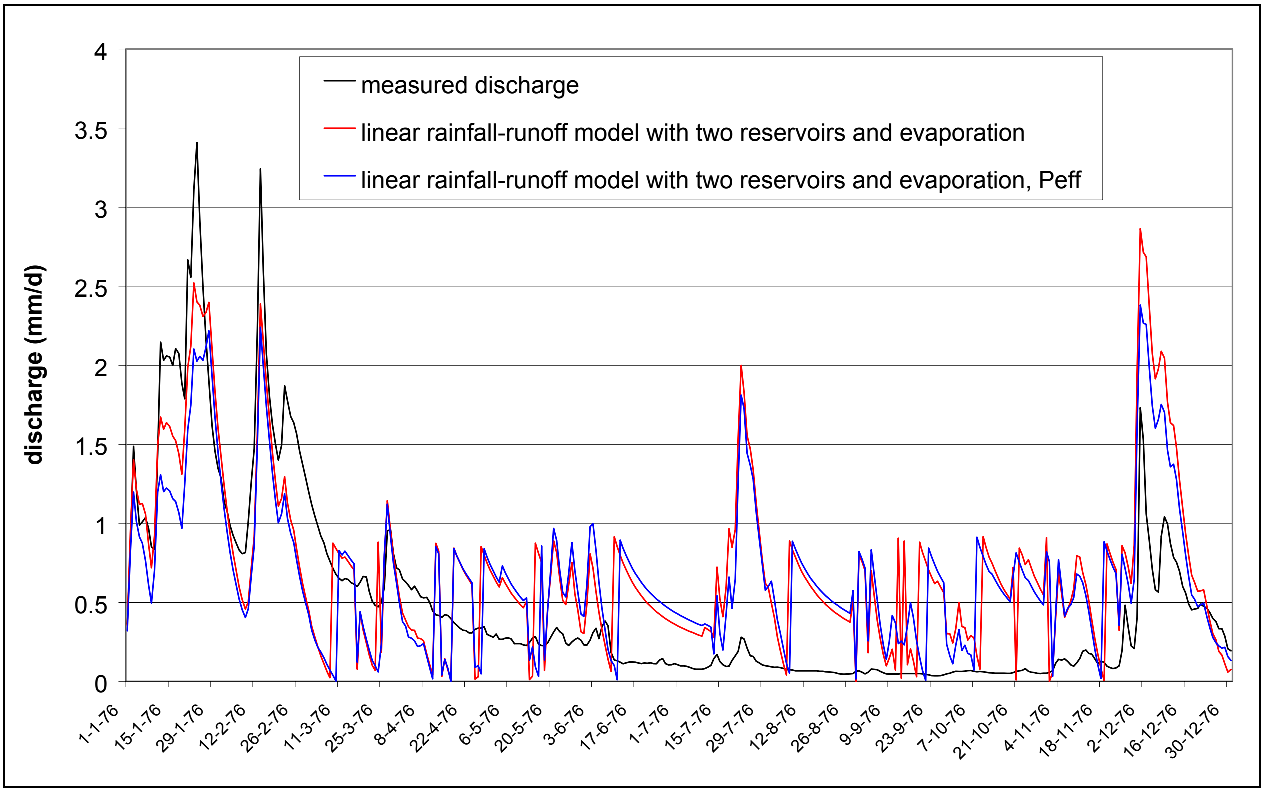


Figure 5.20 Hydrograph of the measured discharge and the simulated discharge of both runs with the linear rainfall-runoff model with two reservoirs and evapotranspiration.

5.6.2 Validation period

Table 5.11 shows the results for both runs with the linear rainfall-runoff model with two reservoirs and evapotranspiration data.

For the first run, the results are a little bit better for the validation period than for the calibration period. This difference was already seen before in the simulations of the other models. The results for the second run are almost the same for the validation as for the calibration period.

Table 5.11 The values of the parameters, efficiency coefficients and relative differences for the two runs with the linear rainfall-runoff model with two reservoirs and evapotranspiration for the validation period.

	Linear rainfall-runoff model with two reservoirs and evapotranspiration	
	P	Peff
α (mm)	-0.8634	-0.8474
β (–)	0.0295	0.0291
γ (–)	0.4525	0.5161
δ (–)	0.5187	0.4145
k1 (d)	8.0023	7.0380
k2 (d)	49.9969	47.9974
R^2 (-)	0.6261	0.5573
RDq (%)	4.3513	1.5828

Chapter 6 HBV model description and results

In this chapter, the description of the HBV model, section 6.1, and the results of the simulations section 6.2) will be shown.

6.1 The HBV model

The HBV-model is a conceptual rainfall-runoff model, developed at the Swedish Meteorological and Hydrological Institute (SMHI) in Norrköping in Sweden by Bergström (1976). For this study the HBV96 IHMS, version 4.4 is used, described in detail by SMHI (1999). This is the most recent version.

The model simulates river discharge using precipitation, temperature and potential evapotranspiration as input and is semi-distributed, since differences can be made between forested and non-forested areas and areas with different altitudes.
A basin can be subdivided into several subbasins and the parameters can as well be specified for each subbasin as for the basin as a whole. A schematic overview of the model is shown in figure 6.1.

The model consists of 6 modules, as can be seen in figure 6.1
-Precipitation routine: representing rainfall, snow accumulation and snow melt
-Soil moisture routine: determining overland and subsurface flow and actual evapotranspiration
-Fast runoff routine: representing stormflow
-Base flow routine: representing base flow
-Transformation function: for flow delay and attenuation
-Routing routine: flow through river reaches

The difference with the linear rainfall-runoff model with two reservoirs and evapotranspiration or the linear rainfall-runoff model with two reservoirs with effective precipitation as input are a third reservoir in the soil routine, a transformation function and a calculation for snowfall and snowmelt.

In the next sections the first five routines will be described. The Routing routine, used if several catchments are connected to each other, will not be described in this report, since only one single catchment is used in this research. A description of this routine can be found in SMHI, 1999.

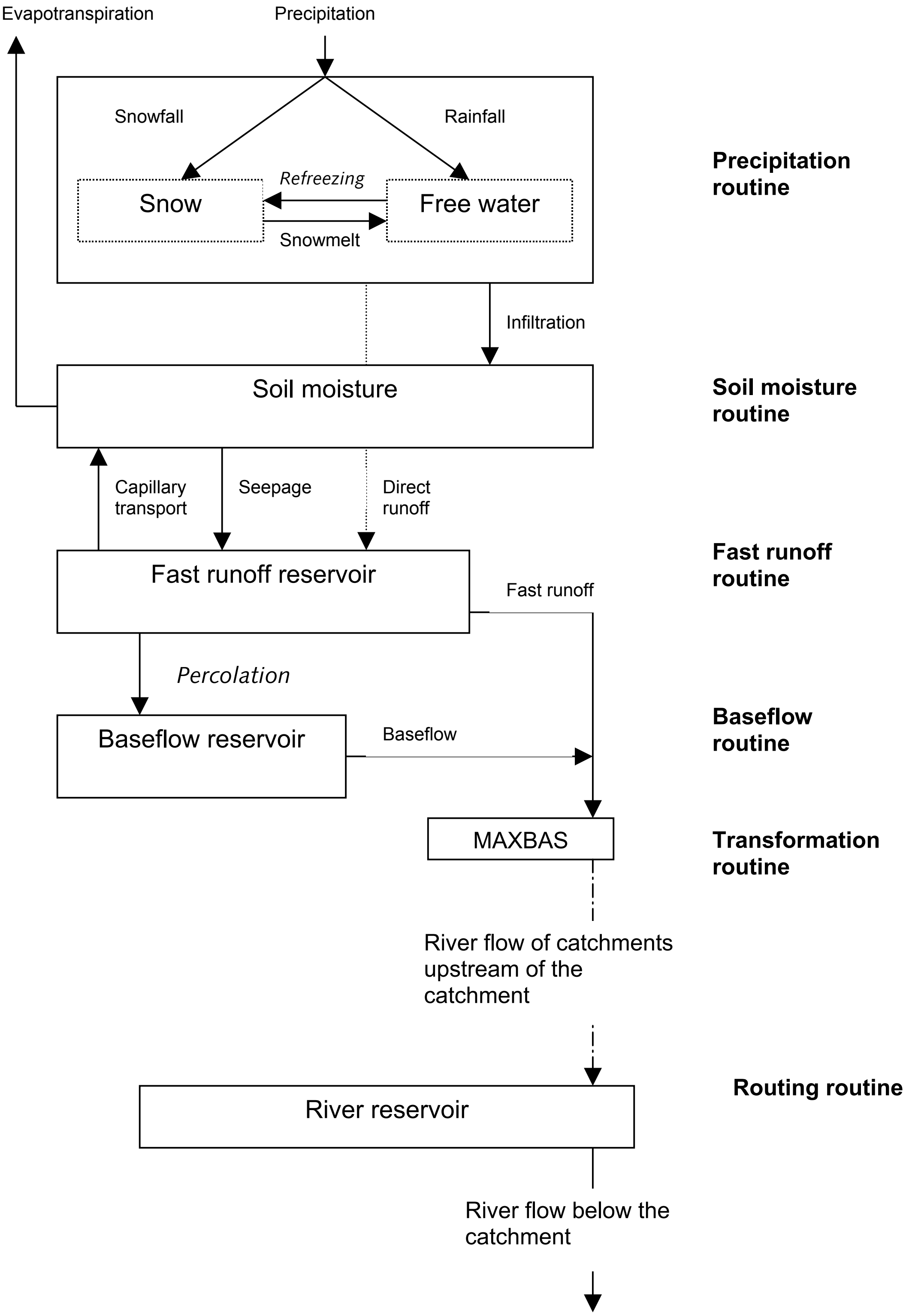


Figure 6.1 Schematisation of the HBV model with six routines

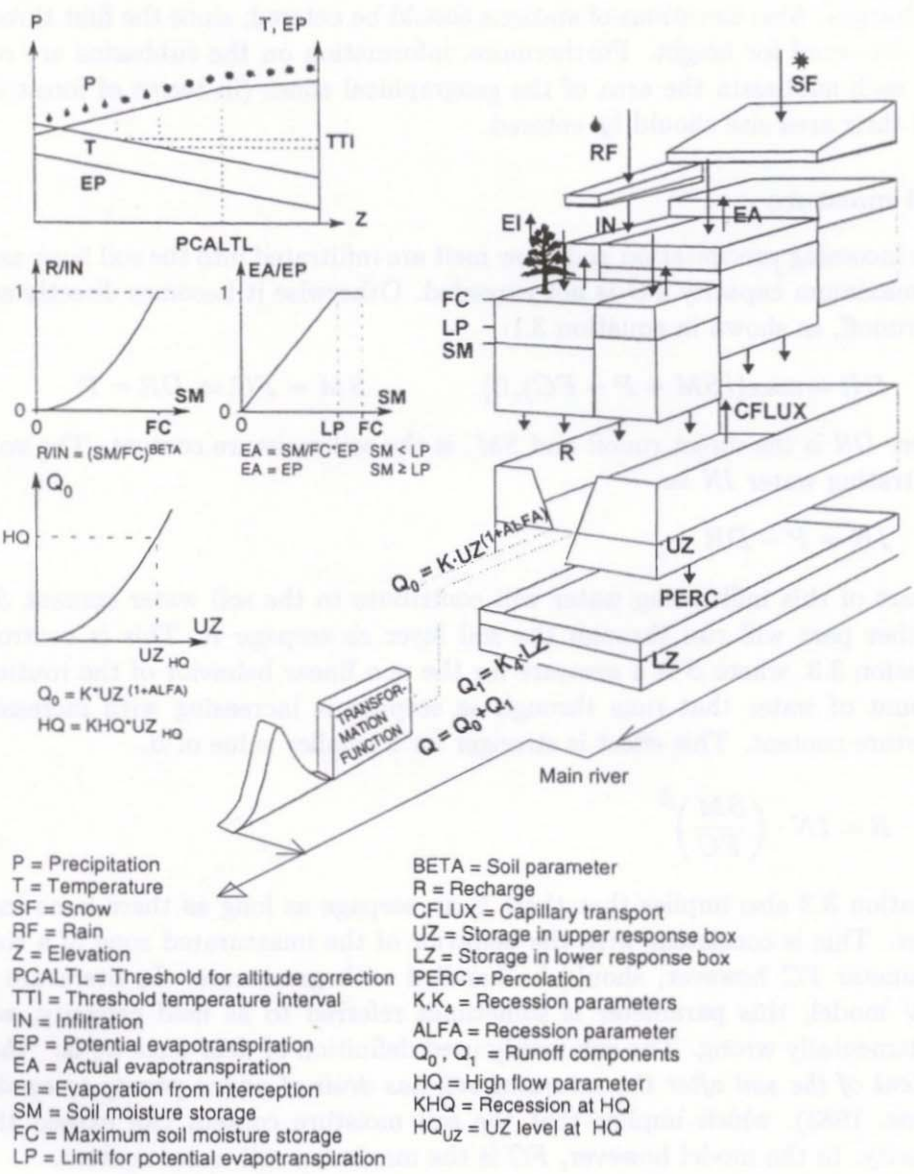


Figure 6.2 Structure of the HBV model (source: SMHI, 1999)

6.1.1 Precipitation routine

Precipitation can occur as rainfall or snowfall. Snowfall occurs if the air temperature T [°C] is below a defined temperature TT [°C] and rainfall occurs if $T > TT$ (figure 6.2). Snowfall is added to the dry snow reservoir (within the snow pack) and rainfall is added to the free water reservoir, which represents the liquid water content of the snow pack. Interactions between these two components take place through snowmelt and refreezing.

$$snow\ \ melt = CFMAX \cdot (T - TT) \tag{6-1}$$

$$refreezing\ melt\ water = CFR \cdot CFMAX \cdot (TT - T) \tag{6-2}$$

$CFMAX$ = melting factor [mm/(d x °C)]
CFR = refreezing factor [-]

The free water reservoir content is at most equal to a specified fraction (0-1) of the water equivalent of the dry snow content. If this fraction is exceeded through rainfall or snowmelt, the water becomes available for the soil moisture routine.

6.1.2 Soil moisture routine

The amount of soil moisture in the catchment is computed with a soil moisture reservoir, representing the unsaturated zone (figure 6.2). The volume of soil moisture in this reservoir is symbolised by SM (soil moisture content). The maximum storage of the reservoir, the maximum soil water content of the reservoir, is represented by FC. The inflow of this reservoir is the precipitation and snowmelt, symbolised by P. The inflow is divided into direct discharge (DR, [mm/d]), indirect discharge or seepage (R, [mm/d]) and evapotranspiration (EA, [mm/d]). If the maximum soil moisture storage in the reservoir is exceeded ((SM+P)>FC), direct discharge occurs.

$$DR = \max\{(SM + P - FC),0\}\ SM = FC \Rightarrow DR = P \tag{6-3}$$

The volume of infiltrating water into the soil moisture reservoir (IN, [mm/d]) is:

$$IN = P - DR \tag{6-4}$$

A part of this infiltrating water will contribute to the soil moisture content SM, the other part will run through the soil layer as indirect discharge R.

The indirect discharge (R, [mm/d]) through the soil layer is determined by the amount of infiltrated water (IN) and the soil moisture content (SM, [mm]), through a power relationship with parameter β.

$$R = IN \cdot \left(\frac{SM}{FC}\right)^{\beta} \tag{6-5}$$

From this relation follows that the indirect discharge is increasing with increasing soil moisture content. For a smaller value of β, the increase is stronger. In equation 6-5 it is also assumed that as long as there is no infiltration, there is no indirect runoff. This is consistent with the behaviour of the unsaturated zone of a soil.

The amount of water that does not run off is added to the soil moisture.

The third outflow of this routine is the actual evapotranspiration (EA, [mm/d]), computed with the potential evapotranspiration (EP, [mm/d]).

$$EA = \frac{SM}{LP \cdot FC} \cdot EP \qquad SM < LP \tag{6-6}$$

$$EA = EP \qquad SM \geq LP \tag{6-7}$$

where LP (limit for potential evapotranspiration) is a fraction between 0 and 1. The actual evapotranspiration is thus equal to the potential evapotranspiration if the actual soil moisture is above a specified threshold (LP).

The general effect of the soil routine is a small contribution to the runoff from rain or snow melt if the soil is dry, and a great contribution during wet conditions. The actual evapotranspiration decreases as the soil dries out.

6.1.3 Fast runoff routine

The outflow of the soil moisture routine, $DR + R$, is available for the fast and base flow routine. The runoff delay is simulated through the use of two reservoirs. One reservoir represents fast runoff (overland flow and interflow) and the other represents baseflow. The direct (DR) and indirect discharge (R) percolate into the baseflow reservoir, until the baseflow reservoir gets saturated and a specific threshold (PERC, [mm/d]) is exceeded, the redundant water flows into the fast runoff reservoir. The fast runoff out of this (fast) reservoir Q_0 into the river network is defined as follows

$$Q_0 = K \cdot UZ^{(1+\alpha)} \tag{6-8}$$

where UZ is the storage in the fast runoff reservoir [mm], α a measure for the nonlinearity of the reservoir [-] and K a recession coefficient [d^{-1}]. The recession coefficient K is determined by using α and two additional parameters hq and khq, representing respectively a high flow rate [mm/d] and a recession coefficient [d^{-1}] at a corresponding reservoir volume [mm].

Parameter hq is determined by:

$$hq = khq \cdot UZ_{hq} \tag{6-9}$$

The parameter hq is a peak flow, and khq the corresponding recession coefficient. The high flow rate hq can be directly derived from observed average flow rate mq and average annual maximum flow rate mhq (both in mm/d)

$$hq = \sqrt{mq \cdot mhq} \tag{6-10}$$

The combination of equation 6-8, 6-9 an 6-10 with chosen α and khq finally gives recession coefficient K

Another process in this routine is the capillary upward transport into the soil moisture reservoir. The capillary flow [mm/d] depends on the amount of water stored in the soil moisture zone. The parameter $CFLUX$ [mm/d], a maximum value of capillary flow, determines a limitation for the capillary flow. The capillary flow depends on the soil moisture deficit, the difference between FC (maximum storage of the soil moisture reservoir, [mm]) and SM (storage in the soil moisture reservoir, [mm]). If the difference is positive, a fraction of $CFLUX$ will flow capillary upward.

$$capillary\ flux = CFLUX \cdot (FC - SM) / FC \tag{6-11}$$

It should be noticed that the actual evapotranspiration and the capillary flux are both a function of the maximum storage of the soil moisture reservoir.

6.1.4 Baseflow routine

The baseflow Q_1 [mm/d] out of the baseflow reservoir is the second part of the response function. The reservoir represents the groundwater storage of the catchment contributing to the baseflow. The recession coefficient K_4 [d^{-1}] is the only calibration parameter of this linear reservoir. The baseflow is represented by the following equation:

$$Q_1 = K_4 \cdot LZ \tag{6-12}$$

in which LZ is the water level in the reservoir [mm].

6.1.5 Transformation routine

The total discharge $Q = Q_0 + Q_1$ can be further transformed to get a proper shape of the hydrograph by using a transformation function. The transformation function is a simple filter technique with a triangular distribution of the weights, which is controlled by the parameter $MAXBAS$, see figure 6.3. A value of 1 distributes the runoff of a certain day over the same day. A higher value of $MAXBAS$ will distribute the runoff of one day over a larger period of time. This procedure results to a delay in the subbasin discharge.

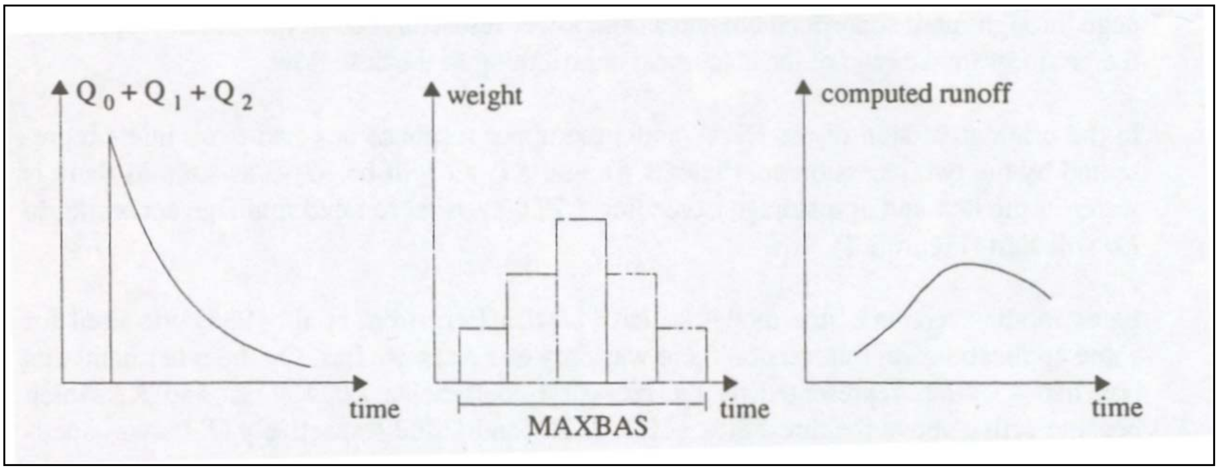


Figure 6.3 The transformation function (SMHI, 1999)

6.2 The results of the HBV model

In this chapter the results of the HBV model will be shown and discussed.

A lot of research is already done with this model, of which two studies of HBV application in the Ourthe catchment. The first study, by Velner (2000), concentrated on the temporal scale for simulation of high discharge events. From this study it can be concluded that a timescale of 6 hours is optimal for predictions of extreme events in the Ourthe. In the second study, by Booij (2001), an appropriate spatial model scale was determined for the assessment of the impact of climate change on river flooding in the Meuse basin. From this study can be concluded that a spatial model resolution of 10 km^2 is appropriate. As explained in chapter 3, the input data used in these studies is different from the input data used in this study. If the input data of Wójcik and Buishand from the KNMI used as input for the model with the parameters of the studies done before, the efficiency values (R^2) are lower and the relative difference in total discharge is very high (see table 6.1). To obtain a better result of the simulation of the model with the KNMI input data, the model was calibrated with these input data. Table 6.1 shows in the first column the parameter values of the research of Velner and the results of the model with these parameters and the input of the meteorological data, delivered by the KNMI. In the second column the results of the model with the parameters of the study of Booij for this catchment and the KNMI input data are shown. In the last column, the third column, the parameters of the calibration and the results of the calibration and validation of the model with these parameters for the KNMI input data are shown. In the next section, section 6.2.1, a short description will follow about the changed parameters in the calibration and why these were changed.

Table 6.1 Parameter sets for the HBV model

	1	2	3
Parameter	**Value**	**Value**	**Value**
fc	180	180	200
lp	0.66	0.71	0.53
beta	1.8	1.5	1.8
cflux	1.3799	1.3799	2
khq	0.1	0.116	0.116
alfa	1.1	1.1	1.1
hq	3.4	3.27	3.4
k4	0.02307	0.025	0.02307
perc	0.4	0.4	0.4
maxbas	1	1	2
sfcf	1.01758	1.01758	1.01758
fosfcf	0.8	0.8	0.8
cfmax	3.75653	3.75653	3.75653
tt	-1.41934	-1.41934	-1.41934
dttm	0.54391	0.54391	0.54391
rfcf	0.99714	0.99714	0.99714
tti	1	1	1
pcorr	1	1	1
pcalt	0	0	0
tcalt	0.6	0.6	0.6
focfmax	0.6	0.6	0.6
cfr	0.05	0.05	0.05
whc	0.1	0.1	0.1
cevpl	1	1	1
recstep	999	999	999

critstep	1	1	1
ecorr	1	1	1
sfdistfi	0.5	0.5	0.5
sclass	1	1	1
sfdistfo	0.2	0.2	0.2
cevpfo	1.15	1.15	1.15
ecalt	0	0	0
Calibration			
start	19700101	19700101	19700101
end	19841231	19841231	19841231
R2 (-)	0.76112	0.73587	0.81358
acc. Diff. (mm)	582.1303	884.0849	-5.09807
rel. acc. Diff. (-)	0.08872	0.13473	-0.00078
Validation			
start	19850101	19850101	19850101
end	19961231	19961231	19961231
R2 (-)	0.88066	0.8659	0.91448
acc. Diff. (mm)	246.7312	496.116	-231.30238
rel. acc. Diff. (-)	0.04654	0.09358	-0.04363

6.2.1 Recalibration of HBV with new meteorological data

A study about the sensitivity of the parameters of the HBV model was already done by Velner (2000). The results of this study were used to change the parameters to give a better fit of the model, with the KNMI data as input.
The main aim of the new calibration was, to find a smaller value for the accumulated difference between simulated and measured discharges. The accumulated difference is very high, if the parameters of the studies of Booij and Velner are used, as can be seen in table 6.1.
A second point of attention are the peak events, which are simulated one day to early.

The calibration procedure is started with the parameters as used by Velner, since these showed already better results (table 6.1) and the sensitivity analysis's of the parameters are already done by Velner (2000).

In the calibration procedure, the values of the parameters cflux and FC were changed to a higher value and the value of the parameter LP was lowered. The parameter cflux is a maximum value for capillary flow in mm/d, the parameter FC stands for the maximum soil water content of the upper reservoir, the reservoir in which the soil moisture routine takes place and the parameter LP stands for a limit for potential evapotranspiration. In section 6.1 all the routines of the HBV model are already described.

Figure 6.4 shows the graph of the sensitivity analysis for the parameter cflux. It can be seen that a change of the value of this parameter has no influence on the value of the efficiency coefficient R^2, only on the accumulated difference. A higher value for cflux decreases the accumulated difference. If the value of the parameter cflux is changed to a higher value, means that the maximum value for the capillary flux is also changed to a higher value.

The parameter FC (the maximum soil water content) influences the capillary flux and the actual evapotranspiration. Figure 6.5 shows the sensitivity analysis for this parameter. There can be seen that a higher value for FC decreases the accumulated difference, but for the value of R^2 an optimum can be found for a value of 170 for FC. A higher value for FC causes a lower actual evapotranspiration (equation 6-6). The actual evapotranspiration is also influenced by the parameter LP (limit for potential evapotranspiration). If LP has a lower value, the actual evapotranspiration is higher. By changing both parameters FC and LP to a lower, respectively higher value, the influence of changing these parameters on the actual evaporation can be minimized. The sensitivity analysis for the parameter LP, figure 6.6, shows that a lower value of LP decreases the accumulated difference. For the value of R^2 an optimum can be found for the parameter LP, around the value 0.66. Changing the value of the parameter LP to a lower value, but not a lot, changes the value for the R^2 not a lot, but the influence for the accumulated difference is large. If the value of the parameter FC is also not changed too much, a change in actual evaporation is also not very large and this change causes a lower accumulated difference.

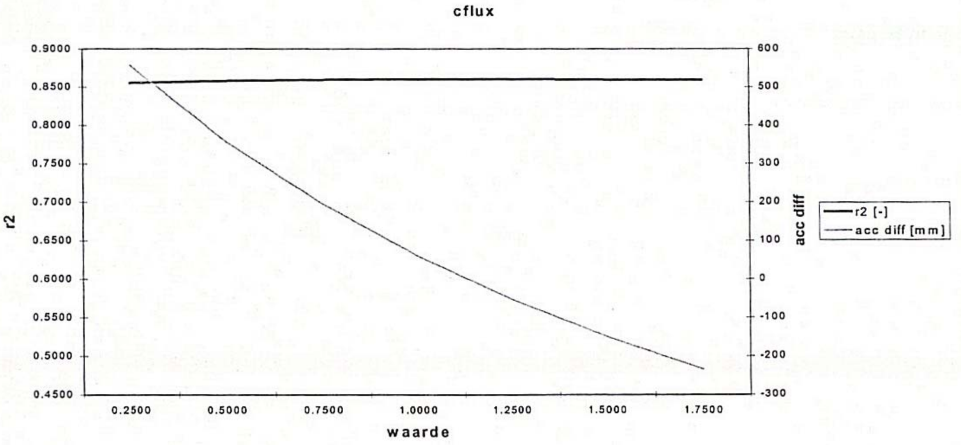


Figure 6.4 Sensitivity analyses cflux (source: Velner, 2000)

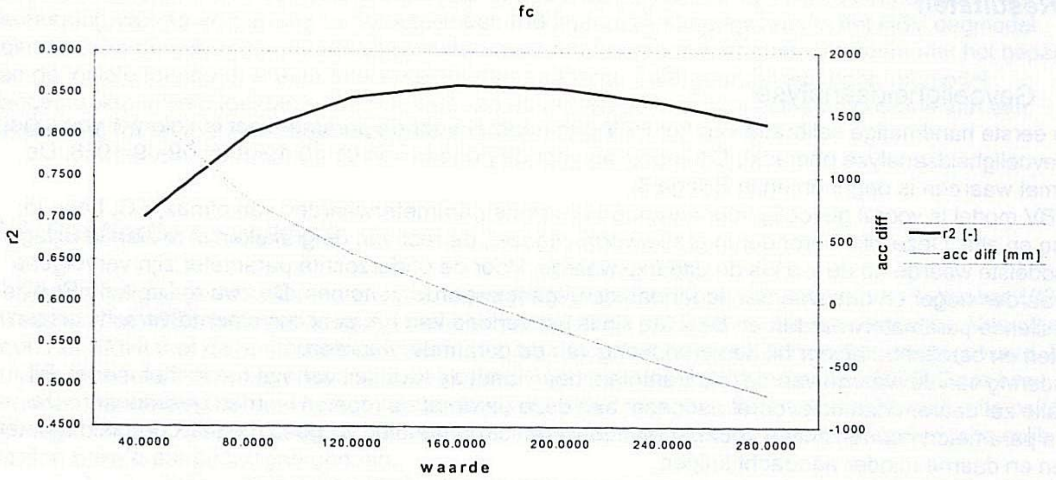


Figure 6.5 Sensitivity analyses fc (source: Velner, 2000)

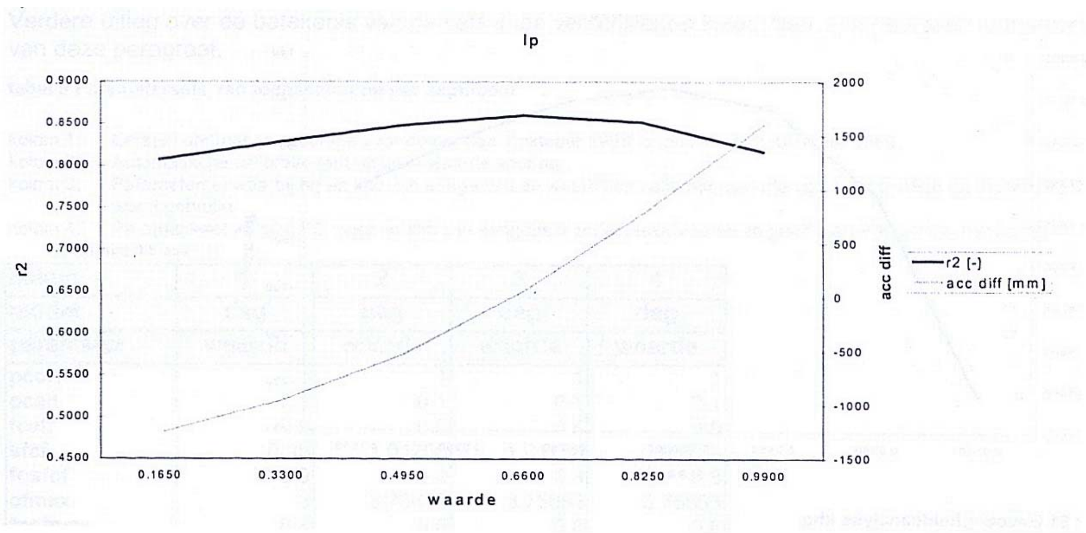


Figure 6.6 Sensitivity analyses lp (source: Velner, 2000)

The value of the parameter maxbas was also changed in the calibration. The reason for this can be seen in figure 6.7. The peaks are earlier simulated in model run 1 and 3a than measured. If the parameter maxbas is changed to a value 2, these peaks are simulated at the same time (model run 3b). Table 6.2 shows the change in R^2 and accumulated difference between the two simulations with a maxbas of 1 (number 3a) and with a value for maxbas of 2 (number 3b), for the simulation of the HBV model in which the other parameters (FC, LP and cflux) are already changed.

Table 6.2 The values of the parameters, efficiency coefficients and (relative) accumulated differences for runs with different parameters with the HBV model for the calibration period.

	1	3a	3b
Parameter	Value	Value	Value
fc	180	200	200
lp	0.66	0.53	0.53
cflux	1.3799	2	2
maxbas	1	1	2
Calibration			
start	19700101	19700101	19700101
end	19841231	19841231	19841231
R^2 (-)	0.76112	0.77595	0.81358
acc. Diff. (mm)	582.1303	-4.6973	-5.09807
rel. acc. Diff. (-)	0.08872	-0.00072	-0.00078

Figure 6.8 shows the total hydrograph of the calibration period for the measured and simulated discharge (model run 3b). For some of the peak events, the simulated discharges are to high, but the timing of these peaks is very good. Figure 6.9 shows some of the graphs as can be displayed in the HBV model for the years 1970-1976.

It can be concluded that the results of the new calibrated HBV model with the KNMI data as input are very good. A value for the efficiency coefficient R^2 of 0.81 is reached and the accumulated difference is changed into a difference of only –5 mm, which is 0.08%.

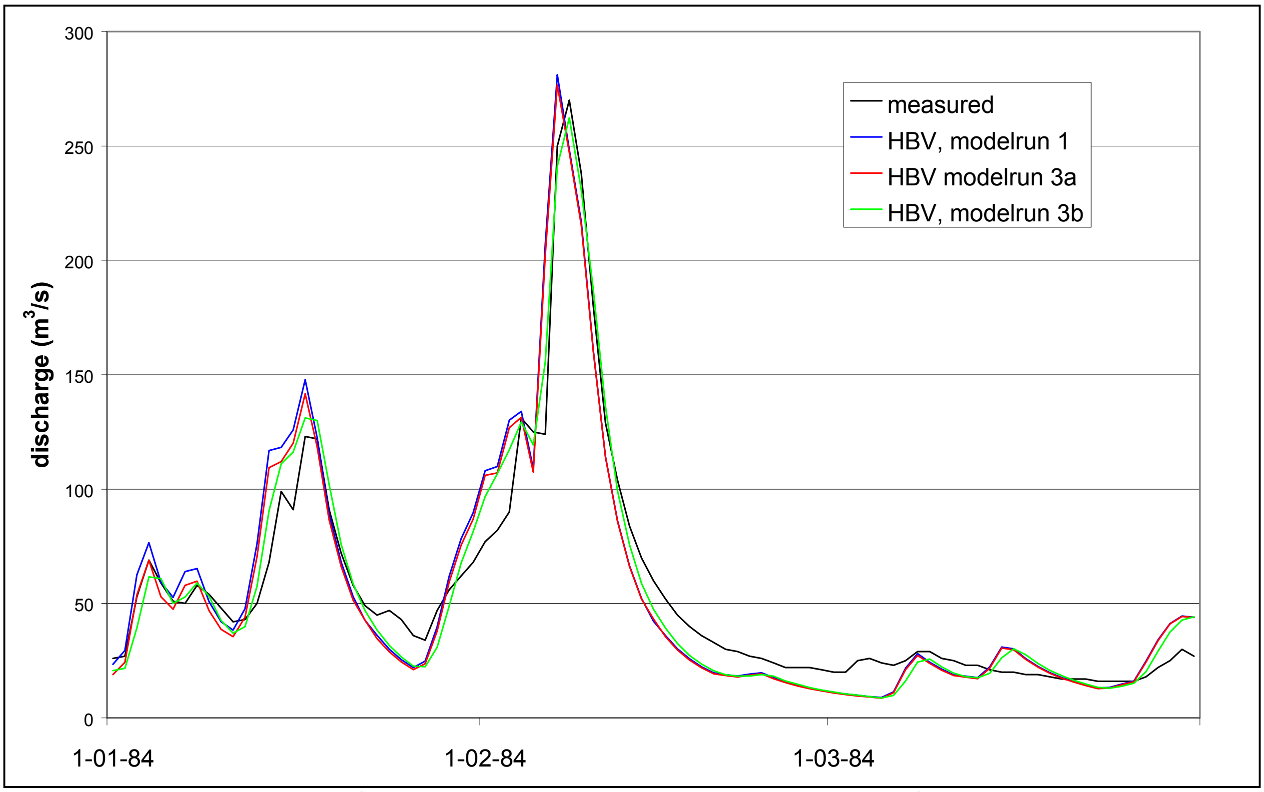


Figure 6.7 Hydrograph of the measured and simulated discharge of model run 1, 3a and 3b for the months January, February and March in the year 1984.

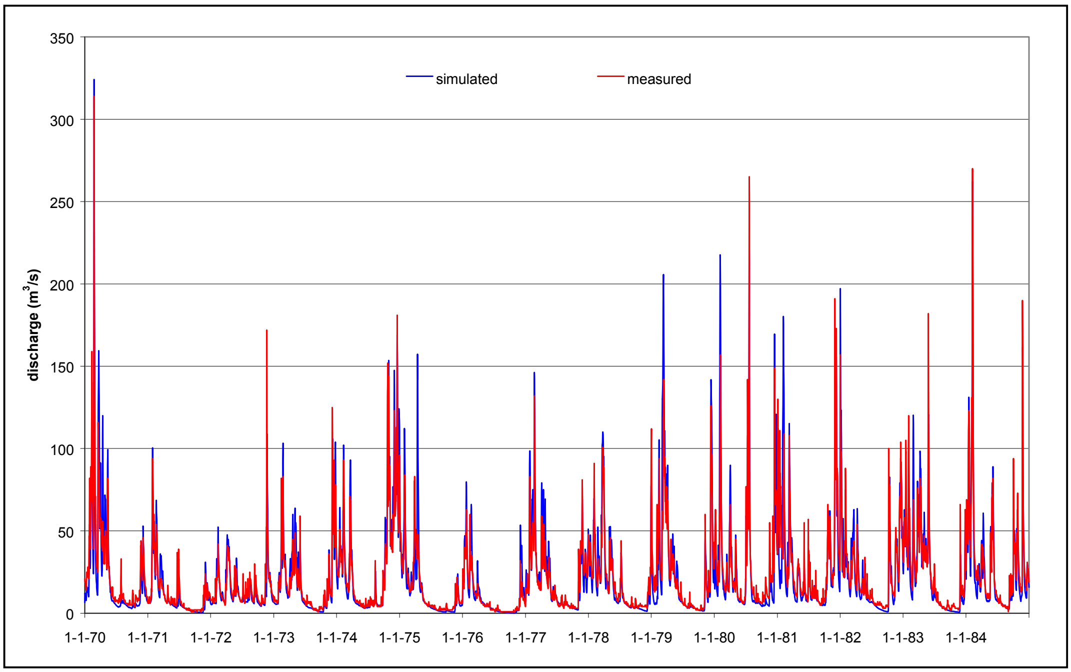


Figure 6.8 Hydrograph of the measured and simulated discharge (model run 3b) for the total calibration period

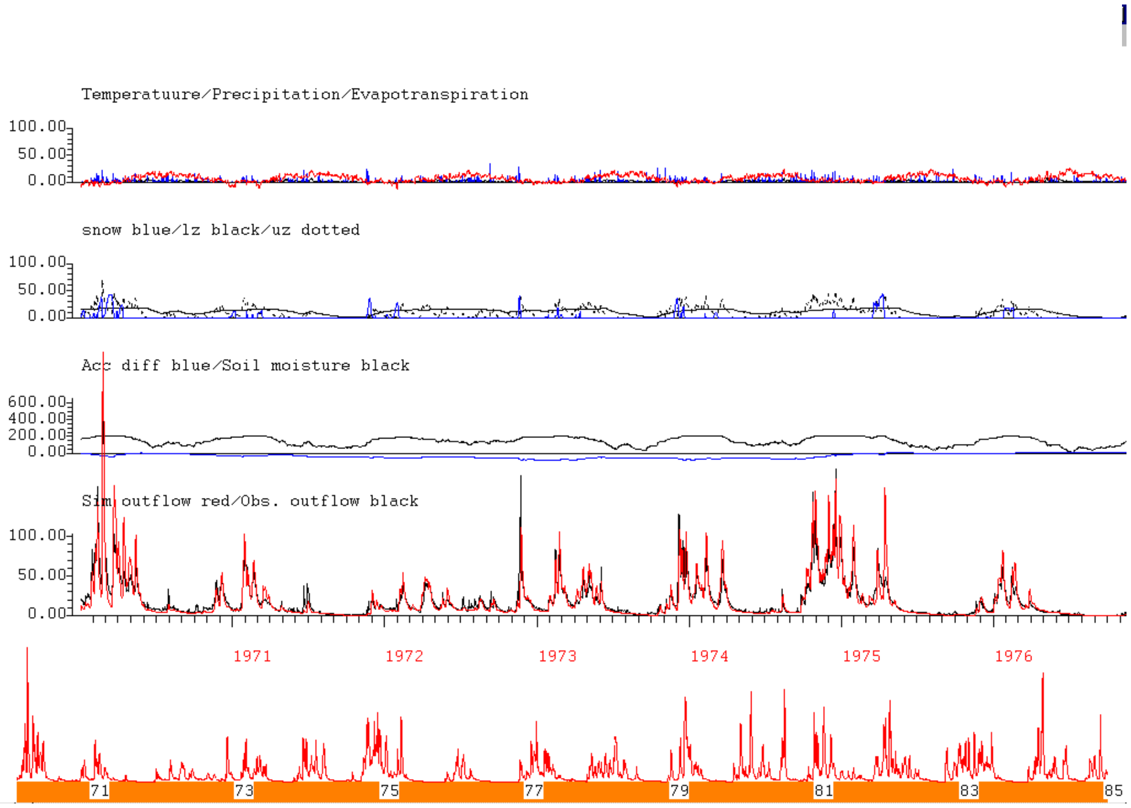


Figure 6.9 The results of the simulation with the HBV model for the years 1970-1976, as displayed in the model HBV

6.2.2 Validation period

For the validation period 1985-1996, very good results can be found with the new values for the parameters in the HBV model. The R^2 of Nash and Sutcliffe has a value of 0.91 for the validation. This means that the model gives a very good result with an efficiency of 0.91. The accumulated difference is not low, as can be seen in table 6.1, with a value of 231 mm (4%). This difference in accumulated differences is still low for the validation. In the simulations with the other “simple” models, high values for the relative difference were also found for the validation period. Figure 6.10 shows a graph of the measured and simulated results with the “old” and “new” parameters (model run 1 and 3b) for the peak event in January, February 1995. The peaks of the event are at the same time for the measured and “new” simulated discharge. Figure 6.11 shows the hydrographs of the measured and “new” simulated discharge for the total validation period.

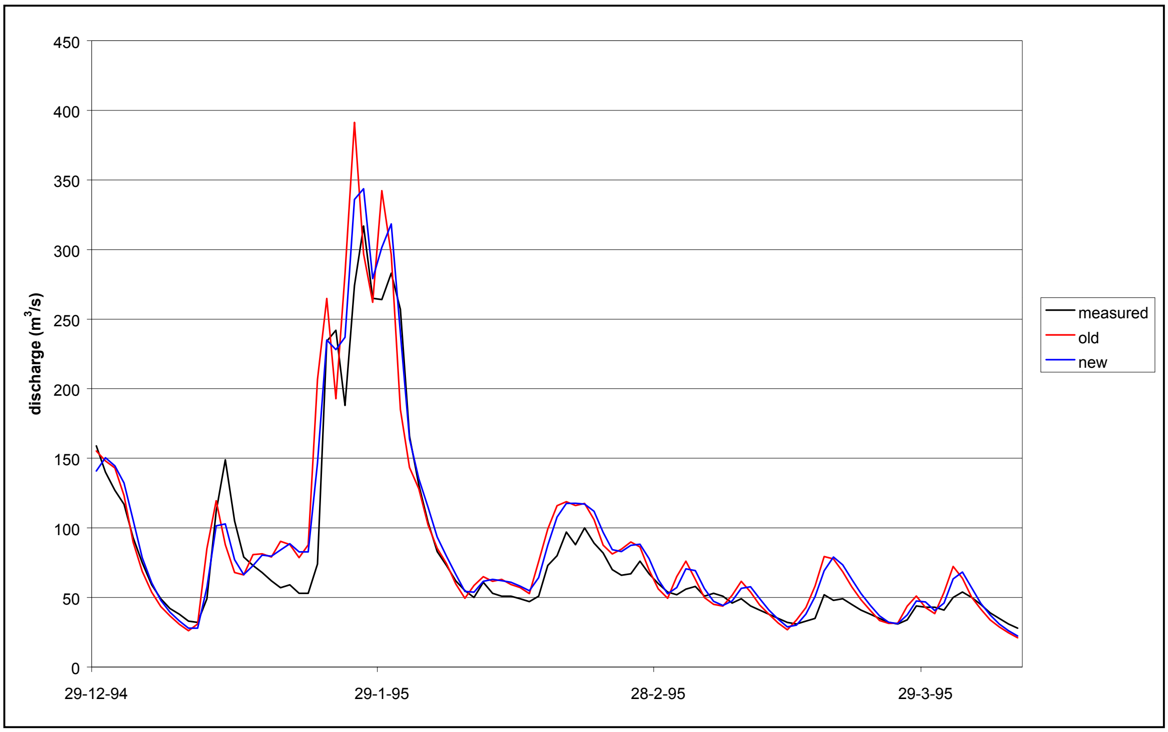


Figure 6.10 Hydrograph of the measured and simulated discharges (model run 1 and 3b) for the peak event in January/February 1995

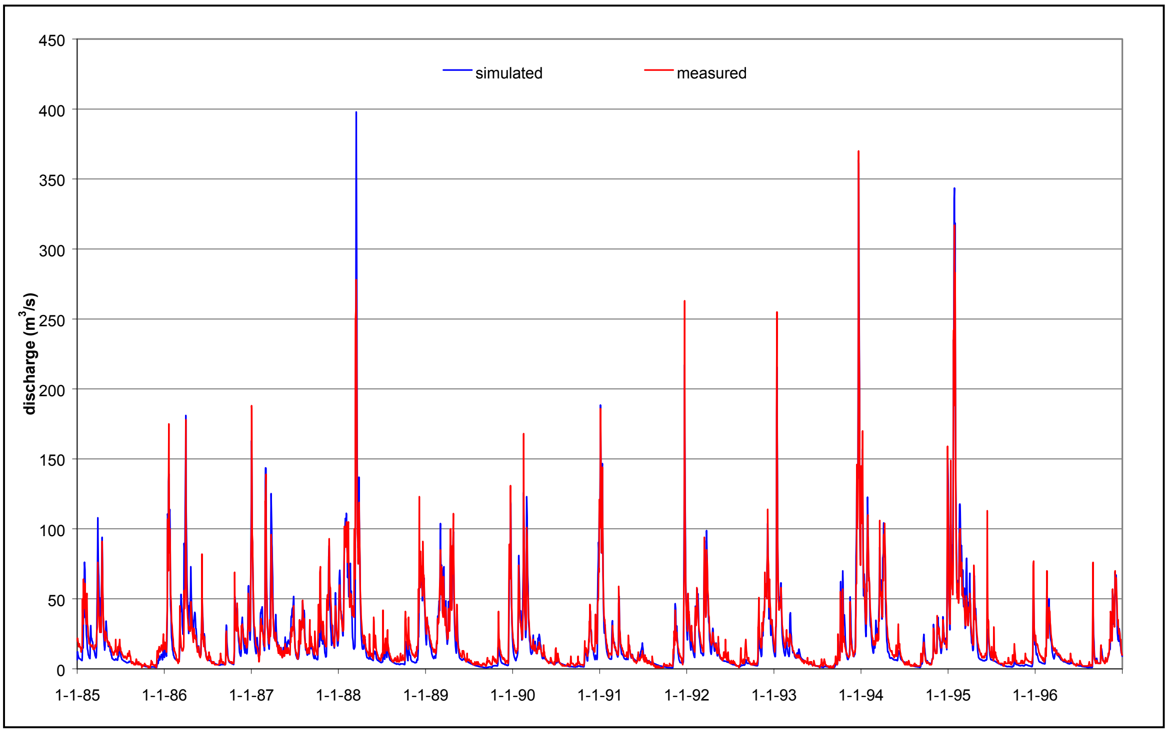


Figure 6.11 Hydrograph of the measured and simulated discharge (model run 3b) for the total validation period

Chapter 7 Comparison and discussion of the model results

The main objective of this research is to analyse if a simple model, which looks like a part of the HBV model, gives already almost the same as the HBV model for the Ourthe catchment. In order to do so, a model is being build up in different stages, step by step, starting from a very simple model, with a relative complex model as the final. In each step a certain conceptual process is being added to the model, so the effect of each process to the simulation of the discharge in the model can be determined.

In this section, a summary and an interpretation of all the results of all the models will be given. In appendix E, a table with all the efficiency coefficients and relative differences in total discharge can be found. Figure 7.1, 7.2 and 7.3 show these results in a graphical overview. First the efficiencies of the models will be compared and discussed (section 7.1), followed by the relative differences in total discharge (section 7.2) and the cumulative discharges (section 7.3). A comparison and discussion of the different additions in the simple models will follow in section 7.4 and some limitations for the results will be discussed in the last sections of this chapter, section 7.5.

7.1 Efficiency coefficients

Figure 7.1 shows the efficiency coefficients for each model simulation for the calibration and validation. The difference between the results of the “simple” models and the HBV model is very obvious. The values of the efficiency coefficients for the HBV model are the highest.

Comparing the results of the “simple” models, there can be seen that the addition of a linear function causes a large change in efficiency. This large change is also caused by the use of the effective precipitation as input for the model. The addition of a linear reservoir gives a better result, but not significantly. A second reservoir added to the model, doesn’t have large influence on the efficiency of the model. The last addition, another method of effective precipitation changed a lot, comparing the results of this model with the results of the linear rainfall-runoff model with two reservoirs and normal precipitation as input. The calibration of the HBV model changed the results for the efficiency of the HBV model also quite a lot (old and new).

From this figure can also be seen that the values of the efficiency coefficients are always higher for the validation period than for the calibration period. This is not expected, since the optimalisation of the model is done for the calibration period and not for the validation period. A possible reason for this could be the input data. It can be that these data are more suitable for the model process for the later period.

Another point of interest is the difference in the values of the efficiency coefficients of the “simple” model between the runs with effective precipitation as input and the model runs with total precipitation as input. These values are higher for the runs with effective precipitation as input, except for the linear rainfall-runoff model with two reservoirs and evapotranspiration. Figure 7.2 shows this in another format, the line for the efficiency coefficient of the model runs with effective precipitation, as input, is always higher than the line for the model runs with precipitation as input, except for the last “simple” model. These results are caused by the potential evapotranspiration, which is taken into account for the calculation of the effective precipitation (section 3.4). In the last “simple” model is the effective precipitation calculated with an evaporation coefficient on a monthly bases, instead of a yearly bases, used in the runs of the other models. From these results, strong preferences can be made for using an effective precipitation, computed with an evapotranspiration coefficient, averaged over the total calibration period, and not averaged for each month over the total calibration period.

It should be noticed that the calculation of the evapotranspiration coefficient (computed from the difference between the total precipitation and the total discharge and divided by the total potential evapotranspiration) is not totally correct, since the influence of the storage components of the soil are not taken into account, creating a delay for the evapotranspiration and discharge. Since the calibration period, for which this evapotranspiration coefficient is calculated is large (15 years) this is being neglected.

Such a point of discussion about the delay in time between precipitation and discharge through evaporation and the filtering effect of storage in the soil can also be made for the linear rainfall-runoff model. In this model is the discharge a function of the precipitation during a period of T days, differing from 1 to 15 days. If a time period of 1 day is used, this means that all the precipitation is running out of the catchment during the same day, as discharge. Therefore, the model results for averaging 15 days are much better than for 1 day. In the next “simple”vmodel a reservoir is added to the model, so the delay and attenuation between precipitation and discharge was introduced.

Figure 7.2 shows also the differences in efficiencies between “peak” runs and “normal” runs with both linear-rainfall runoff model with reservoirs. In the “peak” runs, the simulated discharges for which the measured discharge had a value higher than 2 mm/d were emphasized (section 5.4.1). The efficiency coefficients are higher for the peak model runs for the validation, than for the validation of the “normal” model runs. Two explanations can be found for this. Either the number of days with a discharge above 2 mm/d during the validation period is higher or there has been a change in the recession curves for the validation period.
The number of days with a measured discharge higher than 2 mm/d for the calibration period is 990, for the validation period 720. Since both periods do not have the same number of days, also the number of days is taken into account. The calibration period counts 5478 days and the validation period 4382 days. Dividing the number of days with discharges above 2 mm/d by the number of days for each period, gives a value of 0.18 for the calibration period and 0.16 for the validation period. These values mean, that the chance of a discharge, higher than 2 mm/d is 18% for a certain day in the calibration period and 16% in the validation period. From these numbers can be concluded that the chance of a day with a measured discharge higher than 2 mm/d is not higher during the validation period, so there must have been a small change in the recession curves of the discharges between the calibration and validation period.

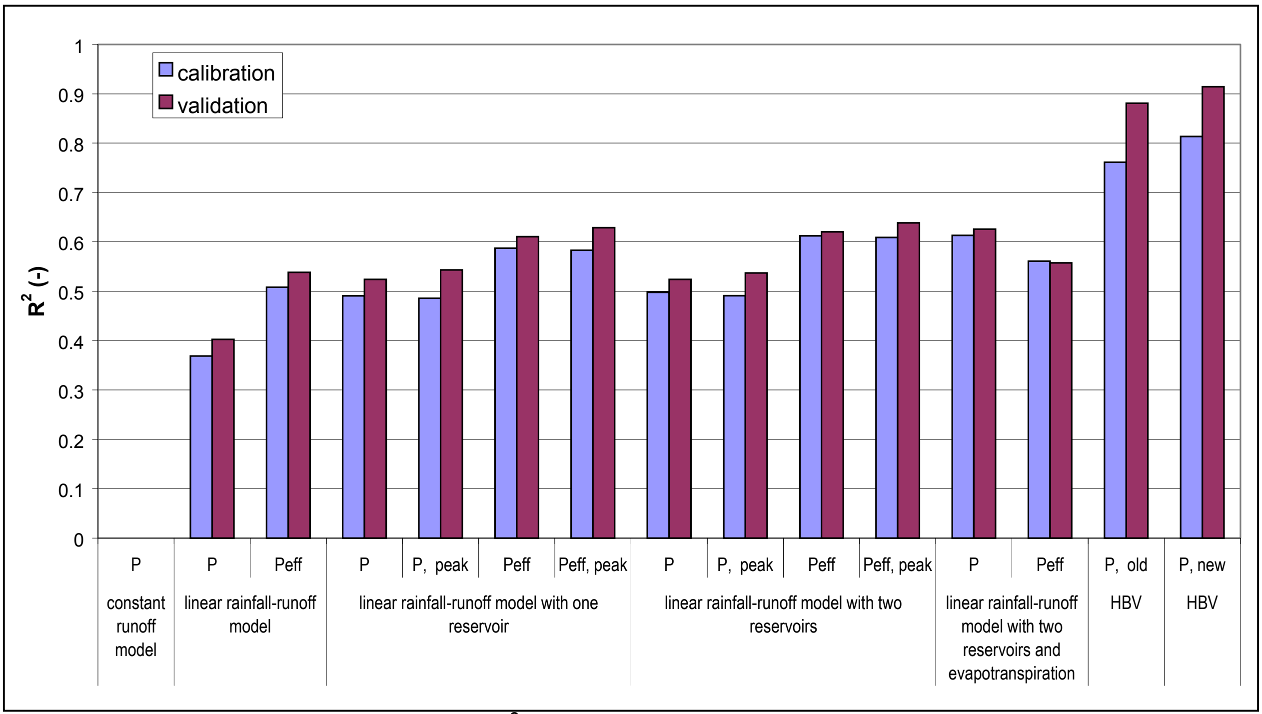


Figure 7.1 The efficiency coefficients R^2 for all model simulations

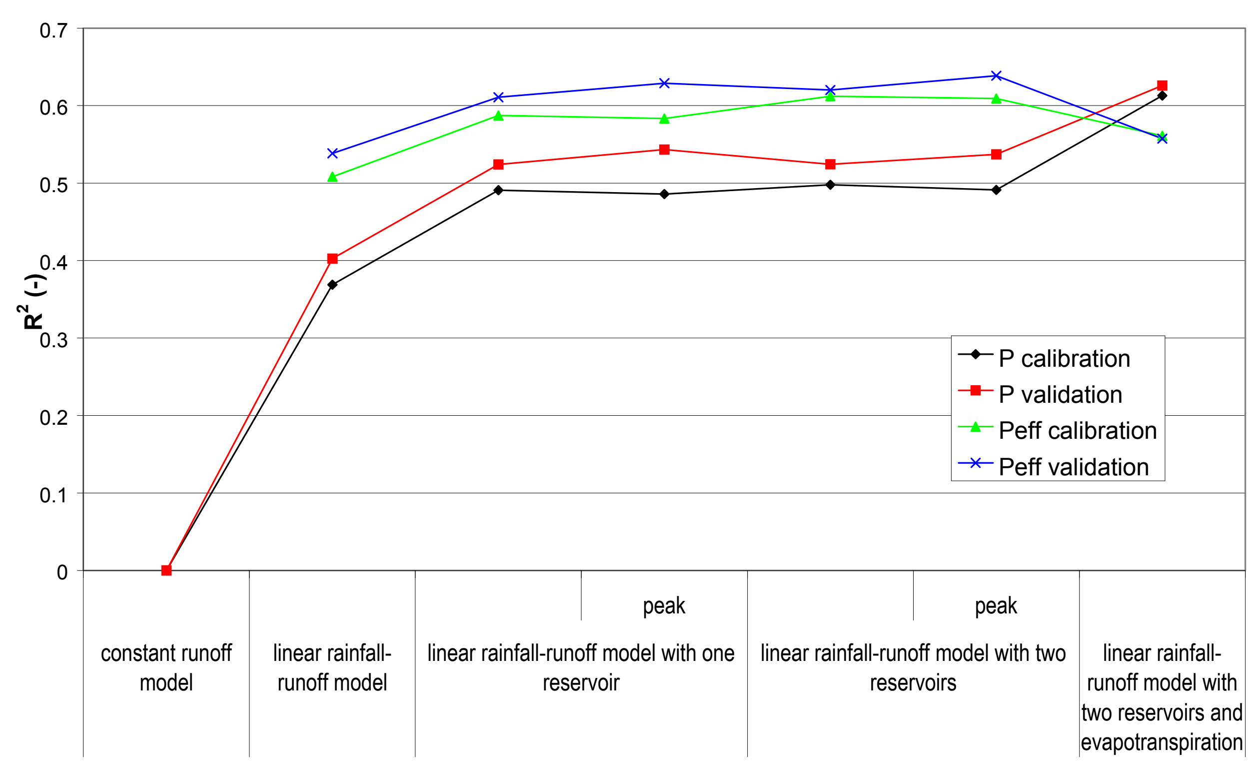


Figure 7.2 The efficiency coefficients R^2 for the model simulations of the “simple” models

7.2 Relative differences in total discharge

Figure 7.3 shows the values for the relative differences in total discharge. This is a value to judge if the water balance of the simulation is close to the water balance, as measured. The values are around 0 for all model simulations for the calibration period. For the validation period, the RDq values are sometimes negative, sometimes positive, but don't show a lot of difference for the water balance (absolute maximum around 4.5%).

The difference in relative discharge values between calibration and validation is due to the method of using the optimalisation function for the calibration of the model. This function is set to give parameters for the highest possible value of R^2 for which the relative difference is around zero. In the validation of the "simple" models, these parameters are just applied and no optimalisation takes place, so a difference between simulated and measured discharge occurs.

Remarkable is the difference in RDq percentages between the model run with "normal" precipitation and the run with effective precipitation for the linear rainfall-runoff model. The value of RDq for the last run is negative, which means that there is less discharge simulated than measured. A reason for this can be found in the calculation of the effective precipitation. In this calculation an evapotranspiration coefficient is used, based on the water balance of the calibration period (see section 3.4).
The evapotranspiration coefficient has a value of 0.93 for the calibration period and 0.87 for the validation period. Since the evapotranspiration coefficient of the calibration period is used for the validation period as well, more actual evapotranspiration is assumed than has happened in reality for this period. Therefore, less precipitation is used as input for the model than in reality, causing a negative relative difference of total discharge for the validation period. For the other "simple" models, the value of RDq is positive. A possible explanation for this can be found in the use of the reservoir and its restrictions.

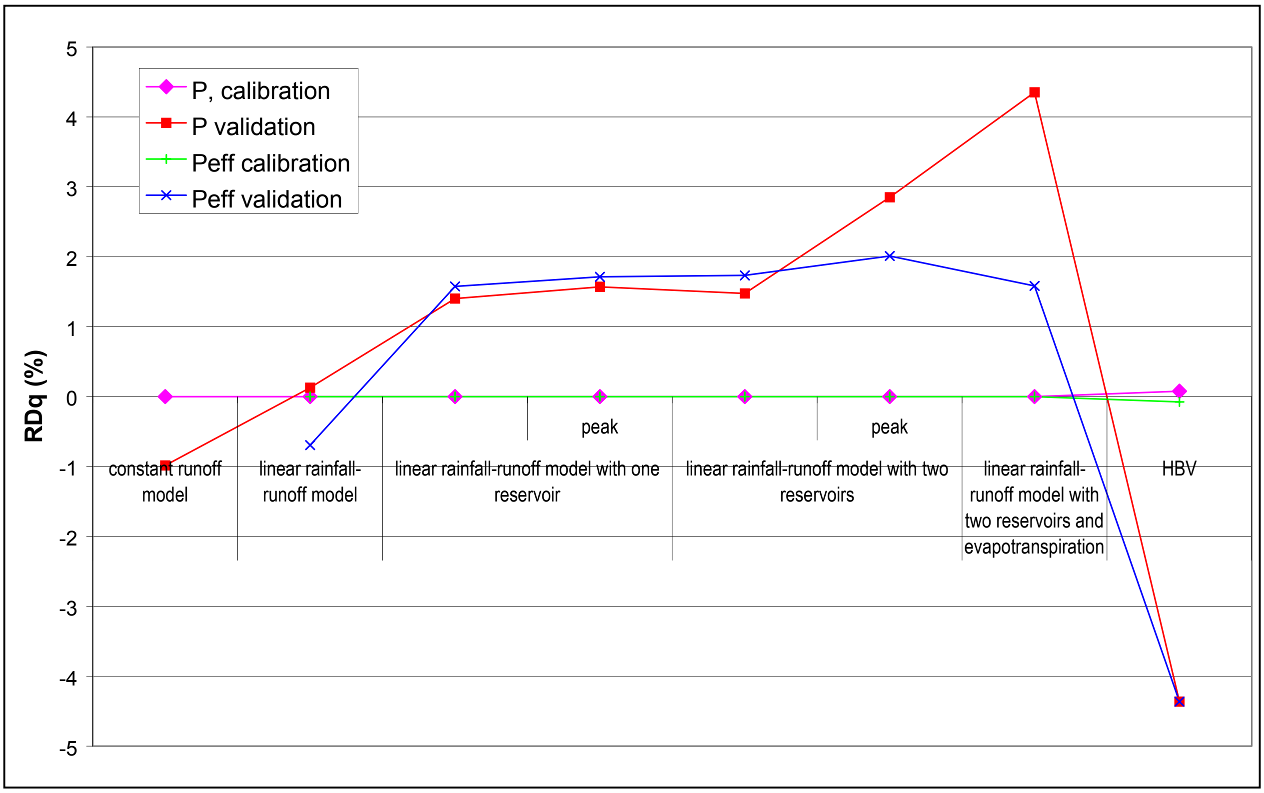


Figure 7.3 The relative differences in total discharge for all model simulations

7.3 Cumulative discharges

In figure 7.4 is the cumulative discharge from low discharge values to high discharge values plotted. Remarkable is the graph for the cumulative discharge of the simulation with the HBV model, lying at the other side of the graph of the measured discharge, than the graphs of the “simple” model simulations. There can be concluded that lower discharge values are overestimated in the “simple” models and higher values are underestimated. The graph for the HBV model shows the opposite result, low discharge values are underestimated and high discharge values are overestimated. The difference between the model run with the linear rainfall-runoff model with two reservoirs with effective precipitation as input and normal precipitation as input can also be seen in figure 7.5.

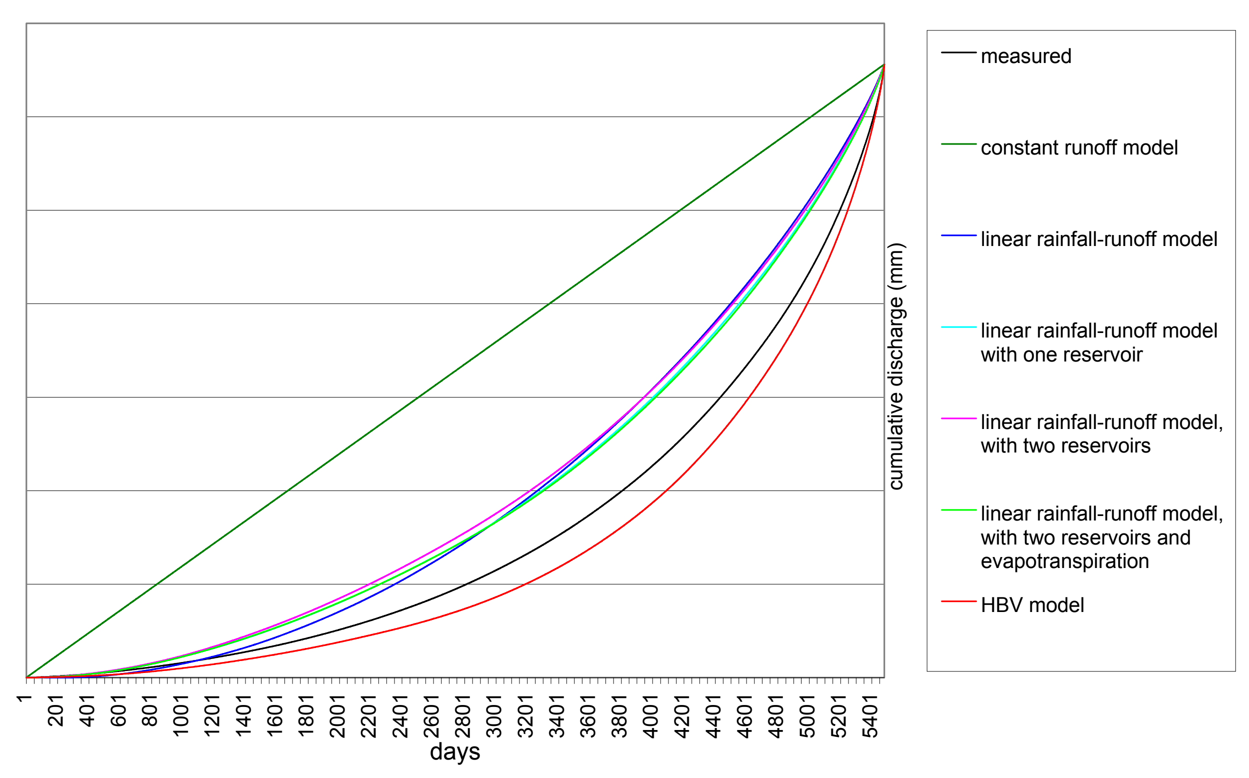


Figure 7.4 Cumulative discharge from low discharge values to high discharge values for the “simple” models with precipitation as input and the HBV model

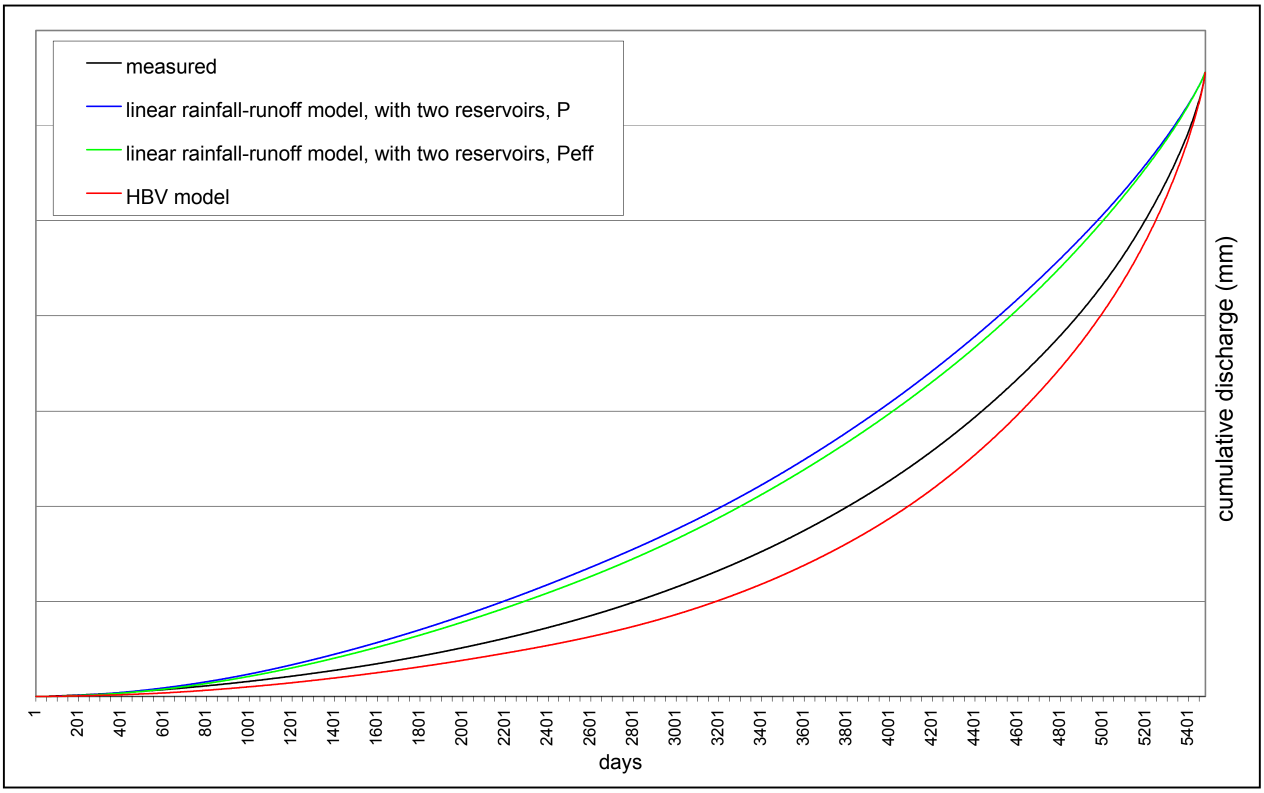


Figure 7.5 Cumulative discharge from low discharge values to high discharge values for the linear rainfall-runoff model with two reservoirs with precipitation and effective precipitation as input and the HBV model

7.4 Processes in the “simple” models

The “simple” models used in this research are build up, step by step, using more complexity. There was started with the constant runoff model, as a basic model and in each step, a process was added to the simple model before, like a linear function, a reservoir or a function with the evapotranspiration. So the improvement of each addition of a new process description can be seen in the results. Table 7.1 gives an overview of all the simulations for the “simple” models. Table 7.2 is the same overview, but now with the differences between the results of the model simulation and the results of the simulation with the model without the addition.

There can be observed can be seen from the differences in results for the runs with total precipitation as input, that the addition of a linear function to the constant runoff model gives a large improvement (0.36). The addition added to this linear rainfall-runoff model, was the addition of a linear reservoir. A change of 0.12 in the efficiency coefficient is the result of this addition. A second reservoir added to the model, doesn’t change the efficiency coefficient (+0.012). The change of using effective precipitation instead of precipitation, as in the last “simple” model, gives a significant result as well (+0.12). The order from the largest change in efficiency to the smallest is: adding a linear function, adding a reservoir, adding an effective precipitation function and adding a second reservoir. For the validation period, the same order can be found.

If the effective precipitation is used as input, the order from the largest change in efficiency to the smallest change for the calibration and validation period, is as follows: adding a linear function, adding a reservoir, adding a second reservoir, adding an effective precipitation function. The addition of the monthly effective precipitation function is even negative.

It can be concluded that the additions of a linear function and a linear reservoir are worth to do. If the effective precipitation is used, the addition of a second linear reservoir is also needed. If the second reservoir is added to the model, the addition of a function for the effective precipitation gives also very good results.

Comparing the results of the first run of the linear rainfall-runoff model with two reservoirs and evapotranspiration (R^2 = 0.61) with the results of the run with the linear rainfall-runoff model with two reservoirs and precipitation as input (R^2 = 0.50) a large difference can be seen. This difference could already be expected, since in the run with the model with the evapotranspiration, the evapotranspiration is taken into account and the use of the effective precipitation instead of the “normal” precipitation in the models before produced already much better results. So, the results of the run with the linear rainfall-runoff model with two reservoirs and evapotranspiration should actually be compared with the results of the linear rainfall-runoff model with two reservoirs and effective precipitation as input. There is no real difference between the values of the efficiency coefficients of these two runs, so, from these results can not be concluded, which method of effective precipitation computation should be preferred. The addition of an evapotranspiration function can be done in two ways and have the same result:

1. The evapotranspiration is taken into account with an evaporation coefficient averaged over many years and using the potential evapotranspiration for each day (called the effective precipitation, as described in section 3.4)). This is done in the model run with the linear rainfall-runoff model with two reservoirs and effective precipitation as input

or

2. An effective precipitation is computed with an mean daily actual evapotranspiration per month, calculated from the water balance for each month and is used as in the first run of the linear rainfall-runoff model with two reservoirs and evapotranspiration (section 4.2.6).

The second method can be used if no potential evapotranspiration data are available.

Table 7.1 The efficiency coefficients for all the simulations of all the models

Model		**Calibration**	**Validation**	**Calibration**	**Validation**
		P	P	Peff	Peff
constant runoff model		0	0		
linear rainfall-runoff model		0.37	0.40	0.51	0.54
linear rainfall-runoff model, with one reservoir		0.49	0.52	0.59	0.61
	peak	0.49	0.54	0.58	0.63
linear rainfall-runoff model with two reservoirs		0.50	0.52	0.61	0.62
	peak	0.49	0.54	0.61	0.64
linear rainfall-runoff model with two reservoirs and evapotranspiration		0.61	0.63	0.56	0.58
HBV		0.81	0.91		

Table 7.2 The differences in efficiency coefficients for each addition to each model

Model		**Calibration**	**Validation**	**Calibration**	**Validation**
		P	P	Peff	Peff
constant runoff model		0	0		
linear rainfall-runoff model		0.37	0.40	0.51	0.54
linear rainfall-runoff model, with one reservoir		0.12	0.12	0.08	0.07
	peak	-0.00	0.02	-0.00	0.02
linear rainfall-runoff model with two reservoirs		0.012	-0.02	0.03	-0.01
	peak	-0.01	0.01	-0.00	0.02
linear rainfall-runoff model with two reservoirs and evapotranspiration		0.12	0.09	-0.05	-0.08
HBV		0.20	0.288		

Table 7.1 and table 7.2 also show the results and differences for the HBV model. It can be seen that the difference between the best “simple” model, used in this study and the results with the HBV model is quite large, 0.2. This means that the HBV model simulates the measured discharge 20% better than the best “simple” model (the linear-rainfall-runoff model with two reservoirs and evapotranspiration or the linear-rainfall-runoff model with two reservoirs with effective precipitation as input). The difference between this model and the HBV model are especially a soil moisture routine, a transformation routine and the occurrence of snow and snowmelt in the precipitation routine. The fast runoff and the base flow reservoir are parallel instead of in series, as used in the “simple” models. From the results of the change of the parameters in the transformation routine (maxbas), which gave a much better calibration result for the HBV model, can be concluded that this routine and the soil moisture routine have large influences on the results of the model and can not be missed in a model, to give good results.

7.5 Limitations of the results

The performances of the models and the differences between them should be seen with the uncertainties involved. Meteorological input data, discharge observations, model structure and concepts, parameter values and the use of the Solver technique in Microsoft Excel are the main sources of uncertainty. The uncertainties of the input data and the discharge observations are not only about how accurate they are measured, but also at what time they are measured. In the results of the model simulations can be seen that the timing of peak events is very important. If there is not known for which time period the data are exactly, this gives an extra uncertainty for the model simulation. In this research is tried to reduce the uncertainty, with a small research about the time of the data (chapter 3), but it is still uncertain if this shift, as assumed in this research, is correct. After the shift of 6 hours, used in this research, there is still a difference of 2 hours between the discharge data and the input data, assuming that the observed discharge data are mean values from midnight to midnight for each day.

For a model with too many parameters, using the solver technique, a tool of Microsoft Excel, used in this study for optimalisation, can cause small problems, since local minima and maxima are found for the models. A trial and error technique is used to find the best fit to solve this problem, but this is not very secure.

Chapter 8 Conclusions and recommendations

8.1 Conclusions

In this chapter an answer will be given to the research questions, as formulated in chapter 1.

1. Does the relatively complex conceptual model HBV give a better result than a simple conceptual model?

   The results of the simulation for the Ourthe with the simple rainfall-runoff models and the HBV model show that the result with the HBV model for the simulation of the discharge is definitely the best.

2. How much does every addition of a new process description to the model improve the results and is it worth making this addition?

   All additions, except one, showed improvement for the model results and are worth making.

   If the precipitation is used as input for the model, the following improvements for each addition can be given. The addition of a linear function improves the results of the simulated discharge with 37% from the most simple model, the constant runoff model. Adding a linear reservoir, improves the result with 12% again. For an improvement of the results with 12% more, a second linear reservoir has to be added and an evaporation function base on the difference between precipitation and discharge within each month. Comparing this last “simple” model with the HBV model, the results for the HBV model sow an improvement of 20% more.

   If the effective precipitation is used as input for the models, the percentages of improvement are slightly different. 50% for the addition of the linear function, 8 % for one linear reservoir and 3% more for the addition of the second linear reservoir. The change of the effective precipitation with a yearly evaporation coefficient to a monthly evaporation coefficient, did not improve the result and so, the model with this addition or change can not be valued and is not worth making .

3. What are the most relevant processes for the simulation of rainfall-runoff processes in the catchment?

   The results of the simulation with the “simple” models and the HBV model show that all processes, used in this study, are relevant for the simulation of the rainfall-runoff process.
   The processes, added in the simple models, like a linear function, a linear reservoir and effective precipitation, are all relevant for the rainfall-runoff process, as the results show. The difference in results between the relatively complicated linear rainfall-runoff model with two reservoirs and evaporation with precipitation as input and the results of the HBV model, show that also some processes, not added in the “simple” models, but used in the HBV model, are necessary to give good results for the simulation of the discharge. The processes are especially the soil-moisture routine and the transformation function.

4. Are there any differences between the input data used in the studies before for the Ourthe catchment (Booij(2002), van der Wal (2001)) and the data of Wójcik and Buishand (2001)?

   The comparison of these data shows that there are differences between these data. The largest difference is a systematic difference in temperature data of 2.2 ^{0}C and is caused by the area of the research. In the studies of Booij (2002) and van der Wal (2001) temperature data for the total Meuse catchment were used. The temperature data of Wójcik and Buishand,are specifically computed for the Ourthe catchment.
   Because of this difference and the random differences in precipitation and potential evapotranspiration data the HBV model for the Ourthe catchment should be calibrated if the data of Wójcik and Buishand are used.

5. What are the results of the HBV model obtained with the meteorological data of Wójcik and Buishand (2001) with or without a new calibration of the parameters?

   The results of the HBV model with these input data and a new calibration are very good. The efficiency coefficient has a value of 0.81 for the calibration and 0.91 for the validation. The relative differences in total discharge are also very small, 0% for the calibration and -4.4% for the validation period.

8.2 Recommendations

Considering the good performance of the HBV model, there should be focused on the accuracy of the measurements. For example if the data of the validation period (1985-1996) are more accurate than the calibration data (1970-1984), which is suggested, since the efficiency coefficients for the validation period are higher than their values for the calibration period. Another point of interest is the time period for which the data are valid. This is very insecure at the moment and if solved, this could give better simulation results.

One of the most important aspects of hydrological modelling is the model calibration and validation. The HBV model contains several parameters, of which the optimal values are determined in a trial and error process. This process is manually and time consuming. Therefore, it is strongly recommended to use an automatic calibration procedure, which can adjust parameter values during the model run to reach the optimal model performances. This automatic calibration procedure will save time.

The best results are given with the HBV model in this research. Some processes of the HBV model are not added in the simple models, like the soil-moisture routine and transformation function. Their influence on the improvement of the results is not known from the results of this study. In further research, these processes can be added to the “simple” model. Also some other additions can be done for better results of the “simple” models. A maximum storage level can be added to the reservoirs, like in the HBV model, for instance and the evapotranspiration process can be changed in the models. In the models in this study, it is suggested that the evaporation depends on the amount of precipitation fallen at a certain day, which is not true in reality. The evaporation depends on the amount of water in the upper layer of the soil and the vegetation. This evapotranspiration process can be a part of the soil moisture routine. An automatic calibration procedure could also be added to the “simple” model, saving time and errors.

Further research on the HBV model can be done on the influence of the snowfall and snowmelt functions in the precipitation routine on the discharge simulation. Also the influence of the scaling of the temperature data, used in this routine is not known. Does it cause a difference for the simulated discharge if, for instance, temperature data of the Ourthe catchment are used instead of temperature data for the total Meuse basin? How and how much is the influence of snowfall on the discharge in the rivers?

For the application of the HBV model to the Meuse basin, some recommendations can be given:

- pay attention to the time of the input data and the observed discharge used for the modelsimulation
- the parameter maxbas can also be varied and has large influences on the results
- it is maybe worth to switch the calibration and validation period, depending on the aim of the model simulations with the HBV model

References

- Berger, H.E.J., 1992. flow forecasting for the river Meuse. Ph.D.-thesis. Delft University of Technology, Delft.
- Bergström, S., 1991. Principles and confidence in hydrological modelling. Nordic Hydrology, 22, 123-136.
- Booij, M.J., 2002. Appropriate modelling of climate change impacts on river flooding. Ph.D.-thesis. University of Twente, Enschede.
- Bos, S.A. van den, 2001. Rainfall-runoffmodelling with a neural network (in Dutch). MSc-thesis. Wageningen Univrsity, Wageningen.
- Bruijn, K. de, 2000. HBV_Meuse (in Dutch). Report Q2633.00. WL I Delft Hydraulics, Delft.
- Dijksma (ed), R., H.A.J. van Lanen and W.J. Ackerman, -. Hydrogeological Fieldwork Ardennes (in Dutch). Wageningen University, Wageningen.
- Lindström, G., B. Johansson, M. Persson, M. Gardelin and S. Bergström, 1997. Development and test of the distributed HBV-96 hydrological model. J.Hydrol.,201,272-288.
- Nash, J.E. and J.V. Sutcliffe, 1970. River flow forecasting through conceptual models. Part I –A discussion of principles. J. Hydrol., 10, 157-172.
- Passchier, R.H., 1996. Evaluation hydrologic model packages. Q 2044. WL I Delft Hydraulics, Delft.
- Parmet, B., T.A. Buishand, T. Brandsma and R. Mülders, 1999. Design discharge of the large rivers in The Netherlands---towards a new methodology. IAHS Publ.no. 255, 269-272.
- SMHI, 1999. Integrated Hydrological Modelling System (IHMS). Manual Version 4.3. SMHI,Norrköping.
- Tilmont, J., M. de Roeck, J. Lambion, and C. Debulpaep, 1984. Atlas. Wesmael-Charlier, Namen.
- Torfs, P.J.J.F., 2000. Solvingtechniques in the Hydrology (in Dutch). Wageningen University, Wageningen.
- Uijlenhoet, R., M.J.M. de Wit, P.M.M. Warmerdam and P.J.J.F. Torfs, 2001. Statistical Analysis of Daily Discharge. Data of the River Meuse and its Tributaries (1968-1998): assessment of Drought Sensitivity. Wageningen University, Wageningen.
- Velner, R.G.J., 2000. Rainfall-runoff modelling of the Ourthe catchment with the HBV model. A study for extension of the lead time for flood forecasting in the Meuse (in dutch). RIZA working document 2000.091X. Wageningen University, Wageningen.
- Wal, K.U. van der, 2001. Meuse model moulding. On the effect of spatial resolution. MSc.-thesis. University of Twente, Enschede.
- Wal, K.U. van der, 2002. Rainfall-runoff modelling with generated rainfalldata in the HBV model (in Dutch). Report 2002W-002/WMW-005. University of Twente, Enschede.
- WHM (Werkgroep Hoogwater maas), 1998. Actieplan hoogwater Maas. Francis Hambye, Namur.
- Wit, M.J.M. de, J. van Essen and B. van de Pas, 2002. Hydrological GIS Database Meuse Basin (in Dutch). Report 2002.186x. RIZA, Arnhem.
- Wójcik, R. and T.A. Buishand, 2001. Rainfall Generator for the Meuse Basin. Simulation of 6-hourly rainfall and temperature for the Ourthe catchment. KNMI-publication 196-I. KNMI, De Bilt.

Appendix A Shift of precipitation for the peak event of January 1993

For the research about the shift in 6-hourly precipitation sums, as explained in section 3.3.1, also the data of the station Ortho for the peak event of January 1993 was used. The plots of the 6-hourly precipitations with and without a shift (figure A-1 and A-2) are presented in this appendix.

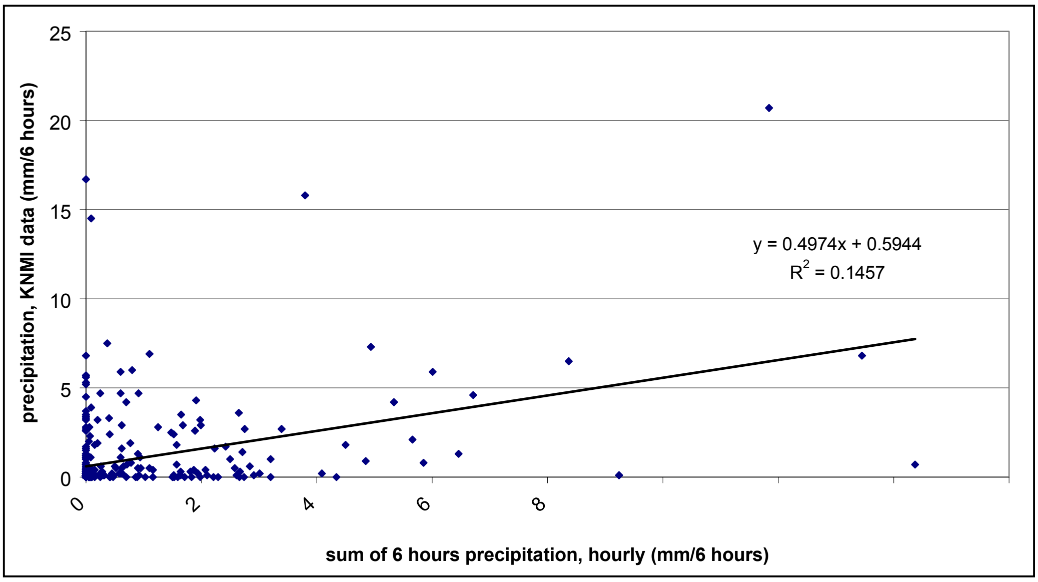


Figure A-1 Precipitation (mm/6 hours) of the KNMI data and 6 hour sums of hourly precipitation data of the station Ortho(M61280015), for which the time 6:00 is set to 6:00

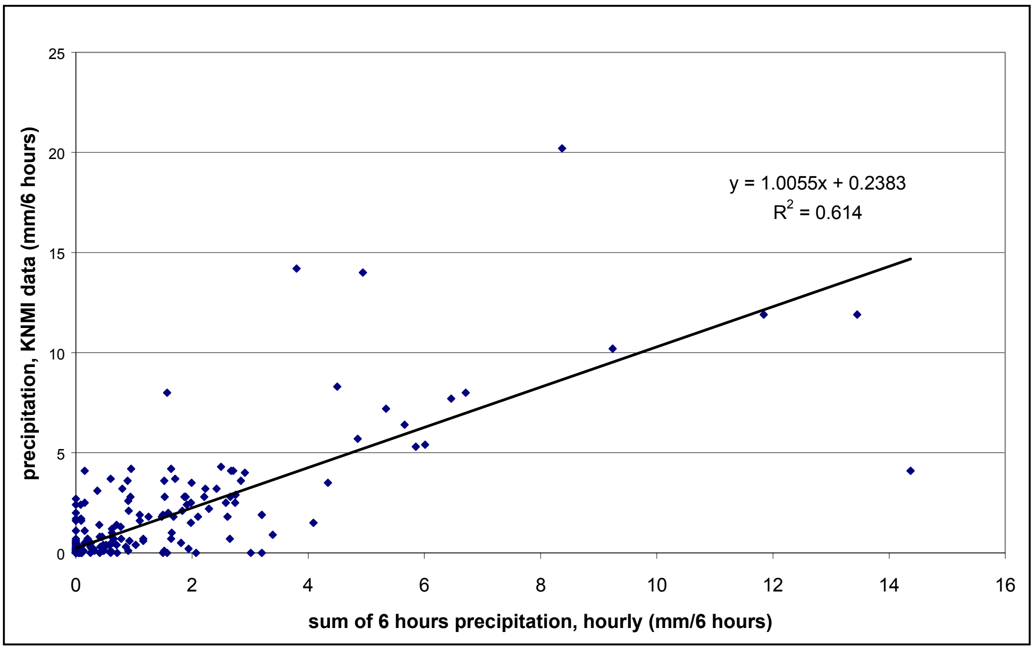


Figure A-2 Precipitation (mm/6 hours) of the KNMI data and 6 hour sums of hourly precipitation data of the station Ortho (M61280015), for which the time 6:00 is set to 14:00, 12:00 is 20:00 in real time, 18:00 is 2:00 in real time and 0:00 is 8:00 in real time.

Appendix B Description of the linear rainfall-runoff model with one reservoir and effective precipitation as input, as build in Microsoft Excel

In this appendix a description of one of the models is given as an example. This serves as an example for how the “simple” models, used in this study are build in the program Microsoft excel.

Columns:

A	Date
B	Precipitation (KNMI), mm/d
C	Measured discharge, Tabreaux, m3/s
D	Measured discharge, Tabreaux, mm/d
E	Potential evapotranspiration (KNMI), mm/d
F	Effective precipitation, mm/d
G	-
H	Parameters
I	Values of parameters
J, K, L	Calculations for the reservoir
J	Input reservoir (mm/d)
K	Output reservoir (mm/d)
L	Storage reservoir (mm)
M	Simulated discharge (mm/d)
N	-
O+P	Calculations for the Nash-Suthcliff R^2 O: $(Q_s - Q_m)^2$ P: $(Q_m - \overline{Q_m})^2$
Q	Calculations for the relative difference in total discharge Q: $(Q_s - Q_m)$

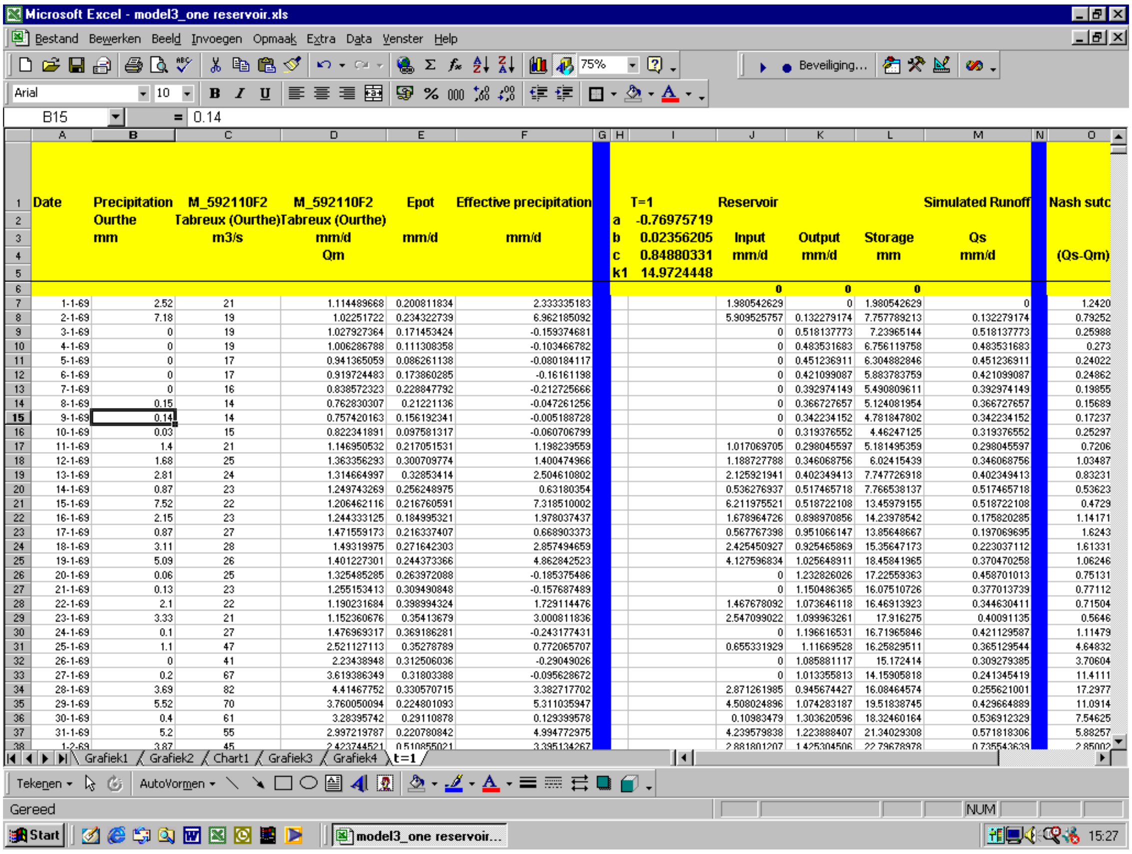
Formulas:

A7	value
B7	value
C7	value
D7	=C7*(86400/(1597*1000))
E7	value
F7	=B7-$E$5857*E7
G7	-
H7	-
I7	-
J7	=IF(($I$4*F7)>0;$I$4*F7;0)
K7	=(1/($I$5))*L6
L7	=IF((L6+J7-K7)>0;L6+J7-K7;0)
M7	=IF(($I$2+$I$3*F7+K7)>0;$I$2+$I$3*F7+K7;IF((K7>0);K7;IF((K7+$G$2)>0;K7+$G$2;0)))
N7	-
O7	=(M7-D7)^2
P7	=(D7-$D$5854)^2
Q7	=M7-D7

Rows at the end (yellow)

5852Total sum
5853-
5854Average
5855–
5856–
E5857 Evaporation coefficient =(B5852-D5852)/E5852
O5858 Nash-Sutcliffe R^2 =1-(O5852/P5852)
Q5860 Relative Difference in total discharge RDq =(Q5852/D5852)*100

The red cells in rows 5858 (O5858) and 5860 (Q5860) are the cells used as calibration criteria. The solver, used for the optimalisation is set to find a value as closest to the value 1 for cell O5858, with the restriction that cell Q5860 is close to zero.

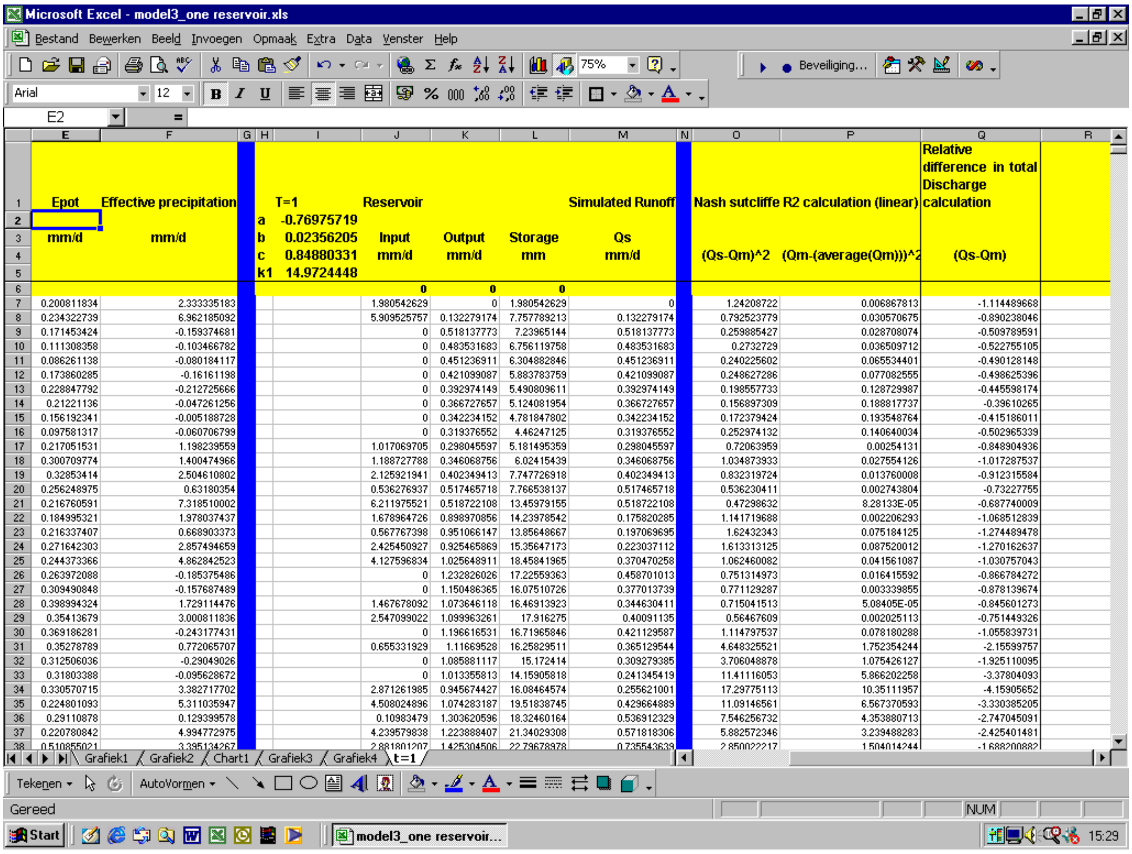


B15 = 0.14

T=1
a -0.76975719
b 0.02356205
c 0.84880331
k1 14.9724448

	Date	Precipitation Ourthe mm	M_592110F2 Tabreux (Ourthe) m3/s	M_592110F2 Tabreux (Ourthe) mm/d Qm	Epot mm/d	Effective precipitation mm/d	Reservoir Input mm/d	Output mm/d	Storage mm	Simulated Runoff Qs mm/d	Nash sutc (Qs-Qm)
6							0	0	0		
7	1-1-69	2.52	21	1.114489668	0.200811834	2.333335183	1.980542629	0	1.980542629	0	1.2420
8	2-1-69	7.18	19	1.02251722	0.234322739	6.962185092	5.909525757	0.132279174	7.757789213	0.132279174	0.79252
9	3-1-69	0	19	1.027927364	0.171453424	-0.159374681	0	0.518137773	7.23965144	0.518137773	0.25988
10	4-1-69	0	19	1.006286788	0.111308358	-0.103466782	0	0.483531683	6.756119758	0.483531683	0.273
11	5-1-69	0	17	0.941365059	0.086261138	-0.080184117	0	0.451236911	6.304882846	0.451236911	0.24022
12	6-1-69	0	17	0.919724483	0.173860285	-0.16161198	0	0.421099087	5.883783759	0.421099087	0.24862
13	7-1-69	0	16	0.838572323	0.228847792	-0.212725666	0	0.392974149	5.490809611	0.392974149	0.19855
14	8-1-69	0.15	14	0.762830307	0.21221136	-0.047261256	0	0.366727657	5.124081954	0.366727657	0.15689
15	9-1-69	0.14	14	0.757420163	0.156192341	-0.005188728	0	0.342234152	4.781847802	0.342234152	0.17237
16	10-1-69	0.03	15	0.822341891	0.097581317	-0.060706799	0	0.319376552	4.46247125	0.319376552	0.25297
17	11-1-69	1.4	21	1.146950532	0.217051531	1.198239559	1.017069705	0.298045597	5.181495359	0.298045597	0.7206
18	12-1-69	1.68	25	1.363356293	0.300709774	1.400474966	1.188727788	0.346068756	6.02415439	0.346068756	1.03487
19	13-1-69	2.81	24	1.314664997	0.32853414	2.504610802	2.125921941	0.402349413	7.747726918	0.402349413	0.83231
20	14-1-69	0.87	23	1.249743269	0.256248975	0.63180354	0.536276937	0.517465718	7.766538137	0.517465718	0.53623
21	15-1-69	7.52	22	1.206462116	0.216760591	7.318510002	6.211975521	0.518722108	13.45979155	0.518722108	0.4729
22	16-1-69	2.15	23	1.244333125	0.184995321	1.978037437	1.678964726	0.898970856	14.23978542	0.175820285	1.14171
23	17-1-69	0.87	27	1.471559173	0.216337407	0.668903373	0.567767398	0.951066147	13.85648667	0.197069695	1.6243
24	18-1-69	3.11	28	1.49319975	0.271642303	2.857494659	2.425450927	0.925465869	15.35647173	0.223037112	1.61331
25	19-1-69	5.09	26	1.401227301	0.244373366	4.862842523	4.127596834	1.025648911	18.45841965	0.370470258	1.06246
26	20-1-69	0.06	25	1.325485285	0.263972088	-0.185375486	0	1.232826026	17.22559363	0.458701013	0.75131
27	21-1-69	0.13	23	1.255153413	0.309490848	-0.157687489	0	1.150486365	16.07510726	0.377013739	0.77112
28	22-1-69	2.1	22	1.190231684	0.398994324	1.729114476	1.467678092	1.073646118	16.46913923	0.344630411	0.71504
29	23-1-69	3.33	21	1.152360676	0.35413679	3.000811836	2.547099022	1.099963261	17.916275	0.40091135	0.5646
30	24-1-69	0.1	27	1.476969317	0.369186281	-0.243177431	0	1.196616531	16.71965846	0.421129587	1.11479
31	25-1-69	1.1	47	2.521127113	0.35278789	0.772065707	0.655331929	1.11669528	16.25829511	0.365129544	4.64832
32	26-1-69	0	41	2.23438948	0.312506036	-0.29049026	0	1.085881117	15.172414	0.309279385	3.70604
33	27-1-69	0.2	67	3.619386349	0.31803388	-0.095628672	0	1.013355813	14.15905818	0.241345419	11.4111
34	28-1-69	3.69	82	4.41467752	0.330570715	3.382717702	2.871261985	0.945674427	16.08464574	0.255621001	17.2977
35	29-1-69	5.52	70	3.760050094	0.224801093	5.311035947	4.508024896	1.074283187	19.51838745	0.429664889	11.0914
36	30-1-69	0.4	61	3.28395742	0.29110878	0.129399578	0.10983479	1.303620596	18.32460164	0.536912329	7.54625
37	31-1-69	5.2	55	2.997219787	0.220780842	4.994772975	4.239579838	1.223888407	21.34029308	0.571818306	5.88257
38	1-2-69	3.87	45	2.423744521	0.510855021	3.395134267	2.881801207	1.425304506	22.79678978	0.735543639	2.85002

Figure B-1 The linear rainfall-runoff model in Microsoft Excel

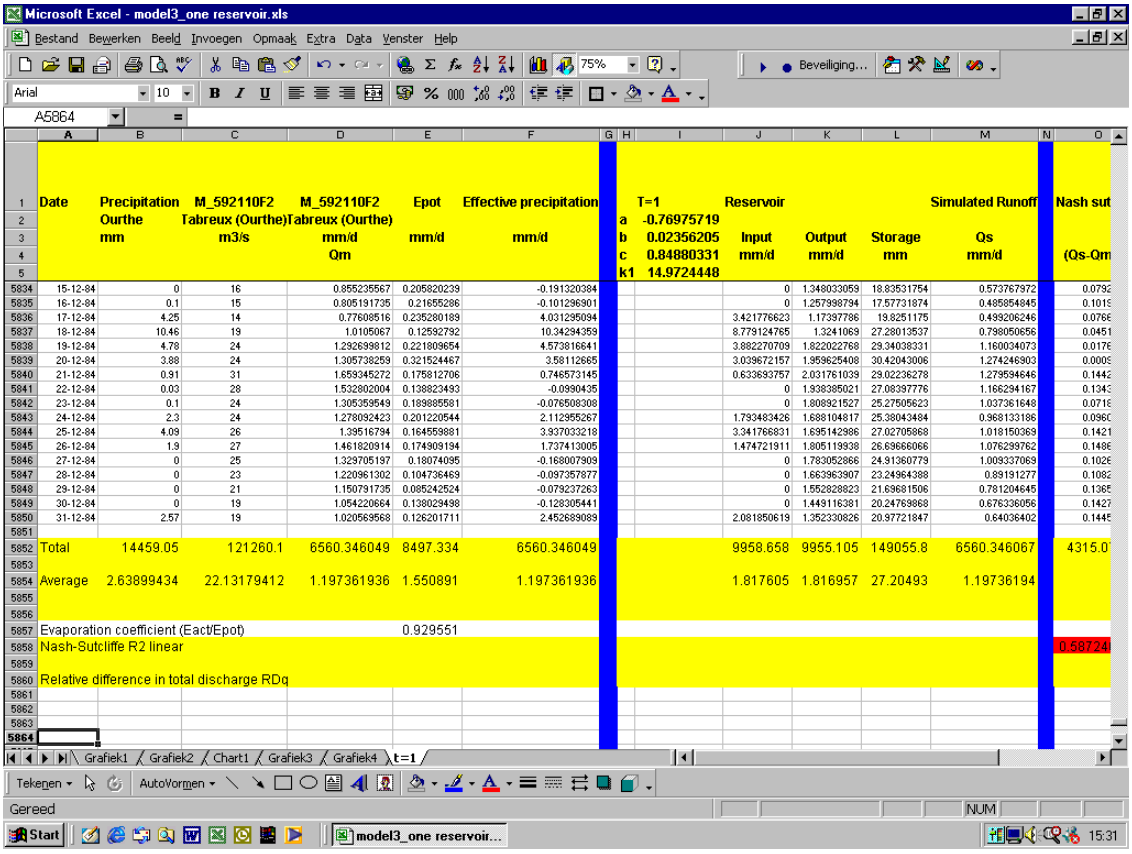


E2 =

T=1
a -0.76975719
b 0.02356205
c 0.84880331
k1 14.9724448

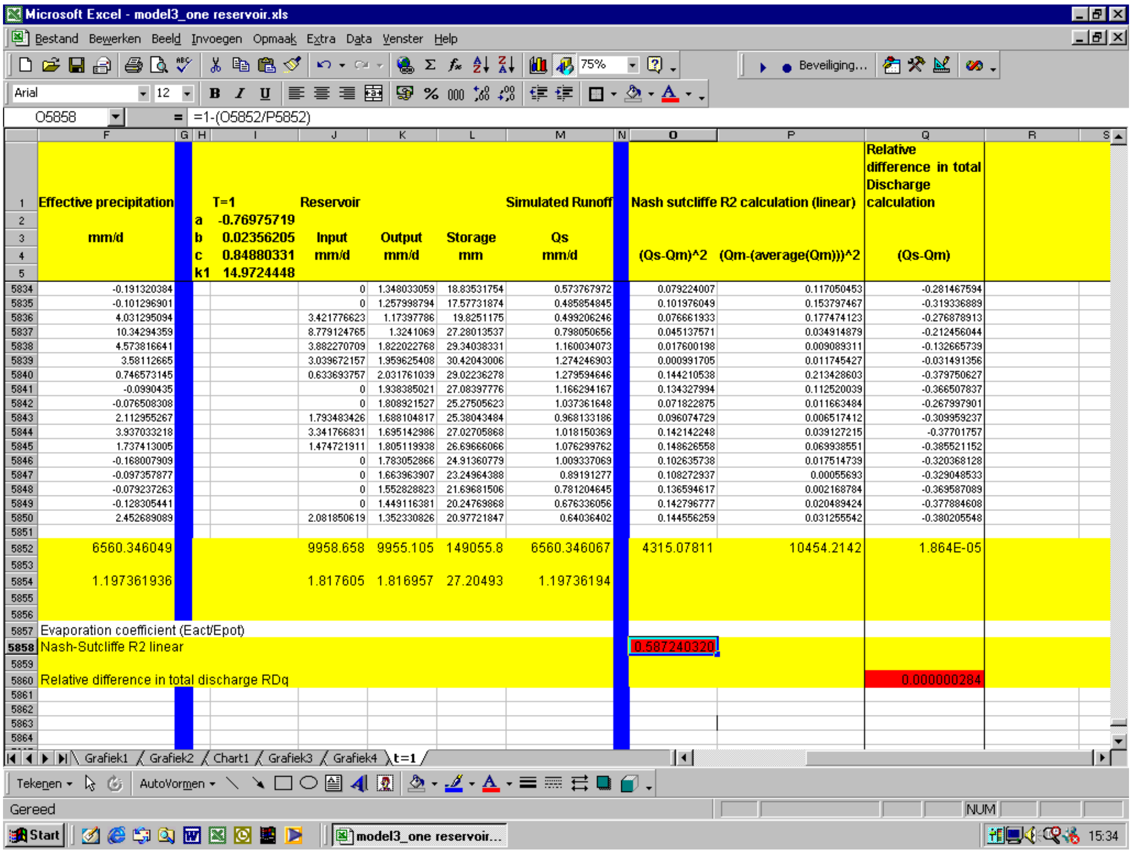
	Epot mm/d	Effective precipitation mm/d	Reservoir Input mm/d	Output mm/d	Storage mm	Simulated Runoff Qs mm/d	Nash sutcliffe R2 calculation (linear) (Qs-Qm)^2	(Qm-(average(Qm)))^2	Relative difference in total Discharge calculation (Qs-Qm)
6			0	0	0				
7	0.200811834	2.333335183	1.980542629	0	1.980542629	0	1.24208722	0.006867813	-1.114489668
8	0.234322739	6.962185092	5.909525757	0.132279174	7.757789213	0.132279174	0.792523779	0.030570675	-0.890238046
9	0.171453424	-0.159374681	0	0.518137773	7.23965144	0.518137773	0.259885427	0.028708074	-0.509789591
10	0.111308358	-0.103466782	0	0.483531683	6.756119758	0.483531683	0.2732729	0.036509712	-0.522755105
11	0.086261138	-0.080184117	0	0.451236911	6.304882846	0.451236911	0.240225602	0.065534401	-0.490128148
12	0.173860285	-0.16161198	0	0.421099087	5.883783759	0.421099087	0.248627286	0.077082555	-0.498625396
13	0.228847792	-0.212725666	0	0.392974149	5.490809611	0.392974149	0.198557733	0.128729987	-0.445598174
14	0.21221136	-0.047261256	0	0.366727657	5.124081954	0.366727657	0.156897309	0.188817737	-0.39610265
15	0.156192341	-0.005188728	0	0.342234152	4.781847802	0.342234152	0.172379424	0.193548764	-0.415186011
16	0.097581317	-0.060706799	0	0.319376552	4.46247125	0.319376552	0.252974132	0.140640034	-0.502965339
17	0.217051531	1.198239559	1.017069705	0.298045597	5.181495359	0.298045597	0.72063959	0.00254131	-0.848904936
18	0.300709774	1.400474966	1.188727788	0.346068756	6.02415439	0.346068756	1.034873933	0.027554126	-1.017287537
19	0.32853414	2.504610802	2.125921941	0.402349413	7.747726918	0.402349413	0.832319724	0.013760008	-0.912315584
20	0.256248975	0.63180354	0.536276937	0.517465718	7.766538137	0.517465718	0.536230411	0.002743804	-0.73227755
21	0.216760591	7.318510002	6.211975521	0.518722108	13.45979155	0.518722108	0.47298632	8.28133E-05	-0.687740009
22	0.184995321	1.978037437	1.678964726	0.898970856	14.23978542	0.175820285	1.141719688	0.002206293	-1.068512839
23	0.216337407	0.668903373	0.567767398	0.951066147	13.85648667	0.197069695	1.62432343	0.075184125	-1.274489478
24	0.271642303	2.857494659	2.425450927	0.925465869	15.35647173	0.223037112	1.613313125	0.087520012	-1.270162637
25	0.244373366	4.862842523	4.127596834	1.025648911	18.45841965	0.370470258	1.062460082	0.041561087	-1.030757043
26	0.263972088	-0.185375486	0	1.232826026	17.22559363	0.458701013	0.751314973	0.016415592	-0.866784272
27	0.309490848	-0.157687489	0	1.150486365	16.07510726	0.377013739	0.771129287	0.003339855	-0.878139674
28	0.398994324	1.729114476	1.467678092	1.073646118	16.46913923	0.344630411	0.715041513	5.08405E-05	-0.845601273
29	0.35413679	3.000811836	2.547099022	1.099963261	17.916275	0.40091135	0.56467609	0.002025113	-0.751449326
30	0.369186281	-0.243177431	0	1.196616531	16.71965846	0.421129587	1.114797537	0.078180288	-1.055839731
31	0.35278789	0.772065707	0.655331929	1.11669528	16.25829511	0.365129544	4.648325521	1.752354244	-2.15599757
32	0.312506036	-0.29049026	0	1.085881117	15.172414	0.309279385	3.706048878	1.075426127	-1.925110095
33	0.31803388	-0.095628672	0	1.013355813	14.15905818	0.241345419	11.41116053	5.866202258	-3.37804093
34	0.330570715	3.382717702	2.871261985	0.945674427	16.08464574	0.255621001	17.29775113	10.35111957	-4.15905652
35	0.224801093	5.311035947	4.508024896	1.074283187	19.51838745	0.429664889	11.09146561	6.567370593	-3.330385205
36	0.29110878	0.129399578	0.10983479	1.303620596	18.32460164	0.536912329	7.546256732	4.353880713	-2.747045091
37	0.220780842	4.994772975	4.239579838	1.223888407	21.34029308	0.571818306	5.882572346	3.239488283	-2.425401481
38	0.510855021	3.395134267	2.881801207	1.425304506	22.79678978	0.735543639	2.850022217	1.504014244	-1.688200882

Figure B-2 The linear rainfall-runoff model in Microsoft Excel



	A	B	C	D	E	F	H	I	J	K	L	M	O
1	Date	Precipitation	M_592110F2	M_592110F2	Epot	Effective precipitation		T=1	Reservoir			Simulated Runoff	Nash sut
2		Ourthe	Tabreux (Ourthe)	Tabreux (Ourthe)			a	-0.76975719					
3		mm	m3/s	mm/d	mm/d	mm/d	b	0.02356205	Input	Output	Storage	Qs	
4				Qm			c	0.84880331	mm/d	mm/d	mm	mm/d	(Qs-Qm
5							k1	14.9724448					
5834	15-12-84	0	16	0.855235567	0.205820239	-0.191320384			0	1.348033059	18.83531754	0.573767972	0.0792
5835	16-12-84	0.1	15	0.805191735	0.21655286	-0.101296901			0	1.257998794	17.57731874	0.485854845	0.1019
5836	17-12-84	4.25	14	0.77608516	0.235280189	4.031295094			3.421776623	1.17397786	19.8251175	0.499206246	0.0766
5837	18-12-84	10.46	19	1.0105067	0.12592792	10.34294359			8.779124765	1.3241069	27.28013537	0.798050656	0.0451
5838	19-12-84	4.78	24	1.292699812	0.221809654	4.573816641			3.882270709	1.822022768	29.34038331	1.160034073	0.0176
5839	20-12-84	3.88	24	1.305738259	0.321524467	3.58112665			3.039672157	1.959625408	30.42043006	1.274246903	0.0009
5840	21-12-84	0.91	31	1.659345272	0.175812706	0.746573145			0.633693757	2.031761039	29.02236278	1.279594646	0.1442
5841	22-12-84	0.03	28	1.532802004	0.138823493	-0.0990435			0	1.938385021	27.08397776	1.166294167	0.1343
5842	23-12-84	0.1	24	1.305359549	0.189885581	-0.076508308			0	1.808921527	25.27505623	1.037361648	0.0718
5843	24-12-84	2.3	24	1.278092423	0.201220544	2.112955267			1.793483426	1.688104817	25.38043484	0.968133186	0.0960
5844	25-12-84	4.09	26	1.39516794	0.164559881	3.937033218			3.341766831	1.695142986	27.02705868	1.018150369	0.1421
5845	26-12-84	1.9	27	1.461820914	0.174909194	1.737413005			1.474721911	1.805119938	26.69666066	1.076299762	0.1486
5846	27-12-84	0	25	1.329705197	0.18074095	-0.168007909			0	1.783052866	24.91360779	1.009337069	0.1026
5847	28-12-84	0	23	1.220961302	0.104736469	-0.097357877			0	1.663963907	23.24964388	0.89191277	0.1082
5848	29-12-84	0	21	1.150791735	0.085242524	-0.079237263			0	1.552828823	21.69681506	0.781204645	0.1365
5849	30-12-84	0	19	1.054220664	0.138029498	-0.128305441			0	1.449116381	20.24769868	0.676336056	0.1427
5850	31-12-84	2.57	19	1.020569568	0.126201711	2.452689089			2.081850619	1.352330826	20.97721847	0.64036402	0.1445
5851													
5852	Total	14459.05	121260.1	6560.346049	8497.334	6560.346049			9958.658	9955.105	149055.8	6560.346067	4315.07
5853													
5854	Average	2.63899434	22.13179412	1.197361936	1.550891	1.197361936			1.817605	1.816957	27.20493	1.19736194	
5855													
5856													
5857	Evaporation coefficient (Eact/Epot)				0.929551								
5858	Nash-Sutcliffe R2 linear												0.58724
5859													
5860	Relative difference in total discharge RDq												
5861													
5862													
5863													
5864													

Figure B-3 The linear rainfall-runoff model in Microsoft Excel



O5858 = =1-(O5852/P5852)

	F	H	I	J	K	L	M	O	P	Q
1	Effective precipitation		T=1	Reservoir			Simulated Runoff	Nash sutcliffe R2 calculation (linear)		Relative difference in total Discharge calculation
2		a	-0.76975719							
3	mm/d	b	0.02356205	Input	Output	Storage	Qs			
4		c	0.84880331	mm/d	mm/d	mm	mm/d	(Qs-Qm)^2	(Qm-(average(Qm)))^2	(Qs-Qm)
5		k1	14.9724448							
5834	-0.191320384			0	1.348033059	18.83531754	0.573767972	0.079224007	0.117050453	-0.281467594
5835	-0.101296901			0	1.257998794	17.57731874	0.485854845	0.101976049	0.153797467	-0.319336889
5836	4.031295094			3.421776623	1.17397786	19.8251175	0.499206246	0.076661933	0.177474123	-0.276878913
5837	10.34294359			8.779124765	1.3241069	27.28013537	0.798050656	0.045137571	0.034914879	-0.212456044
5838	4.573816641			3.882270709	1.822022768	29.34038331	1.160034073	0.017600198	0.009089311	-0.132665739
5839	3.58112665			3.039672157	1.959625408	30.42043006	1.274246903	0.000991705	0.011745427	-0.031491356
5840	0.746573145			0.633693757	2.031761039	29.02236278	1.279594646	0.144210538	0.213428603	-0.379750627
5841	-0.0990435			0	1.938385021	27.08397776	1.166294167	0.134327994	0.112520039	-0.366507837
5842	-0.076508308			0	1.808921527	25.27505623	1.037361648	0.071822875	0.011663484	-0.267997901
5843	2.112955267			1.793483426	1.688104817	25.38043484	0.968133186	0.096074729	0.006517412	-0.309959237
5844	3.937033218			3.341766831	1.695142986	27.02705868	1.018150369	0.142142248	0.039127215	-0.37701757
5845	1.737413005			1.474721911	1.805119938	26.69666066	1.076299762	0.148626558	0.069938551	-0.385521152
5846	-0.168007909			0	1.783052866	24.91360779	1.009337069	0.102635738	0.017514739	-0.320368128
5847	-0.097357877			0	1.663963907	23.24964388	0.89191277	0.108272937	0.00055693	-0.329048533
5848	-0.079237263			0	1.552828823	21.69681506	0.781204645	0.136594617	0.002168784	-0.369587089
5849	-0.128305441			0	1.449116381	20.24769868	0.676336056	0.142796777	0.020489424	-0.377884608
5850	2.452689089			2.081850619	1.352330826	20.97721847	0.64036402	0.144556259	0.031255542	-0.380205548
5851										
5852	6560.346049			9958.658	9955.105	149055.8	6560.346067	4315.07811	10454.2142	1.864E-05
5853										
5854	1.197361936			1.817605	1.816957	27.20493	1.19736194			
5855										
5856										
5857	Evaporation coefficient (Eact/Epot)									
5858	Nash-Sutcliffe R2 linear							0.587240320		
5859										
5860	Relative difference in total discharge RDq									0.000000284
5861										
5862										
5863										
5864										

Figure B-4 The linear rainfall-runoff model in Microsoft Excel

Appendix C The parameters, efficiency coefficients and relative differences in total discharge of the linear rainfall-runoff model

Table C-1 The parameters for each Time step T and each run of the model

	Linear rainfall-runoff model P		Linear rainfall-runoff model Peff		Linear rainfall-runoff model Peff, limit Q	
	a	b	a	b	a	b
T=1	1.0529	0.0547	1.1121	0.0712	1.1121	0.0712
T=2	0.8442	0.1338	1.0274	0.1420	1.0340	0.1350
T=3	0.6680	0.2006	0.9626	0.1961	0.9212	0.2050
T=4	0.5405	0.2490	0.9180	0.2334	0.8340	0.2505
T=5	0.4380	0.2878	0.8834	0.2622	0.7083	0.3106
T=6	0.3561	0.3188	0.8563	0.2849	0.5836	0.3662
T=7	0.2887	0.3444	0.8345	0.3032	0.5351	0.3946
T=8	0.2308	0.3664	0.8162	0.3185	0.5119	0.4177
T=9	0.1752	0.3874	0.7991	0.3328	0.4844	0.4369
T=10	0.1262	0.4060	0.7840	0.3454	0.4368	0.4678
T=11	0.0797	0.4236	0.7697	0.3573	0.4174	0.4819
T=12	0.0339	0.4410	0.7559	0.3689	0.3927	0.4993
T=13	-0.0075	0.4567	0.7433	0.3794	0.3557	0.5198
T=14	-0.0440	0.4705	0.7321	0.3887	0.3452	0.5302
T=15	-0.1386	0.5052	0.7213	0.3978	0.3523	0.5367

Table C-2 The efficiency coefficients R^2 for each time step T and each run of the model

	Linear rainfall-runoff model P		Linear rainfall-runoff model Peff		Linear rainfall-runoff model Peff, limit Q	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
	R^2 (-)	R^2 (-)	R^2 (-)	R^2 (-)	R^2 (-)	R^2 (-)
T=1	0.0321	0.0440	0.0652	0.0785	0.0652	0.0803
T=2	0.1226	0.1438	0.1772	0.1956	0.1761	0.1946
T=3	0.2100	0.2379	0.2705	0.2929	0.2713	0.2974
T=4	0.2655	0.2978	0.3267	0.3522	0.3342	0.3626
T=5	0.3026	0.3379	0.3634	0.3911	0.3829	0.4188
T=6	0.3247	0.3674	0.3860	0.4194	0.4183	0.4663
T=7	0.3376	0.3852	0.3999	0.4365	0.4396	0.4929
T=8	0.3457	0.3935	0.4092	0.4452	0.4541	0.5074
T=9	0.3529	0.3985	0.4176	0.4508	0.4671	0.5166
T=10	0.3573	0.4020	0.4237	0.4553	0.4775	0.5289
T=11	0.3616	0.4024	0.4299	0.4570	0.4871	0.5323
T=12	0.3662	0.4028	0.4362	0.4586	0.4967	0.5358
T=13	0.3685	0.4022	0.4405	0.4592	0.5029	0.5390
T=14	0.3685	0.4009	0.4429	0.4592	0.5059	0.5391
T=15	0.3688	0.4025	0.4452	0.4592	0.5082	0.5383

Table C-3 The relative differences in total discharge for each time step T and each run of the model.

	Linear rainfall-runoff model P		Linear rainfall-runoff model Peff		Linear rainfall-runoff model Peff, limit Q	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
	RDq (%)	RDq (%)	RDq (%)	RDq (%)	RDq (%)	RDq (%)
T=1	0.0000	-0.8427	0.0000	-0.9146	0.0000	-1.4938
T=2	0.0000	-0.6318	0.0000	-0.8389	0.0000	-2.0701
T=3	0.0000	-0.4573	0.0000	-0.7853	0.0000	-1.2955
T=4	0.0000	-0.3354	0.0000	-0.7526	0.0588	-0.6269
T=5	0.0000	-0.2378	0.0000	-0.7276	0.0000	-0.5593
T=6	0.0000	-0.1597	0.0000	-0.7082	-0.8748	-1.2108
T=7	0.0000	-0.0925	0.0000	-0.6901	-0.9753	-1.4479
T=8	0.0000	-0.0288	0.0000	-0.6699	0.0000	-0.8905
T=9	0.0000	0.0341	0.0000	-0.6495	0.0000	-0.8365
T=10	0.0000	0.0843	0.0000	-0.6362	-0.0005	-0.5908
T=11	0.0000	0.1300	0.0000	-0.6253	-0.1077	-0.7437
T=12	0.0000	0.1762	0.0000	-0.6138	-0.2198	-0.8055
T=13	0.0000	0.2226	0.0000	-0.5997	-0.7871	-1.4375
T=14	0.0000	0.2683	0.0000	-0.5832	-0.7846	-1.5150
T=15	0.0000	0.1266	0.0000	-0.5583	0.0000	-0.6938

Appendix D Reservoir coefficients

To determine the reservoir coefficients, recession curves can be analysed. A recession is a period with overall dropping values of the discharge. If the discharge of a recession period is plotted on semi-logarithmic paper against time, frequently a straight line can be found (see figure D.1). The reservoir coefficient can be found from these straight lines as the reciproke of the slope of the recession curve, see equations D-1 –D-3.

The outflow of a linear reservoir can be calculated with the following equations:

$$R_{out}(t+t_0) = R_{out}(t_0) \cdot e^{-\frac{t}{k}} \tag{D-1}$$

$$\ln(R_{out}(t+t_0)) = \ln(R_{out}(t_0)) - \frac{t}{k} \tag{D-2}$$

$$k = -\frac{t}{\ln(R_{out}(t+t_0)) - \ln(R_{out}(t_0))} = \frac{1}{RCF} \tag{D-3}$$

$R_{out}(t+t_0)$	Outflow of the reservoir at time t+t_0 [mm/d]
$R_{out}(t_0)$	Outflow of the reservoir at time t_0 [mm/d]
t	Time [d]
k	Reservoir coefficient [d]

Figure D.1 shows some recession curves, as the black lines. The process of determining the coefficients of the recession curves can be done by hand, but is not very secure. Because all the parameter values in the models (except for the HBV model) are solved with the solver function of Microsoft Excel, in this study some reservoir coefficients are calculated (for 43 recessions curves) by hand, just to give an indication for a starting value of the reservoir coefficient.

As figure D.1 shows, two slopes can be recognized for the recession curves a steep and a somewhat flatter slope.

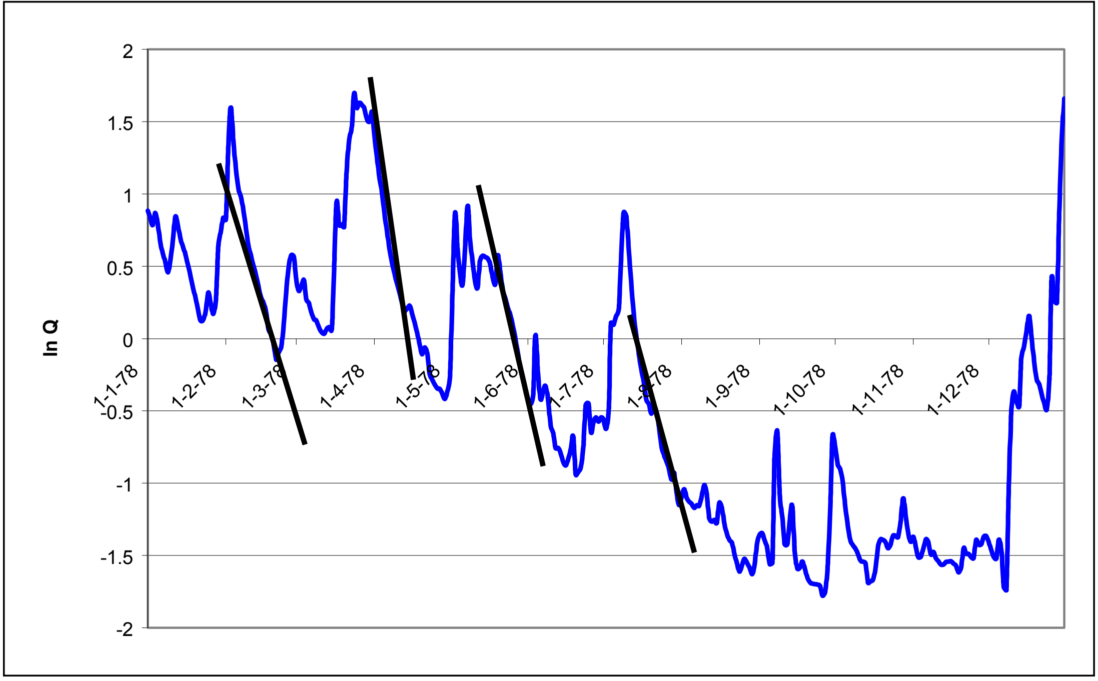


Figure D.1 The logarithmic discharge for the year 1978 of the Ourthe at Tabreux.

In table D-1 all the time periods and values of the recession curves, computed in this study, are reported. Figure D.2 shows the reservoir coefficients for all these recession curves, from low to high values. These coefficients can be separated into three groups, as figure D.2 shows, one with all the values between 0 and 25 days, one with values between 25 and 90 days and the third one exists only of two dots, between 120 and 140 days.

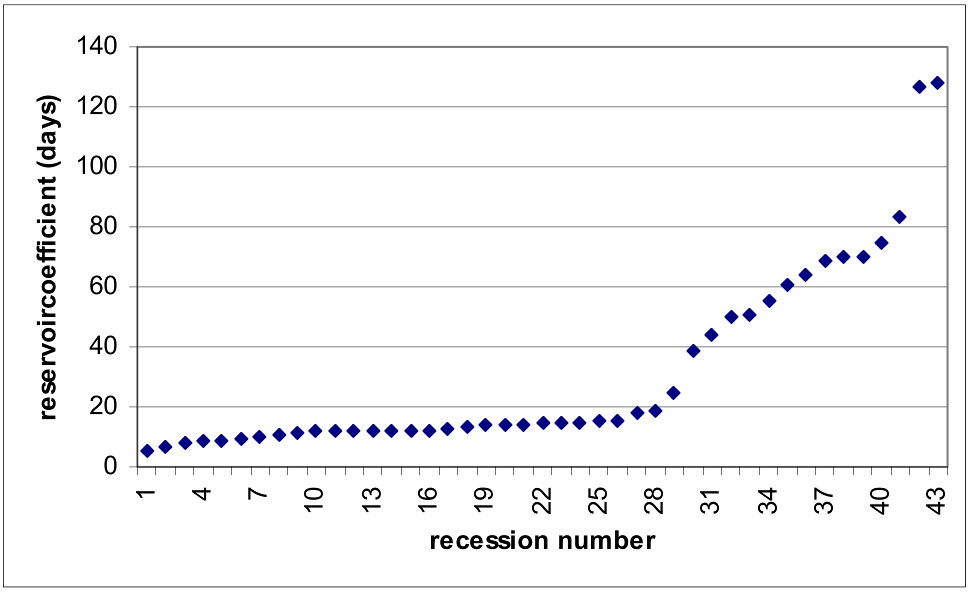


Figure D.2 Reservoir coefficients calculated by hand, selected from low to high values and given a certain recession number.

These last two dots are from recession curves in the year 1977, which was a very dry year. Since there are only two points, these values are not taken into account in this study. The average value for the first group of reservoir coefficients is 12.66 days (fast reservoir) and for the second group 70.47 days. These will be used as the starting values for the optimalisation with the Solver function in Microsoft Excel for the linear rainfall-runoff model with one reservoir and the other model with two reservoirs, described in section 5.4 and 5.5.

In a study of Uijlenhoet et al (2001), recession coefficients for dry spells only, were also determined for the river Meuse and its tributaries. A recession coefficient of 60.4 days was computed in this study for the discharge gauging station Tabreux. The difference between this coefficient and the other reservoir coefficient for the slow running reservoir is not very large.

Table D-1 The reservoir coefficients of the recession curves

period		RC	Reservoir coefficient	period		RC	Reservoir coefficient
from	to			from	to		
14-2-74	2-3-74	-0.0698	14.3	15-3-79	22-4-79	-0.0408	24.5
23-3-74	7-4-74	-0.0729	13.7	18-3-79	28-7-79	-0.0226	44.2
23-3-74	18-4-74	-0.0663	15.1	6-4-79	18-4-79	-0.0926	10.8
23-4-74	9-6-74	-0.0156	64.1	3-6-79	28-7-79	-0.0256	39.1
17-8-74	31-8-74	-0.0551	18.1	13-8-79	12-10-79	-0.018	55.6
1-4-76	25-7-76	-0.0145	69.0	13-11-79	26-11-79	-0.0751	13.3
1-4-76	15-9-76	-0.0143	69.9	8-2-80	1-3-80	-0.0828	12.1
25-2-77	9-3-77	-0.0895	11.2	5-4-80	19-4-80	-0.0833	12.0
21-5-77	2-6-77	-0.0833	12.0	16-5-80	17-6-80	-0.0143	69.9
1-6-77	31-10-77	-0.0079	126.6	26-7-80	16-8-80	-0.072	13.9
1-8-77	12-8-77	-0.0851	11.8	1-9-80	5-10-80	-0.02	50.0
20-8-77	27-8-77	-0.1128	8.9	4-9-80	6-10-80	-0.0164	61.0
4-11-77	16-11-77	-0.1836	5.4	18-11-80	24-11-80	-0.1211	8.3
28-11-77	5-12-77	-0.1121	8.9	8-1-82	20-1-82	-0.1	10.0
4-2-78	21-2-78	-0.0823	12.2	1-2-82	6-2-82	-0.1541	6.5
1-4-78	12-4-78	-0.106	9.4	22-3-82	5-4-82	-0.0673	14.9
21-5-78	31-5-78	-0.0794	12.6	10-4-82	29-4-82	-0.0641	15.6
10-6-78	27-9-78	-0.0134	74.6	12-6-82	20-9-82	-0.012	83.3
13-7-78	28-7-78	-0.0687	14.6	9-7-82	30-9-82	-0.0078	128.2
1-8-78	31-8-78	-0.0196	51.0	25-10-82	6-11-82	-0.0537	18.6
1-10-78	14-10-78	-0.0692	14.5	28-11-82	4-12-82	-0.0829	12.1
18-2-79	1-3-79	-0.0858	11.7				

Appendix E The parameters and results of all the simulations

Table E-1 The parameters, efficiency coefficients and relative differences in total discharge for the calibration with precipitation as input

Calibration	P	α (mm)	β (–)	γ (–)	δ (–)	k1 (d)	k2 (d)	**R^2 (-)**	**RDq (%)**
constant runoff model	P							0.0000	0.0000
linear rainfall-runoff model	P	-0.1386	0.5052					0.3688	0.0000
linear rainfall-runoff model, with one reservoir	P	-0.9085	0.0194	0.7326		12.5702		0.4908	0.0000
	P, peak	-1.0018	0.0158	0.7398		9.7271		0.4859	0.0000
linear rainfall-runoff model with two reservoirs	P	-0.9802	0.0150	0.5305	0.2442	9.4921	63.9985	0.4979	0.0000
	P, peak	-1.1324	0.0215	0.5263	0.2690	7.4898	56.9976	0.4912	0.0000
linear rainfall-runoff model with two reservoirs and evapotranspiration	P	-0.8634	0.0295	0.4525	0.5187	8.0023	49.9969	0.6129	0.0000
HBV								0.8136	0.0780

Table E-2 The parameters, efficiency coefficients and relative differences in total discharge for the validation with precipitation as input

Validation	P	α (mm)	β (–)	γ (–)	δ (–)	k1 (d)	k2 (d)	**R^2 (-)**	**RDq (%)**
constant runoff model	P							0.0000	-0.9850
linear rainfall-runoff model	P	-0.1386	0.5052					0.4025	0.1266
linear rainfall-runoff model, with one reservoir	P	-0.9085	0.0194	0.7326		12.5702		0.5241	1.4002
	P, peak	-1.0018	0.0158	0.7398		9.7271		0.5432	1.5698
linear rainfall-runoff model with two reservoirs	P	-0.9802	0.0150	0.5305	0.2442	9.4921	63.9985	0.5242	1.4767
	P, peak	-1.1324	0.0215	0.5263	0.2690	7.4898	56.9976	0.5370	2.8490
linear rainfall-runoff model with two reservoirs and evapotranspiration	P	-0.8634	0.0295	0.4525	0.5187	8.0023	49.9969	0.6261	4.3513
HBV								0.9145	-4.3630

Table E-3 The parameters, efficiency coefficients and relative differences in total discharge for the calibration with effective precipitation as input

Calibration	Peff	α (mm)	β (–)	γ (–)	δ (–)	k1 (d)	k2 (d)	**R^2 (-)**	**RDq (%)**
linear rainfall-runoff model	Peff	0.3523	0.5367					0.5082	0.0000
linear rainfall-runoff model, with one reservoir	Peff	-0.7698	0.0236	0.8488		14.9724		0.5872	0.0000
	Peff, Peak	-0.7763	0.0273	0.8320		11.9560		0.5832	0.0000
linear rainfall-runoff model with two reservoirs	Peff	-0.7858	0.0306	0.4628	0.4101	8.0045	49.9987	0.6121	0.0000
	Peff, Peak	-0.8360	0.0302	0.3968	0.4751	6.9740	47.9985	0.6092	0.0000
linear rainfall-runoff model with two reservoirs and evapotranspiration	Peff	-0.8474	0.0291	0.5161	0.4145	7.0380	47.9974	0.5610	0.0000

Table E-4 The parameters, efficiency coefficients and relative differences in total discharge for the validation with effective precipitation as input

Validation	Peff	α (mm)	β (–)	γ (–)	δ (–)	k1 (d)	k2 (d)	**R^2 (-)**	**RDq (%)**
linear rainfall-runoff model	Peff	0.3523	0.5367					0.5383	-0.6938
linear rainfall-runoff model, with one reservoir	Peff	-0.7698	0.0236	0.8488		14.9724		0.6108	1.5749
	Peff, Peak	-0.7763	0.0273	0.8320		11.9560		0.6289	1.7118
linear rainfall-runoff model with two reservoirs	Peff	-0.7858	0.0306	0.4628	0.4101	8.0045	49.9987	0.6202	1.7340
	Peff, Peak	-0.8360	0.0302	0.3968	0.4751	6.9740	47.9985	0.6385	2.0121
linear rainfall-runoff model with two reservoirs and evapotranspiration	Peff	-0.8474	0.0291	0.5161	0.4145	7.0380	47.9974	0.5573	1.5828