Modelling ungauged lowland basins: Does complementary groundwater data add value to topography driven conceptual modelling?

Msc Thesis
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Modelling ungauged lowland basins:

Does complementary groundwater data add value to topography driven conceptual modelling?

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A common practice for hydrologists to determine the performance of a hydrological model and its parameter values, is by calibrating the model parameters on observed discharge data, but this data is not always available. For this reason, other data should be used as complementary data in order to reduce the uncertainty of outflow and processes in the ungauged basins.

A case study has been performed on an area in Baden-Württemberg, Germany, to see whether groundwater level data can be used as complementary data for hydrological models of ungauged basins. The use of groundwater level data for hydrological models has been tested before, but only on small scaled (<20 km$^2$) gauged basins, where homogeneity of hydrological processes can be expected earlier than for larger basins. The case study area has a size of around 1000 km$^2$. It has been divided into two Hydrological Response Units (Lowland and Hillslope) with use of the surface slope and the height above the nearest drainage (HAND) algorithm. Data from two discharge stations was available for part of the Hillslope area. The model performance has been evaluated with use four evaluation criteria: the Nash-Sutcliffe efficiencies for the flows, log of the flows, flow duration curve and log of the flow duration curve. It is confirmed that extrapolation of the model structure and parameter values to other areas that are similarly classified as Hillslope is a valid procedure.

The parameter values for the Lowland areas are constrained with use of groundwater level data. A selection of the groundwater level data is made with use of time series analyses performed with use of the PIRFICT model. The input data used was precipitation data, potential evaporation data and Rhine water levels. Weekly data from twelve groundwater level stations showed a high explained variance. The model parameters are constrained with use of three criteria on the waterlevels of the saturated zone reservoir of the model: A correlation coefficient $r$, the Nash-Sutcliffe efficiency of a normalized height curve and the autocorrelation. In addition to groundwater level data, it is tested whether the addition of three realistic relationships between parameters of the Hillslope and Lowland areas does reduce the uncertainty of the model.

A combined addition of groundwater level measurements and constraints did show reduced uncertainty, and thus improvement, of the internal model processes, especially the fluxes towards and out of the slow responding reservoir. Validation of these processes still remains difficult in ungauged areas, but it is believed that valid results can be made on the outflow out of the lowland areas with a combination of constraints and groundwater measurements to determine internal processes, and evaporation estimates obtained from satellite imagery to reduce the uncertainty of the total runoff out of the area. At the end, recommendations are made for improvements on the approach.
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# Table of Contents

Chapter 1. Introduction 1  
1.1 Ungauged basins 1  
1.2 The GRADE project 3  
1.3 Hydrological models of lowland areas 6  
1.4 Groundwater as complementary data 7  
1.5 Research objectives 8  

Chapter 2. Area Description 11  
2.1 The Rhine basin 11  
2.2 Case study area 18  

Chapter 3. Method description 23  
3.1 Perceptual model of the case study area 23  
3.2 Area classification 25  
3.3 Model descriptions 26  
3.4 Model input 33  
3.5 Initial parameter ranges 35  
3.6 Hillslope model evaluation 36  
3.7 Lowland model evaluation 38  

Chapter 4. Results 43  
4.1 Area classification 43  
4.2 Hillslope 45  
4.3 Lowland 57  

Chapter 5. Discussion 69  
5.1 Area classification 69  
5.2 Hillslope 70  
5.3 Lowland 73  

Chapter 6. Conclusions 77  

Appendices 81
CHAPTER 1. INTRODUCTION

1.1 UNGAUGED BASINS

A common practice for hydrologists to determine the performance of a hydrological model and its parameter values, is by calibrating the model parameters on observed discharge data. This is understandable from an engineering point of perspective, since the outflow is a large entity in the waterbalance of an area. Also, calibrating on discharges is a relatively easy method to apply. When also taking into account the quantity of research performed on calibration and the amount and robustness of currently available software to do so, one can explain the popularity for these methods.

Unfortunately, discharge data is not available for all catchments due to the lack of a flow gauge in the area or insufficient data at the required space-time scales. These catchments are defined as ‘ungauged basins’ (Parajka et al., 2013). This lack of data results in a large uncertainty of the hydrological processes involved in these catchments.

In an attempt to tackle the main and associated problems with ungauged basins, the International Association of Hydrological Sciences launched an initiative in the year of 2003: the PUB initiative (Predictions in Ungauged Basins). This initiative was set out to shift the scientific culture from calibration, sometimes referred to as parameter fitting (Hrachowitz et al., 2013), towards an improved scientific understanding of hydrological processes, as well as associated uncertainties and the development of models with increasing realism and predictive power (Hrachowitz et al., 2013; McDonnell et al., 2007).

In the mind of this decade, Savenije (2010) suggested that break-up of model structures of a catchment area into hydrological response units (HRU’s) should be based on topography, resulting in a model structure for each different HRU. This is also an answer to the earlier criticized ‘one-size-fits-all’ approach for model structures that is widely used in engineering (Savenije, 2009; McMillan, 2011). He was not the first, as Beven (2001) and Winter (2001) already suggested that landscape characteristics might be the best way to map conceptual model structures and relationships. But the suggestion made
by Savenije was followed by a lot of research done at the Technical University of Delft in testing or expanding the FLEX-Topo approach (e.g. Gao et al., 2014; Gharari et al., 2011; Gharari et al., 2013; Bouaziz, 2012).

Within the approach, two of the often used model types, distributed and lumped, are combined to form the semi-distributed approach. Whereas distributed models often suffer under the worst consequences of equifinality (Beven, 1993), lumped models are usually found to be too simple to be realistic or representative of the dominant hydrological processes (Savenije, 2010). Also, usually there is more information available on the processes within a catchment than what is included in a completely lumped model structure. This does involve a large variety of available data other than streamflow (e.g. landcover or topography maps, groundwaterlevel measurements) as well as expert knowledge on the processes involved in a catchment.

The semi-distributed approach tries to find the golden mean in between the lumped and distributed modelling approaches to distribute parameters and model structures where possible, while keeping the model as simple as possible to reduce the effect of equifinality. The suggested main distributed driver is topography, and a break-down of the catchment area is suggested to be: cultivated plateaus, forested hillslopes and lowland area either cultivated or used as wetland area. Other distributed data can be linked to the parameters in the distributed model structures, such as the maximum interception capacity or the depth of the unsaturated zone in the soils. Where data for parameter values can not be directly determined, constraining the parameters between the HRU’s with simple expert knowledge is proven to reduce the uncertainty involved in these parameters (Gharari et al., 2013).

The approach makes it possible to extrapolate model structures and parameters towards the hydrological response units in other areas which share the same visual characteristics (e.g. slope, land cover, distance and height to the nearest drainage system), even across catchment borders (Swapalan, 2005). The uncertainty of the hydrological processes involved in ungauged basins is reduced tremendously, resulting in a way to give the right answers for the right reasons (Kirchner, 2006).
1.2 The GRADE Project

The Generator of Rainfall And Discharge Extremes project (GRADE), performed by the Dutch organisations KNMI, Deltares and Rijkswaterstaat WVL, aims to establish a new approach to define the design discharges flowing into the Rhine Estuary at Lobith and for the Meuse at Borgharen. An outline of the project can be seen in Figure 1.

GRADE consists of four steps: 1) Very long (i.e. 50,000 years) synthetical weather time series for the Rhine and Meuse are generated with use of historical records of precipitation and temperature. 2) The Rhine basin is subdivided into a number of subcatchments (currently 148) for which HBV-based hydrological model structures are set up, with the model structure as defined by Lindström (1997). For all of these subcatchments, the parameters used in the HBV-model are calibrated by performing a GLUE analysis on high flows with use of the Nash-Sutcliffe efficiency (Hegnauer and Becker, 2013) on the available historical data (1989-2006) (Wensemius et al., 2013). Via the calibration, the synthetical weather time series are used as input for the HBV-models. 3) A selection of the annual maxima of the output of the HBV-models (various percentiles, to span the uncertainty of the HBV model) is used as input for a hydraulic model of the Rhine in the SOBEK-software. 4) Discharges of the Rhine, calculated by the hydraulic model, along with the probability of occurrence for the long time series, make it possible to estimate the expected return period of a high flow. These return periods can be used to determine the design discharges of the Rhine water systems in the Netherlands.

The way this method differs from currently used methods, such as the Gumbel estimation (Al-Mashidani et al., 1978), is that GRADE does not extrapolate currently available discharge data to estimate the discharge at the desired return period. Instead, these discharges are calculated with use of generated weather time series, as presented in Figure 2.

During the second step, the HBV-models are calibrated on discharge data. For some subcatchments no flow gauge measurements are available, making this method of calibration on these areas not possible. These areas are in GRADE referred to as the ZwischenEinzugsgebieten (ZWE-areas) and are represented in Figure 3 as the grey, uncalibrated areas. The flow from these areas is during the calibration of the HBV-models assumed to be zero. The results of the calibration showed an offset which increases for further downstream situated flow gauges in the Rhine (e.g. Figure 4). This offset was accounted towards the ZWE-areas, and therefore in the further steps of GRADE the outflow out of these areas could not be neglected.
**INTRODUCTION**

The parameter values for the ZWE areas were copied from other basins. For all HBV sub-catchments, the average slope was determined. Based on the average slope it was decided which parameter set each ZWE was given. The choice for the average slope was made on the fact that the slope is related to the rainfall-runoff processes that play a important role in an area (Hegnauer and Becker, 2013b).

Extra research for the rainfall-runoff mechanisms of the ZWE-areas is suggested to get a better understanding of how these areas respond under extreme conditions (Winsemius et al. 2013).

**Figure 1.** Component structure of GRADE (Source: de Wit and Buishand, 2007).

**Figure 2.** The difference between the currently used and GRADE method to determine design discharges. (Source: de Wit and Buishand, 2007).
**Figure 3.** Division of the Rhine basin into 148 HBV-models. The grey areas indicate the location of the ZWE-areas (Source: Hegauer and Becker, 2013).

**Figure 4.** Double Mass curve of the observe for the and with use of the HBV-models simulated discharges at Lobith (Source: Winsemius et al., 2013).
**1.3 HYDROLOGICAL MODELS OF LOWLAND AREAS**

The ZWE-areas are mainly lowland areas close to the river Rhine. Lowland areas are either flat areas with managed surface water levels, which is the case in large areas of the Netherlands, or mildly sloping, freely drained catchments.

These areas are often used for agricultural purposes, and have complex and dense draining networks for routing of the surface water. Therefore, hydrologic models of the lowland areas are also often complex (e.g. SOBEK (DELTAres, 2014) or MIKE-SHE (REFSGAARD AND STORM, 1995)). Most of them contain a distributed grid-based model structure. Some have a very detailed vertical schematisation (e.g. SWAP (VAN DAM ET AL., 2008)) or are coupled to a groundwater model, such as MODFLOW (MCDONALD AND HARBAUGH, 1984).

An example is the very data intensive study performed by van der Velde et al. (2009), who used groundwater level and catchment discharge data to test a high-resolution spatially distributed hydrological model. The probability of groundwater depth was distributed spatially, and a relation was made with groundwater storage. This relation, together with spatially distributed soil properties, vegetation and drainage networks made it possible to include a changing active channel network, unsaturated zone and surface ponding in the model.

The above described procedures are not feasible within the project scale of GRADE, since the available spatial data does not have a similar high resolution. Also, preference is given to simpler, lumped or semi-distributed conceptual model types since these models are often equally good at reproducing an output signal, due to a catchment being a self-organizing system (SAVENJIE, 2001). For these reasons and to reduce the effects of equifinality, zooming out instead of zooming in (and thus averaging of processes) is performed in this study.
1.4 **GROUNDWATER AS COMPLEMENTARY DATA**

Groundwater level data are widely available in the ZWE-areas. In the Rhine-Meuse basin, more than four thousand point-scale groundwater level measurement stations are present that hold recent (after 1992) time series of daily, weekly, monthly or quarterly intervals that stretch at least five years (Sutanudjaja et al., 2013). Most of these stations are situated near the Rhine floodplain.

The addition of groundwater level data as complementary and soft data to a hydrological model is tested earlier in multiple studies (e.g. Seibert, 2003; Freer et al., 2004; Fenicia et al., 2008; Chen and Hu, 2004). In the first three of these exemplary studies, new objective functions were formulated for which the assumption was made that the water level in the saturated soil reservoirs are not just conceptual reservoirs for all slow responses, but instead that the water level of the saturated soil reservoirs are directly correlated with the groundwater level.

Seibert (2003) used groundwater level data available in four catchments in Sweden with areas ranging from 6 to 18 km$^2$, with 4-10 groundwater level measurements each. The measurements taken were averaged to form a lumped groundwater signal for which a correlation coefficient ($r^2$) was used as objective function. Freer et al. (2004) tested a dynamic TOPMODEL on a catchment in New Zealand with an area size of 3.8 ha, with use of 20 tensiometers with which fuzzy groundwater level time series were made that had to match under fuzzy performance measures with the simulated water levels in the saturated reservoir. Fenicia et al. (2008) used groundwater level data to figure out the subsurface flow dynamics along a hillslope on the same catchment in New Zealand, for which they made use of two groundwater level measurements.

Chen and Hu (2004) introduced a conceptual model with a soil column consisting of four reservoirs. This way, they were able to implement vertically varying hydraulic conductivity and extra fluxes to capture the influence of the groundwater on the unsaturated zones.

The areas on which experiments were performed are small compared to the size of the catchments in the GRADE project. However, a reduction of behavioural parameter sets was observed in the method of Freer et al. (2004). Based on these results and the quantity of available groundwater level data in the Rhine basin, the addition of this data is tested during this study to see if reductions of process uncertainty can be observed, even in this larger scale.
INTRODUCTION

1.5 RESEARCH OBJECTIVES

To gain a better insight in the possible risks the discharges out of the ZWE-areas can cause, the rainfall runoff mechanism of these areas should be identified and the quantity uncertainty range reduced as much as possible. Therefore, the main research objective is as follows:

The objective of the research project is to identify and quantify the rainfall-runoff mechanisms of ungauged areas close to the river Rhine and the circumstances in which peak discharges out of these areas occur.

To be able to answer the research project, one area has been chosen as a case study area. For the research area, the main research objective can be broken down into project goals. The main project goals for this work are to:

- Classify the area into separate hydrological response units.
- Create a hydrological model structure suitable for each hydrological response unit.
- Investigate new means of constraining model outcomes by using groundwater level data instead of discharge data.

Another goal of the project is to keep the model structure relatively simple, as it should be of use on the scale of the GRADE project. This means that a conceptual model will be made which should be as simple as possible, while providing the required information to reach the main project goals.
CHAPTER 2. AREA DESCRIPTION

2.1 THE RHINE BASIN

2.1.1 GENERAL OUTLINE

The River Rhine has its origins in the Alps, in the Swiss canton of Grison. The river collects water from nine countries: Italy, Liechtenstein, Belgium, Luxemburg, Austria and larger portions of Switzerland, Germany, France and the Netherlands, while running through the latter four to reach the North Sea. The length of the Rhine is around 1320 km long and the catchment size is 160,000 km\(^2\) up to Lobith (Liefveld and Postma, 2007), which is the most downstream situated gauge and thus the most important gauge for evaluating the discharge of the Rhine in the North Sea. When including the deltaregion in the Netherlands, the catchment size is around 185,000 km\(^2\). It is inhabited by approximately 60 million people (Belz et al., 2007).

The river has many uses. About 800 km in between Basel and Rotterdam are navigable, and this stretch of the Rhine is one of the busiest waterways in the world (Belz et al., 2007). The water supplied by the main river and the tributaries is used by industrial plants as process water and by thermal power plants as cooling water. A lot of cities obtain part of their drinking water via river bank filtration out of the Rhine (Weiler et al., 2012).

The Rhine is usually classified into six regions: The Alpine Rhine, the High Rhine, the Upper Rhine, the Middle Rhine, the Lower Rhine and the Rhine Estuary (Figure 5). The Alpine Rhine starts south of Chur, where the Vorder and Hinter Rhine join each other. This river then flows into Lake Constance west of Bregenz. The section from Lake Constance up to Basel is referred to as the High Rhine. The Upper Rhine is the section between Basel and Bingen. The section between Bingen and Bonn is known as the Middle Rhine, the area between Bonn and Lobith is known as the Lower Rhine, and the delta region behind Lobith is known as the Rhine Estuary.

The largest inflows into the Rhine are the Aar in the High Rhine, the Neckar and Main into the Upper Rhine, the Moselle in the Middle Rhine and the Ruhr and Lippe in the Lower Rhine. The most important cities situated close to the main stream of the Rhine are, from most upstream to
downstream, Basel, Karlsruhe, Mainz, Koblenz, Bonn, Cologne, Nijmegen and Rotterdam, the main port of the Netherlands.

2.1.2 THE REGIME OF THE RHINE

Belz et al. (2007) have investigated the runoff of the various regions of the Rhine with use of long daily mean discharge time series of 38 flow gauges. The time series used have data ranging from 1901 and 1951 until 2007. This large dataset gives a good view of the average runoff regime of the Rhine over the previous century and current times.

When starting at Lake Constance and following the Rhine in a downstream direction, the measured average annual discharges are 442 m³/s at the Rekingen gauge (before the Aar (560 m³/s) joins the Rhine), 1060 m³/s at Basel, 1250 m³/s at Maxau (Karlsruhe), 1410 m³/s at Worms, 2010 m³/s at Andernach, 2080 m³/s at Cologne and 2220 m³/s at Lobith. The Neckar, Main and Moselle contribute on average with respectively 135 m³/s, 210 m³/s and 315 m³/s (Figure 5, Belz et al., 2007).

Up till Basel the river has a nival (snow-melt) regime. Here, the river has high flows during summer months, mainly during June, and low flows during winter months. In between Basel and the inflow of the Neckar the river has a mixed nival and pluvial regime, but the highest monthly average is still in June. Because of the inflow of the Neckar (high average discharge in February and March: low in September), Main (high average in March: low in August and September), Moselle (high average in December and January: low in August and September) and other inflows with a pluvial regime, the Rhine changes from having the highest monthly average discharge in early summer, to the highest monthly average in December and January at Andernach and the remaining sections of the Rhine.

Figure 6 shows the change of the regime expressed in the Pardé coefficient. The Moselle is used as an example of the influence of tributaries with a pluvial regime on the discharge of the Rhine. The dimensionless Pardé coefficient $C_p$ is defined as the ratio between the long term average monthly discharge $Q_{i,avg}$ (m³/s) and the long term average annual discharge $Q_{y,avg}$ (m³/s):

$$C_p = \frac{Q_{i,avg}}{Q_{y,avg}}$$
**The Rhine basin**

**Figure 5.** Schematic of the longitudinal altitude and discharge sections of the Rhine River. Discharge (m$^3$/s) is displayed by long-term (100 years, 1901 to 2000) mean flow (MQ), absolute high flow (HQ) and absolute low flow (NQ) values for each gauging station. Along the x-axis also major gauging stations (red) and tributaries (blue) are shown. (Source: Belz et al., 2007).

**Figure 6.** Typical discharge regime in the Rhine basin according to Pardé for the reference period of 1961-1990 (Source: Belz et al., 2007).
2.1.3 Measured historical changes of the regime of the Rhine

In order to see if there is a visible trend towards a decrease or increase of the Rhine discharge in the available time series between 1901 and 2000, Belz et al. (2007) investigated the available discharges at the 38 gauges. Their results are presented in Figure 7.

When going from upstream to downstream areas, for the Alpine and High Rhine the winter runoff has increased significantly (>95% significant trend) in seven regions, while summer runoff has decreased in five regions (>80% significant trend). The increased winter runoff is said to be due to an increased amount of precipitation and due to the fact that because of higher air temperatures, more precipitation falls as rain rather than snow (Belz et al., 2007; Pinter et al. 2006). The latter is also one of the reasons for the decreasing runoff in late summer, since there’s less interim storage of runoff water available. Human influences might also be the reason for the change, mainly due to the timing of filling and spilling of artificial retaining lakes in Switzerland and in the Ruhr.

The mean annual discharges of the Upper and Middle Rhine show a good correlation with the increased amount of precipitation. Probably due to the precipitation, at these areas the annual discharge has increased over the last 50 years with 7-10%. This effect is mainly visible in winter; the summer runoff is slightly less because of the decrease in snowmelt in upstream areas.

![Figure 7](image_url). The measured increase and decrease of discharge over the stretch of the Rhine for the reference period of 1901-2000 (Source: Belz et al., 2007).
Up until Lobith, the Lower Rhine receives water originating from a couple of tributaries with a pluvial regime, which have an increased amount of rainfall during winter over the last century. The winter discharge at Lobith has therefore increased with around 12%, from an average of 2300 m³/s to 2600 m³/s, but this trend is only >80% significant for the month of February. Also, when only taking the last fifty years into account instead of the hundred year period, the trend is less significant.

The general outcome over the whole stretch of the Rhine is that there is an increasing trend for the discharge in hydrological winter (Nov.-Apr.) but a slight decreasing trend in late summer (May-Oct). The annual average discharge for all flow gauges combined does not display a significant trend.

2.1.4 Historical changes in river high flows

Due to the larger amount of precipitation and the land-use changes, flood peaks have occurred more often over the whole stretch of the Rhine over the course of the 20th century (Belz et al., 2007; Diermanse et al., 2010; Pinter et al., 2006). There is a noticeable increase in flood peaks in the Alpine and pre-alpine basins for the data series of the 20th century. This effect continues in the Upper Rhine, where measures have been implemented to reduce the flood peaks with up to 30 cm (10 cm up to Cologne). Also, due to possible superimposing of flood waves of the Rhine with those of the Neckar (due to canalisation), an increase from 6000 to 6700 m³/s in the 200-year-recurrence floods is calculated for the Rhine stretch just below the mouth of the Neckar (Belz et al., 2007).

Floodings in the Middle and Lower Rhine can occur when heavy rainstorms (possibly combined with snowmelt) coincide with a flood wave from the Upper Rhine. Since there’s an increase of precipitation in late winter, there's also a noticed increase in intensity of these flood waves in the Middle and Lower Rhine. Especially the Moselle plays a large role in all this, where the peak values can increase up to 4200 m³/s (as comparison, 2600 m³/s of the Aar, 1200 m³/s of the Main).

Pinter et al. (2006) identified a statistically significant increase in frequency for all discharge subsets ranging from >5000 m³/s up to 7500 m³/s at nine gauges in Germany. Increases for the very large floods (>8000 m³/s) drop below the 90% confidence threshold, because of the relatively small number of these events during the last century.

Measurements at Lobith show that there is an increase in average flood peak discharges, which is mainly caused by the high floods that occurred in the last three decades of the 20th century. The largest value at Lobith, however, was measured in January 1926, approximately 13000 m³/s (Belz et al., 2007). Diermanse et al. (2010) found the increase of annual maximum discharges for Lobith (running from the years of 1901 to 2003) to be 8 m³/s per year (or 13%), but this trend is not found to be statistically significant for four different statistical tests (Pearson t-test, Spearman’s
rank correlation test, Mann-Kendall test and Wilcoxon-Mann-Whitney test). The significance levels obtained by Diermanse et al. were in between 15 and 32%.

The difficulty of identifying statistically significant trends over time in past flooding behaviour has at least three reasons: the large interannual variability in river flow data, the complex and overlapping nature of changes that may alter flood behaviour and the short duration of instrumental records compared to the return time of the flood peaks. Therefore, even though in some studies the reported significance levels are relatively high, one can argue that there is still a visible signal towards larger maximum discharges. There is still a lot of debate on-going concerning to what extent climate change is the reason for the change in flood occurrences in the Rhine, and whether there is a visible climate change signal which can be derived from the available data. According to Pinter et al. (2006) change of instream mechanisms (channel constriction, aggradation, loss of floodplains, acceleration of flood flows) is most likely not the reason for the change in flood occurrence. Other anthropological effects, such as land-use change and intensification and industrialisation of agriculture, can however still well be a cause of the changes in flood occurrence.

2.1.5  HISTORICAL CHANGES IN RIVER LOW FLOWS

In addition to floods, low flows can cause large problems for the Rhine in terms of for instance ecology, lack of cooling water for industries or problems for navigation. Unlike flood waves, it is not a distinctive low that causes these problems, but an extensive depression curve. In comparison to floods, far less research has been done on river low flows.

In the Alpine, High Rhine and Upper Rhine, where due to the nival regime the low flows occur during winter, there's an increase of the 7-daily arithmetic mean of these low flows found in the data from 1901 up to 2000. The reason for this is the redistribution of summer runoff to winter. In the Middle Rhine up to Cologne, where low flows occur during summer, only a slight increase in the arithmetic mean is found, while upstream of Cologne no trend can be identified. The lowest measured 7-daily arithmetic mean at Lobith is 624 m$^3$/s, but values below 700 m$^3$/s have not been recorded after 1960 (Belz et al., 2007).

2.1.6  FUTURE PREDICTIONS ON THE RHINE RIVER FLOW

There have been a lot of model studies on the Rhine in order to determine the sensibility of the system to climate changes or changes of land-use in the basin. In order to do so, possible scenarios are derived from results of global and regional climate models and land use data, which were used as input for hydrological and hydraulic models (e.g. Kwadijk and Rotmans, 1995, Middelkoop et al., 2001; Shabalova et al., 2003; Lenderink et al., 2007; Görgen et al., 2010; Hurkmans et al., 2010).
The general outcomes of the models for projections up to 2050 and 2100 are that summer discharges will decrease even further and the volumes of winter discharges will increase in both variance and quantity. The results of the model studies indicate that the percentage of increase of average daily discharges during winter ranges between 15% and 30%, depending on the used climate scenarios. The percentage of expected decrease of average daily discharges during summer ranges between 5% and 40%.

Most of the models also give a reserved opinion that the occurrence of low-probability flood events will increase during winter, but due to the small amount of data available on flood events, there’s still a lot of uncertainty involved. The most extensive research on this matter has been done by te Linde et al. (2010), who used a weather generator and the output of a regional climate model to simulate long, resampled time series of climate change scenarios. The results indicate a basin-wide increase in 2050 of 8% to 17% for probabilities of peak discharges between 1/10 and 1/1250 years, with only a statistical uncertainty of 3%.

2.1.7 Final remarks

Even though there are a lot of uncertainties involved, the many statistical researches show that the regime of the Rhine has changed in the past century, and will most likely continue to change in the upcoming century. Due to these changing circumstances, extrapolating currently measured discharges to get the design discharges is not sufficient and GRADE is a step in the right direction.

What can be concluded is that the change of the regime of the Rhine and the modelled estimates on future conditions emphasize the need for process understanding of the rainfall runoff mechanisms in order to really be able to estimate the effects of possible future changes of the circumstances.
AREA DESCRIPTION

2.2 CASE STUDY AREA

2.2.1 GENERAL OUTLINE

From the GRADE project, one HBV-catchment (area 117) has been chosen as the case study area due to the availability of data (Figure 8). This area is situated in the province of Baden-Württemberg, South-Western Germany. The Rhine is the physical border in between France and Germany and the western border of the area. The low mountain ranges of the Schwarzwald natural resort are situated on the eastern border of the area. The closest larger cities are Strassbourg in France and Karlsruhe in Germany.

The area has been slightly revamped with use of a more detailed DEM compared to the DEM used to delineate the HBV-catchments in GRADE. Only the German area has been taken into account during this research. The closest upstream Rhine water level measurement station is situated at Kehl-Kronenhof and the outflow point of the research area is situated at the water level measurement station at Maxau (Figure 16).

The area size is approximately 1000 km$^2$ and the elevation ranges between 80 and 1110 m above mean sea level, with the lowest point being the Rhine water level measurement station at Maxau (Figure 9). The slope of the area ranges between 2° and 84° with an average of 5.6° (Figure 10).

As can be seen in Figure 8, the landscape is dominated by small streams of which discharge values are unknown. The water which generates these streams originates from precipitation, groundwater seepage from the hilly eastern areas and seepage water from the Rhine at areas where the elevation is lower than the Rhine water levels.

![Research Area](image)

**Figure 8.** The outline of the research area located in Baden-Württemberg.
**Case Study Area**

**Figure 9.** Surface elevation of the case study area.

**Figure 10.** Surface slope of the case study area.

**Figure 11.** Landuse in the case study area.


**2.2.2 LANDUSE AND SOIL TYPE**

The area originally was a wetland due to the gentle slope of the basin. It was around the start of the 20th century that large parts of the Rhine got canalized with the idea of transporting water more rapidly towards the lower lying areas and to reclaim land for new settlements (Moss and Monstadt, 2008). This resulted in an increased availability of fertile land, which is why most of the area is now used for agricultural purposes, and is heavily drained during winter periods. The typical soil type in the lowland area is loam (Weiler et al., 2012), which is composed of sand, silt and clay in relatively even proportions (40%, 40%, 20%). Loam is known for holding water very effectively (slow outflow out of the layers) and it usually also holds a high concentration of organic matter (Verrulit and Baars, 2001). This is also the reason the soil is ideal for agricultural uses.

The soil type in the higher situated hillslope areas goes from sandy loam in the upper layers to loam in the lower situated layers. Due to the larger porosity of the top sandy loam layers in comparison with loam, these areas are less suitable for agriculture. For that reason, the eastern hills are mostly covered by large areas of forests, with at the bottom of the hills vineyards and large berry and apple orchards (Figure 11).

**2.2.3 INFLUENCE OF THE RHINE ON THE AREA**

Because of the canalisation, some areas closer to the Rhine which were originally part of the wetlands have a lower surface elevation compared to the Rhine water level. This results in groundwater seepage from the Rhine towards these lower areas.

The main streams flowing into the Rhine can be closed off at high Rhine water levels to prevent water from the Rhine flowing into the area via the tributaries. However, some areas are pointed out as retention areas. These areas have been installed during the “Rheinvorland Süd” project (Moss and Monstadt, 2008) and during the Integrated Rhine Programme (Griesbaum et al., 1997), to improve both the ecological and hydrological conditions of the Rhine floodplain. Another function of these areas is to capture the peak of critical flood waves in the Rhine, with the goal to reduce occasional peak heights to make the areas situated further downstream less vulnerable to flooding.

Apart from the retention areas, there is a lot of human activities close by and in the Rhine, such as gravel mining facilities, harbours with privately managed sluices and water offtakes for drinking water. All these activities have a distorting effect on groundwater levels, which increases groundwater seepage from the Rhine into the area.
2.2.4 HYDROMETEOROLOGY OF THE CASE STUDY AREA

All information here is obtained from Weiler et al. (2012), unless stated otherwise, and all average values are obtained from data series ranging from 1961 to 1990.

Average annual precipitation values range from 700-800 mm/y in the lowland area towards 1300-1700 mm in the higher situated hillslope areas. On average, 65 % of the precipitation in the lowland area falls in summer periods (450-550 mm/y), while on the hillslope areas the summer precipitation values are around 50% of the average annual values (650-750 mm/y).

Average annual potential evaporation rates range between 600-650 mm/y in the hillslope areas and around 750 mm/y in lowland areas when calculated with use of the grass-reference method of Penman-Monteith (Allen et al., 1994). Values are around 50 mm/y higher when calculated with the method described by Haude (1955). In hydrological summer (May-Oct.), potential evaporation rates are around 50-100 mm higher in lowland areas, compared to hillslope areas, in winter these values are comparable. Estimates of actual evaporation rates, however, show higher average annual values for the hillslope compared to the lowland area. Comparable results for actual and potential evaporation rates were found by Uhlenbrook (1999) for the Brugga catchment, which is situated a little higher in elevation (434-1493 m AMSL): around 550 mm/y of actual and 660 mm/y of potential evaporation.

Snowfall is an issue mainly in the hillslope areas, with average values of around 50-100 mm/y, up to 125-150 mm/y in the highest parts, compared to 25 mm/y or less in the lowland areas. On average, snow is present for around 50-100 days per year in the hillslope areas, while in the lowland areas this value decreases to 15 days or less.

As described in Appendix B.2, the hydrological year is assumed to be ranging from May up till April, hydrological summer from May up till October and hydrological winter ranges from November up till April. This is in line with the definitions used by Belz et al. (2010) and Weiler et al. (2012).
CHAPTER 3. METHOD DESCRIPTION

3.1 PERCEPTUAL MODEL OF THE CASE STUDY AREA

Geology, land use and topography hold the key to identify areas which behave hydrologically the same (Gharari et al., 2011). The case study area is subdivided into two hydrological response units based on a field investigation (September 2013; Appendix A) and a visual comparison of the soil type, landuse and slope maps. These two HRU’s are lowland and hillslope areas.

A comparison of what was seen in the field and the various maps has shown that soil type, landuse and slope of the area are related to each other. Where areas are hilly, the soil is more sandy. This results in a larger unsaturated zone which in turn gives more space for the roots of trees to grow. Where areas are relatively flat with the natural groundwater level close to ground surface, the soil is less pervious and loamier, which makes it ideal to grow seasonal crops. Plateau areas as defined by Savenije (2010) were not found during the field investigation. Also only very small areas of wetlands were seen close to the Rhine, too small to take into account for a model study on the whole area.

The hillslope areas are the forested areas at the border of the Schwarzwald. The presence of trees hints towards a large unsaturated zone, otherwise the trees would drown during winter times. Therefore, drainage mechanisms are formed naturally in the soil. Due to the slope gradient and the subsurface drainage systems, the main conceptual rainfall runoff mechanism is storage excess subsurface flow (SSF).

The lowland areas are highly cultivated and therefore drained. Large areas where maize and other seasonal crops are grown were found during the field investigation. Water is expected to percolate through the soil towards the drainage systems. In case of extreme precipitation events, water will flow over land towards the same drainage systems (saturation excess overland flow (SOF)).
Precipitation falling in the hillslopes can fall in the form of snow in winter times, where it sometimes is stored for multiple weeks or even months. In the lowlands, the duration and depth of snow cover is negligible and thus not taken into account for this area.

The perceptual model is visualized in Figure 12.

Figure 12. Perceptual model of the case study area.
### 3.2 Area Classification

Area classification into the two HRU’s that were identified during the field investigation was done with use of two algorithms: the Height Above Nearest Drainage (HAND; Rennó et al., 2008) and the surface slope. The delineation of hydrological landscapes with use of these two algorithms has been proven to be effective in earlier studies (e.g. Gao et al., 2014; Gharari et al., 2011).

HAND was directly derived with use of a DEM map and a LDD map (Local Drainage Direction). The DEM as well as the LDD map were obtained via Hydrosheds (Lehner et al., 2008) and both had a resolution of 3 * 3 arcseconds (~ 90 m * 60 m for lat/lon). Since some of the smaller streams in the lowland area were not identifiable in the LDD, use was made of a more detailed stream map (Weiler et al., 2012) which was ‘burned’ into the LDD.

The classification method requires two thresholds to be determined, which concern the HAND and the surface slope. These thresholds determine for which HAND and for which surface slope the area is either considered as a lowland area, or as a hillslope area. They are chosen such that the results coincide with what was seen in the field, and at least 95% of the agricultural area is encompassed within the lowland area. The 95% threshold has been chosen to exclude random errors.
3.3 **MODEL DESCRIPTIONS**

3.3.1 **HILLSLOPE MODELS**

The Hillslope model structure is presented in Figure 13. It contains an interception module, modules for the processes in the unsaturated and the saturated soil zones and a module for the deeper groundwater flow towards the lowland area (Model structure A). The addition of a snow module has been evaluated on both performance and consistency (Model structure B). The model runs with a daily timestep.

![Hillslope model structure, with the snow module excluded in model structure A.](image)

**SNOW MODULE**

The snow module is only included in model structure B. In some hydrological models (e.g. HBV; Lindström et al., 1997), a single threshold temperature for snowfall is chosen to form the so called degree-day approach. When temperature $T$ (°C) reaches below a threshold with value $X_1$ (°C), precipitation $P$ (mm/d) is assumed to fall as snow $P_{snow}$ (mm/d). Since correlation between a single threshold value and the measured presence of snow in Freudenstadt did not prove to be effective (Appendix B.3), another condition for snowfall is implemented. Therefore, in addition to a temperature threshold, the derivative of the snow depth $[d_{snow}]'$ (mm/d) in Freudenstadt should also be positive. Following this procedure, precipitation falling as snow is stored in a snow reservoir:
MODEL DESCRIPTIONS

**Equation 2.** \[ T < X_1 \land [d_{snow}]' > 0: \]
\[ P_{snow}(t) = P_h(t) \]
\[ P_{rain}(t) = 0 \]

**Equation 3.** \[ T \geq X_1 \lor [d_{snow}]' \leq 0: \]
\[ P_{snow}(t) = 0 \]
\[ P_{rain}(t) = P_h(t) \]

**Equation 4.** \[ S_{snow}(t) = S_{snow}(t-1) + P_{snow}(t) \Delta t \]

When the temperature reaches threshold value \( X_1 \) (°C), the snow stored in the snow reservoir will melt and come to runoff or will infiltrate to the saturated areas \( Q_{snow,out} \) (mm/d) with coefficient \( K_{snow} \) (1/d):

**Equation 5.** \[ Q_{snow}(t) = K_{snow} \ast S_{snow}(t) \]

with \( S_{snow} \) (mm) being the snow storage volume per area.

**INTERCEPTION MODULE**

Interception is an important process for calculating the water balance in hydrology, since on average it can amount 20-50% of the precipitation (Breuer et al., 2003; Gerrits, 2010). Among other places, like rooftops or concrete roads or buildings, the majority of the interception is stored on and directly below the canopy. In this study interception covers both canopy and forest floor interception.

In the model, precipitation falling as rain \( P_{rain} \) (mm/d) is processed through the interception module. This module uses an interception reservoir with a maximum interception capacity \( I_{max,h} \) (mm) to firstly intercept rainfall and then allow any excess water to infiltrate into the soil and contribute to runoff. The snowmelt \( Q_{snow,out} \) (mm/d) is afterwards added to the excess water to form the effective rainfall \( P_{e,h} \) (mm/d):

**Equation 6.** \[ P_{e,h}(t) = \max ( P_{rain}(t) - I_{max,h}/\Delta t, 0) + Q_{snow,out}(t) \]

Considering the time scale of the interception process (de Groen and Savenije, 2006) and since the model runs with a timestep of a day, the assumption is that, depending on the potential evaporation, all intercepted water will evaporate within a day, or one time step, resulting in an empty reservoir for consecutive timesteps.

**UNSATURATED SOIL MODULE**

The (effective) rainfall \( P_{e,h} \) (mm/d) will infiltrate into the unsaturated soil layer \( Q_{iu,h} \) (mm/d). A part of the water will remain in the upper layers \( Q_{if,h} \) (mm/d) where part will infiltrate via preferential flow paths towards the saturated soil layer \( Q_{iwp,h} \) (mm/d) and part will contribute to runoff in the subsurface \( Q_{uf,h} \) (mm/d). The proportion of water which will remain in the upper layers is depending on the actual soil moisture, and can be presented as a beta distribution function:
**Method Description**

**Equation 7.**

\[ Q_{if,h}(t) = P_{e,h}(t) \cdot (1-(1-S_{u,h}(t)/S_{umax,h})^\beta) \]

**Equation 8.**

\[ Q_{iu,h}(t) = P_{e,h}(t) - Q_{if,h}(t) \]

**Equation 9.**

\[ Q_{uf,h}(t) = a \cdot Q_{if,h}(t) \]

**Equation 10.**

\[ Q_{wgw,h}(t) = (1-a) \cdot Q_{if,h}(t) \]

with \( S_{umax,h} \) (mm) representing the field capacity, \( S_{u,h} \) (mm) representing the actual soil moisture, \( \beta \) being the coefficient which accounts for the non-linearity of the runoff process and \( a \) being the splitting parameter for the amount of water either infiltrating to the deeper layers, or contributing to the runoff.

In addition to the fast response, a part of the water infiltrating into these upper soil layers will percolate as matrix percolation through the unsaturated soil towards the lower layers \( Q_{us,h} \) (mm/d) with a maximum percolation rate \( P_{max,h} \) (mm/d):

**Equation 11.**

\[ r_{us,h}(t) = P_{max,h} \cdot (S_{u,h}(t) / S_{umax,h}) \]

The transpiration \( E_t \) (mm/d) depends on the potential evaporation \( E_p \) (mm/d) and the proportion of the actual soil moisture \( S_{u,h}(t) \) (mm) and the field capacity \( S_{umax,h} \) (mm) according to the following formula:

**Equation 12.**

\[ E_a(t) = E_p(t) \cdot (S_{u,h}(t) / S_{umax,h} \cdot C_e) \]

\( C_e \) is a constant, which accounts for the percentage of soil moisture of the soil porosity under which the evaporation is assumed to follow a linear reduction function. In this study this is assumed to be 50%, which agrees with the procedure generally used in agricultural engineering (e.g. Ritjema and Aboukhaled, 1975).

**Saturated Soil Module**

As described by equation 9, part of the water infiltrates into the upper soil layers \( S_{f,h} \) (mm) which results in a fast response out of these layers \( Q_{f,h} \) (mm/d) with coefficient \( K_{f,h} \) (1/d):

**Equation 13.**

\[ Q_{f,h}(t) = K_{f,h} \cdot S_{f,h}(t) \]

Water reaches the lower laying saturated soil layers through direct infiltration of the rainfall via preferential flow paths (equation 10) and matrix percolation through the unsaturated soil (equation 11). Water that reaches the lower saturated soil layers will flow through the soil as subsurface discharge. The groundwater outflow \( Q_{s,h} \) (mm/d) can be represented well by a reservoir with linear outflow (Fenicia et al., 2008), which means that it is directly proportional to the storage:

**Equation 14.**

\[ Q_{s,h}(t) = K_{s,h} \cdot S_{s,h}(t) \]

where \( K_{s,h} \) (1/d) is a coefficient which accounts for the linearity of the process.
**Deeper Saturated Soil Module**

As pointed out in Appendix B.1, a deeper groundwater flow exists which feeds the lower areas with water. Whether this is a result of pressure difference or of water actually flowing through a more porous aquifer, this will result in an increase of water in the saturated zone of the lowland area.

In the model, water may percolate from the saturated but more shallow zones to the deeper groundwater layer. The outflow out of the deeper groundwater is assumed to be a linear process:

\[
Q_{gwdeep}(t) = K_{s,h} \cdot S_{gwdeep}(t)
\]

**Equation 16.**

It should be noted that no new parameters are introduced in the deeper saturated soil module to make sure that the equifinality of the model is not increased.
3.3.2 Lowland Model

The model structure for the lowland area consists of three modules: an interception module, a module for the unsaturated soil zone and a module for the saturated soil zones (Figure 14). Snow storage is not a dominant process in the lowland areas and is therefore not taken into account for these areas. Furthermore, a connection is made between the hillslope and lowland model for the groundwater flow: the saturated zone in the lowland model receives water from the deeper saturated soil module of the hillslope model.

**Figure 14.** Lowland model structure.

**Interception Module**

The interception module follows the same procedure as the interception module described for the Hillslope model, with maximum interception capacity $I_{\text{max},l}$ (mm). Effective rainfall out of the interception module is calculated as follows:

$$P_{\text{e},l}(t) = \max \left( P_{\text{rain}}(t) - \frac{I_{\text{max},l}}{dt}, 0 \right)$$

**Unsaturated Soil Module**

Irrigation and drainage are processes largely present in the lowland areas. Drainage is the fast responding process that ‘switches on’ when a specific groundwater level threshold is reached, much like the saturation excess overland flow process that occurs in wetlands. Here, saturation excess overland flow and drainage are combined as one process $Q_{\text{uf},l}$ (mm/d), and it is assumed on the scale of the study area this is a non-linear process with coefficient $\beta_{l,1}$ ($\cdot$):
The, in terms of volume, largest process following the precipitation is the transpiration and soil evaporation. It depends on the potential evaporation \( E_{p,l}(\text{mm/d}) \) and the proportion of the actual soil moisture \( S_{u,l}(\text{mm}) \) and the field capacity \( S_{umax,l} \) according to the following formula:

\[
E_a(t) = E_p(t) \cdot (S_{u,l}(t) / S_{umax,l} \cdot C_e)
\]

Water flows through the unsaturated zone towards the saturated zone through preferential flow paths and matrix percolation. It is assumed that on a daily timescale these fluxes can be combined in the lowland area. The process is thus conceptualized with the following formula:

\[
Q_{us,l}(t) = P_{max,l} \cdot (S_{u,l}(t) / S_{umax,l})
\]

with \( P_{max,l}(\text{mm/d}) \) being the maximum percolation rate in the lowland area.

**Saturated soil module**

The saturated soil gets fed by percolation according to equation 20 and via deep percolation from the hillslope area according to formula 16. Groundwater seepage out of the saturated zone is assumed to be a linear process and thus occurs with a coefficient \( K_{s,l}(1/d) \), which stands for the linearity of the process:

\[
Q_{s,l}(t) = K_{s,l} \cdot S_{s,l}(t)
\]

with \( S_{s,l}(\text{mm}) \) being the storage of the saturated reservoir in the lowland area.

One could argue that thresholds for drainage or saturation excess overland flow have to be included in the saturated soil module. However, on the scale of the catchment, sudden changes in discharge for reaching local thresholds values is hardly ever observed, because spatial variability in groundwater depth, drainpipe depth and microtopography cause these thresholds to be reached at different moments at different locations (Appels, 2013). For this reason the thresholds are not included in the model structure, and the assumption is made that the processes can be described as average values, as is done in the described equations.
**METHOD DESCRIPTION**

**IRRIGATION**

A third and fourth process that occur between the unsaturated and saturated zones in the heavily cultivated lowland are irrigation and capillary rise. These processes are usually significant in areas where the groundwater level is near the surface (Chen and Hu, 2004). It is tested whether the coupling with use of an irrigation flux did improve the performance of the model structure (Figure 15).

The assumption is that the irrigation flux $Q_{irr}$ (mm/d) always brings the soil moisture content at least up to a quantity $C_e$ of the field capacity, either with capillary rise or by irrigation. Both fluxes are subtracted from the saturated zone. This will make sure that transpiration is never constrained by soil moisture content. It is tested whether this assumption is valid for:

1) hydrological summer periods, the crop growing season.

\[ Q_{irr} (t) = \frac{(C_e \times S_{umax,l} - S_{u,l}(t))}{dt} \]

2) the whole hydrological year.

\[ Q_{irr} (t) = \frac{(C_e \times S_{umax,l} - S_{u,l}(t))}{dt} \]

![Figure 15. Lowland model structure with the irrigation flux included.](image)

Two more influences on the saturated zone have not been discussed yet. Firstly, anthropological processes, such as pumping and groundwater seepage from water retention basins also disturb the groundwater level measurements. Secondly, seepage water and backwater curves from the Rhine and its tributaries influence the water level in the saturated zone. In general, these processes are very spatially distributed, and most likely require detailed research with use of a distributed groundwater flow model and have thus been left out for simplicity of the model.
3.4 **Model Input**

For precipitation, data from six synoptical stations was available for use with data ranges from 2008-2012 (Figure 16). The data has been tested on irregularities with use of a double mass analysis. Furthermore, cumulative distribution functions were made to determine spatial differences between the stations and thus to determine which stations could be hold representative for the hillslope and the lowland area (Appendix B.2).

Potential evaporation estimates were determined with use of two methods: Hamon (1961) and Penman-Monteith (FAO: Allen et al., 1998). The first method only makes use of temperature data, which was available for four stations (Rheinau, Rheinstetten, Baden-Baden and Freudenstadt). The second method also makes use of additional meteorological data, which was only available in two stations, but these stations are positioned outside the case study area (Freudenstadt and Rheinstetten). Differences between the results of the two methods are discussed in Appendix B.2.

The hillslope model performance is tested on evaporation data estimated with Hamon obtained from data at Baden-Baden (positioned inside the catchment area) and evaporation data estimated with Penman-Monteith at Freudenstadt (positioned around 80 km outside the catchment area). The evaporation data used in the lowland model depended on the results, and was data obtained at either Rheinstetten (Penman-Monteith) or Rheinau (Hamon).

The hydrological year, summer and winter are determined visually with all available precipitation data and evaporation estimates obtained at Freudenstadt. Based on the result presented in Appendix B.2, the hydrological summer is assumed to range between May and October and winter between November and April.
**Figure 16.** Synoptical stations and flow gauges in the case study area.
### 3.5 **Initial Parameter Ranges**

The case study area is not completely ungauged, as there are three flow gauges present at Baden-Baden, Altschweier and Oberkirch (Figure 16). Unfortunately, an offtake situated a few hundred meters upstream of the flow gauge at Oberkirch resulted in completely different responses for the low flows compared to the other two flow gauges. The data obtained at this flow gauge has therefore not been used in this study. Since Baden-Baden and Altschweier were located at the border of the hillslope area during the fieldwork, the assumption is that the flow measured at these stations represents the response of the hillslope areas.

Table 1 presents the initial parameter ranges used for the hillslope areas, in this case the Baden-Baden catchment. Values for $K_{s,h}$ are different for the Altschweier and Baden-Baden/Altschweier combined catchments, as explained in Appendix B.3. Table 2 presents the initial parameter values for the lowland areas.

Values for the maximum interception capacities $I_{\text{max},h}$ and $I_{\text{max},l}$ are derived from Breuer et al. (2003). It should be noted that this parameter value depends on land cover instead of topography. However, the assumption is that most of the land cover in the hillslope areas is forest and the land cover in the lowland area is cropland.

The temperature threshold for precipitation falling as snow in the hillslope areas ($X_i$ in equation 2 and 3) is fixed on 2.5 °C, as further explained in Appendix B.3.

<table>
<thead>
<tr>
<th>Model</th>
<th>$I_{\text{max}}$</th>
<th>$S_{\text{max}}$</th>
<th>$\beta$</th>
<th>$P_{\text{max}}$</th>
<th>$K_s$</th>
<th>$a$</th>
<th>$K_{h}$</th>
<th>$C_a$</th>
<th>$a_{\text{snow}}$</th>
<th>$K_{\text{snow}}$</th>
</tr>
</thead>
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<tr>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
<td>(-)</td>
<td>(mm/d)</td>
<td>(1/d)</td>
<td>(-)</td>
<td>(1/d)</td>
<td>(+)</td>
<td>(-)</td>
<td>(-)</td>
</tr>
<tr>
<td>Model A</td>
<td>1-8</td>
<td>0-500</td>
<td>0-5</td>
<td>0.001-0.5</td>
<td>0-1</td>
<td>0-1</td>
<td>0-1</td>
<td>0-1</td>
<td>0.5</td>
<td>0-1</td>
</tr>
<tr>
<td>Model B</td>
<td>1-8</td>
<td>0-500</td>
<td>0-5</td>
<td>0.001-0.5</td>
<td>0-1</td>
<td>0-1</td>
<td>0-1</td>
<td>0-1</td>
<td>0.5</td>
<td>1-0</td>
</tr>
</tbody>
</table>

**Table 1.** Initial parameter sets for the Baden-Baden catchment.

<table>
<thead>
<tr>
<th>$I_{\text{max}}$</th>
<th>$S_{\text{max}}$</th>
<th>$\beta$</th>
<th>$P_{\text{max}}$</th>
<th>$K_s$</th>
<th>$K_{\text{f}}$</th>
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</thead>
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<td>(mm)</td>
<td>(-)</td>
<td>(mm/d)</td>
<td>(1/d)</td>
<td></td>
</tr>
<tr>
<td>1-4</td>
<td>0-200</td>
<td>0-5</td>
<td>0.001-1</td>
<td>0-0.1</td>
<td>1-0</td>
</tr>
</tbody>
</table>

**Table 2.** Initial parameter sets for the lowland area.
3.6 **Hillslope Model Evaluation**

The hillslope parameters are constrained with means of Monte Carlo sampling with a sampling size of a million runs. Two years of data are used for constraining (May 2009 - April 2011), which follow on 16 months of data used as start-up time of the model.

Four objective functions are formulated with which the performance of the model is determined. All objective functions are based on the Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970):

\[
E_{ns} = 1 - \frac{\sum (X_i - Y)^2}{\sum (Y_i - \bar{Y})^2}
\]

with \(E_{ns}(\cdot)\) being the Nash-Sutcliffe efficiency value, ranging from -\(\infty\) to 1, \(X_i\) being the modelled value, \(Y_i\) being the observed value and \(\bar{Y}\) being the average observed value. The four objective functions are the following Nash-Sutcliffe Efficiencies. A flow duration curve is constructed from the discharge data for the third and fourth objective function.

- \(E_{ns,Q}\) = \(E_{ns}\) of the discharges
- \(E_{ns,\log Q}\) = \(E_{ns}\) of the log of the discharges
- \(E_{ns,fdc}\) = \(E_{ns}\) of the flow duration curve values
- \(E_{ns,fdc,\log}\) = \(E_{ns}\) of the log of the flow duration curve values.

A model is considered behavioural if it has an efficiency value of at least 0.6 for all objective functions. The performance of the model structure is determined visually with use of Pareto optimal fronts. Via this method it is determined whether potential evaporation rates estimated with FAO Penman-Monteith or Hamon give the best performance for the Baden-Baden catchment. It is furthermore determined whether model structure A or B performs best for the Baden-Baden catchment, the Altschweier catchment and the combined Baden-Baden / Altschweier catchment.

The highest performing parameter sets are determined with an absolute ranking method. The efficiencies of all behavioural models are ranked from 1 to \(N\) and divided by \(N\), with \(N\) being the quantity of behavioural models, giving a ranked efficiency value that goes from 0 to 1. The overall performance of the behavioural model is determined via the average of the ranked efficiencies:

\[
P = \text{avg} \left( \sum E_{ns,\text{ranked},x} \right)
\]

with \(E_{ns,\text{ranked},x}\) being the ranked efficiency for the respective objective function and \(P\) being the overall performance of the behavioural model, ranging from 0 to 1. A performance of 1 corresponds to the behavioural model that performs best on all four objective functions compared to all other behavioural models.
The consistency of the model structure is determined visually with the ten highest average behavioural models. These behavioural models will be positioned on or very close by the Pareto optimal front of the efficiency values of the calibration period. It is tested visually whether the efficiency values of the highest ranked parameter sets are still close to the Pareto optimal front of the efficiency values of the validation period.

It is also determined visually whether extrapolation of the highest ranked parameter sets towards other catchments leads to a loss in performance. In order to do so, the highest ranked parameter sets obtained at one catchment are extrapolated towards a different catchment, and the objective function values are determined again. The resulting efficiency values are plotted with the Pareto optimal front for these catchments.
3.7 **LOWLAND MODEL EVALUATION**

3.7.1 **GROUNDWATER MEASUREMENTS**

The performance of the lowland model structure is determined with use of weekly measured groundwater data obtained at various locations in the area (Figure 17).

![Figure 17. Locations of the groundwater level stations used in this study.](image)

These groundwater measurements show the influence on the groundwater level of 1) precipitation, 2) evaporation, 3) groundwater seepage out of the hillslope, 4) groundwater seepage out of the Rhine and its largest tributaries and 5) other human activities, which are mentioned above. Groundwater seepage out of the Rhine and out of the hillslope area is further explained in Appendix B.1.

A problem is that groundwater measurements are usually only taken at points of interest, meaning that they are most likely not randomly taken throughout the area. This results in a lot of uncertainties when constraining the model parameters on this data.

In order to derive the groundwater measurements that showed the natural response of the area, in other words in order to exclude the groundwater measurements that have a large influence of
human activities, a time series analysis is performed with use of the PIRFICT model incorporated in the MENYANTHES software programme. With use of this model, the explained variance can be determined for a time series for various explanatory time series as input. This explained variance is a ‘measure of fit’ of the groundwater level time series on the explanatory time series, and it is determined with various time series analyses incorporated in the model. For a full description of these time series, reference is made to publications on the model (von Asmuth et al., 2002; von Asmuth and Bierkens, 2005; von Asmuth et al., 2008).

Sixteen months of start-up time for all time series is used for the time series analysis, ranging from January 2008 till April 2009. This is followed by three years of time series for which the explained variance is determined with various combinations of three explanatory time series as input. These explanatory time series are: 1) Precipitation time series obtained at the rain gauge situated at Rheinau. 2) Evaporation time series estimated with either FAO Penman-Monteith calculated with data obtained from Rheinstetten, or Hamon with data obtained at Rheinau; The choice between these two time series did depend on the result of the performance for both methods at the hillslope area. 3) Rhine water level time series measured at Kehl-Kronenhof.

As can be seen, two influences on groundwater level time series could not be introduced as explanatory time series: groundwater seepage from the hillslope and local human activities. However, the three explanatory time series that are used give an indication which groundwater level time series represent ‘natural behaviour’ of the area, since a high explained variance shows that the observed groundwater level is most likely the result of these three influences.

### 3.7.2 Evaluation Criteria

The lowland model is connected to the hillslope model. For this reason, the four objective functions used for the hillslope model are also applied for the lowland model evaluation. In addition, three more objective functions are added which are based on the dynamics of the groundwater.

- The cross-correlation coefficient $R$, which ranges from -1 to 1.
- $E_{ns}$ of the normalized height curve.

The amplitude of the groundwater levels depends highly on the location where these measurements are taken. This is indicated in Figure 18, and it is clearly an example of the issue of scale, which is troubling hydrological models (Savenije, 2009). At locations further away from drainage systems and locations where the depth towards the groundwater level is higher, this amplitude can be much larger.
Therefore, the water levels are normalized, in order to neglect this effect. This is done for the observed and modelled water levels via the following equation:

\[
X_{i,\text{norm}} = \frac{X_i - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}
\]

with \(X_i\) being the observed or modelled groundwater level at timestep \(i\) and \(X_{\text{min}}\) and \(X_{\text{max}}\) being the minimum and maximum observed or modelled groundwater level during the calibration period. The Nash-Sutcliffe efficiency is determined on the resulting normalized height curves with use of equation 24.

- Autocorrelation.

The autocorrelation is a measure of smoothness of a time series. A high autocorrelation means a small difference between two consecutive time steps (Euser et al., 2013) and can be used to represent the timing of the peaks. Here, the autocorrelation is determined for the observed and the modelled groundwater level time series via the following equation:

\[
X_{ac} = \frac{\sum (X_i - \bar{X})(X_{i+1} - \bar{X})}{\sum (X_i - \bar{X})^2}
\]

\[
P_{ac} = \left| \frac{X_{ac,\text{mod}}}{X_{ac,\text{obs}}} \right|
\]

with \(X_i\) being the observed or modelled groundwater level at timestep \(i\), \(X_{i+1}\) being the observed or modelled groundwater level at timestep \(i+1\) and \(X\) being the average observed or modelled groundwater level. \(P_{ac}\) is the objective score, ranging from 0 to 1. The timelag taken is one week, the timestep between the observed groundwater level measurements. Different sample sizes are combined together to increase the value of the objective function:

\[
P_{ac,\text{comb}} = \frac{P_{ac,1} + P_{ac,2} + P_{ac,12}}{3}
\]

with \(P_{ac,1}\), \(P_{ac,2}\) and \(P_{ac,12}\) being the autocorrelation obtained for respectively the first year, second year and first and second years combined.
With use of the four objective functions for the hillslope model, and the three objective functions for the lowland model, all parameters are constrained with means of Monte Carlo sampling with a sample size of a million runs. This is done for each groundwater level measurement station independently. Two years of data are used for constraining (May 2009 - April 2011), which follow on 16 months of data used as start-up time of the model. Behavioural models are the ones that have:

- $E_{ns}$ of at least 0.6 for the four hillslope objective functions,
- R value of at least 0.7,
- $E_{ns}$ of at least 0.6 for the normalized groundwater height curves,
- $P_{ac,1}$, $P_{ac,2}$, $P_{ac,12}$ and $P_{ac,comb}$ values of at least 0.95.

As is also the case for the hillslope model, the highest performing parameter sets are determined with the earlier described absolute ranking method.

### 3.7.3 Parameter and Process Constraints

In addition to the constraining of parameters on groundwater measurements, it is tested whether implementing two other types of restrictions give different model results. These types of restrictions are described by Gharari et al. (2013).

The first type, called a priori “parameter constraints”, is based on realistic relationships that must hold between different parameters of the model. In this study, the following relationship is defined between the interception of the hillslope and of the lowland. Since lowlands are less vegetated than hillslopes, it is logical to assume that:

\[
I_{\text{max},l} < I_{\text{max},h}
\]

The second type, called a posteriori “process constraints”, is based on realistic relationships that must hold between different fluxes and state variables of the model. In this study, two relationships are defined between the fluxes of the Hillslope and of the Lowland. The first one is based on the annual actual evaporation rates estimated by Weiler et al. (2012). It was seen that overall the annual actual evaporation rates of the hillslope are higher than the rates of the lowland. Therefore, the following constrained is used:

\[
E_{a,h,y} + E_{t,h,y} > E_{a,l,y} + E_{t,l,y}
\]

The second a posteriori constraint is based on the fact that due to the difference in slope between the two land characterisations, the hillslope will have a larger annual fast response compared to the annual fast response of the lowlands:

\[
Q_{f,h,y} > Q_{f,l,y}
\]
CHAPTER 4. RESULTS

4.1 AREA CLASSIFICATION

A HAND threshold of 5.9 m and a slope threshold of 6 degrees show good results for the delineation between the lowland areas and the hillslope areas. The hillslope and lowland areas encompass around 24% and 76% respectively of the total catchment area (235 km$^2$ and 675 km$^2$; Figure 19).

Of the two defining factors, the slope turned out to be the main determining factor for the delineation between lowland and hillslope areas. A higher threshold for slope would result in an increasing amount of open areas on the hillslope, which would be classified as plateaus in the FLEX-Topo approach (Gharari et al., 2011), but plateaus were not seen during the field investigation. Thus, the slope threshold was chosen such that these areas were encompassed within the hillslope. A lower threshold for slope would result in small areas of the agricultural land to be classified as hillslope, which should also not be the case.

What can also be notified in the results is the very clear correlation between land cover and the HAND threshold (Figure 20). Especially the forests and the fruit and berry farmlands on the lowland area tend to have a HAND higher than surrounding areas.
**RESULTS**

**Figure 19.** Topographical classification of the research area into different hydrological response units. The black area is defined as Hillslope and the remainder of the research area defined as Lowland.

**Figure 20.** Correlation of landuse and HAND in the research area.
4.2 HILLSLOPE

4.2.1 BADEN-BADEN CATCHMENT

A choice was made whether implementing a snow module into the model would improve the performance of the model. The performances of model structure A, without a snow module, and model structure B, which includes a snow module have been evaluated with use of the method described in chapter 3.6.

The results presented in Figure 21 - 23 show that including a snow model does improve the performance of the model performance during the calibration period. When looking at the pareto optimal fronts presented in Figure 21 all four objective functions show an improvement on model performance, especially the objective functions representative for the higher flows. The improvement can also be seen in the observed and modelled discharge curves. Some peaks that were not captured by model A, most likely originate from snow melt (Figure 22a and 23a, day 300-350).

The consistency of both model structures is visualized by showing the performance of the ten behavioural models with the highest average ranking for the validation period (Figure 21b). No large differences can be seen in the performance during the validation period, which is a direct result of not much snowfall during the validation period (a total of 8 mm of snowcover measured during this period at Freudenstadt). Due to the improved performance during the calibration period, model structure B is used for the remainder of the study.

There is still a lot of equifinality visible in the results as can be seen in the dotty plots presented in Appendix C. Parameter sets that performed relatively good during the calibration period, performed less during the validation period. Therefore, the parameters were not calibrated to get a single good performing parameter set. While some parameters could be fixed based on their performance on the objective functions, most parameters only had their range minimized instead. The resulting parameter ranges are presented in Table 3.

The ten behavioural models with the highest average ranking during calibration period favoured the performance of the low flows over the high flows, as can be seen in Figure 21 (the red and cyan squares). The performances of the low flows were close to the optimal obtained value as indicated by the pareto fronts, while the performances of the high flows for these parameter sets were lower.
**Baden-Baden**

<table>
<thead>
<tr>
<th>Model</th>
<th>I_max</th>
<th>S_max</th>
<th>beta</th>
<th>P_max</th>
<th>K_s</th>
<th>a</th>
<th>K_fh</th>
<th>C_e</th>
<th>a_snow</th>
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<td>(1/d)</td>
<td>(1/d)</td>
<td>(1/d)</td>
<td>(1/d)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model A</td>
<td>1-8</td>
<td>100-300</td>
<td>0.5-2.5</td>
<td>0.001-0.1</td>
<td>0.1</td>
<td>0-1</td>
<td>0-1</td>
<td>0.5</td>
<td>0-1</td>
<td>0-1</td>
</tr>
<tr>
<td>Model B</td>
<td>1-8</td>
<td>100-300</td>
<td>0.5-2.5</td>
<td>0.001-0.1</td>
<td>0.1</td>
<td>0-1</td>
<td>0-1</td>
<td>0.5</td>
<td>1(0)</td>
<td>0-1</td>
</tr>
</tbody>
</table>

**Table 3.** Model parameter sets for the Baden-Baden catchment after stepwise calibration, with in bold the reduced parameter ranges.

![Pareto optimal fronts for model A and B. The red and cyan squares represent the objective scores for the ten behavioural models with the highest average ranking during calibration period.](image)

**Figure 21.** Pareto optimal fronts for model A and B. The red and cyan squares represent the objective scores for the ten behavioural models with the highest average ranking during calibration period.
FIGURE 22. Hydrographs of the observed and the modelled discharges of model A for A) the calibration period and B) the validation period. The red curves are the ten behavioural models with the highest average ranking during the calibration period.

FIGURE 23. Hydrographs of the observed and modelled discharges of model B for A) the calibration period and B) the validation period. The red curves in graph A and B are the ten behavioural models with the highest average ranking during the calibration period. Graph C and D present the modelled discharge out of the snow module.
4.2.2 EVAPORATION INPUT

Evaporation time series estimated with use of Penman-Monteith (Freudenstadt) and Hamon (at Baden-Baden) have been used as input for the hillslope model. The graphs and correlation of these timeseries are presented in Appendix B.2.

The performances of the model for the different evaporation inputs have been estimated with use of the method described in section 3.6 A comparison of the pareto fronts presented in Figure 24a and 24b shows that the model performs better for evaporation rates estimated with Penman-Monteith, even though the measurements for the Hamon method were taken inside the catchment area. This can be seen by the Pareto optimal front for the Nash-Sutcliffe efficiency of the flows and of the log of the flows being closer to zero. Therefore, the potential evaporation rates estimated with Penman-Monteith were used for the remainder of this study. For the hillslope and lowland area, this means data obtained at respectively Freudenstadt and Rheinstetten was used.

**Figure 24.** Pareto fronts for model structure B for different potential evaporation inputs.
4.2.3 Altschweier Catchment

To justify the use of model structure B for the hillslope area, the performance and consistency of the model structures has been tested on the Altschweier catchment.

The reduced parameter ranges after stepwise calibration are presented in Table 4, the resulting pareto optimal fronts in Figure 25 and the hydrographs for the parameter sets with the highest performance in Figure 26.

For the Altschweier catchment, model structure B also performs better than model structure A. However, both model structures perform less when compared to the results for the Baden-Baden catchment, especially for the high flows. Values for the objective scores are, according to the pareto optimal fronts, 0.1-0.2 point lower for the objective functions representing high flows, and around 0.05 point lower for the objective functions representing low flows. Especially the performance for the flow duration curves for the high flows shows a decrease when compared to the model performance for the Baden-Baden catchment.

Some peaks, such as the one encircled in Figure 26b, were missed completely. This is most likely the result of a missed precipitation event by the rain gauge in Baden-Baden.

The model structure seems to have a high consistency for Altschweier, with the ten behavioural models with the highest ranking during the calibration period, also being close to the pareto front for the validation period.
Altschweier

<table>
<thead>
<tr>
<th>Model</th>
<th>Imax</th>
<th>Sumax</th>
<th>beta</th>
<th>Pmax</th>
<th>Ks</th>
<th>a</th>
<th>Kfh</th>
<th>Ce</th>
<th>a</th>
<th>Kfh</th>
<th>Ce</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
<td>(-)</td>
<td>(mm/d)</td>
<td>(1/d)</td>
<td>(-)</td>
<td>(1/d)</td>
<td>(-)</td>
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<td></td>
</tr>
<tr>
<td>Model A</td>
<td>1-8</td>
<td>50-200</td>
<td>0.25-2</td>
<td>0.001-0.5</td>
<td>0.125 (f)</td>
<td>0.1</td>
<td>0.015</td>
<td>0.5 (f)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Model B</td>
<td>1-8</td>
<td>50-200</td>
<td>0.25-2</td>
<td>0.001-0.5</td>
<td>0.125 (f)</td>
<td>0.1</td>
<td>0.015</td>
<td>0.5 (f)</td>
<td>1 (f)</td>
<td></td>
<td>0.1</td>
</tr>
</tbody>
</table>

**Table 4.** Model parameter sets for the Altschweier catchment after stepwise calibration, with in bold the reduced parameter ranges.

**Figure 25.** Pareto optimal fronts for the Altschweier catchment. The red and cyan squares represent the objective scores for the ten behavioural models with the highest average ranking during calibration period.
**Figure 26.** Hydrographs of the observed and modelled discharges for the Altschweier catchment for model structure B. The red curves in figure A and B are the resulting hydrographs of the ten behavioural models with the highest average ranking during the calibration period. The red curves in figure C and D are the resulting hydrographs of the ten behavioural models with the highest performance for the Nash-Sutcliffe efficiency. The green circle in figure B is an example of a ‘missed peak’ due to a rainfall event not measured by the rain gauge in Baden-Baden.
4.2.4 BADEN-BADEN AND ALTSCHWEIER COMBINED

The Baden-Baden and Altschweier catchment area combined cover a large part of the hillslope area (101 km$^2$ out of the 240 km$^2$). It is therefore assumed that the discharge out of the two areas represents the outflow out of the hillslope best. This assumption can be made due to the daily calculation timestep. It would not be valid if the modelled timestep would be smaller. Due to the different timing of the storms, the measured discharge peaks at Baden-Baden and Altschweier would average each other out. Some peaks are still averaged out, however, especially the ones that were only visible in the Altschweier hydrograph which are most likely the result of precipitation events missed by the rain gauge in Baden-Baden.

The reduced parameter ranges after stepwise calibration are presented in Table 5, the resulting pareto optimal fronts in Figure 27 and the hydrographs for the parameter sets with the highest performance in Figure 28.

The performance of the combined discharge is, as can be expected, in between the performances of Baden-Baden and Altschweier, and also here, model structure B performs better than model structure A during the calibration period, and around the same during validation period. However, the consistency of the model structure for the two catchment areas combined seems low. This can be seen by the performances of the ten parameter sets which performed best during calibration period being spread out during the validation period (Figure 27).

As is the case for the Baden-Baden and Altschweier catchments, the peaks are underestimated when using the parameter sets with the highest average ranked performance. This underestimation is less compared to the peak discharges for the Altschweier catchment alone, since Nash-Sutcliffe values of the flows of the pareto fronts are closer to 1.
**Table 5.** Model parameter sets for the Altschweier/Baden-Baden combined catchment after stepwise calibration, with in bold the reduced parameter ranges.

<table>
<thead>
<tr>
<th>Model</th>
<th>( I_{\text{max}} ) (mm)</th>
<th>( S_{\text{max}} ) (mm)</th>
<th>( \beta )</th>
<th>( P_{\text{max}} ) (mm/d)</th>
<th>( K_s ) (1/d)</th>
<th>( a )</th>
<th>( K_{\text{fh}} ) (1/d)</th>
<th>Ce</th>
<th>( K_{\text{snow}} ) (1/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model A</td>
<td>1.8</td>
<td>0.150</td>
<td>0.5-2</td>
<td>0.001-0.5</td>
<td>0.105 (f)</td>
<td>0.1</td>
<td>0.025</td>
<td>0.5 (f)</td>
<td></td>
</tr>
<tr>
<td>Model B</td>
<td>1.8</td>
<td>0.150</td>
<td>0.5-2</td>
<td>0.001-0.5</td>
<td>0.105 (f)</td>
<td>0.1</td>
<td>0.025</td>
<td>0.5 (f)</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 27.** Pareto optimal fronts for the Altschweier/Baden-Baden combined catchment. The red and cyan squares represent the objective scores for the ten behavioural models with the highest average ranking during calibration period.
**Figure 28.** Hydrographs of the observed and modelled discharges for the Altschweier/Baden-Baden combined catchment for model structure B. The red curves in figure A and B are the resulting hydrographs of the ten behavioural models with the highest average ranking during the calibration period. The red curves in figure C and D are the resulting hydrographs of the ten behavioural models with the highest performance for the Nash-Sutcliffe efficiency.
4.2.5 **INTERCHANGEABILITY OF THE HILLSLOPE PARAMETER VALUES BETWEEN THE CATCHMENTS**

To justify the interchange of a high ranked parameter set to a different but equally classified area, or in this case to be representative for the whole Hillslope area, the performance and consistency of the model structures have been tested when interchanging parameter sets between the Baden-Baden, Altschweier and Baden-Baden/Altschweier combined catchments.

Figure 29 shows the results of the model for the Baden-Baden catchment. The yellow squares represent the performances of the behavioural models with the highest average ranking obtained for this catchment. The red and cyan squares represent the performances of the highest ranked behavioural models of respectively Altschweier and the Altschweier/Baden-Baden combined catchments, when tested on the discharges measured at Baden-Baden.

The same method has been performed for the Altschweier and the Altschweier/Baden-Baden combined catchments, of which the results are presented in Figure 30 and 31.

What can be seen in the results is that especially the performance on the low flows is reduced when extrapolating parameter sets between the Altschweier and Baden-Baden catchments. For the parameter sets extrapolated from the Baden-Baden catchment towards the Altschweier catchment, almost half of the parameter sets are not considered behavioural anymore, since the Nash-Sutcliffe Efficiency value for log of the flows is smaller than 0.6. For the high flows, the performances can be considered relatively equal, with a slight reduction when extrapolating the highest ranked parameter sets from Altschweier to the Baden-Baden catchment.

For the combined catchment, all extrapolated parameter sets perform very similar to the parameter sets obtained through calibration. The objective scores representative for the high as well as the scores representative for the low flows can arguably be considered equal.
Figure 29. Pareto optimal fronts for the Baden-Baden catchment, including the objective scores when using the highest ranked parameter sets obtained for the Altschweier and Baden-Baden / Altschweier combined catchments.

Figure 30. Pareto optimal fronts for the Altschweier catchment, including the objective scores when using the highest ranked parameter sets obtained for the Baden-Baden and Baden-Baden / Altschweier combined catchments.

Figure 31. Pareto optimal fronts for the Altschweier / Baden-Baden combined catchments, including the objective scores when using the highest ranked parameter sets obtained for the Baden-Baden and Altschweier catchments.
4.3 **Lowland**

4.3.1 Results of the PIRFICT model

To determine which groundwater data encompass mainly natural behaviour, the time series have been tested with use of a time series analysis of the PIRFICT model in the Menyanthes software. The output of the model, the explained variance, is a measure for how well the groundwater time series can be simulated with use of various explanatory time series, in this case precipitation measured at Baden-Baden, evaporation estimated with data measured at Rheinstetten and the Rhine waterlevels measured at Kehl Odelshofen (Figure 16).

Figure 32 shows the resulting explained variance for the available groundwater level time series (30 groundwaterlevel stations, May 2009 - April 2012). It shows that for many groundwater time series taken relatively close to the Rhine, only using precipitation and evaporation as explanatory series does not result in a high explained variance. The addition of the Rhine water level does result in a higher explained variance for some, but even then it can be seen that there are other external effects influencing the groundwater levels.

After what seems to be a breakpoint (between 5 and 7 km lateral distance to the Rhine), the explained variance is relatively high when only using evaporation and precipitation as explanatory series. The addition of the Rhine waterlevel time series does not show a significant improvement for the explained variance for these time series.

When taking the distance towards the closest hillslope, instead of the lateral distance towards the Rhine, no correlation between discharge and the explained variance or a breakpoint could be notified. It therefore seems that the groundwater seepage and the anthropological activities close to the Rhine have a larger effect on the groundwater level variability than the hillslope groundwater seepage, which functions on a seasonal and thus much larger timescale. This seasonal timescale is also already present in the evaporation time series.

The one groundwater time series which shows a lower explained variance for the explanatory series of evaporation and precipitation (red circle in Figure 32) belongs to SBR 677, which is situated close to the Murg River. This river has its origins in a different catchment, and it is therefore very likely that influences from this catchment are measured at this groundwater level station.

For calibration of the lowland model, time series from 12 groundwater level stations have been used, which are all stations at a lateral distance of 7 kilometer and further from the Rhine, with the exception of SBR 677. These time series are presented in Figure 33.
Figure 32. Explained variance of the groundwater measurements for various combinations of explanatory series. Figure A) shows the explained variance against the distance towards the Rhine. The red circle highlights the explained variance of SBR 677. Figure B) shows the explained variance against the distance towards the closest Hillslope area.

Figure 33. Time series of all groundwater measurements at a lateral distance of at least 7 km. from the Rhine, with the exception of SBR 677.
4.3.2 Lowland Model Results

The lowland model has been tested on performance when implementing realistic constraints, when calibration on groundwater level measurements and a combination of these two. Figure 34-37 show the results for respectively the model outflow, the breakup of the evaporation out of the model into interception and transpiration, the fluxes in and out of the slow reservoir and the observed and modelled normalized height curves for ex- and including constraints to the model. The results for all groundwater measurements individually for both in- and excluding constraints are presented in Appendix D.

Model Outflow and Evaporation

One of the most important information a hydrological model gives, is the outflow. Figure 34 shows the outflow out of the lowland model, including the 95% confidence intervals which are calculated with use of a student’s t distribution test. In case of the model which only makes use of realistic constraints to the parameter, the outflow and confidence intervals are estimated with use of the 120 highest ranked behavioural models. In case of the models which make use of the groundwater measurements, for each groundwater station, the ten highest ranked behavioural models were taken. Thus, by combining results of the twelve stations, this also results in 120 time series of outflow and confidence intervals, which makes the sample size of all methods equally large.

Not much differences can be seen between the methods used concerning the timing of the total outflow out of the lowlands. Events with a large precipitation intensity result in higher peaks of discharge, followed by a depletion curve out of the slow reservoir. Higher outflows tend to happen in between December and February, when the porous zones are filled. This is the case for all three methods used.

Also quantities of the outflow are similar between the used methods, as indicated in Table 6 and 7. The outflow during the calibration period ranges between 370 and 420 mm/y and average runoff coefficients are within a range of 0.46-0.50. The main difference is the interception/transpiration ratio, which is higher for the two methods that make use of constraints.

The peak discharges are sometimes very high (> 20 mm/d) and even higher than the values measured at the hillslope flow gauges.
### Results

#### Calibration period

<table>
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<th>Method</th>
<th>Precipitation</th>
<th>Actual evaporation</th>
<th>Gw-inflow</th>
<th>Outflow</th>
<th>RC</th>
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</thead>
<tbody>
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<td>825 (mm/y)</td>
<td>476 (mm/y)</td>
<td>263 (mm/y)</td>
<td>129 (mm/y)</td>
<td>37 (mm/y)</td>
</tr>
<tr>
<td>GWM</td>
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<td>502 (mm/y)</td>
<td>221 (mm/y)</td>
<td>281 (mm/y)</td>
<td>45 (mm/y)</td>
</tr>
<tr>
<td>Const. + GWM</td>
<td>825 (mm/y)</td>
<td>447 (mm/y)</td>
<td>227 (mm/y)</td>
<td>220 (mm/y)</td>
<td>34 (mm/y)</td>
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</tbody>
</table>

**Table 6.** Mean model results for the calibration period of the 120 behavioural models with the highest average ranking for all three methods.

#### Validation period

<table>
<thead>
<tr>
<th>Method</th>
<th>Precipitation</th>
<th>Actual evaporation</th>
<th>Gw-inflow</th>
<th>Outflow</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Const.</td>
<td>676 (mm/y)</td>
<td>451 (mm/y)</td>
<td>241 (mm/y)</td>
<td>138 (mm/y)</td>
<td>32 (mm/y)</td>
</tr>
<tr>
<td>GWM</td>
<td>676 (mm/y)</td>
<td>455 (mm/y)</td>
<td>198 (mm/y)</td>
<td>257 (mm/y)</td>
<td>40 (mm/y)</td>
</tr>
<tr>
<td>Const. + GWM</td>
<td>676 (mm/y)</td>
<td>425 (mm/y)</td>
<td>204 (mm/y)</td>
<td>221 (mm/y)</td>
<td>29 (mm/y)</td>
</tr>
</tbody>
</table>

**Table 7.** Mean model results for the validation period of the 120 behavioural models with the highest average ranking for all three methods.
Figure 34. Model results for the total outflow, estimated with use of the 120 highest ranked behavioural models. The confidence intervals are determined with use of a student's T distribution.
**Figure 35.** Model results for the interception ($E_{i,l}$), transpiration and soil evaporation ($E_{a,l}$) and total evaporation ($E_{t,\text{total}}$), estimated with use of the 120 highest ranked behavioural models.
THE SLOW RESERVOIR

The fluxes to and from the slow reservoir are presented in Figure 36a,c and e. The hydrographs for the slow, fast and total flow out of the model are presented in Figure 36b, d and f.

A large difference between the methods used can be observed when looking at the mean of the matrix percolation, $Q_{us,l}$. For the method which only takes constraints into account, the time series for $Q_{us,l}$ are very spikey and heavily depending on the rainfall. For the two methods that do take groundwater measurements into account, $Q_{us,l}$ shows a much smoother time series. The outflow quantities out of the slow reservoir do not seem to differ much between the three methods, as can be seen in Table 6 and 7, and Figure 36b, d and e.

Figure 37 shows the twelve observed and normalized height curves, together with the twelve modelled normalized height curves, respectively for each groundwater station. When looking at the highest ranked result for each station individually, which are presented in Appendix D, the dynamics of the groundwater are simulated relatively good most of the time. Some results are a bit further off from what is observed than others, e.g. GWM 832. When plotting the twelve normalized height curves together, the results tend to go to a single result. This can be seen by the reduction of the spreading of the modelled normalized height curves, which is even less wide when including constraints.

Even though the dynamics are simulated relatively good, the actual groundwater level values are not comparable. In the model, the amplitude of the saturated zone reservoir had maximum values of around 30 - 40 mm. The observed amplitude at the groundwater measurement stations is around 1 to 2 meter.

The dotty plots of the parameter values for all behavioural models for each groundwater measurement station are presented in Appendix D. The results show that, by implementing calibration on groundwater measurements in the model, some parameters show a (slight) reduced range for favourable values. This is mainly noticeable for the splitting parameter $a$ and matrix percolation $P_{max,h}$.

When adding constraints to the model, the amount of behavioural model parameter sets is significantly reduced, but there's still a lot of equifinality visible in the dotty plots. Also here, some parameters show a (slight) reduced range for favourable values, mainly noticeable for the value of $S_{umax,h}$. 
Figure 36. Model results for the slow reservoir and the model outflow, estimated with use of the 120 highest ranked behavioural models. Figures A, C and E present the fluxes towards and out of the slow reservoir in the lowland area. Figure B, D and F present the total, slow and fast outflow out of the lowland area.
**Figure 37.** Observed and modelled normalized groundwater levels for the calibration period for all twelve groundwater measurement stations combined. The observed graphs are the highest ranked behavioural models. Figure A) presents the results when only calibrating on groundwater measurements and figure B) presents the results when including constraints.
4.3.3 **Effect of adding irrigation flux in the lowland area.**

To test whether the unsaturated and saturated zones could be seen as a single reservoir, the addition of a flux, here mentioned as an irrigation flux, has been tested on performance. This flux makes sure that the unsaturated zone is always on field capacity, in other words, that the unsaturated reservoir is at least half full.

It has been tested under the assumption that the flux is 1) active throughout the whole year, or 2) that the flux is only active in the summer period (May-October), the crop growing period where the land will be irrigated often.

Out of a million model runs, not a single parameter set resulted in a behavioural model for the first assumption. For the second assumption, only one parameter set performed behavioural for one groundwater measurement station, GWM 130. The result for this parameter set is presented in Figure 38. Based on the normalized height curves for the validation period, also this single parameter set can be disregarded.

When taking away the constraint on evaporation between the hillslope and lowlands, out of a million model runs, only a handful was considered behavioural (none for GWM1, GWM 1676, GWM 3146, GWM 3150 and GWM Eisenbahnstrasse, and up to five for the other measurement stations).

![Figure 38](image-url)  
*Figure 38.* Result for GWM 130 when adding irrigation in hydrological summer to the model structure.
CHAPTER 5. DISCUSSION

5.1 AREA CLASSIFICATION

It was possible to delineate hillslope from the lowland areas through visual inspection and with use of only two simple algorithms on an elevation map. This makes it possible to delineate different rainfall-runoff mechanisms as well on a larger scale, and even extrapolate model structures to other basins where areas are identified with the same characteristics.

The surface slope appeared to be the main topographical driver to classify the area. HAND showed irregularities in the lowland areas, where especially the forests and the fruit and berry farmlands on the lowland area tend to have a HAND higher than surrounding areas. This is most likely the result of the satellite measuring the elevation of the top of the canopy instead of the surface level. Also, the need for a detailed stream map to calculate HAND accurately on lowland areas makes use of solely the HAND algorithm on a DEM map for landscape classification not a viable option.

Field investigations do still play a very important part in area classification: the classification of the area calculated with the algorithms should ‘fit’ with what is seen in the field. For instance, a different slope was determined in comparison with the slope found by Gharari et al. (2011) to delineate lowland from hillslope areas. Therefore, this method requires more resources in time than traditional methods of conceptual modelling, and an expert view of the hydrologist, which is part of the ‘art’ of hydrology (Savenije, 2009).
Discussion

5.2 Hillslope

Snow module

The addition of a snow module was a valuable addition to the hillslope model. It does introduce an extra parameter in the model structure ($K_{\text{snow}}$ (mm/d)) which does increase the chance of equifinality, but the uncertainty of the parameter was reduced by the assumption that precipitation would only fall in the form of snow when there was actually a measured snow cover increase in Freudenstadt. This uncertainty of the parameter can, in future researches, be reduced further by adding another constraint, namely that the snow reservoir in the model should be empty at the moment that in Freudenstadt the measured snow cover would be zero or close to zero as well.

The found temperature threshold value of 2.5 °C can also be justified, even though it’s higher than the often used temperature threshold of 0 °C, the actual freezing point of water. Temperature is usually measured at two meters above the ground. The temperature higher up in the air, the place where snow is formed, always differs from the measured temperature. Also, the temperature at ground surface is usually lower than the measured temperature, which results in an increased chance of snow not melting when it hits the ground.

Since snowmelt largely depends on available energy (Cazorzi and Fontana, 1996), other forcings, such as incoming radiation, aspect and shading effects of the hillslope may be included in the snowmodule in future researches. Also sublimation might be an important process.

Potential evaporation

The results showed that using FAO Penman-Monteith to determine potential evaporation resulted in a better performance of the hillslope model. This is a little surprising, since measurements for this method are taken around 80 km outside the catchment area, while temperature measurements used in Hamon’s method are taken inside the catchment area.

The lower performance might be the result of the small time lag of Hamon in comparison with FAO Penman-Monteith. This is most likely due to temperature values lagging behind on incoming radiation values. Evaporation rates estimated for spring and summer are therefore a little lower for Hamon, while evaporation rates estimated in autumn and winter are a little higher.

Even though the performance of using Hamon-based evaporation rates is a little lower, it’s still shown to be a very feasible method as the performances for both methods were not far off. In this case, the weatherstation situated in Freudenstadt had a comparable elevation to the Hillslope area. In areas where where this is not the case for the nearest situated weatherstation, use of Hamon or other temperature-based evaporation rates might show a better performance and should therefore be reconsidered.
It might be interesting to see whether implementing the Jarvis model into the model structure (Jarvis, 1976) does improve the model performance. In the currently used approach, evaporation is only constrained by soil moisture content and the potential evaporation, making the plant itself a ‘dead’ plant. In reality, the transpiration of a plant is also depending on other factors. In the Jarvis model, a total of five factors are taken into account: light intensity, leaf temperature, vapour pressure deficit, ambient CO₂ concentration and leaf water potential. This approach results in the plant being an active part of the transpiration process.

**Extrapolation of hillslope model structure**

Between the Baden-Baden and Altschweier catchments differences were identified while investigating the model performances, even though they are both classified as hillslope. This difference was visible mainly in the performance on high flows and is most likely due to one or more of the following reasons: Topographical differences between the catchments, different circumstances at the location of the flow gauges or the distance of the rain gauge towards the catchment area.

- Compared to the Baden-Baden catchment, the Altschweier catchment has a smaller surface area (71 vs 30 km²) but the average surface slope is larger (14.7° vs 15.7°). This will result in a higher proportion of fast runoff and more spiky flows out of the area. As can be seen in Figure 26a–d especially the larger peaks are underestimated by the model, even when the parameters are calibrated only on high flows.

- The gauge at Altschweier is located in a more narrow valley, and the river and surroundings are lined with concrete (Appendix A). This results in a larger measured runoff coefficient, as less flow will bypass the flow gauge through the saturated or hyporheic zones as subsurface flow. It can also be notified in the lower ranges after parameter constraining of the parameters $P_{max,h}$ and $S_{u,max,h}$, compared to the reduced ranges for of the Baden-Baden catchment.

- Some peaks in the Altschweier discharge measurements can not be explained by the measurements taken at the rain gauge at Baden-Baden (for instance, day 270-280 of the validation year; Figure 26b). It is likely that these peaks originate from local storms which were not captured by the rain gauge located in the Baden-Baden catchment. More distribution of the forcing (e.g. by implementing radar precipitation data) could reduce this uncertainty (Euser, 2014).

**Extrapolation of hillslope parameter values**

Even though a lower performance was observed when extrapolating the parameters between the catchments, almost all parameter sets still performed good (all obj scores > 0.5). This shows that parameter sets can be extrapolated in order to gain a good estimation of the outflow of the total hillslope area.
The performance was especially lower for the low flows when extrapolating parameter sets of Baden-Baden to Altschweier and vice versa. This is most likely due to the differences between the catchments and circumstances of the location of the flow gauges mentioned above. In contrary, extrapolation of the parameters into the combined Baden-Baden/Altschweier catchment showed very good results, with the performances of the extrapolated parameter sets being close to the performances obtained through calibration for both low and high flows. For this reason, ideally, the catchment area measured should still be as large as possible. The research on uncertainty involved when extrapolating model structures and parameter values can be expanded by taking other catchments into account, such as catchment area covered by the flow gauge in Oberkirch.

Also, in the currently used method, some parameters which are depending on land cover are now distributed based on topography (interception capacity). These parameter values can be distributed per landuse instead of per catchment. Since the Altschweier catchment has a higher percentage of urban area (7 vs 15%), distributing the parameter values might result in a better performance for the low flows, when extrapolating the parameter sets between the catchments.

The highest average ranked behavioural models all showed a slightly less performance on the Nash-Sutcliffe efficiency of the flow curves (visualised in Figure 29b). This might be due to the absolute ranking method used, since this method, in comparison to a relative ranking method gives a higher weight to (according to one objective function) very good performing outliers. The selection of the highest average ranked parameter sets may be distorted due to the large quantity of parameter sets being behavioural for low flows with similar efficiency values, and a lower quantity of parameter sets being behavioural for high flows. It is therefore suggested that for high flows, an absolute ranking can be used to give more weight to the very few good performing outliers, but for low flows use should be made of a relative ranking method.
5.3 **Lowland**

**Groundwater measurements**

It was possible to differentiate groundwater responses with use of a time series analysis of the PIRFICT model. Some groundwater measurement time series had a high explained variance when only precipitation and evaporation were used as explanatory series input. This was mainly the case for groundwater measurements taken on a lateral distance of at least 5 to 7 km away from the Rhine. These groundwater measurement time series were all similar for the fact that they showed seasonality. The seasonality present in the evaporation time series can therefore be seen as the main factor for the high explained variance of these groundwater measurements.

With decreasing distance of groundwater measurements to the Rhine, the explained variance for precipitation and evaporation as explanatory series input also decreases. This is a logical result due to the large amount of anthropological activities near the Rhine, and due to the influence of groundwater seepage out of the Rhine itself. The explained variance for nearly all groundwater measurements was close to or above 80% when Rhine water level time series were added as explanatory time series.

A breakpoint on the influence of the Rhine was noticed at a distance between 5 to 7 km of the Rhine. It is likely that this distance is influenced by seasonality. In summer, the breakpoint distance is less due to lower Rhine water levels, whereas in winter it is possibly larger. Also, some anthropological activities (e.g. using Rhine water level as cooling water for a mining facility or industrial area) are restricted to only occur during winter periods. Performing the same time series analysis on summer and winter half years might therefore result in a better insight into which groundwater levels represent the natural responses best during the respective period. This may extend or reduce the amount of groundwater time series used for calibrating the hydrological model during a specific half-year.

**Model evaporation and outflow**

The three methods used (constraints, calibration on groundwater measurements, and a combination of the two) showed similar results for the quantity of the total outflow. Also, it was visible with use of the 95% confidence intervals presented in Figure 34 that the outflow out of the model was similar for different behavioural parameter sets.

Differences were identified for the evaporation values, with lower values of evaporation, but higher interception/evaporation ratios for the methods that make use of constraints. This is a logical result of the constraint that assumes that yearly evaporation values in the lowland area are lower than yearly evaporation values in the hillslope area. Since the lowland part of the model is
not calibrated on quantity, in order to get a better estimate of the outflow out of the model, it is suggested to apply evaporation estimates obtained from satellite data to further constrain model results (Winsemius et al., 2008). These estimates can for instance be obtained with use of the SEBAL method (Bastiaanssen et al., 1998) or the similar EWBMS method (Roesma et al., 2008), which both make use of the surface energy balance.

The peak flows out of the area are higher than what can be expected from lowland areas, since these peak values are larger than the ones observed at flow gauges at the hillslope area. This is due to a couple of processes which are not included in the model structure: temporary storage of water in the countless irrigation and drainage canals and temporary storage on top of the ground surface (ponding). Both ways of storage reduce the flow peak heights towards the Rhine. Therefore, a routing module such as the method applied by Arora and Boer (1999), or the more complex 2D overland flow module in the SOBEK software based on the Saint-Venant equations (Deltarès, 2014) is suggested to be used instead or in consequence of the fast responding reservoir in the model. This requires that assumptions should be made with regards to the surface roughness (Manning coefficient) which is used in these methods, but it will most certainly give a better insight in the timing and distribution of the peaks out of the lowland area.

**The slow reservoir**

For two methods, twelve different groundwater level gauges were used in order to calibrate the model. Some of the highest ranked behavioural models did not show good results when looking at a single normalized height curve, which are presented in Appendix D. When combining the highest ranked behavioural models for all twelve groundwater level gauges, however, a tendency was observed towards a single model result. This is highly remarkable. Even though there are sometimes large differences between the observed groundwater level measurements, apparently, a single system response can still be identified.

Significant differences were observed between the methods for the fluxes in and out of the slow reservoir. These differences were mainly observed in the matrix percolation and the variance of the outflow out of the slow reservoir.

The methods that made use of calibration on the groundwater level measurements did show a much slower percolation rate compared to the method that only made use of constraints. Apparently, a high influence of precipitation on the groundwater level was not observed in the groundwater measurements taken. Therefore, introducing calibration on groundwater measurements does constrain some of the parameters used for the maximum percolation rate, which was also observed in the dotty plots presented in Appendix D. The slow response is arguably also more realistic, since the soil type is clay loam, which has a low permeability.
When looking at the actual water levels of the saturated zone reservoir, a difference was observed of a factor around 30-40, depending on the groundwater measurement station being looked at. Taking porosity of the soil into account is not sufficient to overcome this factor. The reason for the large difference could not be found in available literature, but the guessing of the author is that the reason might be found in the surfacewater-groundwater coupling, which is most likely very important in lowland areas, in combination with a low slope of the canal beds (resulting in surface water not running off as quickly as is assumed in the conceptual model presented in this study). It is recommended to address this issue in future research.

The study on connecting the saturated and unsaturated zones with use of an irrigation flux did not improve the model performance. In fact, this connection made it impossible to get good model results according to the groundwater levels being measured. It is possible that the irrigation flux is not conceptualized correctly. Farmers most likely don’t pump water directly out of the ground, but will use surface water out of the drainage canals, or let in Rhine water into the area.

It would be very interesting to see whether the method can be improved by placing groundwater measurement stations randomly in the area, instead of the places where they are measured now. The groundwater measurements are all taken within a range of 3 km of town centers. This means that urban drainage systems will have an effect on the measurements taken, and it is likely that (slightly) different results are observed if the measurements are taken only in crop fields.
CHAPTER 6. CONCLUSIONS

Based on the results, the following conclusions on the project goals can be made.

It was possible to derive different hydrological response units with use of topographical characteristics present in a DEM. Observations made in the field, however, were proven to be of great value, since earlier estimated threshold values of HAND and slope in different studies were shown to not be fully applicable in this area.

It is a valid procedure to extrapolate model structures and parameter values between areas that are similar classified. A snow module was proven to be a good addition in the hillslope area. Potential evaporation estimated with Penman-Monteith resulted in better model performance compared to potential evaporation estimated with Hamon. The irrigation process is not conceptualised good during this study. Water is most likely not substracted from the groundwater, but from surface or river water.

A combined addition of groundwater level measurements and constraints did show reduced uncertainty, and thus improvement, of the internal model processes (especially the fluxes towards and out of the slow responding reservoir). Validation of these processes still remains difficult in ungauged areas, but it is believed that valid results can be made on the outflow out of the lowland areas with a combination of constraints and groundwater measurements to determine internal processes, and evaporation estimates obtained from satellite imagery to reduce the uncertainty of the total runoff out of the area.

The main research objective:

“The objective of the research project is to identify and quantify the rainfall-runoff mechanisms of ungauged areas close to the river Rhine and the circumstances in which peak discharges out of these areas occur.”

is not yet fully answered. In order to do so, the following recommendations are made on improving the method used and for practical implementation of the method into the GRADE project.
CONCLUSIONS

RECOMMENDATIONS FOR IMPROVEMENTS ON THE METHOD USED IN THIS RESEARCH

- The highest average ranked behavioural models had a relatively low performance on the Nash-Sutcliffe efficiency for the flow duration curve of the higher flows. This is the result of the absolute ranking method, and therefore a relative ranking method should be applied for further studies.

- More distributed forcing will most likely give better model results. Distributed precipitation input gained from radar data will reduce the amount of ‘missed peaks’, which were now observed in the hydrographs of the Altschweier hillslope area. Implementation of distributed evaporation estimates gained from satellite data does give more certainty of the water balance, and thus most likely the pattern of the outflow out of the lowland areas. Outflow values will still be difficult to obtain.

- The transpiration processes can be described in more detail with use of the Jarvis model. By adding this model to the current model structure, the plant becomes an active part of the transpiration process.

- Assumptions were made for the constraints concerning interception, evaporation and the unsaturated zone depth. In this method, these constraints were linked to the hillslope and lowland area, where in fact they should be linked to the land cover. Although a large quantity of the lowland area is agricultural land and almost all of the hillslope area is covered with forests, implementing distribution of the parameters and constraints based on land cover instead of topography gives results for a better reason and does therefore improve the model structure.

- Differences are observed between modelled and observed time series when looking at the normalized height curves of each groundwaterlevel measurement independently. When looking at the results of various groundwaterlevel measurements all together, the model behaviour tends to go to a single model result. For this reason, distribution of the saturated soil module of the lowland areas should be avoided to keep the model relatively simple, as groundwaterlevel measurements can be very dependant on locational characteristics.

RECOMMENDATIONS FOR IMPLEMENTATION INTO THE GRADE PROJECT

- The method has shown that extrapolating model structures and even parameter values between equally classified areas based on topography and visual inspection can be a good working procedure. Even though there are still some questions unanswered for the lowland area, performing the method to get the outflow out of the hillslope areas does already reduce the ungauged part of the ZWE-areas significantly. It is even possible to classify hillslopes in already calibrated areas in order to get the parameter values of closely ungauged hillslope areas. Trivial, but still worthy to mention, is that the method does introduce the need for field investigation, which results in an increase of the human resources.

- There are still questions left unanswered for the outflow of the lowland area, which is mostly
due to the absence of a surface flow and drainage flow routing method. Since calibration on outflow is not possible, implementing a routing module with an assumption made for a range of the Manning coefficient present in these models, will give more realistic outflows out of the lowland area, instead of the peaky responses observed now.

**RECOMMENDATIONS FOR FUTURE RESEARCH**

- It was observed that the water levels modelled in the saturated zone reservoir had a much lower amplitude than groundwater level measurements taken in the field. It is not yet known what the reason is for this difference in amplitude, but if groundwater level measurements are to be used more often in conceptual modelling, it is very interesting to find an answer for this difference.
- Irrigation is a difficult process to conceptualise, but it probably is an important process in cultivated areas, such as the case study area of this research. It is therefore suggested that new conceptualisations of the irrigation process are formulated and tested in future research.
**APPENDIX A. FIELD INVESTIGATION**

**Figure 39.** Landscape classification during the field investigation, with the location number of the photo's taken. For a full overview of the photo's, see attached CD-rom.

**Figure 40.** Typical view of the lowland areas at A) location 21 and B) location 30. The hillslope areas can be seen in the back of figure B.
**Figure 41.** Typical view of the (beautiful) hillslopes at A) location 26, B) location 27 and C) location 33.

**Figure 42.** Activities close to the Rhine, with A) oil pumping facilities at location 16, B) Gravel mining facilities at location 37, C) water inlets towards the retention areas and D) harbors with privately operated sluices at location 42. Figure D also shows the water level of the Rhine being much higher than the surface level of surrounding areas.
Figure 43. Flow gauges at Baden-Baden (A and B, location 28) and Altschweier (C and D, location 29).

A local subsurface retention basin is under construction in Altschweier.
APPENDIX B. DATA ANALYSES

B.1 GROUNDWATERLEVEL MEASUREMENTS

Figure XX and XX prove the influence of the groundwater seepage of respectively the Rhine and out of the hillslope on the groundwater measurements in the research area. Figure XX shows that the correlation ($r^2$) of the Rhine water levels and the groundwater level measurements taken closely to the Rhine is much higher than further away from the Rhine.

In figure X XB hystereses can be seen for groundwater level measurements taken at GWM 1 and GWM 1676. Measurements taken at GWM 1676 show a delay when compared to GWM 1, which means that a seasonal wave flows out of the hillslope towards the lower areas. The lag between measurements taken on a hillslope was also identified by Seibert et al. (2003). The storage might be related to snow fall (figure X XC), which is not covered by this research.

![Figure 44](image)

**Figure 44.** Correlation between Rhine water levels measured at Kehl-Odelshofen (figure XX) and groundwater level time series at various lateral distances of the Rhine. The time series are those of three hydrological years (May '09 - Apr. '12).

![Figure 45](image)

**Figure 45.** Figure A) Detail of figure XX, which shows the position of GWM 1 (48.923°N; 8.369°E) and GWM 1676 (48.898°N; 8.368°E) on the hillslope. The contourlines represent 25 meter in elevation each. Figure B) Comparison of groundwater level time series measured at GWM 1 and GWM 1676. Figure C) Delay of groundwater level time series, compared with snow cover measured at Freudenstadt.
B.2 METEOROLOGICAL DATA

PRECIPITATION

A double mass analysis on the data of all six stations showed three periods (two for the Oppenau rain gauge and one for the Rheinstetten rain gauge), for which the data was not in line with the data of the other stations. It concerns the periods: January-April 2008 and May-December 2012 for Oppenau and January-November 2008 for Rheinstetten. The data for these three periods is therefore considered unreliable and are not used for further research.

The cumulative distribution functions for all stations for the years 2009-2012 show that there is a clear distinction between measurements taken at lower positioned rain gauges (Durbach-Ebersweier, Kehl, Rheinau-Memprechtshofen and Rheinstetten) and higher positioned gauges (Baden-Baden and Oppenau, FIGURE XX. The measured annual precipitation values at stations in the hillslope areas are in a higher order of magnitude compared to the lowland areas.

Most of the events, however, are captured by all stations. This is visualized in figure XXa, where the daily precipitation values of the two stations which are the furthest apart (Baden-Baden and Kehl-Odelshofen) are plotted together. The direct correlation between the two stations over three hydrological years (May 2009 – April 2012) is 0.74.

Baden-Baden lies in the middle of the hillslope areas and on a reasonable elevation compared to the rest of the hillslope area. Therefore, measurements taken at this gauge are assumed to be representative for the precipitation falling on the steep hillslope areas. Rheinau is assumed to capture precipitation values representative for the lowland areas.

![Graph showing daily precipitation values and intensities for Baden-Baden and Kehl over 2009. Figure 46.](image)

**Figure 46.** Comparison of A) timing and B) daily intensity of precipitation events measured at Baden-Baden and Kehl.
**Meteorological data**

**Figure 47.** Double mass analyses of each rainfall gauge against the average of all other stations.

**Figure 48.** Cumulative rainfall of all stations for four calendar years.
**Potential evaporation**

Potential evaporation time series estimated with use of FAO Penman-Monteith (Freudenstadt) and Hamon (at Baden-Baden) have been used as input for the hillslope model. The annual values are comparable, with FAO Penman-Monteith having slightly higher values (table XX). The time series show a time lag of the Hamon potential evaporation rates in comparison with the Penman-Monteith potential evaporation rates, which can be explained because of temperature reaching higher values later over the year than incoming radiation. During winter periods, evaporation rates estimated with Hamon are significantly higher than evaporation rates estimated with FAO Penman-Monteith (Figure XX). This explains the regression line being tilted compared to the 1:1 line (figure XX).

<table>
<thead>
<tr>
<th>Hyd. Year</th>
<th>Freudenstadt Penman (FAO)</th>
<th>Hamon</th>
<th>Rheinstetten Penman (FAO)</th>
<th>Hamon</th>
<th>Baden-Baden Hamon</th>
<th>Rheinau Hamon</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009-2010</td>
<td>747</td>
<td>693</td>
<td>778</td>
<td>708</td>
<td>691</td>
<td>715</td>
</tr>
<tr>
<td>2010-2011</td>
<td>730</td>
<td>689</td>
<td>761</td>
<td>692</td>
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<td>743</td>
<td>700</td>
<td>772</td>
<td>706</td>
<td>698</td>
<td>720</td>
</tr>
</tbody>
</table>

**Table 8.** Annual potential evaporation estimates (in mm/yr) obtained with FAO Penman-Monteith and Hamon methods for various stations.

**Figure 49.** Potential evaporation time series estimated with use of the Hamon and FAO Penman-Monteith methods.
HYDROLOGICAL YEAR

The deviation of the hydrological year in a summer and winter period is determined with use of five years of precipitation and potential evaporation data (Figure XX). For these five years, relatively low average monthly values for precipitation were found in the months April and September. For this reason, and for the relatively high potential evaporation rates, it is assumed that the starting conditions of the model in the period following these months are most comparable, therefore resulting in a summer period ranging between May and October, and a winter period ranging between November and April. This is in line with the definition of hydrological summer and winter used by for instance Belz et al. (2007) and XXXX.

**Figure 50.** Scatterplot of the potential evaporation rates estimated with use of the Hamon and FAO Penman-Monteith methods.

**Figure 51.** Monthly averages of five years of data for precipitation measured at the hillslope and lowland stations, and potential evaporation estimated for data obtained at Freudenstadt.
## B.3 Initial Parameter Values

### Snow Threshold

The threshold for temperature for which precipitation is likely to fall in the form as snow rather than rain is estimated with use of the correlation between two events:

- The daily average, lowest or highest measured temperature at Freudenstadt drops below value x in °C.
- A precipitation event resulted in an increase in the measured snow volume at Freudenstadt.

This method has been performed on four calendar years of data (Jan. '09 - Dec. '12). No good temperature threshold could be distinguished in the results (table XX). Therefore, in the model, it is assumed in the hillslope model that rain falls in the form of snow under the following two conditions:

- The average measured daily temperature at Freudenstadt drops below 2.5 °C.
- There was a measured increase in snow volume at Freudenstadt at the same day.

<table>
<thead>
<tr>
<th>value for x (°C)</th>
<th>-2</th>
<th>-1</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>2,5</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average T&lt;x</td>
<td>0,519</td>
<td>0,545</td>
<td>0,548</td>
<td>0,550</td>
<td>0,534</td>
<td>0,509</td>
<td>0,480</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lowest T&lt;x</td>
<td>0,425</td>
<td>0,481</td>
<td>0,504</td>
<td>0,516</td>
<td>0,490</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Highest T&lt;x</td>
<td>0,348</td>
<td>0,426</td>
<td>0,486</td>
<td>0,523</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 9.** Correlation coefficients to determine the snow threshold value.
HILLSLOPE - DEPLETION CURVES

groundwater outflow behaves like a linear reservoir (REFERENCE), thus the outflow is considered proportional to the amount of storage:

\[ Q = \frac{1}{K} \times S \]

**Equation 33.**

where \( Q \) is the discharge in \( m^3/time \), \( S \) is the storage in \( m^3 \) and \( K \) is a conveyance factor in seconds. In addition to the water balance equation (formula XX) and ignoring the effect of rainfall and evaporation, an exponential relation between the discharge \( Q \) and time \( t \) can be derived:

\[ Q = Q(t_0) \times \exp\left(-\frac{t - t_0}{K}\right) \]

**Equation 34.**

For the Altschweier and Baden-Baden catchments, the value for \( K \) has been estimated with use of this formula, by plotting the discharge on a semi-logarithmic scale (figure XX) and estimating the depletion curves. It resulted into values of \( K \) for Altschweier, Baden-Baden and Baden-Baden/Altschweier combined of respectively 8, 10 and 9.5 days.

**Figure 52.** Estimation of the depletion curves for the catchments of A) Altschweier, B) Baden-Baden and C) Baden-Baden/Altschweier combined.
APPENDIX C. DOTTY PLOTS HILLSLOPE MODEL B

**Figure 53.** Dotty plots of the parameters used in model structure B. The blue dots represent the objective scores when calibrating on only that single objective score. The red dots represent the objective scores of the behavioural models. From A to D respectively, the dotty plots represent the Nash-Sutcliffe Efficiency of the flows, the Nash-Sutcliffe Efficiency of the log of the flows, the Nash-Sutcliffe Efficiency of the flow duration curve and the Nash-Sutcliffe Efficiency of the log of the flow duration curve. As can be seen, a lot of equifinality is involved.
APPENDIX D. LOWLAND MODEL RESULTS

GWM 1

**Figure 54.** Results for GWM 1 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 55.** Results for GWM 1 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
**Figure 56.** Results for GWM 1088 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 57.** Results for GWM 1088 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
**Lowland model results**

**Figure 58.** Results for GWM 1089 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 59.** Results for GWM 1089 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
**APPENDICES**

**GWM 130**

**Figure 60.** Results for GWM 130 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 61.** Results for GWM 130 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
**GWM 832**

**Figure 62.** Results for GWM 832 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 63.** Results for GWM 832 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
FIGURE 64. Results for GWM 1676 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

No behavioural models were obtained for GWM 1676 when adding constraints.
GWM 1721

Figure 65. Results for GWM 1721 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

Figure 66. Results for GWM 1721 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
GWM 3146

**Figure 67.** Results for GWM 3146 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 68.** Results for GWM 3146 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
**Lowland model results**

**GWM 3150**

**Figure 69.** Results for GWM 3150 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 70.** Results for GWM 3150 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
Figure 71. Results for GWM 3336 without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

Figure 72. Results for GWM 3336 with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
Figure 73. Results for GWM Eisenbahnstrasse without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

Figure 74. Results for GWM Eisenbahnstrasse with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
**APPENDICES**

**GWM Rheinwald**

**Figure 75.** Results for GWM Rheinwald without the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.

**Figure 76.** Results for GWM Rheinwald with the addition of constraints. Figure A-B) observed and modelled discharges out of the Hillslope area for calibration and validation period. Figure D-E) observed and modelled normalized groundwater levels for calibration and validation period. Figures C) and F) dotty plots for the hillslope and lowland parameters respectively.
In April 2014, C. Brauer defended her PhD thesis at the Wageningen University. Her thesis was entitled ‘Modelling rainfall-runoff processes in lowland catchments’. It was too late to incorporate her research within this MSc thesis, but since the research objectives and approach appear to be very similar with what is done during this study, a short comparison is made between both approaches and the main results. Her thesis is freely downloadable at: edepot.wur.nl/296285.

As was the case during this study, also Brauer identified the problems with the currently used complex models for lowland areas, which are the overparameterisation and parameter identification, and the applicability of the model elsewhere. Therefore, the WALRUS model was designed (an open source model, Figure 77). This model is very similar with the lowland model as described in this study, with the exceptions that interception is not implemented in the model structure but an additional module is included for groundwater-surface water feedbacks. Also, a coupled reservoir is used for the unsaturated and saturated zones. The model is tested on two small catchments (0.5 and 6.5 km²). In addition to groundwater measurements, also discharge and soil moisture observations were available.

A few of her most important conclusions are as follows: A single storage-discharge relation between catchment storage and catchment outflow is not possible in these areas, but internal catchment fluxes might still be modelled adequately with local storage-discharge relations. Soil moisture contents show a similar temporal variation as groundwater levels. Most flowroutes are wetness dependant (as is also modelled in this study). The addition of soft data (field surveys) and complementary data such as groundwater measurements does provide valuable information, while making the whole more than a sum of its components.

**Figure 77.** WALRUS Model structure.
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APPENDICES

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