Predicting discharge at ungauged catchments

Parameter estimation through the method of regionalisation

$$\hat{\theta}_L = H_R(\theta_R \mid \Phi)$$

University of Twente
November 2006
Dave Deckers

- Master Thesis -

Date:	24.11.2006
Title:	Predicting discharge at ungauged catchments: Parameter estimation through the method of regionalisation.
Author:	D.L.E.H. Deckers
E-mail:	dave.deckers@gmail.com
Graduation Committee:	Dr. M.S. Krol (University of Twente) Dr. ir. M.J. Booij (University of Twente) Dr. ing. T.H.M. Rientjes (International Institute for Geo-Information Science and Earth Observation)

Photo cover: www.ramblingreports.com

I. Preface

Exactly two and a half years ago I stood for an important decision. After just ending my previous study I had to decide what my next step would be. Making choices is tough. One of the options was to start applying for work. Though, an other interesting option arose by means of an information day at the University of Twente. It persuaded me to enter a new study and my choice was made: Civil Engineering and Management with the differentiation Watermanagement.

Two years went by. But suddenly I stood at the beginning of the end of my second study. At first I tried finding an external assignment since it would hopefully had some practical aspects. However it was not the case. Happily, my current supervisor had posted an interesting research on the intranet and an internal assignment it became. The result lies in front of you.

Half a year I have worked on my master thesis and eventually everything comes to an end. Instead of a more practical side, I can honestly say the assignment turned out to be pretty scientific. Moreover, I can affirm that it has been a very exciting and educational period for me and I would recommend everybody to include such 'scientific aspects'. Nevertheless, I could not have established this amount of profound research without good advise, motivation and triggering of my supervisors Martijn Booij (UT), Maarten Krol (UT) and Tom Rientjes (ITC). Therefore my well-meant gratitude.

In addition, I would like to thank my girlfriend Daniëlle for her "long-distance" support throughout the week and distraction in the weekends, my parents for total support during the whole study and my fellow students for the pleasant coffee-times, lunch-strolls and many interesting discussions in room number W-122.

Everybody, thanks.

Dave Deckers

Acknowledgements
This study has been performed at the University of Twente under the department of Civil Engineering and Management at the section Water Engineering & Management. My gratitude for making room at your facility and generating a nice work environment. Also I would like to thank the Top Down modelling Working Group from the PUB initiative for the availability of the used hydrometric data, the British Atmospheric Data Centre for granting access to their data base from which the required climatic data was gathered and the National River Flow Archive from which the physiographic data of all catchments was gathered.

II. Summary

The ability to predict flows at gauged and ungauged catchments is an important goal in hydrology. The reason why prediction is of importance is for instance the ability to estimate impacts of climate or land use change on the discharge regime. For such purposes hydrological models are generally used all over the world. However, in order to be able to predict discharge values for concerning model parameters have to be determined. In general, this is done by calibrating the model against observed discharge using efficiency criteria which evaluate model performance. Yet, with respect to the ungauged catchment topographic and climatic properties are available, but no observed discharge data. Hence, the ungauged catchment can not be calibrated and model parameter values have to be determined using other sources of information. The objective of this study contributing to this issue is as follows: *Contribute to reducing uncertainty in the prediction of discharge regime at the ungauged catchments through application of the method of regionalisation based on establishing relationships between model parameters of the hydrological model HBV and climatic and physiographic data using 61 well gauged catchments in the United Kingdom.*

The hydrological model HBV is used in this study which can be appointed as a conceptual model. It therefore contains model parameters which not have a direct physical interpretation and hence, model parameter values can not be estimated in the field. The model is run at a time step of one day and requires data on precipitation, actual temperature and potential evapotranspiration in order to be able to simulate discharge. Actual temperature and potential evapotranspiration are calculated using several data sets available at databases from which authorization was requested. For the potential evapotranspiration the formula of Penman-Monteith is applied since it was not directly available. The data sets of precipitation and observed discharge regimes are gathered from another free admissible database.

The classical approach of regionalisation is applied in this study and consists of three steps. The first step implies calibration of the catchments against an observed discharge regime in order to identify model parameter values. Objective functions, which are quantitative measures to estimate model performance, are used to determine the model parameter set which generates the best fit between the observed discharge and the calculated discharge. This is called the optimum parameter set. Secondly, for each selected model parameter it is tried to establish a relationship with climatic and physiographic data. All established relationships together, merged in the hydrological model HBV, are called the regional model. Finally, model parameter values can be estimated by applying the established regional model in order to be able to predict discharge at the ungauged catchment. In this study the performance of the regional model is validated in order to evaluate model performance of the regional model.

With respect to model calibration, at first appropriate model parameters are selected. In this study, the essence is to establish a robust regional model which can adequately predict all the different aspects of the hydrograph such as total average flows, high flows and low flows. Other regionalisation studies, where much experience has been gained are used to select appropriate model parameters. In total 7 model parameters are selected: *FC*, *BETA*, *LP*, *ALFA*, K_f, K_s and *PERC*. The optimum parameter set is determined through application of Monte Carlo simulations executing 10.000 simulation runs. For each simulation run, parameter values are randomly generated from a fixed established parameter space. In order to define which parameter set can be regarded as the optimum parameter set, a multiple objective function is composed in which four single objective functions (SOFs) are added, each proportionally evaluating a particular aspect of the hydrograph. Implementing multiple objective functions in order to identify proper parameter

values has been a reaction to a commonly known problem in model calibration which is called equifinality. It means that many combinations of parameter values provide equally good model fits to the observed data. Applying a multiple objective function deals with the problem of equifinality. For 48 out of 61 catchments the optimum parameter sets are derived. Regarding the remaining 13 catchments, 8 are used for validating the regional model and 5 are omitted due to different reasons. Based on two conditions, satisfactory catchments are selected to be used for establishing the relationships. The conditions are related to the commonly used Nash-Sutcliffe coefficient (R^2) and to the relative volume error (RV_E). In total 17 catchments satisfy both conditions.

In order to be able to determine relationships between model parameters and physiographic and climatic data, so called physical catchment characteristics (PCCs) have to be selected. Based on commonly used PCCs in other regionalisation studies and on availability of the required data, in total 14 PCCs are selected which are the catchment area, mean elevation, hypsometric integral, catchment shape, standard average annual rainfall, five types of land use and four types of geology and soils. Subsequently, relationships are established by performing simple and multiple linear regression analysis. In both cases for each model parameter relationships are derived which are evaluated based on statistical and hydrological significance. Also scatter plots between model parameters and PCCs are evaluated since it is assumable that clear non-linear relationships can occur. Eventually for all model parameters significant relationships are derived with the exception of K_S. However, three out of six selected regression equations still are questionable on the basis of hydrological interpretation.

After having determined the relationships between model parameters and PCCs, the established regional model is validated using the ungauged catchment. In order to be able to draw conclusions regarding model performance well observed discharge data are required and therefore several well gauged catchments are supposed to be ungauged. In order to assess the robustness of the regional model it is assumed that in total 8 well gauged catchments are sufficiently since they are selected based on much physiographic and climatic diversity. Assessing the performance of the regional model is done by comparing it to the performance of the ungauged catchments using the optimum parameter set and using the default parameter set. In this way judgment is made due to change in model performance of the regional model. With respect to model parameter K_s in the regional model, a default value is used.

After evaluation of model performance of the regional model against the optimum parameter set, it can be concluded that in general the model performs not satisfactorily. At the start of this study it was expected that overall model performance which is represented by R^2 would decrease, but within an acceptable range. However, the decrease of R^2 turns out to be considerable for almost all 8 catchments. Additionally, the decrease of the other three SOFs varies from considerable up to very large, especially for the slow flow SOF. Moreover, after having evaluated the performance of the regional model with respect to the default parameter set, it can be concluded that implementing default values at the ungauged catchment favours implementing the regional model. On a total of 32 generated SOF values, the regional model performs better for merely 13 SOFs better than the default parameter set. This all results in a final conclusion which states that the applicability of the classical approach of regionalisation of the hydrological model HBV with respect to adequately predicting all the aspects of the discharge regime at ungauged catchments in general is questioned.

III. Samenvatting

Het voorspellen van afvoer regimes in goed alswel in slecht bemeten stroomgebieden is een belangrijk doel binnen het vakgebied van de hydrologie. Met goed bemeten stroomgebieden worden stroomgebieden bedoeld waar klimatologische data zoals neerslag en temperatuur van beschikbaar is, stroomgebiedbeschrijvende data zoals het gemiddelde verhang en de grootte van het stroomgebied alswel lange termijn data van het gemeten afvoer regime aanwezig is. Reden waarom dit van belang is, is bijvoorbeeld de mogelijk om het effect van klimaatsverandering op het afvoer regime te voorspellen. Hiervoor worden in het algemeen hydrologische modellen gebruikt. Om het voorspellen mogelijk te maken moeten voor betreffende modelparameters waarden worden bepaald. Normaliter worden deze verkregen door het model te kalibreren met de gemeten afvoer regimes. Echter, in slecht bemeten stroomgebieden is deze data niet aanwezig en kunnen derhalve de benodigde parameterwaarden niet worden bepaald waardoor andere bronnen van informatie gebruikt moeten worden. Het doel van dit onderzoek sluit aan bij het laatst genoemde probleem welke is verwoordt als: *Draag bij aan het verkleinen van de onzekerheid in het voorspellen van afvoer regime in het slecht bemeten stroomgebied door toepassing regionalisatie welke gebaseerd is op het vaststellen van relaties tussen modelparameters van het hydrologische model HBV en klimatologische alswel stroomgebiedbeschrijvende gebruik makend van 61 goed bemeten stroomgebieden in het Verenigd Koninkrijk.*

Het hydrologische model HBV is in deze studie gebruikt wat geclassificeerd wordt als een conceptueel model. Hierdoor bevat het modelparameters die niet directe fysiek geïnterpreteerd kunnen worden en daardoor zijn bijbehorende waarden niet direct in het veld te bepalen. Het model simuleert met een tijdstap van een dag en vereist neerslag, actuele temperatuur en potentiële evapotranspiratie om te kunnen simuleren. De actuele temperatuur en de potentiële evapotranspiratie zijn berekend gebruik makend van verschillende data sets die beschikbaar zijn gemaakt door de British Atmospheric Data Centre. De berekening van de potentiële verdamping is gebaseerd op de formule van Penman-Monteith. De vereiste data sets van waargenomen neerslag en afvoer regime zijn verzameld van een andere vrij toegankelijke data base.

De klassieke aanpak van regionalisatie is in deze studie toegepast en is opgebouwd uit drie stappen. In de eerste stap worden de stroomgebieden gekalibreerd met de gemeten afvoer verlopen om geschikte modelparameter waarden te bepalen. Doelfuncties, welke een kwantitatieve maat zijn om de prestaties van het model te bepalen, worden gebruikt om de optimale parameter set te bepalen. Vervolgens wordt in de tweede stap voor elke modelparameter relaties bepaald met de klimatologische en gebiedsbeschrijvende data. Alle vastgestelde relaties tezamen vormen het regionale model. In de laatste stap worden voor elke modelparameter waarden bepaald in het slecht bemeten stroomgebied gebruik makend van het vastgestelde regionale model. Daarnaast is in deze studie ook het regionale model gevalideerd om een oordeel te geven over de prestaties van het regionale model.

Met betrekking tot de kalibratie van het model zijn allereerst geschikte modelparameters geselecteerd. In deze studie is het de essentie om een robuust regionaal model te bepalen die adequaat alle aspecten van een hydrograaf kan voorspellen zoals het gemiddelde afvoer regime maar ook de piek afvoeren en de laag water afvoeren. Andere regionalisatie studies waar veel evaring is opgedaan zijn geëvalueerd en hierop gebaseerd zijn in deze studie in totaal 7 modelparameters geselecteerd, te weten *FC, BETA, ALFA, LP,* K_f, K_s en *PERC.* De optimale parameter set is bepaald door toepassing van Monte Carlo simulaties waarbij er 10.000 simulaties zijn uitgevoerd. Voor elke simulatie zijn voor alle modelparameters willekeurig waarden gegenereerd gebaseerd op een uniforme verdeling binnen vastgestelde grenzen. Door toepassing van een meervoudige doelfunctie is vervolgens bepaald welke van de willekeurig gegenereerde parameter sets de optimale parameter set is. Deze meervoudige doelfunctie is opgebouwd uit vier enkelvoudige doelfuncties die ieder evenredig ten opzichte van elkaar een bepaald aspect van de hydrograaf evalueren. Implementatie van een meervoudige doelfunctie om de optimale parameter set te bepalen is een reactie op een algemeen erkend probleem binnen model kalibratie wat *equifinality* wordt genoemd. Dit impliceert dat verschillende combinaties van parameterwaarden resulteert in even goede model prestaties. Toepassing van een meervoudige doelfunctie pakt het probleem van *equifinality* aan. Voor 48 van de 61 stroomgebieden zijn uiteindelijk optimale parameter sets bepaald. Van de resterende 13 stroomgebieden zijn er 8 geselecteerd om het regionale model te valideren en zijn er 5 weggelaten om verschillende redenen. Stroomgebieden die na de kalibratie zijn geselecteerd om het regionale model vast te stellen, zijn geselecteerd aan de hand van 2 opgestelde voorwaarden. Deze voorwaarden hebben betrekking op de volgende doelfuncties: de Nash-Sutcliffe coëfficiënt (R^2) en de relatieve volume fout (RV_E). In totaal voldoen 17 stroomgebieden aan deze gestelde twee voorwaarden.

Om überhaupt relaties vast te stellen, moeten er naast de optimale parameterwaarden ook zogenaamde fysieke stroomgebiedkarakteristiek (FSK) geselecteerd zetten. Gebaseerd op frequent gebruikte FSKen in andere regionalisatie studies en op beschikbaarheid van de benodigde data zijn in deze studie 14 FSKen geselecteerd, te weten *oppervlakte, gemiddelde hoogte, hypsometrische integraal, vorm van het stroomgebied, gemiddelde jaarlijkse hoeveelheid neerslag, vijf type land gebruik* en *vier classificaties hydrogeologie*. Het daadwerkelijk vaststellen van de relaties is uitgevoerd door enkelvoudige en meervoudige lineaire regressieanalyse. In beide gevallen zijn de relaties geëvalueerd met betrekking tot statistische significantie en vanuit de hydrologische integriteit van de vastgestelde relaties. Daarbij is voor de enkelvoudige lineaire regressieanalyse ook nog een visuele evaluatie van scatter plots tussen modelparameters en FSKen uitgevoerd aangezien het aannemelijk is dat er ook duidelijk niet-lineaire relaties zich voor kunnen doen. Uiteindelijk zijn voor alle modelparameters statistisch significante relaties vastgesteld met de uitzondering van K_S. Echter, de hydrologische integriteit van drie van de zes vastgestelde relaties worden nog steeds sterk in twijfel getroffen.

Nadat de relaties tussen modelparameters en FSKen zijn vastgesteld, is het regionale model gevalideerd op slecht bemeten stroomgebieden. Om conclusies te kunnen trekken met betrekking tot de prestaties van het regionale model is voldoende goed bemeten afvoer data benodigd en daardoor zijn enkele goed bemeten stroomgebieden als slecht bemeten verondersteld. Om de robuustheid van het regionale model te beoordelen is het aangenomen dat 8 goed gemeten stroomgebieden voldoende zijn aangezien de selectie ervan gebaseerd is op diversiteit in klimatologische data alswel gebiedsbeschrijvende data. Beoordeling van de prestaties van het regionale model is gebaseerd op vergelijking met de model prestaties naar aanleiding van de optimale parameter set en naar aanleiding van een standaard parameter set. Met betrekking tot modelparameter K_S is er in het regionale model een standaard parameterwaarde gebruikt.

Na evaluatie van de prestaties van het regionale model met de optimale parameter set kan geconcludeerd worden dat het regionale model inadequaat presteert. Aan het begin van deze studie werd weliswaar verwacht dat de prestaties zouden afnemen met betrekking tot het regionale model, maar in beperkte mate. De afname blijkt echter behoorlijk te zijn voor bijna alle 8 stroomgebieden kijkend naar de enkelvoudige doelfunctie R^2. Bovendien, de afname van de andere drie enkelvoudige doelfuncties varieert van behoorlijk tot extreem veel, specifiek met betrekking tot de laag water doelfunctie. Verder kan geconcludeerd worden dat toepassing van de standaard parameter set de voorkeur verdient boven toepassing van het regionale model, wanneer betreffende model prestaties geëvalueerd worden. Dit allemaal resulteert in een laatste conclusie waarin wordt gesteld dat de toepasbaarheid van de klassieke aanpak van regionalisatie van het hydrologische model HBV met betrekking tot het adequaat voorspellen van alle aspecten van de hydrograaf in slecht bemeten stroomgebieden in twijfel wordt getrokken.

IV. Contents

1. Introduction

1.1. Scope of the research

The ability to predict flows in ungauged and gauged catchments is an important goal in hydrology. Ungauged catchments here refer to catchments where topographic and climatic properties are available, but no observed discharge data. Reason why prediction at the ungauged and gauged catchment is of importance is for instance:

- the possibility to predict high and low flow regimes, set up by respectively rainfall events and dry spells, to evaluate the consequences on socio-economic level or ecological health of the river system;
- estimating impacts of climate or land use change on the discharge regime.

For these purposes, hydrological models are generally used all over the world (Singh, 1995).

Prediction of these discharge regimes in ungauged and gauged catchments brings along a given degree of uncertainty which is reflected in model output. Several underlying aspects as addressed in for instance Hunink (2005) cause this uncertainty, which are:

- Different types of hydrological models which are used as a tool to establish these predictions each have a specific model structure since they represent real world hydrological processes differently.
- Transferring input data from the measurement scale to the model grid scale also introduces uncertainty in model output. The obtained data in the field often has to be aggregated in a way to correspond to the spatial scale required for the hydrological model. Furthermore, the obtained data in the field also has a degree of uncertainty arising from the natural variability these data have.
- The identification of appropriate model parameter values called calibration required for simulating the model also introduces uncertainty in model output.

Minimizing these addressed uncertainties causes predictions to be more accurate and hence, better operational and strategic water management is applicable. Regarding this thesis the main objective concerns the latter cause i.e. reducing the predictive uncertainty associated with identifying appropriate model parameters values.

Since it is possible to predict discharge regimes in well gauged catchments in a relatively simple way, prediction of flows at poorly or ungauged catchments is more complex and brings along a higher degree of uncertainty regarding model output. This because in case of a well gauged catchment the model can be calibrated against observed discharge data and identification of model parameter values is less uncertain. In an ungauged catchment these required data for model calibration are not available or not of sufficient quality and therefore the model parameters are difficult to define. Therefore, the model parameter values used in hydrological models for prediction in ungauged catchments have to be estimated from other sources of information. Several ways of obtaining the required information to be used for prediction in ungauged catchments are addressed in the literature. Commonly, through the method of regionalisation, which is the process of transferring information from comparable catchments to the catchment of interest, it is possible to acquire necessary information. In this study the concept of regionalisation with respect to the ungauged catchment will be part of the main objective of this study. As already determined in the preceding literature study of Deckers (2006), regionalisation will be based on establishing relationships between model parameters and physiographic as well as climatic data.

PUB
Recently, flow prediction in ungauged catchments got more attention, which shows a program launched in 2003 by the International Association of Hydrological Sciences (IAHS) that is aiming to make major research advances, in a coordinated way in this field. This initiative, called Predictions in Ungauged Basins (PUB) aims at "formulating and implementing appropriate science programmes to engage and energize the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make reliable predictions in ungauged basins." (Sivapalan et al., 2003). The objective of this study associates with this initiative. The Top-Down modelling Working Group (TDWG) within PUB made hydrometric data available of 61 well gauged catchments in the United Kingdom in order to contribute to this aim. For more information about IAHS, PUB and the Top-Down modelling Working Group, see appendix A.

1.2. Objective and research questions

The University of Twente is interested in using the data from 61 well gauged catchments in the United Kingdom with respect to the formerly addressed issue i.e. uncertainty in parameter identification. Therefore, the objective of this research is stated as follows:

Contribute to reducing predictive uncertainty with respect to discharge regimes in ungauged catchments through application of the method of regionalisation based on establishing relationships between parameters from the hydrological model HBV and physiographic and climatic data from 61 well gauged catchments in the United Kingdom.

In order to acquire the knowledge that is needed to fulfil the objective in a structured way several research questions are determined.

Main question
Based on a comparison between calibration and validation results, in what way and how is the performance of the regional model applied in ungauged catchments, which comprehends the established relationships merged in the hydrological model HBV, affected?

Sub-questions

1. What are effective and efficient HBV model parameters to relate to physical catchment characteristics?

2. Which criteria should be used in order to calibrate the HBV model as well as to evaluate the performance of the regional model?

3. Which physical catchment characteristics are available and useable to relate to HBV model parameters?

4. Which statistically significant and hydrologically sensible relationships between the model parameters and physical catchment characteristics can be derived?

5. In what way the regional model is going to be validated?

1.3. Outline of the report

In this report a method of regionalization is applied in order to be able to predict discharges at ungauged catchments. Therefore at first in chapter 2 insight is given in hydrological modelling by expounding the hydrological processes playing a role in rainfall-runoff generation and describing different aspects concerning hydrological modelling. In addition, the selected hydrological model used in this study is described in detail. Subsequently, in chapter 3 the study area and data organization with respect to climatic and physiographic data are expounded. In chapter 4 the process of regionalization is described where two commonly used approaches are explained from which the approach used in this study is selected (i.e. first calibrating the gauged catchments, subsequently establishing relationships between model parameters and physical catchments characteristics and at last validating these established relationships). Besides, in the last paragraph an important problem inherent in the process of regionalization (i.e. the problem of equifinality) is addressed. Here it is described in what way this problem is tried to deal with. In chapter 5 the applied methodology with respect to model calibration is described. In more detail, the model parameters used in calibration, the approach of calibration, in what way model calibration is evaluated, the approach applied for determining the optimum parameter set and several requirements for proper model calibration are expounded. Besides, a short description of model parameter sensitivity is given. Which physical catchment characteristics are selected in this study is expounded in chapter 6. In addition, the method of establishing the relationships between model parameters and physical catchment characteristics is described. Chapter 7 incorporates the methodology for validating the established relationships, thus which approach is selected for validation, in what way model performance of the validation catchments is evaluated and in what way and which catchments are selected to be used for validation. In chapter 8 the results of the former three stated phases of regionalization which are calibration, establishing the relationships and validating the model, are described. In chapter 9 conclusions on the stated objective are presented after which a discussion is raised. In addition, some recommendations are made. In the same chapter also the stated research questions are answered.

2. Hydrological modelling

To get insight in hydrological modelling, first insight in hydrological processes is acquired. In paragraph 2.1 the hydrological processes of importance with respect to rainfall-runoff generation are expounded. Furthermore, different aspects concerning hydrological modelling such as the technique of solution and scale issues are described in paragraph 2.2. Subsequently, in paragraph 2.3 selection of the model is expounded which is used in this study. At last, in paragraph 2.4 a brief description of the selected model is given.

2.1. Hydrological processes

The processes occurring in and above a catchment, from formation of rainfall to generation of stream flow that leaves the catchment through a river, are many and complex. The most important ones, with respect to rainfall-runoff transformation, are described here. This will lead to a better understanding of the rainfall-runoff processes conceptualized by the HBV model. This is of importance when the hydrologist's knowledge and expertise is required in assessing model output.

2.1.1. Hydrological cycle

The basis of generating rainfall-runoff processes lies in the hydrological cycle. The hydrological cycle can be explained by the interdependence and movement of all forms of water on earth. It usually is described in terms of six major components which are precipitation, infiltration, evaporation, transpiration, surface runoff and groundwater flow. This is shown in figure 2-1. While the driving force of this circulation is derived from the radiant energy received from the sun, evaporation can be stated as the start of the cycle. Therefore, the ocean is the earth's principal reservoir; it stores over 97 percent of the terrestrial water. Water *evaporates* into water vapour, where it contributes to clouds formation in the atmosphere. Here it condensates and may give rise to *precipitation* (e.g. rainfall or snowfall). In the terrestrial portion of the cycle not all of this precipitation reaches the ground surface because some is intercepted by the vegetation cover or by the surfaces of buildings and other structures, and respectively *transpires* and evaporates back into the atmosphere. The precipitation reaching the ground surface may then collect in order to form *surface runoff*, it may *infiltrate* into the ground or it evaporates back up into the sky (Ward and Robinson, 1990). After infiltration of the precipitation into the soil, the flow process becomes very unpredictable since the catchment runoff behaviour is closely related to the subsurface

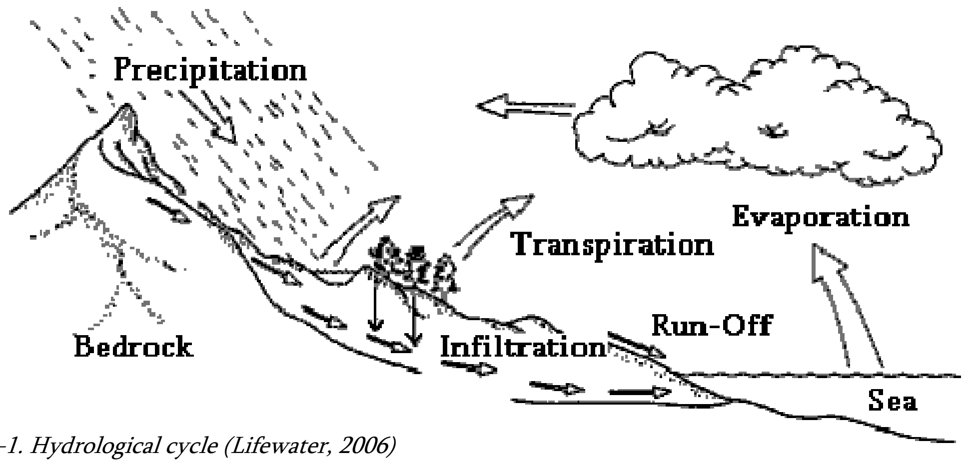


Figure 2-1. Hydrological cycle (Lifewater, 2006)

physiography, geometry and geology (Rientjes, 2005). This aspect (i.e. these flow processes) is expounded in the following section. In addition, another dominating process arising from catchment precipitation which contributes to rainfall-runoff generation is described.

2.1.2. Rainfall-runoff components at catchment scale

Catchment precipitation lies on the basis of runoff generating. Through four aggregated flow processes, precipitation can arrive at the outlet point of the catchment. These are through:

- direct precipitation onto the water surface;
- overland flow;
- throughflow;
- groundwater flow.

These terms are used widely and relatively unambiguously in the literature. However, based on the conditions of the soil which the precipitation bears, the last three flow processes each can embrace several distinctive flow processes. This is outlined below and is illustrated in figure 2-2.

Direct precipitation onto the water surface

Not all of the four addressed flow processes are of equal importance in contributing to the total channel discharge. For example, the contribution of direct precipitation onto the water surface is normally small simply because the perennial channel system occupies only a small percentage of catchment areas. However, where catchments contain a large area of lakes or swamps, open channel precipitation may be persistently important (Ward and Robinson, 1990). This is shown in figure 2-2 by number 8. Furthermore, this flow process is unambiguous.

Overland flow

Precipitation falling on the surface, resulting in a flow of water over the land surface by means of a thin water layer sheet flow is called overland flow. Two types of overland flows can be distinguished based on the conditions of the soil which the precipitation bears. These are the Horton overland flow and the saturation overland flow.

- the Horton overland flow occurs when the intensity of the rainfall is greater than the infiltration capacity of the soil and when the rainfall causes storage of water at the land-surface. This happens when rainfall events are heavy and where mountainous slopes are bare or covered by thin vegetation. This is shown in figure 2-2 by number 1.
- the saturation overland flow occurs when the soil becomes saturated due to the rise of the phreatic groundwater level up to the land surface. Since the infiltration capacity becomes zero, the precipitation cannot infiltrate anymore and will runoff on top of the land surface. It is mostly generated at the bottom part of hill slopes with shallow phreatic groundwater levels. This is shown in figure 2-2 by number 2.

Throughflow

Water that does infiltrate into the soil and then moves laterally through the upper soil horizons towards the stream channel is called throughflow. This throughflow takes place above the phreatic groundwater level. The water above the phreatic groundwater level occurs in two distinct forms, which are in unsaturated form and saturated form. Three types of throughflow can be distinguished, which are the unsaturated subsurface flow, the perched subsurface flow and the macro pore flow.

- Unsaturated subsurface flow arises from infiltrating water entering the subsurface and mostly has a vertical flow direction. This movement of water takes place due to suction head gradients. This is shown in figure 2-2 by number 3.

- Perched subsurface flow occurs where lateral conductivity in the surface horizons of the soil is substantially greater than the overall vertical hydraulic conductivity through the soil profile. When for instance an impermeable rock layer underlies a top layer, subsurface water will be discharged on top of this rock layer. This is shown in figure 2-2 by number 4.
- Water moving through macro pores and / or small natural pipes is called macro pore flow. Water flow exhibits as ‘free’ flow and, as such, is not controlled by suction head gradients (Rientjes, 2005). It can occur either in the saturated as well as the unsaturated form. This is shown in figure 2-2 by number 5.

Groundwater flow

The groundwater flow is the flow of water in the saturated zone. Since water commonly only moves very slowly through the ground, the outflow of groundwater into the channel may lag behind the occurrence of precipitation by several days, weeks or even years. It tends to be very regular since the saturated zone acts as a large storage zone of percolated water. In general, groundwater flow represents the long-term component of total runoff and is particularly important during dry spells when precipitation, overland flow and throughflow are absent. In addition, the groundwater flow contribution can be rapid or delayed (Ward and Robinson, 1990). These are shown in figure 2-2 respectively by number 6 and 7.

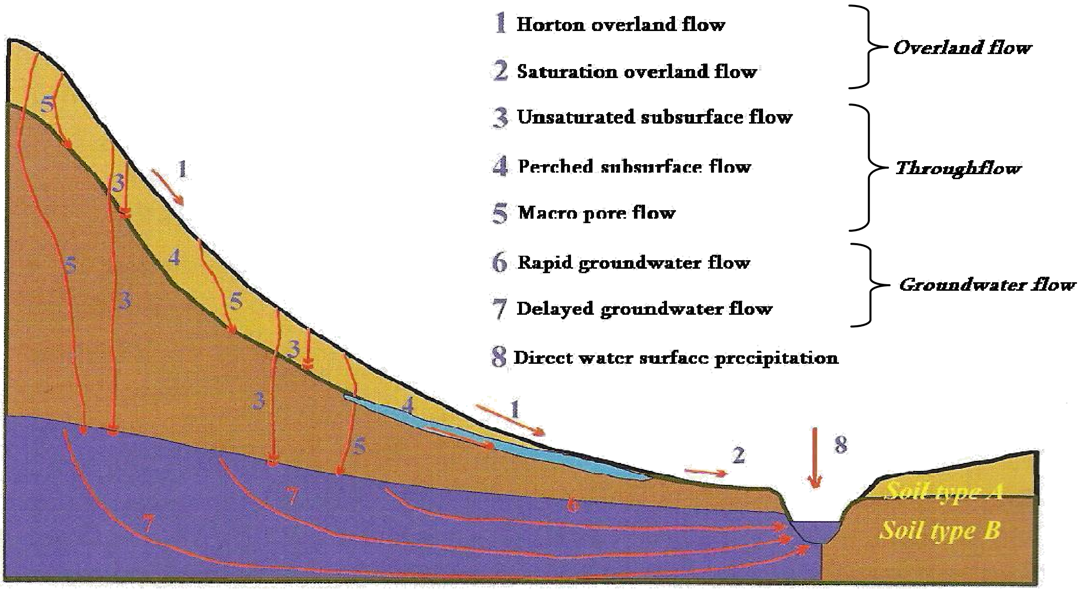


Figure 2-2. Distinctive flow processes of rainfall-runoff (Rientjes, 2005)

However, persistent misuse of other terms which are outlined here such as quickflow and slowflow respectively direct runoff and baseflow can result in unnecessary confusion. In order to provide consistent terminology, these definitions also are expounded. The terms quickflow and slowflow are commonly used with respect to the hydrograph. The hydrograph represents the runoff generated from a catchment against time. It has to be interpreted as the integral effect of all upstream processes due to rainfall. Under quickflow is understood the sum of channel precipitation, the overland flow and rapid throughflow, and will represent the major runoff contribution during storm periods and most floods. The slowflow on the contrary is the sum of the groundwater runoff and the delayed throughflow. This slowflow can be regarded as continuous flow through often long, dry periods. As can be noticed, a distinction is made between rapid and delayed throughflow. This arises from the fact that there is a variety of possible throughflow routes, as described earlier. As addressed in Ward and Robinson (1990), part of the macro pore flow and the perched subsurface flow in general contributes to the quickflow. The unsaturated subsurface flow contributes to the slowflow.

2.2. Classification of hydrological models

Many different types of hydrological models have been developed. Many of these models share structural similarities, because underlying assumptions are the same, but some of the models are distinctly different. In order to gain an overview of the types of model approaches, these are classified on the basis of various characteristics. Underneath, an outline of two classifications is described which are based on the technique of solution and the model scale. It is important to understand the difference between these classes so a suitable hydrological model can be chosen for this study.

2.2.1. Technique of solution

Based on the technique of solution, Beck (1991) classified the models as metric, conceptual and physically-based. Wheater et al. (1993) expounded this classification and described metric models as models primarily based on observations, seeking to characterize hydrological system response from available time-series in- and output data alone. Besides, these models are based on mathematical equations which do not take into account the underlying physical processes. Conceptual models are described as models seeking to represent all of the hydrological processes perceived to be of importance at the catchment scale input and output relationships. And physically-based models are models representing these hydrological processes in a more classical mathematical-physical form by using numerical solution techniques.

Metric models

As mentioned, metric models are based on mathematical equations that do not take into account physical processes which play a role in the hydrological behaviour of a system. The basis for model calibration is formed by analysis of the model input i.e. precipitation and evapotranspiration and output i.e. observed discharge regime. Metric models typically are always catchment dependent and they are not exchangeable. So, when due to climate or land characteristic change the model does not perform well anymore, it has to be re-calibrated (Rientjes, 2005). An example of such a rainfall-runoff model is the Nash cascade model (Nash, 1957).

Conceptual models

Conceptual models are models using physical catchment characteristics and climatic factors in a simplified manner. The algorithms used in the models structure to simulate flows contain parameters values that often do not have a direct physical interpretation and therefore cannot be measured in the field. Instead, they must be estimated using a calibration procedure whereby the model parameters are adjusted until the natural system output and the model output show an acceptable level of agreement. Because of the fact that the required input and output data are usually easily available, consequently these models are mostly used in rainfall-runoff modelling. The HBV rainfall-runoff model is an example of a conceptual model (Bergström, 1995).

Physically-based models

Physically-based models have a high degree of physical representation and are based on physical laws including the equations of conservation of mass, momentum and energy. However, accurately modelling of all processes of the hydrologic cycle becomes very complex, demands an eminent insight in hydrological behaviour and is very demanding for input data. Due to these properties it is a time-consuming and expensive method. An example of such a model is SHE (Abbot et al., 1986).

2.2.2. Model scale

With respect to model scale, a distinction can be made between spatial and temporal scale. Spatial scale refers to the spatial distribution of the real world characteristics within the hydrological model. Temporal scale refers to the time interval used for the data input and internal computations as well as the interval used for the output and calibration of the model (Singh, 1995).

Spatial scale

Models which treat the catchment as a single unit and use input data, which are believed to be representative at the catchment scale and produce output at a single point, are referred to as lumped models. So, in a lumped model, spatial distribution of the real world characteristics is ignored over the entire model domain and characteristics are represented by averaged values. There are, on the other hand, models that subdivide the catchment into smaller units supposed to be homogeneous in terms of their physical characteristics. Input data are required at this smaller homogeneous scale and the output can also be estimated at different points within the catchment. Such models are referred to as distributed models. After all a middle course is possible, which is called a semi-distributed model. In this model approach the system under study is partitioned in relatively large units that often are selected and bounded by topographic divides within the catchment. Each unit can be considered as a sub-catchment and thus are of various size and commonly are of irregular shape. An important characteristic of this classification is that topographic, physiographic and geologic catchment characteristics as well as meteorological variables are lumped within the scale of the sub-catchment (Rientjes, 2005).

Time scale

The time scale, on which the classification is based, can be defined as a combination of two time-intervals. One of the time intervals is used for input and internal computations. The second is the time interval used for the output and calibration of the model. Resulting from this combination, the models can be classified as continuous based or event based. With respect to the continuous-time based models, different time steps can be applied such as, hourly, daily, monthly and yearly and its aim is to simulate continuous discharge regimes (Singh, 1995). Event based models on the contrary are applied in order to simulate single runoff events, such as floods with hourly or daily periods or flood seasons as well as dry seasons with daily or monthly periods.

2.3. Model selection

At first sight, physically-based models are most appropriate in modelling rainfall-runoff generation because they model the rainfall-runoff processes at the most elaborate way. This was supported due to improvement in computer power, through which physically-based models became practically applicable in the 1980s. However, these models suffer from extreme data demand, scale-related problems (e.g. the measurement scales differ from the process and model scales) and overparameterisation i.e. there is a great danger of using to many parameters when it is attempted to simulate all hydrological processes thought to be relevant, and fit those parameters by optimisation against an observed discharge record (Wagener et al., 2004). Therefore, in order to predict rainfall-runoff in gauged and ungauged catchments these models mostly are not practically feasible. Refsgaard and Knutsen (1996) stated that conceptual models normally perform at least as well and furthermore the huge complexity of physically-based models is not required.

Since conceptual models perform at least as well as physically-based models in predicting discharge regimes, and since the required input data are not available at the required discretion, selection of physically-based models is denied. Furthermore, it can be stated that no metric model is chosen since the intention is that a change in climate or land characteristic does not require a re-calibration of the model. The conceptual models on the contrary can be considered as a good compromise between the need for simplicity on the one hand and the need for a firm physical basis on the other hand. This due to the fact that these models are usually able to capture the dominating hydrological processes at the appropriate scale with accompanying formulations (Booij, 2002) and therefore are very suitable when used in the process of regionalisation.

In order to choose the appropriate conceptual model, reference is made to the study of Passchier (1996). Passchier compared between important conceptual hydrological models based on several criteria such as application area, level of complexity and level of detail. The objective of the comparison was to select a model for rainfall-runoff modelling of the Rhine and Meuse catchments based on 4 specific aims which were land use impact modelling, climate change impact modelling, real-time flood forecasting and physically based flood frequency analysis. These aims again were evaluated based on 10 criteria such as reliability, scale and availability. The HBV model together with three other continuous based models performed best. The only criteria on which HBV performed poorly concerned the availability of the model.

Furthermore, the HBV model is used several times with respect to regionalisation (Hundecha and Bárdossy, 2004; Merz and Blöschl, 2004; Seibert, 1999b) and it demonstrated to be a suitable model. Besides, the model is available at the University of Twente and therefore it is selected to be used in this study. The HBV model in its latest version, HBV-96, is expounded in the next section.

2.4. HBV model

The HBV hydrological model has a long history and the model has found applications in more than 50 countries. Its first application dates back to the early 1970s (Bergström and Forsman, 1973). Originally the HBV model is developed at the Swedish Meteorological and Hydrological Institute (SMHI) for runoff simulation and hydrological forecasting, but the scope of applications has increased steadily. For instance it has been used for studies about the effects of climate change in Norway and Finland (Bergström, 1995). The model has also been subjected to modifications over time, so more specific situations could be addressed.

Experience has shown however, that the standard version of HBV had some major drawbacks which are outlined in Lindström et al. (1997). Therefore a re-evaluation has been carried out and a new model version has been developed. The HBV-96 model is the final result of this model revision (Lindström et al., 1997). Henceforward when "HBV model" is used, it is referred to the HBV-96 model.

However, the HBV model is not used in the interface released by the SMHI. The computer language FORTRAN is used and several reasons underpin this decision. When using FORTRAN, adjustments to the model can be made which are not possible in the regular interface. Adjustments which benefits this study such as the method used for calibrating the model and evaluating the performance of the model. Besides, my supervisor M.J. Booij formerly wrote the HBV model in FORTRAN. Adjustments to the model are based on the program my supervisor released to me. Underneath a more profound description of the standard HBV model is expounded, which is compounded through use of several studies which are Arends (2005), Hundecha (2004), Foppes (2005), IHMS (1997), Seibert (2002) and Van der Wal (2001). The numbers between brackets in figure 2-3 refer to the equations used in the model structure. The units of the equations used are also presented. For the time-dependent unit, a time step of one day is utilized.

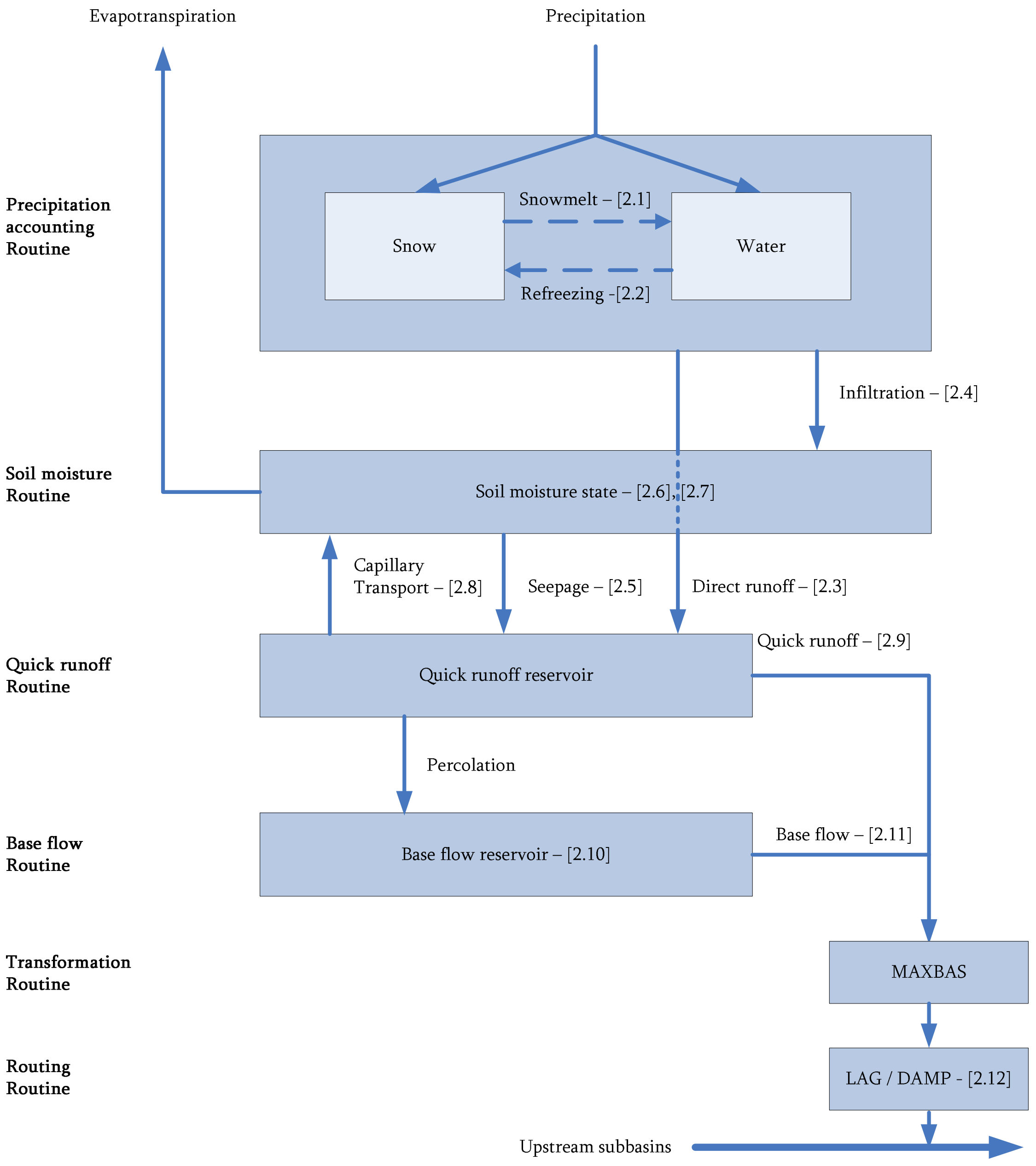


Figure 2-3. Schematisation HBV-96 routine structure

The model consists of 6 modules, which are:

- Precipitation accounting routine, representing rainfall, snow accumulation and melt;
- Soil moisture routine, representing actual evapotranspiration;
- Quick runoff routine, representing quickflow;
- Baseflow routine, representing slowflow;
- Transformation function, representing quickflow and slowflow delay and attenuation;
- Routing routine, representing flow through river reaches.

The HBV model generates rainfall-runoff using precipitation, temperature and potential evapotranspiration as data input. The model's basis is referred to catchments, which can be divided into a number of sub-catchments. The model is semi-distributed, since differences can be made between areas with different altitudes and geographical zones in terms of forest or field. The parameters to be used can be specified for an individual sub-catchment, or for the catchment as a whole.

2.4.1. Precipitation accounting routine

To simulate rainfall-runoff processes the structure of HBV requires three kinds of data input, which are precipitation, air temperature and estimates of potential evapotranspiration. The time scale of the precipitation is a time step of one day, but if desirable it is possible to set a smaller time step. The evapotranspiration values uses monthly averages, but also smaller values up to the simulation's time step are possible. The temperature is used for calculations of snow accumulation and melt, but when desired it can be used to adjust the potential evaporation (Lindström et al, 1997; IHMS, 1997). In order to define precipitation as rainfall or snow, a threshold value is used, TT [^0C]. When temperature, T [^oC], becomes smaller than this value, rainfall devolves to snow. Interaction between these two components takes place through snowmelt (P_s) and refreezing (P_r), respectively shown in equation [2-1] and [2-2]:

$$P_s = CFMAX \cdot (T - TT) \quad [2\text{-}1]$$

$$P_r = CFR \cdot CFMAX \cdot (TT - T) \quad [2\text{-}2]$$

$CFMAX$ = melting factor [mm d^{-1} $^0C^{-1}$]
CFR = refreezing factor [-]

2.4.2. Soil moisture routine

The soil moisture routine is the main part controlling runoff formation. Three output components are generated in this routine, and these are direct runoff, indirect runoff and actual evapotranspiration. Each one of the sub-catchments has an individual soil moisture accounting procedure and response function. Therefore, the runoff is generated independently for each of the sub-catchments.

Direct runoff

The volume of the soil moisture (SM, [mm]) in the catchment is computed with a soil moisture reservoir, representing the unsaturated soil. It uses precipitation (P, [mm/d]) as input which is supplied by the precipitation accounting routine. As long as the maximum soil moisture storage (FC, [mm]) is not exceeded, the precipitation infiltrates into the soil moisture reservoir. Otherwise the precipitation becomes directly available for runoff (DR, [mm/d]) as shown in equation [2-3]:

$$DR = \max\{(SM + P - FC), 0\} \quad [2\text{-}3]$$

From equation [2-3] the volume of infiltrating water (IN, [mm/d]) is generated as shown in equation [2-4]:

$$IN = P - DR \quad [2\text{-}4]$$

Indirect runoff

The infiltrating water (IN) can be separated into two components; it replenishes the soil moisture state or it will seep through the soil layer, which is parameterized by R [mm/d].
This indirect runoff (R) through the soil layer is determined by the amount of infiltrating water (IN) and the soil moisture content (SM) through a power relationship with parameter $BETA$ [-]. This is shown in equation [2-5]:

$$R = IN\left(\frac{SM}{FC}\right)^{BETA} \qquad [2\text{-}5]$$

This relationship between parameters states that indirect discharge increases with increasing soil moisture content and that when no infiltration occurs, no indirect discharge is generated. The amount of water that does not runoff indirectly is added to the soil moisture state.

Evapotranspiration

Actual evapotranspiration (E_a, [*mm/d*]) which occurs at the soil moisture routine is related to the measured potential evapotranspiration (E_p, [*mm/d*]), the soil moisture state and the parameter value *LP* [-]. This latter soil moisture value is a fraction between 0 and 1 and denotes the limit where above the evapotranspiration reaches its potential value. This relation is shown in equation [2-6] and [2-7]:

$$E_a = \frac{SM}{LP \cdot FC} \cdot E_p \qquad with \qquad SM < (LP \cdot FC) \qquad [2\text{-}6]$$

$$E_a = E_p \qquad with \qquad SM \geq (LP \cdot FC) \qquad [2\text{-}7]$$

Thus, the actual evapotranspiration is equal to the potential evapotranspiration if the actual evapotranspiration is above the specified threshold.

2.4.3. Quick runoff routine

The runoff generation routine is the response function which transforms excess water from the soil moisture zone (*DR + R)* to runoff. This response function is represented by an upper non-linear and a lower, linear, reservoir. These reservoirs represent respectively the quickflow and slowflow as defined in paragraph 2.1.2. The quick runoff routine manages the upper non-linear reservoir. In this reservoir three components can be distinguished which are; percolation to the slow reservoir, capillary transport back to the soil moisture reservoir and quick runoff.

Percolation

The direct runoff (DR) and indirect runoff (*R*) together enter the quick runoff reservoir from which a specific amount percolates through to the underlying baseflow runoff reservoir. Percolation (*PERC,* [*mm/d*]) only occurs when there is water available in the quick runoff reservoir.

Capillary rise

The second component within the quick runoff reservoir regards water returning to the soil moisture routine. This capillary flow (C_f, [*mm/d*]) depends on the amount of water stored in the soil moisture reservoir. The parameter *CFLUX* [*mm/d*], a maximum value for capillary flow, determines a limitation for the capillary flow. The capillary flow depends on the soil moisture deficit (*FC – SM*). When there is no soil moisture deficit, no capillary rise will occur. Otherwise, a fraction of the *CFLUX* will flow capillary upward. This is shown in equation [2-8]:

$$C_f = CFLUX \cdot \left(\frac{FC - SM}{FC}\right) \qquad [2\text{-}8]$$

Quick runoff

When the yield from the soil moisture routine is higher than *PERC* and C_f allows, and water is available in the quick runoff reservoir, quick runoff (Q_0, [*mm/d*]) is determined through equation [2-9]:

$$Q_0 = K_f \cdot UZ^{(1+ALFA)} \qquad [2\text{-}9]$$

in which UZ [*mm*] is the storage in the quick runoff reservoir, $ALFA$ [-] a measure for the non-linearity of the reservoir and K_f [d^{-1}] a recession coefficient. The recession coefficient is determined using $ALFA$ and two additional parameters hq [*mm/*d] and khq [d^{-1}] representing respectively a high flow rate and a recession coefficient at a corresponding reservoir volume [*mm*]. This is shown in equation [2-10]:

$$K_f = \frac{khq^{(1+ALFA)}}{hq^{ALFA}} \qquad [2\text{-}10]$$

Both additional parameters are approximated from observation data, but should be determined further during the calibration process (van der Wal, 2001).

2.4.4. Baseflow routine

The baseflow routine is the second part of the response function which transforms excess water acquired from the quick runoff routine. It represents the slowflow of the catchment through Q_0 [*mm/d*]. This is represented by equation [2-11]:

$$Q_1 = K_s \cdot LZ \qquad [2\text{-}11]$$

in which the recession coefficient K_s [d^{-1}] is the only parameter to be determined. LZ [*mm*] represents the water level in the reservoir.

2.4.5. Transformation function

The total discharge, $Q = Q_0 + Q_1$, will be routed separately for each sub-catchment through a transfer function in order to get a proper shape of the hydrograph. This transfer function is a simple filter technique with a triangular distribution of the weights, according to figure 2-4. The generated runoff of one time step is distributed on the following days using one free parameter (*MAXBAS*). A value of 1 will distribute the runoff of one day over the same day. A higher value of *MAXBAS* will distribute the runoff of one day over a larger period of time. As a result, this will lead to a delay and attenuation in the sub-catchment's discharge.

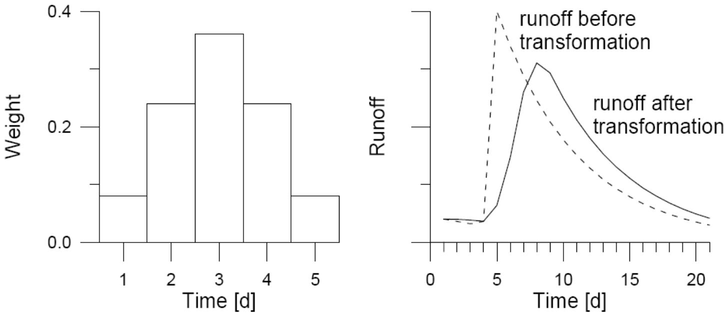


Figure 2-4. Example of the transformation function with MAXBAS = 5 (Seibert, 2002)

2.4.6. Routing routine

With the transformation function, for each sub-catchment discharge runoff will be generated. In the routing routine HBV links the sub-catchments by adding the runoff from accompanying sub-catchments to the local runoff. The inflow from another sub-catchment is assumed to flow through a river channel from the outlet of the upstream sub-catchment to the outlet of the current sub-catchment where the local runoff is added. Besides plain linkage of the sub-catchments, it is possible to delay and attenuate the water in the river channel by using the parameters *LAG* and *DAMP*. A modified version of the Muskingum equation is used for this computation (Shaw, 1994). In brief, this equation simulates the attenuation of the wave amplitude (concerning the parameter *DAMP*) and the travel time (concerning the parameter *LAG*) of the discharge through the sub-catchment.

By the parameter *LAG*, the river channel will be subdivided into a number of segments. When this parameter is an integer, each segment will refer to a delay of one day. If *DAMP* has a value of zero, the outflow from a segment equals the inflow to the same segment during the preceding time step, so that the shape of the hydrograph is not changed. If *DAMP* is not zero, the shape will be changed, as the outflow from a segment will depend on the inflow during the same time step as well as the inflow and the outflow at the preceding time step. This is shown in equation [2-12].

$$Q_{out;i} = Q_{out;(i-1)} \cdot C_1 + Q_{in;i} \cdot C_1 + Q_{in;(i-1)} \cdot C_2 \qquad [2\text{-}12]$$

where i is the current model time step and $i-1$ the previous model time step. The coefficients C_1 and C_2 are derived through equations [2-13] and [2-14].

$$C_1 = \frac{DAMP}{(1+DAMP)} \qquad [2\text{-}13]$$

$$C_2 = \frac{(1-DAMP)}{(1+DAMP)} \qquad [2\text{-}14]$$

2.4.7. Adjustments HBV-model

Since the catchments used in this study do no include any sub-catchments, the routing routine is not programmed in the FORTRAN interface. Also the transformation function is not programmed since it is expected that the response time of the runoff within the catchment elapses within a time step of one day. Furthermore K_f is directly determined in the process of calibration, thus equation [2-10] is not programmed.

3. Study area and data organization

The United Kingdom contains more than 1200 well gauged catchments and all measurements are well documented in large databases. From these extensive datasets, 61 well gauged catchments are used in this study since required hydrometric data are made available free-of-charge by PUB. The information this dataset includes consists of eleven-year records (i.e. from 01-01-1980 till 31-12-1990) of continuous daily mean streamflow [$m^3\ s^{-1}$] and daily catchment precipitation [*mm*]. In addition, because this dataset has undergone extensive analysis as reported in several publications, it is considered to be of substantial utility to PUB participants and hence for this study (Littlewood, 2004). Besides hydrometric data, also data about the characteristics of the catchments are required. This information is derived from the National River Flow Archive website which provides a module called the Catchment Spatial Information (CSI) Pages, from which spatial characteristics for around 1200 gauged catchments can be accessed (CSI, 2006). Each spatial information page features a small map showing the distribution of a given spatial dataset within a specific catchment. However, due to limitations of both datasets only 56 catchments are used in this study. Regarding one catchment, no spatial information is available at the CSI pages. The four other excluded catchments turned out to be sub-catchments of one of the 56 catchments. The remaining catchments are presented in appendix B. Furthermore, regarding the boundaries of the catchments, for England and Wales these are based on regional hydrological boundaries compiled through use of the Integrated Hydrological Digital Terrain Model (IHDTM) from the Centre for Ecology and Hydrology (CEH).

All remaining 56 catchments are situated in England and Wales, thus no catchments are located in Scotland or Northern Ireland. Nevertheless, as can be seen in figure 3-1, they are very well distributed over England and Wales. This contributes to the feasibility of generating a robust regional model due to accompanying variability of climate, topography, geology and land use. The 56 catchments cover 12.398 km^2 of a total of 151.170 km^2 which corresponds with 8,2% of the total area of England and Wales (Encarta, 2006).

3.1. Climatic data

Precipitation and temperature are by far the most important meteorological variables driving the hydrological processes in a catchment. As has been described in paragraph 2.4, precipitation is the main input in the HBV model. Temperature is another input to the model which influences the amount of potential evapotranspiration (which is also a required input) and snowmelt. Proper assessment of their distributions within the catchments is therefore a crucial step in rainfall-runoff modelling practice. Depending on the spatial distribution applied in the HBV model for the soil moisture routine, average areal input has to be defined for the whole catchment or for determined grid cells. Although distributing the soil moisture routine in grid cells can lead to a significantly better calibration of the model, it is chosen for to apply a lumped soil moisture routine since detailed information about the catchments is not available with respect to geographical location and elevation. Also the fact that just one observation station at each catchment is available underpins this choice. Concluding, it means that for every catchment average areal precipitation, temperature and potential evapotranspiration is derived as model input.

Figure 3-1. Distribution of 56 catchments

3.1.1. Precipitation

A very substantial advantage for this study is that for each catchment the daily average areal precipitation is available. In the dataset which is made available by PUB, this information is calculated for each catchment based on several observation stations. The number of minimum observation stations used for calculating average areal precipitation varies from 1 to 48. To get insight in the variability of the precipitation across the catchments, the Standard Annual Average Rainfall (*SAAR*) [*mm year*$^{-1}$] over the period 1961-1990 is shown in figure 3-2. The minimum *SAAR* holds a value of 566 mm and the maximum *SAAR* a value of 2055 mm. As can be concluded, moderate dry as well as wet catchments are considered in this study.

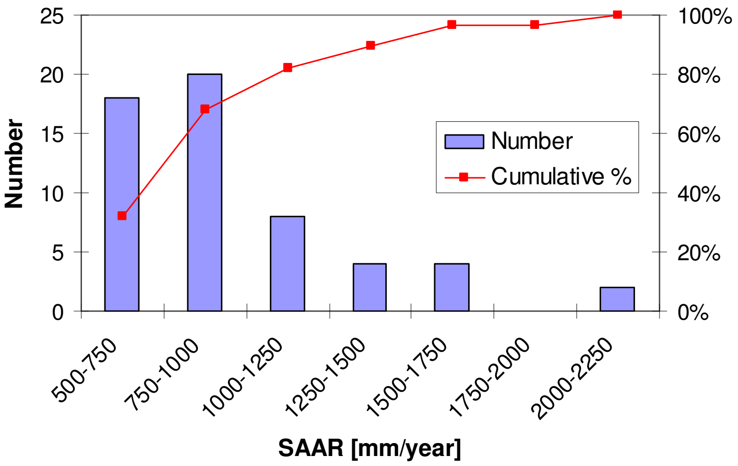


Figure 3-2. Frequency histogram and cumulative frequency distribution of SAAR

3.1.2. Temperature

With respect to actual temperature also average areal temperature for each catchment is required. The dataset provided by PUB however did not include these data. In order to do so authorization is requested at the British Atmospheric Data Centre (BADC, 2006) wherefrom the required data are gathered. The method of acquiring this average areal temperature is described in paragraph 3.1.3. In order to get insight in the variability present across the catchments, the average daily temperature (ADT) is shown in figure 3-3. The minimum ADT across the catchments holds a value of 8.3 ^{0}C and the maximum ADT a value of 11.0 ^{0}C. As can be seen, most catchments have an ADT between 10.5 ^{0}C and 11.0 ^{0}C. Furthermore, many catchments have an ADT between 9.0 ^{0}C and 9.5 ^{0}C. After analyzing the spatial distribution of these ADTs it can be concluded that the highest ADTs are situated in the southern part of England and the lowest ADTs in the northern part of England. This corresponds with the expected spatial distribution of ADT.

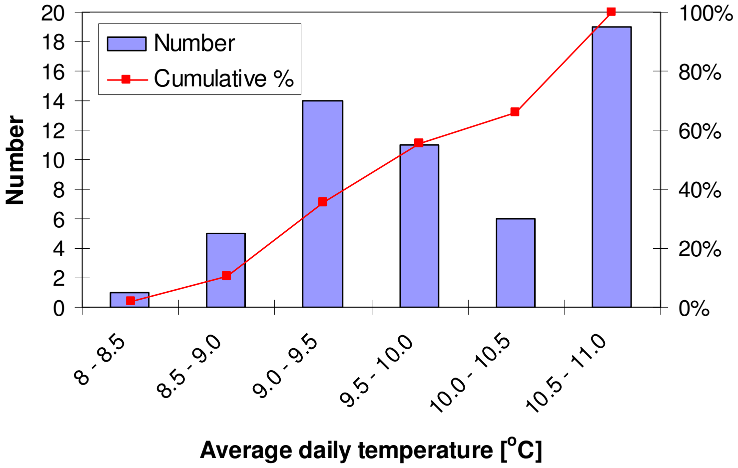


Figure 3-3. Frequency histogram and cumulative frequency distribution of average daily temperature

3.1.3. Potential evapotranspiration

Third and last necessary data input for running the model is potential evapotranspiration (PE). Just as actual temperature, no PE is included in the dataset provided by PUB. At first the intention was to derive monthly average potential evaporation from general accessible databases from the GeoNetwork opensource Community website (GNOCW, 2006) . However, the best possible spatial resolution the GeoNetwork opensource Community website (GNOCW) hold was 0.5 latitude by 0.5 longitude spacing what corresponds with about 35 kilometre spacing. The combination of spatial and temporal loss regarding the discretion of the data however did decide to improve at least one of both conditions. This since spatial and temporal loss regarding the discretion of precipitation and actual temperature are also reduced to a minimum. Therefore, the database at the British Atmospheric Data Centre (BADC) is used. Although this database does not hold calculated PE for each catchment, many observation stations contain numerous types of information required for calculating PE. Therefore this information is used to calculate the PE using the formula of Penman-Monteith. Strong bases for using this formula are that Penman carried out detailed studies in the United Kingdom in order to construct this formula and that this method is recommended for general use in the United Kingdom by the Meteorological Office (Shaw, 1994). The basic formula for calculating PE is shown in equation [3-1]:

$$PE = \frac{(\Delta / \gamma)H_T + E_{at}}{(\Delta / \gamma) + 1} \qquad [3\text{-}1]$$

With:

Δ = slope of the saturation vapour pressure against temperature [$kPa\ ^0C^{-1}$]

γ = hygrometric constant [$Pa\ ^0C^{-1}$]

H_T = available energy based on net radiation measurements [$mm\ day^{-1}$]

E_{at} = evaporation and transpiration rate as function of wind speed and saturation deficit [$mm\ day^{-1}$]

For a complete explanation of this formula, see appendix C.1.

In order to determine average areal PE four variables are required:

T_a = actual temperature [^0C]

e_d = saturated vapour pressure at dew point temperature [*mm of mercury*]

n = bright sunshine [$h\ day^{-1}$]

u_2 = wind speed at 2 meter above the surface [$miles\ day^{-1}$]

With respect to the temporal scale of the data, at first it is evaluated to use daily observations of the four variables. However, they are not available at the database of the BADC. Since hourly measurements are available, daily averages could be determined. Furthermore, instead of the saturated vapour pressure at dew point temperature, e_d, the dew point temperature, T_d, is available. Since these two variables are related, the e_d can be calculated from T_d and therefore the latter variable is used. After having decided which variables are used, the method for calculation of the average areal PE regarding the spatial scale is determined.

Since for every catchment the geographical orientation is determined by the location of the discharge observation station and as no other orientation maps are available, the daily average areal PE is gathered based on this known location. Convenience of the multiple search methods of the database of BADC is that it is possible to search for specific data within a certain radius surrounding a given location. Therefore it is chosen to apply this method and use all stations within a certain radius and calculate the mean of accompanying variables.
At first the square root of the catchment area was applied as a search radius, see equation [3-2].

$$r_a = \sqrt{A} \qquad [3.2]$$

With:

A = area per catchment [km^2]

However, in many cases no observation stations are found and if they were, most of the time the quality of the data is insufficient. Mainly the latter restriction caused that this search criterion was abandoned. Therefore, it is chosen to calculate the mean of the two nearest observation stations with sufficient quality data to determine the values for the variables.

It turned out that not all four variables are measured at the same observation stations. The bright sunshine, n, appeared to be measured solely at other observation stations. In order to gather accompanying values, at first the same search radius is applied. With this search method also no observation stations are found. It appeared that the spatial dispersion of these observation stations was bigger than those of the observation stations with the variables T_a, T_d and u_2. After analyzing the total available observation stations in England and Wales, 38 stations with sufficient quality data regarding the variable n were available at the database. Based on this conclusion, for each catchment the nearest observation station with sufficient quality data of n is chosen.

After gathered the values for the four variables, the quality of the data is analyzed. Missing and incorrect values are replaced and in what way this is performed, is described in appendix D. Furthermore it is mentioned that the average actual temperature T_a, based on averaging of the two nearest observation stations, are also solely used as input variable as described in paragraph 3.1.2. In addition an important decision is made with respect to the length of the period to be used for running the HBV model. It turned out that many data for the variables T_a, T_d and u_2 were missing for the first three years (1980 till 1982). Because of these missing values, it is chosen to adjust the period for simulating the model. Instead of starting on 01-01-1980, simulation will start on 01-01-1983. Eventually, average areal PE is calculated for each catchment. A detailed description about the determination of the appropriate dataset of the four variables, related issues and the used observation stations for averaging is given in appendix C.2.

In order to get insight in the spatial variability of PE across the catchments, the average annual PE is shown in figure 3-4. The minimum average annual PE holds a value of 569 mm whereas the maximum holds a value of 751 mm. More than 70 % of all catchments have an average annual PE between 625 and 700 mm. Because the PE is calculated, it is preferable to verify the outcome to make sure no mistakes are made during calculation. Therefore the results are visually checked based on datasets derived from the GNOCW with 0.5 latitude and 0.5 longitude spacing. After having generated a map, it was observed that nearly the same values are presented. Also many grid cells hold values between 625 and 700 mm. Furthermore some cells hold values lower than 625 mm but no higher values than 700 mm occurred. Nonetheless, it is assumed that the calculated values are applicable since the values of the GNOCW are long term annual averages from 1961 till 1990. Due to climate change it is assumed that the 8 years used for simulation in this study hold higher values than the average over period of 1961-1990. Therefore, the calculated values which are higher than the long term yearly averages from 1960 till 1990 are representatives of real world PE. For the map used in evaluating the average annual PE, see appendix E.

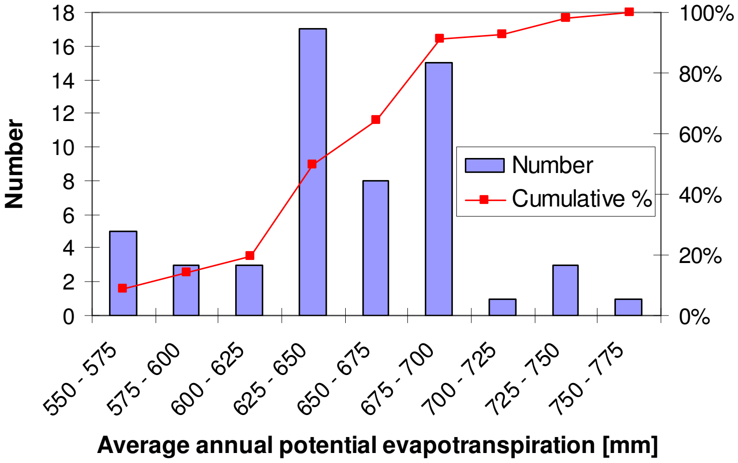


Figure 3-4. Frequency histogram and cumulative frequency distribution of average annual potential evapotranspiration

3.2. Physiographic data

3.2.1. Elevation

For each of the 56 catchments elevation data are available. These data are derived from the CEH Wallingford Integrated Hydrological Digital Terrain Model (IHDTM). It is based on a 50 m grid interval (i.e. each cell represents 50 * 50 m^2) with a 0.1 m vertical resolution. In order to get insight in the spatial variability across the catchments, the mean elevation is shown in figure 3-5. The minimum average elevation holds a value of 25.3 meter above sea level (m.a.s.l.) whereas the maximum holds a value of 430.6 m.a.s.l.. Furthermore most catchments have an average elevation between 100 and 200 m.a.s.l. although several catchments do have higher averages. These differences in average elevation of the catchments imply that the 56 catchments are characterized by different topographic structures. The maximum and minimum elevation within catchments supports this implication since the minimum elevation of a specific catchment holds a value of 2.6 m.a.s.l. whereas the maximum holds a value of 1040.0 m.a.s.l..

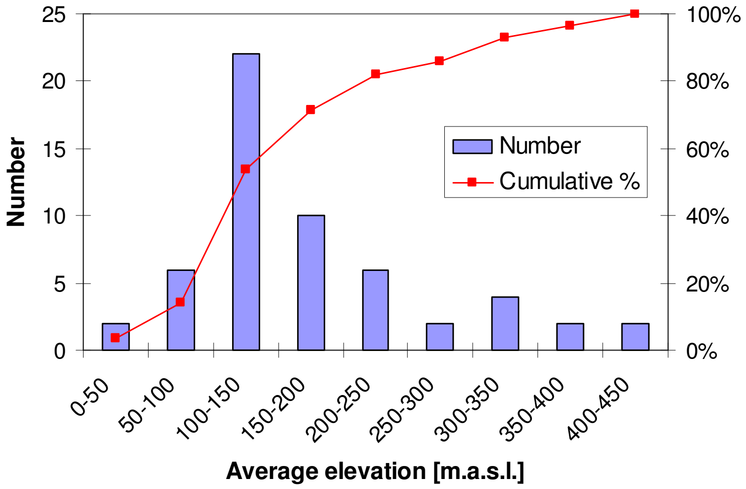


Figure 3-5. Frequency histogram and cumulative frequency distribution of average elevation

3.2.2. Catchment size

Also the distribution of the size of the catchments supports the variability. As can be seen in figure 3-6, most of the catchments have a size between 0 km^2 and 150 km^2. The smallest catchment holds a value of 24.5 km^2, whereas the largest catchment holds a value of 1480 km^2.

3.2.3. Land use

Also different land use distributions characterize the catchments, with different catchments having their own predominant land use. At the CSI pages land use maps with corresponding statistics are available which are derived from the Land Cover Map 2000 which is a part of the Countryside Survey 2000. 27 categories are distinguished which are grouped in 7 broader classes. Therefore, some catchments have a predominantly arable cover structure such as the catchments which corresponds to the observation stations 38029 – Quin @ Griggs Bridge and 36003 – Box @ Polstead. Respectively this land use accounts for 78.9% and 75.1% of the catchment area. An other catchment has for instance predominantly mountain cover structure such as the catchment which corresponds to observation station 25006 – Leven @ Leven Bridge. This land use accounts for 63.6% of the catchment area. In general, the most dominating land use present in all the catchments is grassland. The average of this land use holds a value of 42.6% whereas the largest area (i.e. 80.9%) regards to the catchment which corresponds to observation station 28008 – Dove @ Rocester Weir. In table 3-1 the averages of the 7 land use classes are shown.

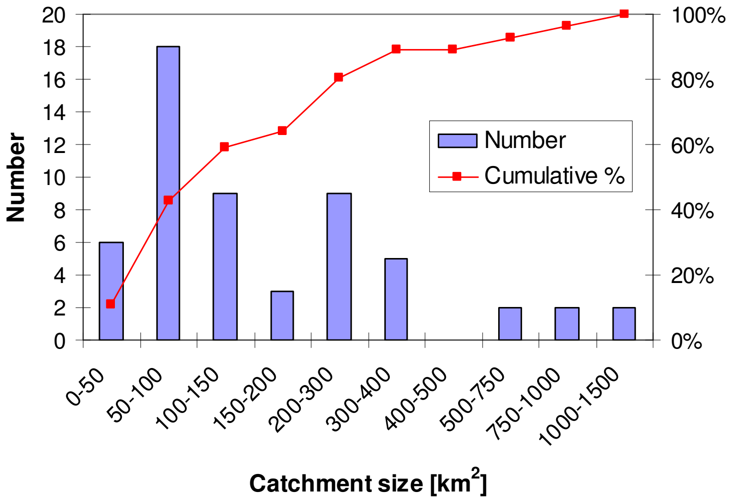


Figure 3-6. Frequency histogram and cumulative frequency distribution of catchment size

Table 3-1. Average percentage land use classes

Land use class	Average %
Woodland	13.4
Arable	30.4
Grassland	42.6
Mountain	7.1
Built-up area	6.4
Water (inland)	0.1
Coastal	0

3.2.4. Geology

The geology of the catchments used in this study also differs considerably. The CSI pages contain geological maps which are derived from the 1:625000 British Geological Survey (BGS) datasets. A dataset with hydrogeological characteristics is used and in collaboration with BGS a bespoke key has been agreed which emphasises the influence of hydrogeology on river flow behaviour. Consequently a distinction is made between permeable and impermeable bedrock and six subdivisions are presented by the CSI pages in which percentages of corresponding classes for each catchment is recorded. In general, different regions of England and Wales contain the same type of geology, thus belonging to the same subdivisions. Wales solely contain very low permeability, which is the lowest subdivision. Also the South-West of England predominantly contains this very low permeability. South England, South-East England and West England on the contrary predominantly contain the highest permeability. North-East England mainly contains a moderate permeability.

4. Process of regionalisation

4.1. Introduction

All rainfall-runoff models currently in use merely are approximations of real world hydrological processes taking place at the catchment scale and none of them are able to completely describe these actual processes, what is also the case for the HBV model. However, in order to simulate the rainfall-runoff transformation processes, values for concerning HBV model parameters have to be defined in some way. Since for the HBV model it is not possible to directly determine the model parameter values, these values are normally estimated through a model calibration process by trying to fit the model output with observed discharge data (Hundecha, 2004). However, not at every catchment well observed discharge data are available. Calibration of the model is therefore difficult and prediction of discharge regimes must be associated with high degree of uncertainty. In order to reduce the parameter uncertainty pertaining to predicting discharge regimes in ungauged catchments, a method has been utilised, called regionalisation. This method is used in this study to contribute to the objective.

Several definitions of regionalisation are used in the literature, but a generic definition as stated in Blöschl and Sivapalan (1995) is used most often: “Regionalisation is the process of transferring information from comparable catchments to the catchment of interest”. This application of regionalisation is expounded more profoundly in the following section after which the final approach which is used in this study is described.

4.2. Approach of regionalisation

The choice of catchments from which information is transferred is usually based on some sort of similarity, i.e. one tends to choose those catchments that are most similar to the one of interest. Merz and Blöschl (2004) mention 2 approaches, which are based on “similarity of spatial proximity” and “similarity of catchment characteristic”.

4.2.1. Similarity of spatial proximity

Regarding the similarity of spatial proximity, this method is based on the rationale that catchments that are close to each other will likely have a similar runoff regime since climate and catchment conditions will often only vary marginally in space. So the assumption is made that catchments are highly homogeneous with respect to topographic and climatic properties. Therefore a particular model approach and accompanying calibrated model parameter values from gauged catchments can be derived and applied at the ungauged catchments in order to predict the discharge regime. Because of this approach parameter uncertainty is reduced. An example of this approach is given by Vandewiele and Elias (1995). They used two techniques, namely the nearest neighbour technique and kriging. The first approach implies to consider gauged catchments in the immediate neighbourhood only, and to compute parameter values in the ungauged catchment as a weighted mean. The second approach implies to consider a broader neighbourhood, and apply an interpolation technique such as kriging to the region of the ungauged catchment to find model parameter values. Vandewiele and Elias (1995) stated that the kriging technique provided the significantly best model performance.

4.2.2. Similarity of catchment characteristics

With regard to the similarity of catchment characteristics, the classical approach of regionalisation consists of three steps. The first step implies calibration of the chosen model structure for a large number of catchments for which sufficiently long and informative observations of discharge regimes are available. This can be done using several criteria which are to be established. Secondly, an attempt is made to derive regression equations, which is the most commonly used method, which predicts the model parameter values using one or a combination of physical catchment characteristics (PCCs). Commonly for each model parameter a separate equation is derived. Finally, parameter values for the ungauged catchment can be estimated using the regional model, which comprehends all the established relationships between PCCs and model parameters merged in the hydrological model, and a runoff prediction can be made (Parajka et al., 2005).

Another approach with respect to similarity of catchment characteristics is introduced by Hundecha and Bárdossy (2004). This approach originated from the fact that the classical way of model calibration, as mentioned above, does not lead to a unique set of parameters when these are calibrated against the observed discharge regime. The parameters in hydrological models generally have a high degree of parameter interaction. Therefore the fitted relationships between the parameters and the PCCs tend to be rather random and the relationships would be weak. The parameters estimated in this way may not properly reflect the dependency they have with the PCCs. Thus, the parameters obtained are a single realisation among many other sets of parameters that would lead to a similar model performance. This problem is called equifinality (Beven, 1993). The new introduced approach by Hundecha and Bárdossy (2004) states that instead of calibrating the model for the individual sub-catchments separately and trying to establish a relationship between the parameters and the PCCs, the calibration process begins by first expressing the model parameters as functions of the PCCs using functions whose form is assumed a-priori. The model is then calibrated for many gauged sub-catchments simultaneously. The model calibration is performed without making any direct reference to the model parameters. Instead, the calibration yield sets of parameters that are used to relate the model parameters to the PCCs in the initially assumed function. Through this method the problem of identifying a unique optimum set of parameter values should be solved.

4.3. Selection of approach of regionalisation

Major disadvantage of the method based on spatial proximity is that it can only be applied to ungauged catchments when it is directly located next to a well gauged catchment. So, well gauged catchments in the near surroundings are required. In contrast to this approach, amenity of regionalisation based on similarity of PCCs is that it can be applied to much more regions. However, the data requirements are higher than that of the spatial proximity approach (i.e. with respect to PCCs). Nonetheless, in underdeveloped as well as well-developed regions, it is easier to gather these data than obtaining long-term discharge regimes. Since in this study the intention is to generate a robust regional model which does not depend on neighbouring homogenous catchments where calibration can take place and which is applicable in different regions, regionalisation is based on similarity of catchment characteristics.

With respect to the method of similarity of catchment characteristics, one of the two addressed approaches has to be selected. A major disadvantage of the approach of Hundecha and Bárdossy (2004) is that the a-priori selected relationships between PCCs and model parameters are required. In order to justify the a-priori relationships to be used in the model, a condition is introduced which has to be satisfied. It states that a firm basis of these relationships (i.e. between PCCs and HBV model parameters) could be found in other studies to allow application of these relationships.

Furthermore, another inherent condition has to be matched, if these a-priori relationships to be used are found. The derived relationships from other studies can not be simply used since relationships between model parameters and PCCs are a function of climate region, model structure and data aspects. Therefore, the relationships to be found should match these similar situations.

4.3.1. Selected approach of regionalisation

A profound literature study resulted in rejecting the stated condition as described in paragraph 4.3, which means that no satisfactory relationships could be found (i.e. the studies evaluated are Booij, (2005), Hundecha and Bárdossy (2004), Merz and Blöschl (2004), Seibert (1999b) and Sefton and Howarth (1998)). Furthermore, the a-priori relationships used in the study of Hundecha and Bárdossy (2004) are not satisfactory either, since they are derived based on hydrological reasoning and therefore do not satisfy the field conditions in the United Kingdom. Due to these reasons and these results, it is chosen to use the classical approach of:

- First calibrating the model structure, i.e. estimating the model parameter values;
- Secondly establishing the relationships between selected PCCs and model parameters which all together merged in the HBV model are called the regional model;
- Finally determining the model parameters at the ungauged catchment to be able to make a prediction.

4.3.2. Problems in model calibration

To be able to establish relationships between model parameters and PCCs, the model has to be calibrated against observed discharge in order to identify proper parameter values. Wheater et al. (1993) address several problems in searching the parameter space. One important result is non-uniqueness of the identified parameter sets: many combinations of parameter values provide equally good fits to the data. This is already addressed in paragraph 4.2.2 which is called the problem of equifinality. Beven (1993) stated that three causes raise this problem, which are overparameterisation of the models, data limitations and structural deficiency of the models. With respect to overparameterisation too many parameters are applied to conceptualize the processes playing a role at the catchment scale and therefore parameters cannot be uniquely identified. With respect to data limitations the transformation of input data from the measurement scale to the model grid scale is meant. The obtained data in the field often has to be aggregated in a way to correspond to the spatial scale required for the hydrological model. By structural deficiency is meant that a specific model structure conceptualizes the real world hydrological processes not exactly although it is assumed that the model structure is correct.

There have been three developments to the problem of equifinality, which are the use of parsimonious model structures, the use of multiple performance criteria which asses the goodness of fit of the observed discharge against calculated discharge and the abandonment that a unique best-fit model (i.e. an optimum parameter set) can be defined. With respect to this study the following can be stated:

- Lindström et al. (1997) evaluated the response function of the standard HBV model since it had long been felt that this function was overparameterized. As a result, they reduced the amount of parameters used. In addition Merz and Blöschl (2004) assessed the issue of over parameterization and concluded that it could not easily be reduced. Although they assessed the HBV model with respect to 308 catchments in Austria, it is assumed that for catchments in England and Wales the model is parsimonious enough. This since it is expected that variability in climate and physiography are within acceptable limits (e.g.

Austria also has a relatively wet climate). However, addressing the issue of overparameterisation is not part of the main objective of this study.

- The assumption that a unique best-fit model can be defined is maintained.
- In order to deal with the problem of equifinality and related uncertainty issues, in this study multiple objective model calibration is practised.

5. Calibration

The first step in the process of regionalisation is calibration of the catchments. In this chapter the choices, requirements en applied methodology with respect to model calibration are described. In paragraph 5.1 the selection of model parameters to be calibrated is described. In paragraph 5.2 the approach of calibration is described. The objective functions used to assess model performance are explained in paragraph 5.3. In paragraph 5.4 the methodology applied to determine the optimum parameter set is expounded. Furthermore, in the latter paragraph the requirements for proper model calibration by the proposed methodology are described. At the end of paragraph 5.5 a short description of model sensitivity is given.

5.1. Feasible model parameters

As has been stated in paragraph 4.3.2 the HBV model is considered to be a parsimonious model although the model still contains more than 30 tuneable parameters. When trying to establish relationships between the model parameters and the PCCs not every parameter should be used. Basic assumption underlying application of successful regionalization is that well identifiable parameters should be used. When all parameters would be involved in establishing relationships, it will be difficult to derive significant statistical relationships (Wagener et al., 2004). Therefore it is important to determine the most sensible model parameters to be incorporate in the process of regionalization. In order to determine these parameters, first the hydrological processes which should be incorporated in the process of regionalization are appointed. Hereafter the parameters used for regionalisation are selected.

5.1.1. Identifying hydrological processes

In this study, the objective is to establish relationships between model parameters and physical catchment characteristics with respect to continuous discharge regime. Since the intention is to generate a robust regional model, the hydrological processes which are considered must concern all the different aspects of the hydrograph and not merely those processes which exert influence on peak flows or low flows. The processes considered are the latter three which are addressed in paragraph 2.1.2. These are the overland flow, throughflow and the groundwater flow. Since the model conceptualizes these processes the specific HBV model routines are appointed. It turns out that the soil moisture routine, the quick runoff routine and the base flow routine conceptualize these processes. The latter two actually incorporate the rainfall-runoff processes. The first routine influences the quick runoff routine and base flow routine. Which of these routines are related to which processes is described below.

- The Horton overland flow, saturation overland flow, the macro pore flow and the perched subsurface flow are quick runoff processes and are conceptualized in HBV by the quick runoff routine;
- The unsaturated subsurface flow, the rapid groundwater flow and the delayed groundwater flow are slow runoff processes and are conceptualized in HBV by the base flow routine.

5.1.2. Selection of parameters

After the identification of the relevant hydrological processes, the parameters for calibrating the model and hence, establishing the regional model, are determined. All parameters pertaining to

the routines do not contribute to the same degree in reproducing the natural rainfall-runoff process. When the most sensitive parameters are used, a chance is offered to develop sensible relationships between parameters and PCCs.
In other studies much experience is gained in demonstrating the most sensitive parameters and these studies are used to select the parameters to be used in this study. However, one should bear in mind that the different studies could address other aspects of the hydrograph. Furthermore different versions of the HBV model are used in the studies since Lindström et al. (1997) modified the standard version of HBV into the HBV-96 version. Adjustments were made with respect to the response function which controls the dynamics of the generated runoff. Two recession components and a threshold value are replaced by a non-linear drainage equation as addressed in paragraph 2.4.3 by equation [2-9].

The studies used to determine the parameters to be calibrated in this study are Harlin and Kung (1992), Lidén and Harlin (2000), Merz and Blöschl (2004) and Seibert (1999b). The following parameters, which relate to the routines, are selected:

- The soil moisture routine incorporates the parameters *FC, LP* and *BETA;*
- The quick runoff routine incorporates the parameters *ALFA* and K_f and *PERC;*
- The baseflow routine incorporates the parameter K_s.

Thus, in total seven parameters are selected to be used in this study. In what way the remaining model parameters are dealt with, is described in paragraph 5.4.6.

5.2. Approach of calibration

5.2.1. Different approaches

Three approaches of calibrating the model in order to identify the optimum parameter set are addressed in literature, namely through manual calibration, automatic calibration and calibration through Monte Carlo simulation (Lidén and Harlin, 2000).

Manual
When calibrating the model manually, the user adjusts the parameters interactively in successive model simulations. Advantage of this approach is the dependency of the user, since it builds on accumulated experience and only intelligent steps through the parameter space will be made. For example, Lidén and Harlin (2000) demonstrated a better model performance over the validation period when manual calibration took place for a dry catchment instead of automatic calibration. However, this dependency on the user can be seen as a weakness, since the process is subjective and the parameters derived may be prone to bias. There is also no clear point at which the calibration process can be said to be completed. Furthermore, manual calibration may be a very time-consuming task, especially for an inexperienced hydrologist (Wagener et al., 2004).

Automatic
Due to the fact that manual calibration is a tedious procedure and requires extensive knowledge about the model structure and parameters, different results are obtained by different hydrologists. Therefore the quality of calibration often is closely related to the skill of the hydrologist. To overcome this feature, automatic calibration schemes have been pursued. For example Bergström (1976) and Gupta and Sorooshian (1985) contributed to the development of such calibration schemes. With regard to HBV, Harlin (1991) developed an automatic calibration scheme (Zhang and Lindström, 1997). Thus, in automatic calibration parameters are adjusted automatically according to a specified search algorithm and numerical measures (i.e. criteria) of the goodness of

fit. As compared to manual calibration, automatic calibration is fast, and the confidence of the model simulations can be explicitly stated (Madsen, 2000).

Monte Carlo simulation
Monte Carlo simulation (MCS) is a technique where through numerous model simulations, by generating parameter values randomly a best objective function value is sought. To be able to perform simulations, for all model parameters a parameter space has to be determined through defining a lower and upper boundary value. Harlin and Kung (1992) for instance applied MCS for the HBV model in order to generate parameter sets of different levels of uncertainty. Seibert (1999b) used MCS to calibrate the model and for each catchment 300.000 parameter sets were generated using random numbers from a uniform distribution within the parameter space.

5.2.2. Selected approach of calibration

Since the intention of this study is not to optimally calibrate the local model, but to establish a robust regional model, writing the algorithm for automatic calibration is estimated to be too time-consuming. Manual calibration on the contrary is also very time-consuming, in particularly given the large number of catchments used. Besides, determining the optimum parameter set will be based on the experience of the hydrologist and it is not in a structural way. Therefore, MCS will be applied in order to select the optimum parameter set based on the objective function. The way MCS is applied is described in paragraph 5.4.

5.3. Objective function

In order to define the values of the parameters to be used in hydrological models, the parameters are calibrated against observed discharges whereby the model parameters are adjusted until the observed natural system output and the model output show an acceptable level of agreement. This goodness of fit is always evaluated by an objective function.

5.3.1. Single objective function

Of importance when selecting an appropriate single objective function (SOF), is the objective of the comparison. As already stated in paragraph 5.1.1, the objective regards to the continuous discharge regime. Therefore the SOFs to be selected should concern the different aspects of the hydrograph. Madsen (2000) stated that the following objectives should be considered and that they have to be assessed through SOFs. This corresponds with the intention of this study, and the objectives stated by Madsen (2000) are:

1. A good agreement between the average simulated and observed catchment runoff volume (i.e. a good water balance);
2. A good overall agreement of the shape of the hydrograph;
3. A good agreement of the peak flows with respect to timing, rate and volume;
4. A good agreement for low flows.

However, using too many SOFs can lead to assessment of equal aspects of the hydrograph, which will give concerning aspect too much influence. Therefore, for all aspects of the hydrograph one SOF is selected. With respect to objective 1 (i.e. good water balance) the SOF RV_E is selected which stands for the relative volume error. This SOF is shown in equation [5-1].

$$RV_E = \left(\frac{\sum_{i=1}^{nr} Q_{sim,i} - \sum_{i=1}^{nr} Q_{obs,i}}{\sum_{i=1}^{nr} Q_{obs,i}} \right) \cdot 100\% \qquad [5\text{-}1]$$

where Q_{sim} stands for simulated flow, Q_{obs} for observed flow, *i* for the time step and *nr* for the total number of time steps used during calibration. This SOF can vary between ∞ and - ∞ but performs best when a value of 0 is generated since no difference between simulated and observed discharge occurs. However, at the same time the temporal distribution of the discharge throughout the calibration period can be completely wrong. Therefore, this SOF should always be used in combination with other SOFs.

Regarding objective 2 (i.e. good overall agreement of the shape of the hydrograph) the Nash-Sutcliffe coefficient is selected instead of the also commonly used overall root mean square error (RMSE). This due to the fact that the Nash-Sutcliffe coefficient is the most widely used SOF in rainfall-runoff modelling, thus preferred above the RMSE. Furthermore, the RMSE is an absolute measure of error where the largest deviations between observed and calculated discharge contribute most. Therefore this SOF does not evaluate the corresponding objective as good as the Nash-Sutcliffe coefficient, also since the latter SOF is normalised with respect to the variance of the observed discharge regime. The Nash-Sutcliffe coefficient, R^2, is shown in equation [5-2].

$$R^2 = 1 - \frac{\sum_{i=1}^{nr} \left(Q_{sim,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{nr} \left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \qquad [5\text{-}2]$$

where Q_{sim} stands for simulated flow, Q_{obs} for observed flow, $\overline{Q_{obs}}$ for the mean of observed flow, *i* for the time step and *nr* for the total number of time steps used during calibration. This SOF can vary between 1 and - ∞ and performs best when a value of 1 is generated. Besides, due to frequent use of this SOF, it is known that when values between 0,6 and 0,8 are generated, the model performs reasonably well. Values between 0,8 and 0,9 indicate that the model performs very good and values between 0,9 and 1 indicate that the model performs extremely well.

With respect to objective 3 and 4 (i.e. good agreement of the low and high flows with respect to timing, rate and volume) several SOFs are used in the literature. Arends (2005) examined many appropriate SOFs for low flow modelling of the Meuse. With respect to objective 4, Arends (2005) addressed two possible SOFs which are the empirical coefficient of correlation and the Nash-Sutcliffe coefficient, both applied when a given threshold value is crossed. The study concluded that due to the fact that the empirical coefficient of correlation ignores relative and absolute, structural errors in the dataset, the Nash-Sutcliffe coefficient for low flows evaluates the low flows at best. Also the fact that receiving a high correlation coefficient does not implicitly state that a good model performance is derived, favours the Nash-Sutcliffe coefficient for low flows. Concluding, the Nash-Sutcliffe coefficient is applied for both the high as the low flow SOF. The high flow SOF, R_H^2, is shown in equation [5-3] and the low flow SOF, R_L^2, is shown in equation [5-4].

$$R_H{}^2 = 1 - \frac{\sum_{i=1}^{nr} {}_{Q_{obs,i} \geq Q_{Threshold,i}} \left(Q_{sim,i} - Q_{obs,i}\right)^2}{\sum_{i=1}^{nr} {}_{Q_{obs,i} \geq Q_{Threshold,i}} \left(Q_{obs,i} - \overline{Q_{obs;Q_{obs,i} \geq Q_{Threshold,i}}}\right)^2} \qquad [5\text{-}3]$$

where Q_{sim} stands for simulated flow, Q_{obs} for observed flow, $\overline{Q_{obs;Q_{obs,i} \geq Q_{Threshold,i}}}$ is a condition which implies the mean of observed flow above the given threshold value $Q_{Threshold}$, *i* for the time step and *nr* for the total number of time steps used during calibration. This SOF can vary between 1 and - ∞ and performs best when a value of 1 is generated.

$$R_L{}^2 = 1 - \frac{\sum_{i=1}^{nr} {}_{Q_{obs} \leq Q_{Threshold}} \left(Q_{sim,i} - Q_{obs,i} \right)^2}{\sum_{i=1}^{nr} {}_{Q_{obs} \leq Q_{Threshold}} \left(Q_{obs,i} - \overline{Q_{obs;Q_{obs} \leq Q_{Threshold}}} \right)^2} \tag{5-4}$$

where Q_{sim} stands for simulated flow, Q_{obs} for observed flow, $\overline{Q_{obs;Q_{obs,i} \leq Q_{Threshold,i}}}$ is a condition which implies the mean of observed flow under the given threshold value $Q_{Threshold}$, i for the time step and nr for the total number of time steps used during calibration. This SOF can vary between 1 and - ∞ and performs best when a value of 1 is generated.

5.3.2. Multiple objective function

Besides selecting the appropriate SOFs to be used in the objective function, also the composition of the objective function is of importance. In this respect it is important to note that, in general, trade-offs exist between the different objectives. For instance, one may find a set of parameters that provide a very good simulation of peak flows but a poor simulation of low flows, and vice versa. Since the intention of this study is to establish a regional model which simulates at the ungauged catchment as best as possible with respect to all the objectives, this trade-off should implicitly dealt with in the objective function in order to determine the optimum parameter set. Normally, this is established through usage of a multiple objective function (MOF). When solving the MOF, it usually is transformed into a single objective optimisation problem by defining a scalar which aggregates the various SOFs based on the hydrologist's insight (Madsen, 2000). In this study also a scalar is applied but no difference is made between the four SOFs. Hence, each objective contributes equally with respect to determining the optimum parameter set which underpins the intention of calibrating the catchments robustly. In order to determine the optimum parameter set, a method which combines the MOF and the MCS is assembled for this study.

5.4. Methodology Monte Carlo Simulation

5.4.1. Composition of multiple objective function

As said in previous paragraph 5.3.2 all four objectives are incorporated in the MOF. To evaluate which parameter set performs best over the four selected SOFs, it is chosen for to scale each SOF value over their own range determined by the values generated through 10000 calibration runs (this latter issue is addressed in paragraph 5.4.3). Thus, each calibration run generates four value for the four SOFs and each SOF value is scaled based on these generated values.

For the SOFs R^2, $R_H{}^2$ and $R_L{}^2$ the maximum value and the value belonging to the 1000th best calibration run are selected. It is chosen for to select the 1000th best calibration run since some randomly selected parameter sets generate extreme values (i.e. outliers) which disturb the scaling when the minimum and maximum value are chosen (i.e. more focus is put on the SOF RV_E since it did not generate similar extreme outliers). Thus, by scaling between the maximum value which receives a scalar of 1, and the 1000th best value, the 1000th best parameter set receives a scalar of 0. So SOF values worse than the 1000th best SOF value receive scalar values lower than 0. The equation used for deriving the scaled values (C_s) of the SOFs R^2, $R_H{}^2$ and $R_L{}^2$ is shown in equation [5-5].

$$C_{s,k,j,m} = \frac{C_{k,j,m} - C_{k,j,m1000}}{\max\left(C_{k,j,mtot}\right) - C_{k,j,m1000}} \tag{5-5}$$

where *C* stands for the value of the SOF, *k* for which SOF, *j* for the specific catchment, *m* for the calibration run number, *m1000* for the 1000th best SOF and *mtot* for all the 10000 calibration runs.

With respect to the SOF RV_E positive values as well as negative values can occur. Since this SOF performs best at a value of 0, the scaled SOF value is determined through equation [5-6].

$$C_{s,RVe,j,m} = 1 - \left(\frac{\left|C_{RVe,j,m}\right| - \min\left|C_{RVe,j,mtot}\right|}{\left|C_{RVe,j,m1000}\right| - \min\left|C_{RVe,j,mtot}\right|} \right) \qquad [5\text{-}6]$$

where *C* stands for the value of the SOF RV_E, *j* for the specific catchment, *m1000* for the 1000th best absolute value of the SOF, *m* for the calibration run number and *mtot* for all the 10000 calibration runs.

The essence of the scaling is to be able to assess each of the scaled SOF values with respect to the other three scaled SOF values. After having scaled all four SOFs, for each calibration run the lowest value of the four SOFs is selected (*C'*). This is shown in equation [5-7].

$$C'_{j,m} = Min\left\{C_{s,R^2,j,m}, C_{s,R_H^2,j,m}, C_{s,R_L^2,j,m}, C_{s.R_{VE},j,m}\right\} \qquad [5\text{-}7]$$

where C_s stands for the scaled value of the SOF, *j* for the specific catchment and *m* for the calibration run number.

While selecting the lowest value of the scaled SOFs for each catchment and for each run, the concerning SOF is decisive for the outcome of the total model performance for that specific run number. Eventually the optimum parameter set for each catchment is determined by selecting the highest value of all decisive values as determined through equation [5-7]. Thus, the parameter set which performs best considering all four SOFs (C_{opt}) is selected and this is shown in equation [5-8].

$$C_{opt,j} = Max\left\{C'_{j,1}, C'_{j,2}, C'_{j,3}, \ldots, C'_{j,mtot}\right\} \qquad [5\text{-}8]$$

where *C'* stands for the decisive scaled value of the four SOFs, *j* for the specific catchment and *mtot* for all the 10000 calibration runs.

5.4.2. Feasible parameter space

In order to determine values for the SOFs, the MCS requires a feasible parameter space from which parameter values are generated on which the HBV model is simulated. The model parameters for which the feasible parameter space is determined, are those selected in paragraph 5.1.2. Different statistical distributions can be applied in order to select the parameter value. Since it is not known for which values of the parameters within the parameter space the model performs best, it is chosen for to apply a uniform distribution from which parameter values are selected randomly. When determining the feasible parameter space, two conditions are taken into consideration. Firstly, it can be determined by physical and mathematical constraints, for example a parameter can have a minimum of zero or a maximum dictated by a physical law or process. Secondly, prior knowledge about the model behaviour can help determining the parameter space (e.g. the model acts unrealistic when the model parameter *ALFA* has a value higher than 3.0). When establishing the parameter space, these conditions are taken into consideration. Furthermore, the parameter spaces as used in other studies with respect to the HBV model are evaluated. Booij (2005) summarized these studies and this is shown in table 5.1.

As shown, for several studies a parameter range is given. This is the parameter range these studies used for determining their optimal parameter set. The initial parameter space used for this study is chosen by selecting the minimum and maximum values for each parameter and reflect them against former stated conditions. As a result, for every catchment the minimum and maximum parameter values are initially used with the following exceptions. With respect to *FC* the minimum value is fixed to 125 mm, since it is assumed that lower values will not occur in the selected catchments. With respect to *PERC,* values higher than 2.5 are assumed not to be realistic for the used catchments. Concerning the parameters *LP* and *ALFA* the lower value is adjusted to 0.1. Also for the parameter *BETA* the upper maximum value is adjusted since it is not expected these values to occur. The parameter space selected is shown in table 5-2.

Table 5-1. Evaluated parameter space (Booij, 2005)

Reference	**Region**	**FC**	**LP**	**BETA**	**ALFA**	**K_s**	**PERC**
		[*mm*]	[-]	[-]	[-]	[day^{-1}]	[$mm\ day^{-1}$]
Bergström (1990)	Sweden	100-300	0.50-1.0	1.0-4.0	-	-	-
Booij (2005)	Meuse	100-660	0.2-0.8	1.0-3.0	0.1-1.9	-	-
Default HBV96	-	200	0.9	2.0	1.0	-	-
Diermanse (2001)	Mosel, Germany	0-580	0.80	3.0	-	0.01	0.6
Harlin and Kung (1992)	Sweden	50-274	0.73-1.0	1.0-5.9	-	0.008-0.05	0.6-2.1
Killingtveit and Sælthun (1995)	Various	75-300	0.7-1.0	1.0-4.0	-	0.0005-0.002	0.6-1.0
Lidén and Harlin (2000)	Various	400-800	0.50-1.0	1-6	0-3	0.0005-0.1	0.2-5
Seibert (1999b)	Sweden	50-500	0.30-1.0	1.0-6.0	-	0.001-0.15	0.0-6.0
Velner (2000)	Ourthe, Belgium	180	0.66	1.8	1.1	0.023	0.4

Table 5-2. Initially used parameter space

Reference	**FC**	**LP**	**BETA**	**ALFA**	**K_f**	**K_s**	**PERC**
	[*mm*]	[-]	[-]	[-]	[day^{-1}]	[day^{-1}]	[$mm\ day^{-1}$]
Minimum value	125	0.1	1	0.1	0.0005	0.0005	0.1
Maximum value	800	1	4	3	0.15	0.15	2.5

5.4.3. Number of calibration runs

As described in previous paragraph 5.4.2 a feasible parameter space is determined from which parameter values are randomly generated. Besides determining this feasible parameter range, it also is required to make a sufficient number of runs in order to be sure the entire range is examined and as Harlin and Kung (1992) stated, to permit statistical treatment of the results. They stated that when the mean of the selected SOF for a specific number of runs shows stability, thus not varying anymore, it can be stated that the parameter space is well examined. For all catchments, after every run the mean is plotted for the four SOFs and it is evaluated if the mean still varies. In figure 5-1 an example is shown for catchment 25005 – Leven @ Leven Bridge. It can be concluded that after 3000 runs for the four SOFs the mean does not vary any more. Thus when applying more than 3000 runs it is justifiable to permit statistical treatment of the results. Due to the progress in programming at the time of examining this subject, it was more convenient to use the preliminary chosen number of runs. Thus, in total 10000 runs are made over the complete data period from 01-01-1983 till 31-12-1990 in order to determine the optimum parameter set for each catchment.

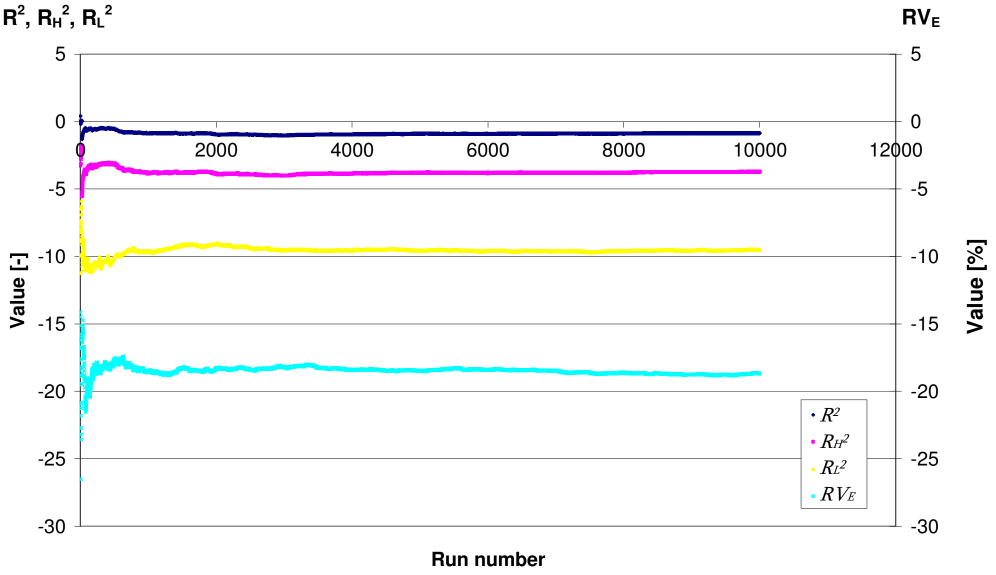


Figure 5-1. Mean of the four SOFs plotted after each run for catchment 25005 - Leven @ Leven Bridge

5.4.4. Critical threshold

With respect to the low and high flow SOFs, a threshold value has to be determined. Since each of the catchments' main branch has a different function (e.g. shipping, cooling-water, recreation) no general value is determined. Hence, the flow-duration curve is used to determine accompanying value which is based on the observed discharge regime. The threshold values are determined for each catchment separately based on the length of the used observed discharge regime (i.e. 8 years from 01-01-1983 till 31-12-1990). With respect to high discharge, it is of importance to assess the performance of those time steps where extreme discharges occur. Therefore the 5-percentile exceeding-chance is selected. With respect to the low discharge, it is of importance to assess those time steps which in long term can lead to difficulties for concerning function of the main branch. Therefore the 90-percentile exceeding-chance is selected.

5.4.5. Moving average

When simulating the rainfall-runoff processes regarding low flow, it is of importance that the long-term influence of discharge is evaluated. Thus, concerning SOF should not emphasize on assessing the small fluctuations during dry spells, but the long term general low flow. The SOF R_L^2 as described by equation 5-4 however evaluates the difference between observed and calculated discharge of specific individual days. In order to evaluate the long-term general low flow and increase the effectiveness of the SOF, a moving average is applied. The number of time steps (i.e. days) the moving average window is applied to is 51 days. This number of time steps used is determined in the study of Arends (2005) which assessed the Meuse catchment. Since this catchment has different hydrologic and physiographic conditions it is preferred to apply a sensitivity analysis. However it is assumed that this number of days also leads to an increase of effectiveness of the SOF and therefore it is applied. Thus, no sensitivity study regarding the number of days is carried out. With respect to the high flow SOF, R_H^2, also a moving average is applied. In contrast to the low flow SOF, a small amount of days is used since for instance the timing of the model and the value for concerning peak discharge are of importance. Again the number of days to be used is based on the study of Arends (2005). The number of time steps (i.e. days) the moving average window is applied to is 7 and again no sensitivity analysis is carried out.

5.4.6. Initial conditions

Before simulating and subsequently evaluating the model, several initial conditions have to be ascribed. With respect to the HBV model, for the remaining required model parameters (i.e. all used parameters without the seven selected parameters as described in paragraph 5.1.2) a constant value has to be assigned such as an evapotranspiration and temperature correction factor for elevation and a threshold value for temperature under which precipitation evolves in snow. The values used in this study are shown in appendix F. Besides, initial conditions for the reservoirs present in the precipitation accounting routine, the soil moisture routine, the quick runoff routine and base flow routine have to be assigned. For the reservoirs present in the precipitation accounting routine, values of zero are applied. For the volume of the soil moisture reservoir, a value of 125 mm is assigned. This is based on the minimum value used in the parameter space which is addressed in paragraph 5.4.2 since higher values leads to termination of the model simulation. For the quick runoff reservoir and the base flow reservoir it is chosen to assign a value which holds 10% of the value applied in the soil moisture reservoir. Thus, a value of 12,5 mm. This is based on the average difference between these reservoirs as applied in the study of Booij (2005).

5.4.7. Calculation of the SOFs

As addressed in paragraph 5.4.6, the initial conditions are experimentally determined. While at the start of the simulation these conditions can be totally wrong, it is likely that large negative influences on the SOFs are generated. As addressed in the literature by Merz and Blöschl (2004), it favours to assign a warm-up period. However, since no data are available before the addressed period in order to determine a correct initial state, it is chosen for to start the calculation of the SOFs at a later time step. Due to the fact that in the summer period no extreme precipitation, thus no extreme discharge occurs, the model reaches its steady state mode. Only the reservoir present in the base flow routine in general produces runoff. Therefore it is chosen for to start calculation of the SOFs at the 31st of August 1983. Besides, this also is considered as the start of the hydrological year in the United Kingdom.

5.4.8. Selection conditions for to be used catchments

In order to assess the calibration results and to determine if catchments are used for regionalisation, two conditions are introduced. These conditions are based on the absolute values of the SOFs R^2 and RV_E. This due to the fact that through multiple usage of these SOFs in the literature some qualitative judgment can be drawn based on their values. Based on the authors' insight, the following two conditions are introduced:

- Regarding the SOF R^2 catchments with values higher than 0.75 are accepted.
- Regarding the SOF RV_E catchments with values between -5 % and 5 % are accepted.

Both conditions have to be satisfied in order to accept the catchment to be used for establishing relationships.

5.5. Model parameter sensitivity

In order to gain insight in the behaviour of the model with respect to model outcome (i.e. the hydrograph) a brief sensitivity analysis is performed with the selected model parameters. Each of the seven model parameters contribute to conceptualizing the rainfall-runoff processes which all together affect the simulated hydrograph. When changing one of the model parameters the hydrograph therefore changes. However, not every model parameter initiates the same change of the hydrograph. When trying to establish relationships between model parameters and PCCs, it is most effective to investigate the most sensitive model parameters. Furthermore, it is useful to understand the influence of change in model parameter values on the hydrograph when evaluating the relationships. An extended description of this brief sensitivity analysis is presented in appendix G.

Concluding from appendix G, it can be stated that *ALFA, LP,* K_f and *PERC* are the most sensitive model parameters. *ALFA* and K_f cause the total hydrograph to change. *LP* influences the hydrograph in summer periods at most when actual evapotranspiration is at its highest. *PERC* also affects the whole hydrograph where it in general levels off the differences between quick and slow flows as addressed in figure G-7 in appendix G. *BETA* also is relative sensitive, at most after dry spells when the system reached steady state. This also concerns to *FC* which influences the peak discharge the most when a contrasting value is applied. K_s on the contrary is not sensitive. Large differences in this parameter value do not change the hydrograph significantly.

In several other studies also sensitivity analysis is applied. In this study an evaluation in comparison to the study of Hundecha and Bárdossy (2004) is made since their study specifically addressed parameter sensitivity for the parameters also used in this study. For the sensitivity of the model parameters from the study of Hundecha and Bárdossy (2004) see table J-2 in appendix J. When evaluating their table of model parameter sensitivity it can be stated that in both studies the parameters *ALFA,* K_f and *PERC* are the most sensitive. Also the fact that *BETA* and K_s are relatively sensitive is consistent. However, in this study it indicates that K_s is not sensitive at all. The most contradictive finding is that in this study *LP* is supposed to be very sensitive whereas in the study of Hundecha and Bárdossy (2004) this parameter turned out to be the least sensitive. Furthermore in Hundecha and Bárdossy (2004) *FC* turned out to be very sensitive whereas in this study it is indicated to be moderate sensitive.

6. Establishing the regional model

The second phase of the process of regionalisation consists of establishing the relationships between the model parameters and the physical catchment characteristics. All these relationships together merged in the HBV model is called the regional model. In this chapter the method of establishing these relationships is described. In paragraph 6.1 the method of selecting the PCCs as well as the selected PCCs are described. In paragraph 6.2 the approach of establishing the relationships is described i.e. by applying regression analysis. In what order the regression analysis is performed is described in paragraph 6.3.

6.1. Physical catchment characteristics

To derive statistically relevant relationships between the selected model parameters and PCCs, a large number of well gauged and distributed catchments with good quality data are required. In chapter 3 the climatic as well as the physiographic variability is demonstrated. Additionally through analysis of the climatic data, the quality of these data also are guaranteed which is addressed in appendix D. This also accounts for the physiographic data since the CEH, which is a renowned research council, supervises these datasets which are compounded based on several acknowledged applications and surveys (e.g. the IHDTM, BGS and LCM2000). However, in order to select the PCCs which have to be derived from this dataset, a good evaluation of PCCs should be carried out. First the method of selecting appropriate PCCs is determined. Subsequently the PCCs are selected and described.

6.1.1. Method of selecting physical catchment characteristics

Wagener et al. (2004) state, since there is no established theory to relate PCCs and model parameters, a trial-and-error approach normally is adopted in which a wide range of available PCCs is considered initially. Furthermore they advise to analyze the initial selected PCCs based on statistical analyses and hydrological reasoning in order to determine feasible PCCs. Not all of the initially selected PCCs should be used due to the fact that some PCCs could be highly correlated and therefore convey similar information. When establishing statistical relationships between model parameters and PCCs, ideally the PCCs should not have any correlation with each other. A generally used method to asses such correlation and determine the feasible PCCs is through correlation analysis. A second approach to reduce the amount of PCCs is through applying a principal component analysis. A principal component analysis deals with the transformation of an existing dataset into new uncorrelated variables using the covariance matrix of the original data. Sefton and Howarth (1998) for instance used this approach to derive new variables such as topography and soils / geology from the initial set of PCCs. Disadvantage of this latter approach is that the newly derived variables reduce the ease with which regional relationships can be interpreted from the hydrological perspective. Another more pragmatic option is to evaluate those PCCs used in other studies and select the PCCs based on hydrological insight, thus inherently the correlation between the PCCs is assessed. In the context of the total extent of this study, the latter more pragmatic approach is applied.

With respect to the pragmatic approach, two approaches are pursued in order to select the appropriate PCCs. One implies evaluating studies where the HBV model already is regionalized independent from the geographical location of the catchments used. The second approach implies studies where catchments in the United Kingdom are regionalized independent from the hydrological model used. However, the essence of the latter approach is to get insight in what kind of PCCs are used in catchments in the United Kingdom. In addition at the same time demonstrated relationships between model parameters and PCCs are evaluated. This contributed to gathering insight in hydrological behaviour of the model (for this part also the study of Booij (2005) is used). In addition, this assessment lies on the basis for selecting the chosen approach of regionalisation as addressed in paragraph 4.3. Eventually the selected PCCs are evaluated with respect to their availability.

6.1.2. Selected physical catchment characteristics

According to Kokkonen et al. (2003) an excess of different PCCs are used in literature in search for relations between the hydrological response of a catchment and some observable PCCs. Nonetheless, the study stated that PCCs can be crudely classified into eight groups, which are dimension of the catchment, shape, topography, geology and soil, stream network structure, vegetation, land use and climate. However, there is some redundancy of this classification, in the sense that many attributes could be placed under more than one group. Therefore it is not necessary that from every group PCCs are selected. This classification is used in order to summarize the PCCs used in the evaluated studies.

The studies assessed for appropriate PCCs are Hundecha and Bárdossy (2004), Merz and Blöschl (2004), Seibert (1999b) and Sefton and Howarth (1998). The first three studies regionalized the HBV model against catchments at a different geographical location than England and Wales. Hundecha and Bárdossy (2004) used 30 sub-catchments which are part of the Rhine catchment situated downstream of Maxau and upstream of Lobith, Merz and Blöschl (2004) used 308 catchments in Austria and Seibert (1999b) used 11 catchments in central Sweden. Sefton and Howarth (1998) regionalized the conceptual, hydrological IHACRES model against 60 catchments in England and Wales. The PCCs used in these studies are shown in table H-1, appendix H. One important condition for assembling this table is the presupposition of the ungauged catchments. Sefton and Howarth (1998) used several PCCs which are based on flow conditions from gauged catchments. These PCCs are determined in the study for low flow estimation in the United Kingdom compounded by the Institute of Hydrology (Gustard et al., 1992). Though, when establishing relationships with these PCCs and making discharge predictions at ungauged catchments, these PCCs can not be derived. Therefore, these PCCs are not added to the table. Furthermore, for two of the groups no PCCs are used which are the group of vegetation and the group of stream network structure. Finally the PCCs are evaluated and the selected ones are shown in table 6-1 with the condition of the presupposition of the ungauged catchments as well as the availability of the PCCs. In total 14 PCC are selected. Below a description is given for each PCC or group of PCCs.

AREA

For each of the catchments the size is available. Since in the study of Booij (2005) the size of the catchment is related to model parameter *BETA* it is also used in this study as a PCC. Also Seibert (1999b) demonstrated a relation between this model parameter and this PCC. What kind of relation is expected is not obvious since Seibert (1999b) positively related *BETA* against *AREA* while Booij (2005) negatively related *BETA* against *AREA*.

Table 6-1. Selected PCCs to be used in this study

Group	**Parameter**	**Physical catchment characteristic**
Dimension	*AREA*	Catchment size [km2]
Topography	*ELEVATION*	Elevation [m.a.s.l.]
	HI	Hypsometric integral [-]
Shape	*SHAPE*	Catchment shape [-]
Land use	*WOOD*	Woodland [%]
	ARABLE	Arable & horticulture [%]
	GRASS	Grassland [%]
	MOUNTAIN	Mountain, heath & bog [%]
	URBAN	Built-up areas [%]
Geology and soils	*HIGHP*	High permeability [%]
	MODERATEP	Moderate permeability [%]
	LOWP	Very low permeability [%]
	MIXEDP	Mixed permeability [%]
Climatic	*SAAR*	Standard annual average rainfall [mm]

ELEVATION

For each catchment the average elevation is available and since this catchment characteristic is used in the assessed studies, it is also used in this study. However, one should be aware of interdependencies between PCCs as stated in Sefton and Howarth (1998). They proved that in catchments in England and Wales, elevation was highly correlated with slope. Thus, caution is necessary when significant relationships between a certain parameter and elevation as well as slope should be established.

Hypsometric Integral

Also the hypsometric integral (*HI*) will be assessed in establishing a regional model. This catchment characteristic however, is not used in other regionalisation studies with respect to hydrological modelling. For this reason and because the hypsometric curves of the catchments are available, it could be interesting to assess. The concept of the hypsometric curve is coupled to the erosion-cycle within the catchment by Strahler (1952) and accompanying characteristic (*HI*) can be computed by equation [6.1].

$$HI = \frac{(H_{mean} - H_{\min})}{(H_{\max} - H_{\min})} \qquad [6.1]$$

With:

H_{mean} = average altitude above sea level [m]
H_{max} = maximum altitude above sea level [m]
H_{min} = minimum altitude above sea level [m]

When *HI* receives a value close to 1, a small drainage system is developed and therefore large erosion will take place. When the value of *HI* declines, flatter slopes and the development of a drainage system with a larger contribution at the downstream part of the basin will arise which leads to less erosion (Verstraeten, 2000). Up till now it is not clear how it will affect the processes that play a role at the catchment scale from the hydrological perspective. However, an important remark is made by Strahler (1952), who stated that *HI* was negatively correlated with the river drainage density and slope. Therefore it is used in this study due to availability of the data for determination.

SHAPE

The catchment characteristic slope is a commonly used PCC in regionalisation studies. Unfortunately, for the 56 catchments no direct data could be retrieved about the slope of the catchments. Since the available maps do not have any geographical orientation and also are not scaled, it is not possible to determine the length of the catchments which is required to determine the slope. To overcome the unavailability of this catchment characteristic, an additional PCC is introduced which is expected to have the same effect on the hydrological processes playing a role at the catchment scale. It is referred to as catchment shape and is determined through equation [6.2].

$$SHAPE = \frac{H_{\max} - H_{\min}}{\sqrt{A}} \tag{6.2}$$

With:

H_{max} = maximum altitude above sea level [m]

H_{min} = minimum altitude above sea level [m]

A = area of the catchment [km^2]

When a high value is retrieved the catchment can be considered as a highly responsive catchment since a large difference between altitudes is present. Reversely, when a low value is retrieved, the catchment can be considered as a slow responding catchment.

Land use

The characteristic land use is one of the most used PCC when determining a regional model. The amount of classes used, differs per study. Seibert (1999b) and Merz and Blöschl (2004) used only two classes, namely forest and glacier. Sefton and Howarth (1998) on the contrary used eight classes. The classes they used are assembled through the Land Cover Map of Great Britain 1990. This application is a precursor of the application used in this study, the Land Cover Map 2000 (LCM2000). However, the LCM2000 uses a more detailed land cover classification and from this classification the land use classes applied in this study are assembled. These classes are assembled based on a hydrological point of view. Eventually, this leads also to eight classes but three of them do not contribute significantly to the selected catchments. Therefore, the following five classes are used:

- Woodland [%]
- Arable & horticulture [%]
- Grassland [%]
- Mountain, heath and bog [%]
- Built-up areas [%]

Geology and soil

Geological maps are available which have been derived using a hydrogeological map. This hydrological characterization is made available because of their water resource's significance and influence on flow regimes. With respect to the hydrogeology, this PCC is used often in other studies of regionalisation and it proved to be of importance in describing the hydrological processes at the catchment scale. Therefore it is also used in this study. The classification presented is based on the influence of hydrogeology on river flow behaviour, in the sense of permeability of the bedrock (i.e. aquifers). Furthermore, a distinction is made based on the mechanisms of vertical water movement (Gustard et al., 1992). However, this difference in mechanism is neglected and corresponding permeability is summed. Therefore, the following 4 PCCs are used in this study:

- High permeability [%]
- Moderate permeability [%]
- Very low permeability [%]
- Mixed permeability [%]

Climatic

With respect to the climatic PCCs the most commonly used characteristic is the standard average annual rainfall (*SAAR*). Also for this characteristic the data are available and although this descriptor is ignored in any relationship between model parameters and this PCC for the assessed studies (Merz and Blöschl, 2004; Sefton and Howarth, 1998) it is evaluated in this study. Reason for this is that *SAAR* turned out to be a proper catchment characteristic which is used in a study for low flow estimation in the United Kingdom compounded by the Institute of Hydrology (Gustard et al., 1992). Furthermore, this is a good characteristic for climatic variability which as a result is expected to influence the processes generating rainfall-runoff.

With respect to the PCCs, the groups stream network density and vegetation are ignored due to data unavailability. In table I-1 in appendix I, all used catchments with accompanying values for every PCC are summarized. The grey shaded catchments are used for validation which is addressed in paragraph 7.3.

6.2. Regression analysis

After having determined the parameters and physical catchment characteristics and calibrated the catchments selected for calibration, a method for establishing the relationships is applied. Wagener et al. (2004) state that the most commonly used approach is through use of regression analysis. A regression analysis is the application of a statistical procedure for determining a relationship between variables (Haan, 2002). This approach is also used in this study. First, the concept of regression analysis is described. Next, the hypothesis testing is addressed and at last the applied approach is expounded.

6.2.1. Concept of regression analysis

As stated, regression analysis is a statistical procedure for investigating a relationship between variables. In its essence the procedure will express a variable as a function of another variable. The to be expressed variable is called the dependent variable which in this study are the 7 model parameters. The latter addressed variable is called the independent variable, which in this study are the selected PCCs. Two types of regression analysis have been applied with respect to regionalisation. One is called simple regression where it is tried to determine a relationship between one independent variable and one dependent variable. The second type is called multiple regression analysis which assesses multiple independent variables to explain the dependent variable. The most generally used regression equations are based on a linear interaction. However, different interactions are also used, for instance a square root or a logarithmic equation. Underneath, an example of each multiple regression equation which based on two independent variables is shown through equation 6-3 till 6-5.

$$Y' = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \qquad [6\text{-}3]$$

$$Y' = \beta_0 + \beta_1 \sqrt{X_1} + \beta_2 \sqrt{X_2} \qquad [6\text{-}4]$$

$$Y' = \beta_0 + \beta_1 \log(X_1) + \beta_2 \log(X_2) \qquad [6\text{-}5]$$

With:
Y'= the estimated dependent variable by the regression equation
β_0 = the intercept which is a constant value
β = the regression weight which assigns the effect of the independent variable X on the dependent variable

When trying to establish regression equations, different regression equations can be determined through use of different values for β_0 and β. In order to determine which regression equation reflects the relationships between the dependent and independent variable at best, in general the least-square root method is used. This method is also used in this study. The method is based on introducing an error term, ε, and selecting the regression equation with the smallest value for the error term. The error term is calculated through summation of squares of the estimated errors. The estimated error is defined for each observation as the difference between the value of Y' along the estimated regression equation and the true value of Y for the same observation. This is shown in equation [6-6].

$$SS_{res} = \sum_{j}^{n_0} \left(Y_j - Y'_j\right)^2 \qquad [6\text{-}6]$$

With:
Y_j = the observed value belonging to catchment j
Y'_j = the estimated value by the regression equation belonging to catchment j

When dividing the sum of squares of the estimated errors by n_0-p, where n_0 is the number of observations used in the data set and p the number of regression coefficients used in the regression equation without the intercept, the variance introduced by this error term (i.e. the residuals) is calculated. This is called the undeclared variance, VAR_{res}.

In order to determine the regression equation with the minimum undeclared variance, statistical tools are used. For this study, the tool Essential Regression is used which is an add-in for Excel. Besides determining the undeclared variance, many more statistical characteristics are calculated by these statistical tools. In general, the statistical characteristics of the determined regression equation are presented in an ANOVA (analysis of variance) table. Besides the undeclared variance, several other important aspects are presented. For instance, the total sum of squares and the sum of squares by the regression equation are presented. These are calculated by equation [6-7] and [6-8].

$$SS_{tot} = \sum_{j}^{n_0} \left(Y_j - \bar{Y}\right)^2 \qquad [6\text{-}7]$$

$$SS_{reg} = \sum_{j}^{n_0} \left(Y'_j - \bar{Y}\right)^2 \qquad [6\text{-}8]$$

With:
Y_j = the observed value belonging to catchment j
Y'_j = the estimated value by the regression equation belonging to catchment j
$\bar{Y}_j$ = the average of all observed values

Furthermore, the degrees of freedom, df, regarding the regression equation and the residuals as well as the total degrees of freedom are shown. These are used to calculate the mean sums of squares, *MS*, which is a statistical characteristic used to determine if the variance declared by the established regression equation is significant which is described in the following section. As already described, the *df* belonging to SS_{res} corresponds with n_0-p. The *df* belonging to SS_{tot} corresponds with n_0-1 and the *df* belonging to SS_{reg} corresponds with p-1 (Davis, 2002).

6.2.2. Significance and strength

When determining the regression equation, a hypothesis test has to be applied in order to determine if the equation is significant. Several hypothesis tests are possible, but for each test, assumptions have to be made. It is assumed that the error terms, ε, are not correlated, are normally distributed, have an average of zero and have a constant variance. In this study, these assumptions are also stated. Furthermore, in this study two hypothesis tests are executed, which are called the null-hypothesis and the specific-hypothesis in order to test the significance of the regression equation. Besides testing the significance, also the strength of the determined regression equation should be calculated. These three aspects are described below.

Null-hypothesis

With the null-hypothesis the significance of the total regression equation is assessed through the F-test (Haan, 2002), which is stated as follows:

$$H_{0,general}: \quad \beta_1 = \beta_2 = \ldots = \beta_p = 0$$

$$H_{a,general}: \quad \textit{at least one regressor weight is not equal to zero}$$

$H_{0,general}$ is rejected when:

$$F > F_{1-\alpha,p-1,n_0-p}$$

With:

$$F = \frac{MS_{reg}}{MS_{res}}$$

As said before, the mean sums of squares are calculated by dividing the sums of squares through the degrees of freedom. For MS_{reg} and MS_{res} corresponding equations are shown respectively by [6-9] and [6-10].

$$MS_{reg} = \frac{SS_{reg}}{p-1} \qquad [6\text{-}9]$$

$$MS_{res} = \frac{SS_{res}}{n_0 - p} \qquad [6\text{-}10]$$

The value of $F_{1-\alpha,p-1,n0-p}$ has to be determined from the F-table as is shown in Haan (2002). It depends on α which is the applied significance level, and the *df* regarding the residuals and the regression equation. Thus, this value depends on the number of independent variables attributed in the regression equation.

Specific hypothesis

With the specific hypothesis each of the independent variables are tested if they significantly contribute to the total regression equation, which is tested through the t-test based on the t-distribution. As stated in Davis (2002), a t-distribution occurs when the number of observations (i.e. in this study the number of catchments which satisfy the conditions as stated in paragraph 5.4.8) is smaller than 30. In this study this is the case, and therefore the specific hypothesis can be stated as follows:

$$H_{0,specific}: \quad \beta_1 = 0$$
$$H_{0,specific}: \quad \beta_2 = 0$$
$$H_{0,specific}: \quad \beta_3 = 0$$
$$H_{0,specific}: \quad \beta_4 = 0$$

etc...

$H_{0,specific}$ is rejected when for the specific regression coefficients:

$$|t_c| > \frac{\beta}{SE}$$

With:

t_c = critical t-value determined from t-table (Davis, 2002) depending on the *df* and α which is the chosen significance level

SE = Standard error, which is presented in the ANOVA table

Strength

The goodness of fit of the regression equation with respect to the data set is defined by r^2. This is shown in equation [6-11].

$$r^2 = \frac{SS_{reg}}{SS_{tot}} \qquad [6\text{-}11]$$

r^2 is called the proportion-declared variance. If r^2 approaches a value of 1, the regression line is a good estimator of the data. Thus, in this case the regression equation explains 100% of the total variance present in the data set. If values lower than 1 are determined, the difference of the variance is explained by the residuals.

6.3. Approach of establishing the regional model

In the literature many regionalisation studies have used regression analysis in order to explore the significance and strength of relationships. In general, at first these studies describe expected relationships between physical catchment characteristics and model parameters based on a hydrological point of view. Also expected relationships based on visual interpretation of the spatial distribution of calibrated parameter values are described as for instance Merz and Blöschl (2004) did. Furthermore, as said in paragraph 6.1.1 in general a correlation analysis is performed in order to determine which significant interactions between model parameters and PCCs can be appointed. After the hydrological and statistical interpretation of the relationships, these are investigated through regression analysis.

In this study two approaches of establishing the regional model are applied. At first simple linear regression is performed with respect to each model parameter. On the basis of simple linear regression lies a correlation matrix, which means significant linear correlations automatically result in significant simple linear regression equations. Thus, instead of testing the null-hypothesis with respect to the simple regression equation, the correlation coefficients (r) themselves are tested. In addition the strength of the relationships could also be derived, because the square of the correlation coefficient results in the proportion-declared variance. The significance of the correlation coefficient (t_{cor}) is tested by equation [6.12].

$$t_{cor} = \frac{|r|\sqrt{n_0 - 2}}{\sqrt{1 - r^2}} \qquad [6.12]$$

The following hypothesis is tested:
H_o : The correlation between the PCCs and model parameters is zero
H_a : The correlation between the PCCs and model parameters is not zero

Thus, if $t_{cor} > t_{crit}$ the null-hypothesis is rejected.

In order to determine the critical value t_{crit} the number of df and the significance level, α, have to be determined. In this study a significance level of $\alpha = 0.10$ is chosen and applied to a two-tailed test. This for the reason that determination of the optimum parameter set is based on a MOF which is based on four SOFs. Thus a robust calibration has been applied in order to incorporate different contrasting aspects of the hydrograph and therefore it is expected that it is more difficult to establish significant regression equations. This in contrast to when for instance regionalisation would have been applied regarding merely high flows. In this case the parameters which emphasize high flow would have been evaluated and the problem of trade-offs between different SOFs would not have been encountered as in this study is the case. With respect to the significance test of a correlation coefficient between two variables, the number of df can be stated as n_0-2. Given this information, for t_{crit} a value of 1.753 is found (Davis, 2002). Solving the test-statistic in order to determine at what value of r the hypothesis is rejected, it resulted in a value of 0.412. Therefore, values of r greater than 0.412 and smaller than -0.412 result in a significant relationship. Besides merely statistically evaluating the relationships between model parameters and PCCs, these significant correlations are also evaluated from the hydrological point of view. As basis for hydrological interpretation, the expected relationships and accompanying interpretations as addressed in the literature are used. The studies used are similar as those addressed in paragraph 4.3.1 and corresponding relationships are summarized in table J-1 in appendix J. However, one should be aware of a-priori interpreting these relationships to be valid since these are established in other regions than in this study. For instance it is assumable that in semi-arid areas PCCs differently influence the hydrological processes taking place at the catchment scale than in wet areas. Eventually, also scatter plots between model parameters and PCCs are evaluated. It is assumable that a clear relationship occurs but that it is not linear. In this case, the correlation coefficient would generate a low value and therefore transformation of the data set should be evaluated. Also outliers, leverage and influence cases are evaluated. For a more profound outline of these latter three issues, see for instance Uoregon (2006).

The second method applied is based on multiple regression analysis. In this case the significant correlations determined through the correlation analysis are being optimized by adding other PCCs. The method used for optimization of the simple regression equation is called the forward entry method (Uni-Hamburg, 2006). In this approach the initially established regression equation, which incorporates the significantly best PCC will be extended by forcing a second independent variable in the regional model. This step will be accepted if the entry statistic (i.e. significance level, α) of both independent variables is not exceeded. The statistical tool chooses the most significant independent variable to be added. After this step more steps will be executed, until the last added independent variable does not significantly contribute to the regression equation. In this way the definite multiple regression equation is determined. In addition on the forward entry method, another method is applied called the backward removal method (Uni-Hamburg, 2006). By this method the initial model will incorporate all PCCs which are forced in the model. The statistical tool will assess if an independent variable could be neglected, based on the statistical exit statistic (i.e. significance level, α). The least significant independent variable will be omitted and the next step will be applied. This will be succeeded until the remaining independent variables do not exceed the exit statistic. In this way also a multiple regression equation is determined. The backward removal method is added due to a weakness of the forward entry method. It could be expected that when applying the forward entry method, at the first step no independent variable could be added. This due to the fact that all expected PCCs exceeds the entry statistic. This will lead to termination of the regression analysis and no regression equation would be established. With the backward removal method all expected PCCs are forced into the model. Certainly for the PCC group geology and soils as well as the group land use, as described in paragraph 6.1.2 it is expected that the PCCs belonging to these groups should be jointly applied in the multiple regression analysis.

In the end after executing both methods for each model parameter a simple or multiple regression equation is selected based on statistical and hydrological interpretation.

7. Validation

A model, constructed for the purpose of predicting discharge regimes in ungauged catchments, is of limited value if it cannot be applied to other catchments. Therefore the established regional model should be validated in order to get insight in model performance. In what way the regional model is validated is described in this chapter. In paragraph 7.1 different methods of validation are outlined. In paragraph 7.2 the selected method is expounded. In what way the catchments are selected to be used for validation is described in paragraph 7.3.

7.1. Methodology of validation

7.1.1. Validation tests

Different kinds of model validation are addressed in the literature. Klemeš (1986) proposed a hierarchical scheme for systematic testing of hydrological models. In addition, each of these systematic tests concerns a specific modelling task which describes for what field they are relevant. Distinctions between these systematic tests are based on temporal and/or spatial differences. These tests are shown in table 7-1 and they are expounded below.

Table 7-1. Validation tests and accompanying modeling task according to Klemeš (1986)

Validation test	Modelling task
Simple split-sample test	Extension of runoff series
Differential split-sample test	Simulation of effects of climatic or land-use changes
Proxy-basin test	Simulation of runoff at ungauged catchments
Proxy-basin differential split-sample test	Simulation of effects of climatic or land-use changes Simulation of runoff at ungauged catchments

Simple split-sample testing

Simple split-sample testing involves dividing the available measured time-series data for the test catchment into two sets. All the catchments are used in turn for calibration and validation, and results from both arrangements are compared. Thus, this test is based on temporal difference but not on spatial difference.

Differential split-sample testing

For differential split-sample testing the same approach is followed as described in the simple split-sample test. However, the data are divided according to certain conditions (climatic or catchment properties) in an attempt to show that the model has general validity in that it can predict for conditions different than for which it is calibrated. For example, if the model is intended to simulate flow for a wet climate scenario then it should be calibrated on a dry set of the historic record and validated on a wet set. Thus, in this test distinction is made based on time as well as space.

Proxy-basin testing

Proxy-basins tests use data from one or several gauged catchments to calibrate the model and use another, but similar gauged catchment to validate the model. Thus, in this test distinction between catchments for calibration and validation is made based on spatial differences but not on temporal differences.

Proxy-basin differential split-sample testing
With proxy-basin differential split sample test, the model will be calibrated on gauged catchments and validated in other catchment with different characteristics. Besides, the observation period on which the catchments are validated differs from the observation period used for calibration. Thus, the catchments used for calibration and validation are based on spatial and temporal distinction.

However, in general more different tests can be distinguished, but based on this hierarchical scheme a choice for this study is made.

7.1.2. Selected validation test

As shown in table 7-1 the most appropriate validation tests to be used for this study are the proxy-basin or proxy-basin differential split-sample test since both tests allow for application in ungauged catchments. The first systematic test only spatially distinguishes the selected catchments for validation whereas the latter distinguishes the catchments on time as well as space. However, due to the short period of data input available in this study (01-01-1983 till 31-12-1990) it is chosen for to validate the catchment only spatially. Therefore the proxy-basin test is selected. However, to put more emphasis on assessing the robustness of the regional model, the catchments for validation are not randomly selected but an approach of selecting the validation catchments is introduced. This is expounded in paragraph 7.3.

7.2. Method of assessing the validated catchments

After having determined which validation test is going to be applied, the method of assessing the performance of validated catchments should be determined. This in order to be able to draw conclusions with respect to the objective stated. The first important presupposition made to contribute to the objective is stated as follows: the selected gauged catchments for validation are supposed to be ungauged although well observed hydrometric data are available. This results from the fact that otherwise no judgment can be made regarding the change of model performance.

The objective of this thesis is to reduce uncertainty in the prediction of discharge regimes in ungauged catchments. In this study evaluation of uncertainty reduction is not based on an uncertainty analysis, but assessment will qualitatively supported by a quantitative evaluation of change in SOFs values. Therefore, the performances of three models are evaluated and intercompared. These are:

- The values of the SOFs of the calibrated ungauged catchments.
- The values of the SOFs of the regional model including the established regression equation.
- The values of the SOFs of the ungauged catchments with default values.

In this way judgment can be made due to the absolute and relative change of model performance of the regional model with respect to the optimally calibrated ungauged catchment and the ungauged catchment with default values.

Optimum parameter set
In order to generate values for the SOFs, with respect to calibration of the ungauged catchments, the same methodology as addressed in paragraph 5.4 is applied. Thus, through using the same parameter space, applying moving average for calculating the SOFs R_H^2 and R_L^2, determining related critical threshold values and using the same initial conditions, an optimum parameter set is calculated. This optimum parameter set results in a model performance which is determined through the procedure as described in paragraph 5.4.

Regional model values
With respect to analysing the performance of the regional model, a single model run is made. This due to the fact that the parameter values are calculated through defined regression equations. Furthermore, the same conditions are maintained as described above with the exception of the initial conditions. These are based on the calculated value of model parameter *FC*. If the initial condition for the soil moisture reservoir exceeds the value for *FC*, the model terminates. Therefore, the value for this reservoir is set equal to the value for parameter *FC* and as described in paragraph 5.4.6, the values for the quick flow reservoir and the base flow reservoir comprehends 10 % of the soil moisture reservoir. In addition it should be noticed that it is assumable that not for every model parameter a significant and strong relationship can be determined. In order to evaluate model performance, in such case for concerning model parameters default values will be used. In what way these default values are derived is explained below.

Default values
With respect to generating the SOF values by using the default values, also a single model run is made. The same conditions occur as stated above and again the initial conditions have to be adjusted as described under *regional model values.* For four out of seven model parameters the values are indicated by IHMS (1997) which are shown in table 5-1 as described in paragraph 5.4.2. Still, for three model parameters values have to be determined. The essence of model performance with respect to the default values as input is that these values would be used if it is not known which parameter values should be used to correctly represent the hydrological processes occurring at an ungauged catchment which jointly would lead to a correct unique discharge regime. And therefore one could be interested in at least a general model performance. The model parameters for which no default values are presented are K_f, K_s and *PERC*. For K_s and *PERC* the values are determined by calculating the averages of the studies mentioned in table 5-1 at paragraph 5.4.2. With respect to the parameter K_f the value is determined through calculation of equation [2-10] as stated in paragraph 2.4.3. Since default values for the parameters used in this equation are known, the value for K_f can be calculated. Concluding, the default values required for the HBV model are shown in table 7-2.

Table 7-2. Parameter values used as default values

Model parameter	**FC**	**LP**	**BETA**	**ALFA**	**K_f**	**K_s**	**PERC**
	[*mm*]	[-]	[-]	[-]	[day^{-1}]	[day^{-1}]	[$mm\ day^{-1}$]
Default values	200	0.9	2.0	1.0	0.00963	0.0315	1.46

7.3. Catchments for validation

7.3.1. Approach of selecting the catchments for validation

As stated proxy-basin testing is applied in this study for assessing the regional model. In order to assess the robustness of the regional model, catchments are selected with as much hydrologic and physiographic diversity. By selecting catchments with dissimilar PCCs, it is assumed that for robustly validating the regional model, eight catchments are sufficient. Selection of the validation catchments is based on four PCCs which in turn are selected based on the hydrologist's insight. That is, it is expected that the diversity of those PCCs are of importance in generating the hydrological processes taking place on the catchment scale. The PCCs selected are *AREA*, *SAAR*, *HI* and the permeability of the soils.

For the PCCs *AREA*, *SAAR* and *HI*, the catchments closest to the 10-percentile and 90-percentile are chosen in order to create a large diversity. These percentages are chosen since percentages closer to the minimum and maximum would inherently incorporate a larger degree of variance and therefore it is possible that concerning values lay outside the confidence belt of the determined regression equation. On the other hand, percentages closer to the 50-percentile do not assure a high degree of hydrologic and physiographic diversity.

With respect to the PCC permeability, it is chosen for to select two catchments that have a contrasting permeability, namely one regarding the 10 percentile exceeding-chance with respect to the PCC low permeability and one regarding the 10 percentile exceeding-chance with respect to the PCC high permeability. For instance, for each catchment an amount of low permeability is assigned. Also for each catchment an amount of high permeability is assigned. Thus, when selecting a catchment which has a high percentage of low permeability, and a catchment which has a high percentage of high permeability, two catchments are selected with contrasting PCC. However, with respect to the low as well as high permeability many catchments have a value of 100% (for the values assigned to each catchment, see appendix I, table I-1). In addition, when selecting the 10-percentile exceeding-chance a catchment would be selected which has 100% of concerning permeability. Since several catchments have a value of 100%, it is allowed to choose between those catchments which all have this value. Therefore, spatial distribution of the already selected catchments for validation will be the basis of the last catchments to be selected. One catchment in the South-West of England (low permeability) and one in South England (high permeability) are chosen.

7.3.2. Selected catchments

The catchments chosen to be used in validating the regional model are:

- 27034 - Ure @ Kilgram Bridge
- 27056 - Pickering Beck @ Foston Mill
- 31010 - Chater @ Fosters Bridge
- 38029 - Quin @ Griggs Bridge
- 42008 - Cheriton Stream @ Sewards Bridge
- 47008 - Thrushel @ Tinhay
- 53013 - Marden @ Stanley
- 60010 - Tywi @ Nantgaredig

These catchments are shown in figure 7-1 indicated by the green colour. The red dots are the catchments used for calibration. Additionally, in table I-1 in appendix I the values of the PCCs for all catchments are shown and those belonging to the above selected validation catchments are shaded in grey.

Figure 7-1. Catchments selected for calibration (red dots) and validation (green dots)

8. Results

In this chapter the results of the three steps of regionalisation are addressed. In paragraph 8.1 the results regarding the calibration is described. In paragraph 8.2 the established relationships between model parameters and PCCs are presented. The results regarding the validation are described in paragraph 8.3.

8.1. Results calibration

Initial calibration of the 48 catchments resulted in poor model performances. As described in paragraph 5.4.8 the catchments are selected based on two conditions. Initially, merely 7 catchments satisfied both conditions. Two adjustments are made in order to increase model performances, which are described below.

8.1.1. Adjusted observed discharge

After having determined the catchments which satisfy the conditions, concerning hydrographs are evaluated in order to assess what could go wrong since only 7 catchments were selected. What was remarkable is that in general the calculated discharge was shifted with respect to the observed discharge. This is shown in figure 8-1. It shows that for peak flows as well as low flows the model calculated the system's response with a delay of one time step i.e. one day with respect to the observed discharge. It is assumable that this problem originates due to the moment on which the input data are recorded. For the data input rainfall, temperature and potential evapotranspiration daily averages are calculated or directly taken from a database. The calculated data are derived through use of hourly observations, as described in paragraph 3.1. However, with respect to the data input of observed discharge it is not obvious if these data are daily average values or point measurements since it could not be concluded from accompanying metadata. Therefore it is possible that the observed discharge is measured at a given moment and this value is used for the corresponding day. When this moment is in the morning the system's response of daily average

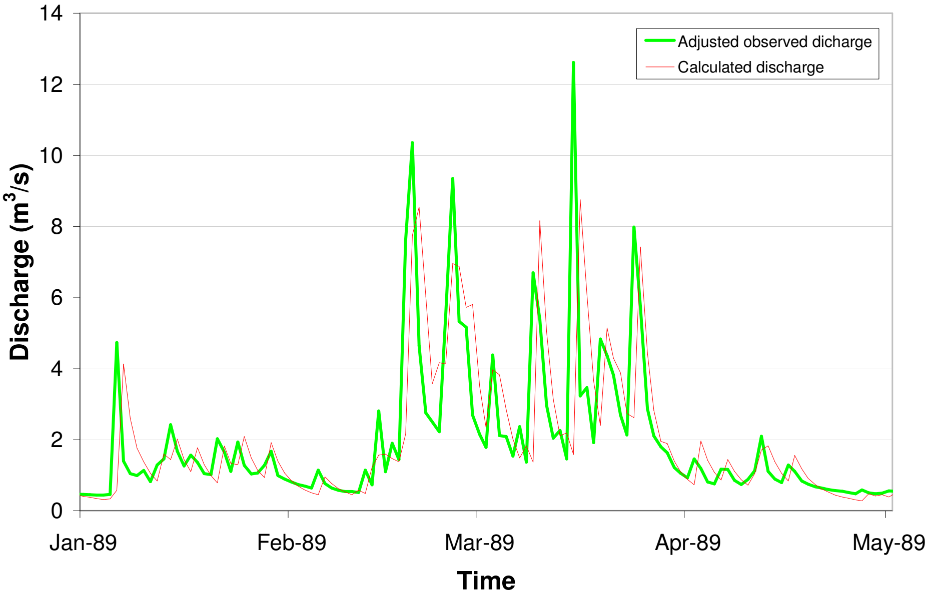


Figure 8-1. Calculated discharge against initially observed discharge for 57010 – Ely @ Lanely

data input are compared with daily observed measurements in the morning. In that case, system's response (i.e. calculated discharge) is evaluated with the wrong observed measurements and with respect to the SOF R^2 poor model performance will arise. Therefore it is chosen for to adjust the observed discharge and shift the recorded measurements one day back in time. This is shown in figure 8-2 and as can be seen, the model visually fits much better. This also is reflected in the number of catchments which satisfy both conditions. With the adjusted observed discharge, in total 36 catchments obtain a significantly better model performance. With respect to the SOF R^2 an average increase of 0,12 is observed. The remaining 12 catchments decreases only slightly with respect to the SOF R^2. Eventually through adjusting the observed discharge 14 catchments would satisfy both conditions.

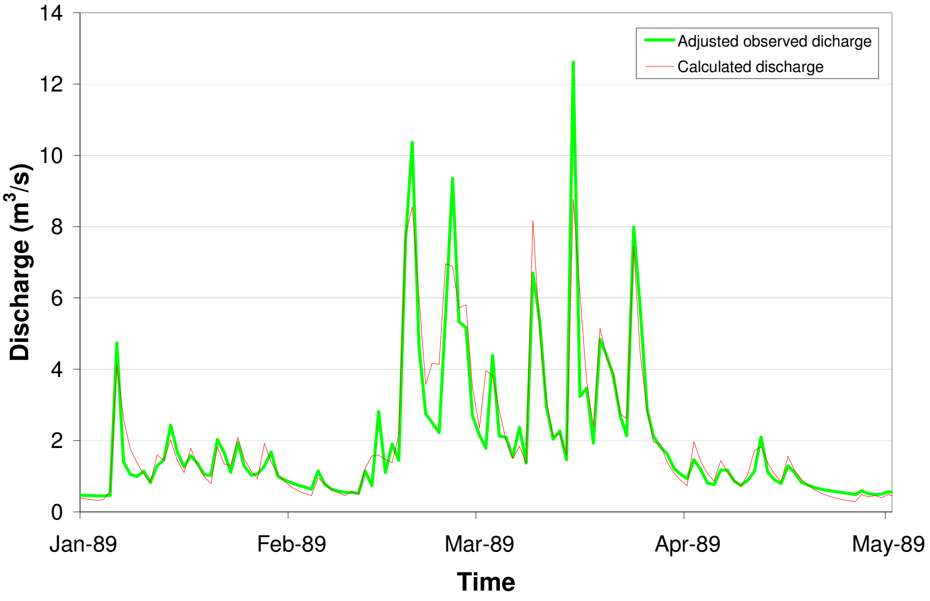


Figure 8-2. Calculated discharge against adjusted observed discharge for 57010 – Ely @ Lanely

8.1.2. Parameter space

After calibrating the model based on the MCS and the defined initial parameter space (table 6-2) an optimum parameter set is derived for each catchment. Yet, if one of the parameters is well identifiable, concerning parameter space can be narrowed. This for the reason that model performance is most sensitive for well identifiable parameters i.e. within a small range of the parameter space the model performs well whereas in the parameter space outside this small range the model performs insufficient. Besides, when narrowing the parameter space, the uncertainty by equifinality will be reduced. Determining the well identifiable parameters is done by making scatter plots of the seven parameters against the 10000 decisive scaled values for every catchment which are generated through equation [5-7]. What should be remarked is that in this study the identifiability of model parameters corresponds to all four SOFs jointly. This is shown in figure 8-3 till figure 8-6 for four of seven parameters for catchment 60006 - Gwili @ Glangwili. As can be seen in figure 8-3 parameter *PERC* is plotted against the decisive scaled values. It can be concluded that *PERC* is not a well identifiable model parameter since for every parameter value within the initial selected parameter space the model can perform equally well. The scatter plots derived for the parameters *BETA*, K_f and K_s show the same distribution, thus it can be concluded that these are also poorly identifiable model parameters. As can be seen in figure 8-4 parameter *LP* is more sensitive for higher values than for lower values and therefore the parameter space can be adjusted. The same is shown in figure 8-5 where the values for *ALFA* are plotted. For this model parameter no output could be generated by the HBV model for parameter values above 2.3. It also can be concluded that for this model parameter the parameter space can be narrowed. In figure 8-6 the seventh parameter, *FC*, is plotted. As can be seen the model performs in general better for lower values than for higher values of *FC*.

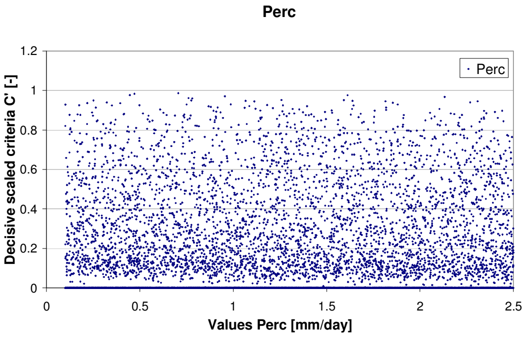


Figure 8-3. Scatterplot of decisive scaled criteria against model parameter PERC for catchment 60006 – Gwili @ Glangwili

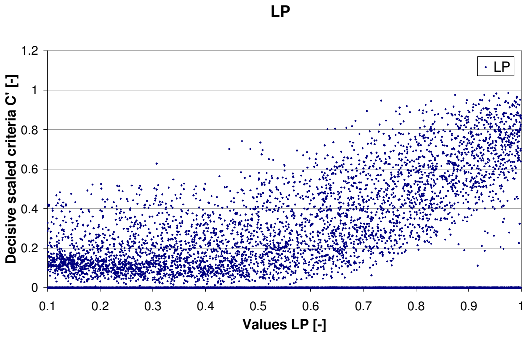


Figure 8-4. Scatterplot of decisive scaled criteria against model parameter LP for catchment 60006 – Gwili @ Glangwili

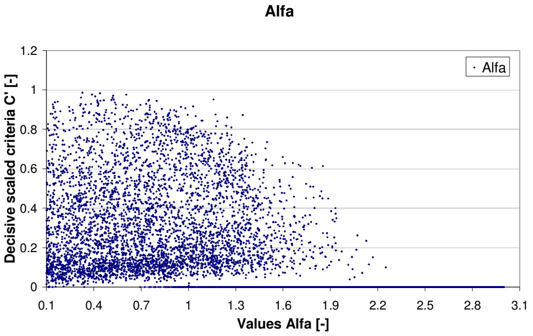


Figure 8-5. Scatterplot of decisive scaled criteria against model parameter ALFA for catchment 60006 – Gwili @ Glangwili

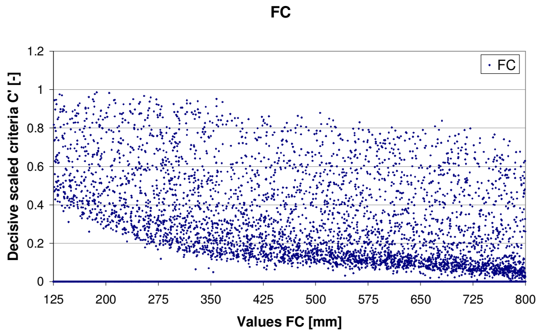


Figure 8-6. Scatterplot of decisive scaled criteria against model parameter FC for catchment 60006 – Gwili @ Glangwili

It is assumed that for almost every catchment the scatter plots show the same coherence and in order to assess all catchments at the same way the following approach is chosen for to narrow the parameter space:

- For each catchment the best 1000 out of 10000 values of the decisive scaled values are derived. This for the reason that it is assumed that no good model performance will be realized when using a parameter set belonging to a poor decisive scaled value.
- Hereafter, for every model parameter values are determined from which the minimum and maximum values of all 1000 best runs are derived.
- These minimum and maximum values are used as a new boundary for the adjusted parameter space.

Thus, for every catchment at the same way an adjusted parameter space is determined which is used to determine the optimum parameter set. These adjustments are shown in table J-1 in appendix K. Since the model parameters *BETA*, *PERC*, K_f and K_s are difficult to identify it turned out that their parameter spaces were slightly adjusted. With respect to *ALFA*, no adjustments are applied for the lower boundary i.e. a value of 0.1. The maximum value on the contrary is adjusted for every catchment. The smallest adjustments are made from the initial parameter value of 3.0 to 2.88. The largest adjustments are made from 3.0 to 1.13. Regarding the parameter *FC* also some adjustments are made. With respect to the upper boundary, most of the values are adjusted slightly (e.g. from 800 to 797.8) with the largest adjustment made from 800 to 788.6. Regarding the lower boundary, in general some small adjustments are made. However, for two catchments the values are adjusted a lot, from 125 to respectively 387.4 and 418.7. With respect to the parameter *LP*, for the upper boundary again the values for two catchments are adjusted respectively from 1 to 0.6689 and 0.6144 while the rest of the catchments are not adjusted. With respect to the lower boundary, almost all catchments are adjusted. The largest adjustment is made from the initial value 0.1 to 0.5222. Concluding, the model parameters *ALFA* and *LP* are best identifiable whereas *FC* turned out not to be.

8.1.3. Optimum parameter set

After calibrating the model and implementing the two adjustments as described above, in total 17 catchments satisfy both conditions as described in paragraph 5.4.8. The values of the SOFs belonging to the derived optimum parameter sets are shown in table 8-1. The dissatisfactory catchments however are not shown. In addition the 17 selected catchments are shown in figure 8-7. Their optimum parameter sets are expounded in table L-1 in appendix L.

Table 8-1. Calculated absolute values of the SOFs belonging to the optimum parameter set; underlined values are catchments performing reasonable with respect to R_H^2 and R_L^2

Calculated absolute values SOFs				
Basin	R^2 [-]	R_H^2 [-]	R_L^2 [-]	RV_E [%]
27035	0.817	-0.099	-1.858	-1.096
33019	0.753	0.380	-5.853	1.537
41022	0.763	0.725	-3.644	0.160
43006	0.796	0.718	-19.723	-1.300
45005	0.783	0.531	-73.591	-0.474
48003	0.865	0.368	-3.266	-0.754
48010	0.940	0.569	-3.602	-1.328
50001	0.813	-2.240	-1.134	-0.401
52010	0.777	0.600	-12.929	-4.138
53009	0.876	0.672	-12.380	-4.019
54016	0.790	0.362	-1.791	-1.914
54029	0.816	0.544	-0.657	-1.534
55013	0.835	0.627	-3.460	0.989
55014	0.887	0.653	-1.509	-0.514
57010	0.878	0.162	0.326	0.656
60006	0.849	0.612	0.633	-2.105
66011	0.795	-0.009	-0.038	-4.197

What is remarkable is that the SOFs R_H^2 and R_L^2 generate negative values for several catchments. This results from the fact that the intention of the regionalisation is to derive a robust regional model i.e. all the stated aspects of the hydrograph are reflected in the applied model calibration and not merely one aspect from the hydrograph such as peak flow. Furthermore, in table 8-1 some values concerning the SOF R_H^2 and R_L^2 are underlined. Since these SOFs have the same underlying basis as R^2, except adjusted with respect to the threshold value, similar qualitative judgments can be made as described in paragraph 5.3.1. In contrast to the selection condition for R^2 (i.e. values higher than 0.75), the selection condition for underlining these SOFs is 0.6. With respect to R_H^2 in total 7 calibrated catchments have reasonable or good model performances. Regarding R_L^2 only 1 catchment has a reasonable model performance. It can be concluded that due to the introduced MOF the HBV model has the most difficulty in deriving parameter values which well simulates the slow flow aspects of the hydrograph. More specifically, the SOFs R_L^2 experience the most influence of the trade-off between the four SOFs. In total just 1 catchment performs reasonably or well with respect to all the SOFs. The observed discharge against calculated discharge of the latter addressed catchment, 60006 – Gwili @ Glangwili, is shown in figure 8-8.

Figure 8-7. Selected catchments satisfying both conditions which are used in the regression analysis (green dots)

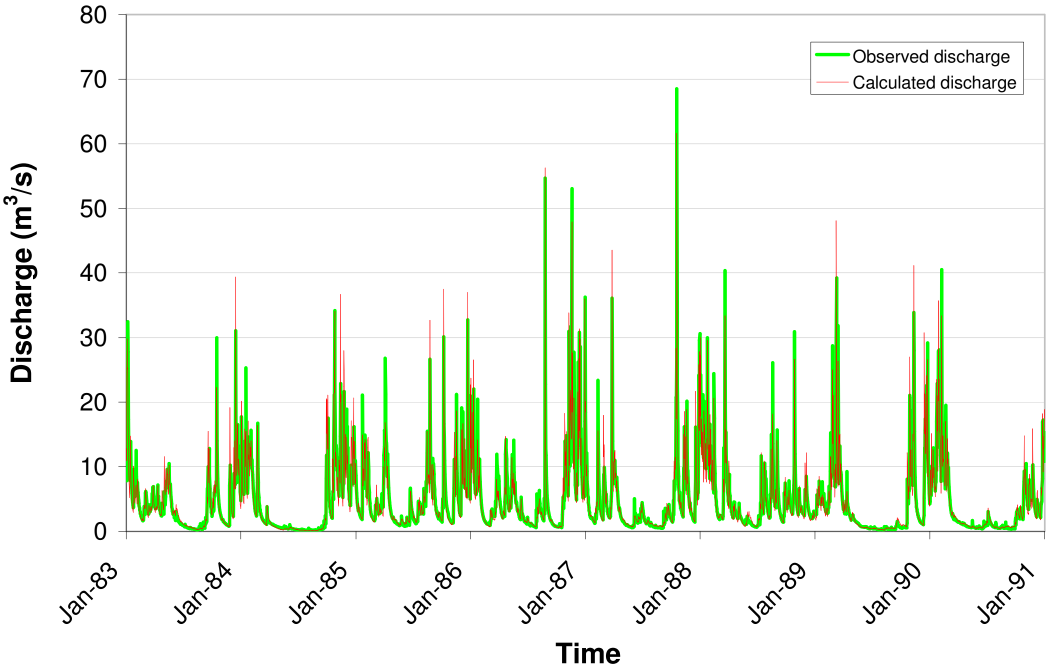


Figure 8-8. Calculated against observed discharge for catchment 60006 – Gwili @ Gwangwili

8.1.4. Rejected catchments

After having adjusted the observed discharge and the parameter space, in total 17 catchments satisfy the stated conditions. Hence, 31 catchments do not satisfy these conditions. The values of the SOFs belonging to the optimum parameter set as well as the values for accompanying PCCs are evaluated. This is outlined below.

SOFs

Regarding the values for the SOFs the division of model performance of the catchments is clarified through figure 8-9.

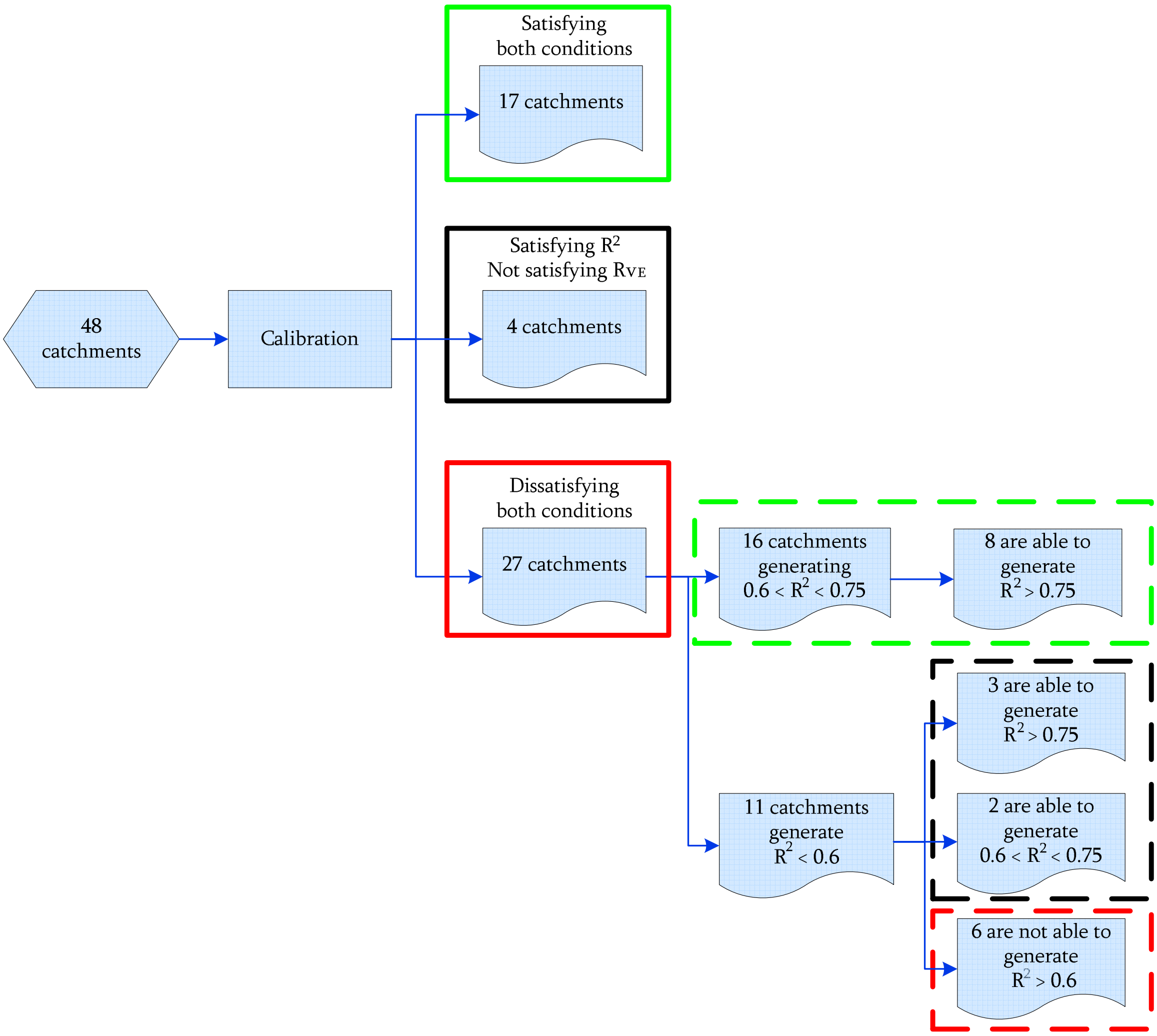


Figure 8-9. Diagram which expounds the performance of all 48 calibrated catchments

From the 31 catchments which do not satisfy both conditions, still 4 catchments satisfy the condition with respect to the value for R^2 higher than 0.75. These 4 catchments are rejected based on the second condition which addresses the SOF RV_E and are embodied by the black line in figure 8-9. These 4 catchments however just slightly exceeds the condition.

As stated in paragraph 5.3.1 when a calibrated catchment generates a value with respect to the SOF R^2between 0.6 and 0.8, the model performs reasonable. From the 27 catchments which do not satisfy both conditions and which is embodied by the red line in figure 8-9, even 16 catchments perform reasonably. However, when evaluating the maximum value of the SOF R^2 of these catchments, it can be concluded that in total 8 catchments are able to satisfy the condition of generating a value for R^2 higher than 0.75 which is shown in figure 8-9 by the green dashed line. Due to trade-off between the four SOFs used in the MOF, these catchments do not satisfy the condition. In general just a slight decrease of R^2 occurs when evaluating the difference between these values with respect to the maximum achievable value and the value corresponding to the optimum parameter set. Concerning all 16 addressed catchments which not satisfy both conditions, an average decrease of 0,05 would occur.

From the remaining 11 catchments which perform inadequately, 3 are able to generate a maximum value for R^2 higher than 0.75 and two are 2 are able to generate reasonable model performance based on the SOF R^2. Remarkable is that these 5 catchments generate large negative values for the SOF R_L^2, which vary from -7.8 till –29.2. In contrast to the trade-off between the four SOFs as addressed above, the trade-off for these 5 catchments is assumed to be much bigger. This can be seen in the average decrease of the value for the SOF R^2. Where in above addressed 16 catchments an average decrease of 0.05 occurred, for these 5 catchments the average decrease is 0.36. The distribution of above stated 5 catchments is shown in figure 8-9 by the dashed black line. For the remaining 6 catchments which are shown in figure 8-9 by the red dashed line, the optimum parameter set is not able to result in an adequate model performance.

PCCs

With respect to the values for the PCCs the following can be said regarding the dissatisfying catchments. One of the catchments, which is not able to generate a reasonable model performance at all as shown by the red dashed line in figure 8-9, has an enormous part of its area contributed to the PCC *URBAN* i.e. 61.3 % of its total area contributes to *URBAN* whereas the second highest percentage has a value of 14.7. From the 10000 runs made to determine the optimum parameter set for this catchment, for not one parameter combination a value for the SOF R_L^2 was generated and therefore no optimum parameter set could be determined. It turned out that in none of the simulations, the calculated discharge exceeds the critical threshold value for low flow.

Furthermore it is remarkable that not one of the catchments which have a large portion of their area (i.e. more than 30%) ascribed to the PCC *MOUNTAIN,* satisfies both conditions. All these catchments geographically are situated in the northern part of England. Additionally, it turns out that most of these catchments have a relatively low value for the PCC *SAAR.*

Moreover it turned out that all dry catchments (i.e. a *SAAR* less than 800 mm) do not satisfy both conditions with the exception of one catchment which has a *SAAR* of 620 mm. In total of the 48 catchments 19 catchments have a *SAAR* smaller than 800 mm, which amounts for 40%.

8.2. Results regression analysis

8.2.1. Simple linear regression

In order to determine which significant relationships between model parameters and PCCs are established, in table 8-2 the correlation matrix is shown. As described in paragraph 6.3 if the correlation coefficient does not present a value between the critical value of – 0.412 or 0.412, the corresponding correlation is significant. Thus, the null-hypothesis is rejected. In table 8-2 the significant correlation coefficients are underlined and presented in bold. Below at first the significant simple relationships are described. Hereafter these significant relationships are interpreted from a hydrological point of view. In addition, the expected relationships as described in the literature are evaluated. These relationships are shown in appendix J. In the end also the scatter plots of all model parameters are visually evaluated. It is assumed that besides linear relationships also transformation of the model parameter values or PCC values result in a significant and strong relationship.

Table 8-2. Correlation matrix between model parameters and PCCs for the 17 selected catchments; bold and underlined correlation coefficients are significant

	FC	BETA	LP	ALFA	Kf	Ks	PERC
AREA	-0.118	0.197	-0.123	-0.127	0.084	0.112	0.009
ELEVATION	-0.200	**0.486**	0.156	-0.318	0.371	0.255	-0.078
HI	0.140	-0.079	-0.025	0.411	**-0.437**	-0.407	**0.639**
SHAPE	-0.033	0.104	0.259	-0.133	0.140	-0.070	0.027
SAAR	-0.040	**0.476**	**0.645**	-0.025	0.383	0.198	-0.203
WOOD	-0.008	-0.042	-0.097	0.288	-0.128	0.297	-0.049
ARABLE	0.209	**-0.565**	-0.310	0.090	-0.332	-0.367	0.211
GRASS	-0.290	**0.594**	0.314	-0.203	0.333	0.235	-0.171
MOUNTAIN	0.157	0.333	0.098	-0.055	0.078	0.189	-0.120
URBAN	0.170	**-0.488**	0.109	-0.027	0.226	-0.303	0.083
HIGHP	-0.074	**-0.423**	-0.234	0.055	-0.228	-0.147	0.131
MODERATEP	-0.148	-0.081	0.212	-0.258	0.370	0.152	-0.140
LOWP	0.157	0.368	0.046	0.207	-0.109	0.037	-0.050
MIXEDP	0.124	0.063	-0.268	-0.051	-0.252	-0.244	0.335

Significance interpretation

As can be concluded, in total nine relationships are significant. The most significant and hence the strongest relationship exists between *LP* and *SAAR*. The proportion-declared variance (r^2) in this case results in a value of 41.6%. An almost equal strong and significant relationship exists between *PERC* and the PCC *HI*. In this case the r^2 results in a value of 40.8%. Furthermore, K_f also generates a significant relationship with the PCC *HI*. The strength of this relationship is clearly lower as it generates a r^2 of merely 19.1%. Formerly three addressed model parameters which are *LP*, *Kf* and *PERC* are only significantly related to one PCC. With respect to *BETA* however six PCCs demonstrate a significant relationship from which three belong to the group land use. The fourth PCC belongs to the group topography, the fifth PCC to the group climate and the sixth PCC to the group geology and soil. In this case the relationship between *BETA* and *GRASS* is the most significant which generates a r^2 of 35.3%. It is assumable that these significant correlations together result in a stronger multiple regression equation. This is described in following paragraph 8.2.3. Thus, from the significant point of view for four out of seven model parameters, simple regression equations are determined. However, the strength of these equations is not extremely well.

Hydrological interpretation

BETA, which is a model parameter that controls the contribution to the quick runoff reservoir, is significantly related to six PCCs. With respect to hydrological interpretation, in the literature *BETA* is positively as well as negatively related to *AREA*, negatively related to *ELEVATION* and it could be expected that it is negatively related to *SAAR*. Hundecha and Bárdossy (2004) also related *BETA* to the PCC group land use and soil type. With respect to the PCC *AREA* no relationship could be demonstrated in this study. Regarding *ELEVATION* a significant positive relationship is proved. However, Merz and Blöschl (2004) stated that based on hydrological interpretation a negative relationship is expected. From this point of view a large *BETA* value prevails in lowland catchments. Thus a high value for *BETA* results in a small runoff coefficient (i.e. little contribution from the soil moisture state to the quick flow reservoir) and a non-linear runoff generation behaviour (i.e. in lower altitude catchments relatively a larger part of the infiltrating precipitation will become available for replenishing the soil moisture state in comparison to higher altitude catchments). Therefore the established relationship in this study does not correspond with what is expected based on hydrological interpretation. With respect to *SAAR* a positive relationship is demonstrated in contrast to what Merz and Blöschl (2004) proved. In addition, they stated that a negative relationship with respect to *SAAR* is consistent with general understanding of runoff processes in different climates (see e.g. Goodrich et al., 1997). With respect to the PCC group land use, three PCCs do incorporate a relationship. Hundecha and Bárdossy (2004) also related the land use to parameter *BETA*. *GRASS* indicates to be positively related and therefore in catchments with large grassland, higher values of *BETA* occur and consequently less precipitation will be available for runoff generation. Since *ARABLE* shows a negative correlation the opposite occurs, thus in catchments with more *ARABLE* smaller *BETA* values are generated and therefore more precipitation will be available for runoff generation. Although reasonable significant relationships are presented, it is not expected that these single PCCs would be an appropriate estimator for *BETA* since the PCCs are interdependent due to the fact they are summed till 100%. Especially between *ARABLE* and *GRASS* a high correlation coefficient is generated, which shows a value of -0.863. Therefore, it is expected that all PCCs belonging to the group land use should be used together in the regression equation in order to be able to demonstrate a hydrological sensible relationship. This is described in paragraph 8.2.2. At last a negative relationship is demonstrated with the PCC *HIGHP*. From hydrological perspective it is a sensible relationship since a higher amount of high permeability available in the catchment, would result in a smaller value for *BETA*. Thus, smaller values of *BETA* result in a larger part of the precipitation becoming available for rainfall-runoff generation.

The strongest simple linear relationship exists between *LP* and *SAAR*. When *SAAR* increases *LP* also increases. *LP* is a limit for the soil moisture content where above the evapotranspiration reaches its potential value. Hence, when *LP* has a low value at a low amount of the soil moisture state the evapotranspiration reaches its potential value and in total more precipitation will evapotranspirate. Consequently, since *LP* is positively related to *SAAR* dryer catchments would at a low amount of the soil moisture state reach the potential value for evapotranspiration and therefore it can be stated that relatively more precipitation would be able to evapotranspirate at dryer catchments than at wetter catchments. From the hydrological point of view this relationship could not be confirmed. On the contrary Merz and Blöschl (2004) expected a negative relationship between *LP* and *ELEVATION*. This relationship however resulted from the fact that *FC* and *LP* are highly correlated, which could not be indicated in this study since a value of 0.075 was generated. Moreover Hundecha and Bárdossy (2004) a-priori related *LP* with soil types. Both addressed relationships could not be appointed in this study although from the hydrological point of view these relationships tend to be more sensible.

K_f presents a negative correlation with *HI* but it generates a weak relationship. From hydrological perspective this is a feasible relationship. Strahler (1952) stated that *HI* is negatively correlated with slope. Thus, geologically older catchments which results in a lower value for *HI* will have a larger slope. In addition Booij (2005) stated that K_f is positively correlated with slope since a larger slope results in quicker runoff reactions. These two statements result in a feasible negative relationship between K_f and *HI*. The relationships addressed by Merz and Blöschl (2004) between K_f and *ELEVATION* however could not be demonstrated.

Between *PERC* and *HI* an equal strong relationship occurs as between *LP* and *SAAR*. At first it looks this is not a hydrological feasible relationship. However, Strahler (1952) stated that *HI* is negatively correlated with the drainage density of the catchment since geologically older catchments which have a low value of *HI* have a large drainage density. In addition Merz and Blöschl (2004) stated that the drainage density of a catchment is negatively correlated with *PERC* since in catchments with few streams a larger portion of water penetrates deep into the subsurface. From these two statements, it is feasible to state that *PERC* is positively related with *HI*. When assessing the relationships addressed in other studies, these do not concur. Hundecha and Bárdossy (2004) related *PERC* with *AREA* and a PCC which incorporates the shape of the catchment. In this study no such relationship is generated. In addition, Sefton and Howarth (1998) related a model parameter which represents the volumetric separation between the two components of the hydrograph (i.e. quick flow and base flow) to geology. With respect to this study the same hydrological process could be related to model parameter *PERC* since this parameter differs between the base flow and the quick runoff reservoir. However, in this study no simple relationship could be found between the PCC group geology and *PERC*.

Visual interpretation

As addressed in appendix K based on hydrological interpretation some relationships are expected which are not demonstrated in this study. Therefore, the scatter plots between the model parameters and PCCs are visually interpreted in order to asses if any transformation would lead to stronger and significant relationships. Also potential outliers, leverage or influence cases are assessed. These latter three issues are assessed using the statistical tool Essential Regression. In addition it should be stated that the PCC group land use as well as geology and soil are not evaluated since these are assessed during the multiple regression analysis.

With respect to *FC* it is expected that this model parameter is related to the PCC *ELEVATION* since higher catchments in general have less active soil depths as Merz and Blöschl (2004) stated. In this study on the contrary a weak negative relationship between *FC* and *ELEVATION* was proved with a correlation coefficient of - 0.2. Furthermore, none of the transformations resulted in a clear increase of significance. No simple linear relationship therefore is demonstrated for *FC*. As an example the scatter plot of the model parameter *FC* against *ELEVATION* is shown in figure 8.8. Although it looks like two observations are potential leverage or influence cases, it is not the case.

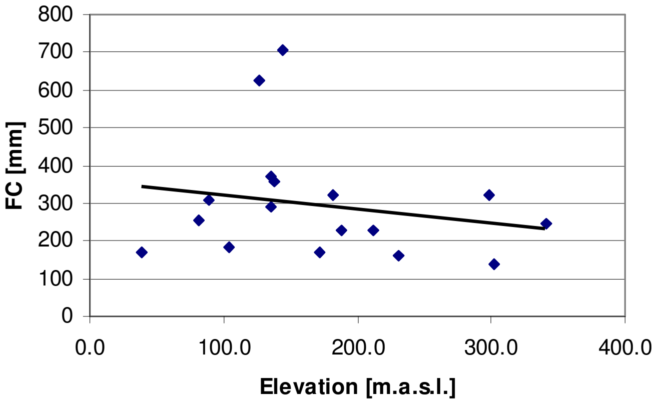


Figure 8-8. Scatter plot between model parameter FC and PCC ELEVATION

With respect to *LP* Merz and Blöschl (2004) demonstrated a negative relationship with *ELEVATION*. However, in this study this relationship does not occur and after transformation of this PCC the significance and strength of the already weak relationship decreases. In addition, it is checked if a potential outlier, leverage or influence case causes this weak relationship. It turned out that two catchments are indicated to be a potential leverage and influence case. After removal of these two catchments the relationship increased tremendously. An increase of significance with respect to the F-value from 0.550 to 0.052 with an r^2 of 26.0% was demonstrated. Both scatter plots are shown in figure 8-9. On the left side of the figure the two catchments are still included, where on the right side the two are removed. However, this relationship between *LP* and *ELEVATION* turns out to be positive, while in the study of Merz and Blöschl (2004) it was expected to be a negative relationship. Furthermore no justification could be found for neglecting the two catchments in the regression analysis. In addition of the already established relationship between *LP* and *SAAR*, it turned out that transformation from *LP* to *exp(LP)* resulted in an increase of r^2 from 41.6 % to 47.7 %. Due to this transformation, the potential leverage case and the influence case are smoothed away.

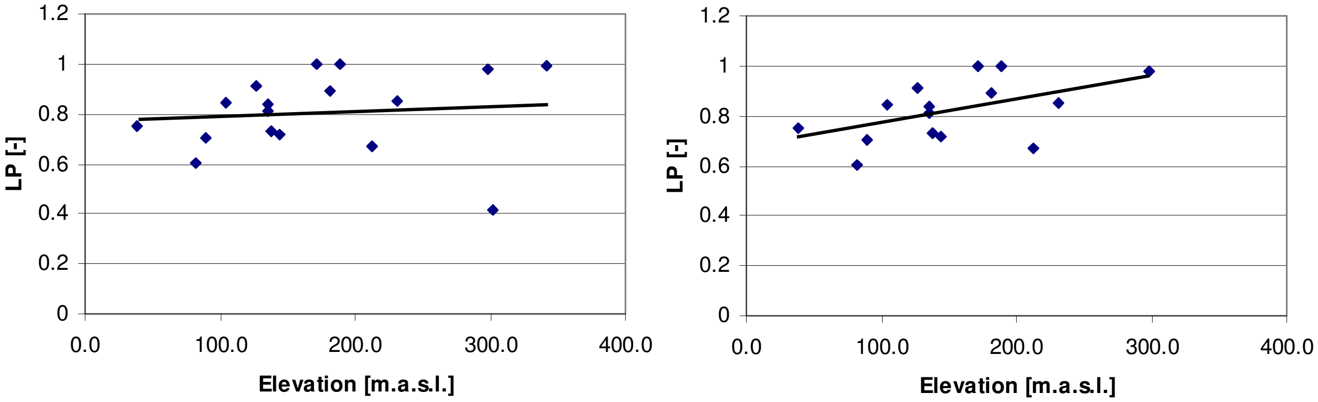


Figure 8-9. Scatter plot between LP and ELEVATION; Left side inclusion of two catchments; Right side exclusion

Regarding *ALFA* in the literature it is indicated that from a hydrological point of view a positive relationship with the slope should occur (Booij, 2005). In this study there was no data available for determination of the slope of the catchments. The PCC *SHAPE* was introduced instead. However, after visual interpretation of the scatter plots no indication of sensible relationships could be determined with respect to *SHAPE*. Since *HI* almost rendered a significant relationship, it also is checked with respect to potential outliers, leverage and influence cases. Also transformation was applied, which led to an increase of significance and strength. After transformation of *HI* to EXP(*HI*) the significance increased from 0.101 to 0.0766 with a strength of r^2 is 19.4 %. With respect to hydrological interpretation no justification could be found. Due to the relative weak relationship and the required transformation, this relationship is questioned.

With respect to *Kf* a negative relationships is established with PCC *HI*. After transformation of *Kf* to 1/*Kf*, a stronger relationship arose. The strength of the relationship increased from 19.1% tot 33.6 %. However when evaluating potential outliers, leverage and influence cases, two cases tended to be a leverage case and therefore could be removed from the data set. When again executing the regression analysis, it turned out that a totally different relationship was determined. A significance value of 0.53 was generated while at least a value below 0.10 is required. However, no justification could be found to neglect both catchments. Therefore the established relationship including all catchments and the transformation is maintained. Furthermore Merz and Blöschl (2004) indicated a positive relationship with *ELEVATION*. At first no relationship could be determined. However, after transformation of the values of *Kf* to LN(*Kf*) a significant relationship with a value of 0.084 and a r^2 of 18.6 was proved. Although it confirms the relationships addressed by Merz and Blöschl (2004) it still is very weak.

Regarding K_s a relationship with PCC *FOREST* is demonstrated by Seibert (1999b) and Hundecha and Bárdossy (2004) also related land use to this parameter. Furthermore, soil type, *AREA,* slope and the shape of the catchment were a-priori related to K_s. However, none of these PCCs proved to be significantly related to the model parameter. *HI* was at best related to K_s and therefore it specifically is evaluated with respect to outliers, leverage and influence cases. It turned out that two catchments were identified as outliers. After removal of the most likely case, the correlation increased from -0,417 to -0,552 what resulted in a significant relationship with an r^2 of 30.5 %. However, no justification could be found to neglect both catchments and therefore the transformation of the relationship is not confirmed. With respect to the other PCCs no significant relationships could be demonstrated after evaluation of the scatter plots.

With respect to parameter *PERC* no increase in correlation coefficients could be determined after evaluation of the scatter plots. As already stated, the PCCs group land use and geology and soil are jointly evaluated during the multiple regression equation.

8.2.2. Multiple linear regression

After having assessed the correlation coefficients based on significance, hydrological interpretation and visual inspection of the scatter plots, several relationships could be determined. However, it is possible that combined PCCs estimate the parameter value better than a single PCC does. Therefore the model parameters are assessed through multiple linear regression analysis. This is done by the methods described in paragraph 6.3 and are called the “forward entry method” and the “backward removal method”. The demonstrated regression equations are evaluated based on significance and are hydrologically interpreted.

FC

With respect to model parameter *FC* no significant relationships are established. In order to be able to perform the forward entry method, an initial model with one regression coefficient is required. Since no significant correlation coefficient was determined, it was not possible to execute this method. With respect to the backward removal method first all PCCs were included. After applying the method a regression equation was determined where the PCCs *ARABLE* and *HIGHP* were included. However, as could be concluded from the ANOVA table based on the F-test the null-hypothesis still was accepted. A value of 0.117 was generated. Therefore, this established relationship is not significant and should not be used for estimating *FC.* Hereafter transformation of model parameter *FC* has been evaluated to enhance the significance of the regression equation. It turned out that transformation from *FC* to 1/*FC* resulted in an increase of the model with respect to the significance and strength from 0.117 to 0.026 with an r^2 of 40.6%. With respect to hydrological integrity it is partially interpreted as a feasible relationship. Table 8-3 is generated which shows the regression coefficients of the PCCs and accompanying significance. It is shown that *ARABLE* negatively contributes and *HIGHP* positively contributes to estimating *FC.* From hydrological point of view it can be interpreted as follows. A higher amount of *ARABLE* available in the catchment will lead to a lower predicted value. A lower predicted value however results in a higher value for *FC* due to the applied transformation. Thus, more *ARABLE* leads to a higher *FC* which is interpreted to be hydrologically feasible. With respect to *HIGHP* a larger amount results in an increase of the predicted value and therefore a decrease of *FC.* However, it is expected that in higher permeable soil a higher maximum soil moisture occurs. Therefore the latter part of the regression equation is questioned.

Table 8-3. Statistical characteristics for regression equation FC after transformation including ARABLE and HIGHP

1/ FC = $\beta_0 + \beta_1$ * ARABLE + β_2 * HIGHP					
	Coefficients	*P value*	*Std Error*	*t Stat*	*VIF*
β_0	0.00542	5.31542E-07	0.000626	8.669	
β_1	-0.000105	0.00872	3.4377E-05	-3.046	3.494
β_2	6.68508E-05	0.01262	2.33827E-05	2.859	3.494

BETA

With respect to the significant correlations as described in paragraph 8.2.1 these are all used as the initial model required for the forward entry method. After executing this method, two significant and equal strong relationships were determined. The first regression equation included the PCCs *ARABLE* and *URBAN.* The second equation included the PCCs *SAAR* and *URBAN.* Only a slight difference occurred in the strength of the equation. Respectively a r^2 with a value of 45.3 % and 46.7 % were generated. Therefore based on hydrological interpretation one of these two equations should be selected. For both equations the statistical characteristics are shown in respectively table 8-4 and 8-5. As can be seen in both equations *URBAN* negatively contributes to the estimated value of *BETA.* Thus, when a larger part of the catchment is contributed to PCC *URBAN*, lower values of *BETA* are generated. Subsequently more precipitation will become available for runoff and less precipitation is used to fill up the soil moisture state and this is interpreted as a hydrological feasible relationship. In addition, in the first regression equation *ARABLE* is assigned. This PCC also is negatively related to *BETA*. Thus, if more area is ascribed to *ARABLE* lower values of *BETA* are generated which means that more precipitation will become available for runoff generation. This is interpreted as a feasible justification. In the second regression equation *SAAR* is added. It positively contributes to *BETA* and as described in paragraph 8.2.1, this relationship is questioned. From these interpretations, the first regression equation is assumed to be the most feasible.

Besides applying the forward entry method, also the backward removal method is executed. Through this method a totally different regression equation was derived, where seven PCCs are incorporated. These are *SHAPE, SAAR, WOOD, ARABLE, GRASS, MOUNTAIN* and *URBAN.* As can be seen, the latter five PCCs all belong to the group land use. Hundecha and Bárdossy (2004) also a-priori related land use to parameter *BETA*. Since all PCCs of the group land use are ascribed, it can be concluded that the group land use collectively leads to estimation of the model parameter. However, it is not desirable to include PCCs which show a large correlation since they therefore convey the same information in the regression equation. In appendix M the correlation coefficients between PCCs are shown, and it can be concluded that the PCC *ARABLE* is highly correlated with three other PCCs within the group land use. The values generated are -0.863, -0.535 and 0.845. For this reason the backward removal method is repeated with the exclusion of *ARABLE.* Now again a totally different equation was determined which corresponds with the second regression equation established through the forward entry method.

Table 8-4. Statistical characteristics for regression equation BETA including ARABLE and URBAN

BETA = $\beta_0 + \beta_1$ * ARABLE + β_2 * URBAN					
	Coefficients	*P value*	*Std Error*	*t Stat*	*VIF*
β_0	3.244	1.63031E-07	0.339	9.558	
β_1	-0.02328	0.03433	0.00993	-2.344	1.058
β_2	-0.09863	0.08537	0.05328	-1.851	1.058

Table 8-5. Statistical characteristics for regression equation BETA including URBAN and SAAR

$BETA = \beta_0 + \beta_1 * URBAN + \beta_2 * SAAR$					
	Coefficients	*P value*	*Std Error*	*t Stat*	*VIF*
β_0	1.542	0.02046	0.590	2.613	
β_1	-0.128	0.02490	0.05113	-2.512	1.000
β_2	0.00115	0.02795	0.000471	2.452	1.000

LP

As initial model used for the forward entry method, the simple regression equation with the PCC *SAAR* is used. However no PCCs could be added to the equation. Henceforward, the backward removal method was executed. Here also the simple regression equation with the PCC *SAAR* remained.

ALFA

With respect to the forward entry method no relationships could be used for the initial model since no significant correlations could be determined. Due to the fact that *HI* almost turned out to be significant, it was forced into the model and the forward entry method was applied. Still, no sensible regression equation was determined even if the data set was transformed. With respect to the backward removal method, a regression equation was determined. The PCCs *ELEVATION, HI* and *LOWP* were incorporated and the equation resulted in a reasonable strong relationships with a value for r^2 of 42.4%. Also no outliers, leverage or influence cases could be determined. In table 8-6 the statistical characteristics are shown and as can be seen *ELEVATION* is negatively related to *ALFA* whereas *HI* and *LOWP* are positively correlated. From the hydrological perspective the following can be said. *ELEVATION* is negatively related to *ALFA* and therefore higher altitude catchments generate lower values for *ALFA* which indicates a more linear rainfall-runoff generation. However, a positive relationship is expected thus in higher altitude catchments a more non-linear rainfall-runoff generation and therefore higher values for *ALFA*. With respect to the negative relationship between *ALFA* and *HI* as already addressed in paragraph 8.2.1 the relationship could not be justified. At last the positive contribution of *LOWP* to *ALFA* seems to be sensible, since at catchments with a larger area of weak permeability higher and more non-linear runoff coefficients are expected. Due to these three interpretations the hydrological feasibility of this relationship is questioned.

Table 8-6. Statistical characteristics for regression equation ALFA including ELEVATION, HI and LOWP

$ALFA = \beta_0 + \beta_1 * ELEVATION + \beta_2 * HI + \beta_3 * LOWP$					
	Coefficients	*P value*	*Std Error*	*t Stat*	*VIF*
β_0	-0.06649	0.841	0.324	-0.205	
β_1	-0.00155	0.06726	0.000775	-1.997	1.136
β_2	1.652	0.04896	0.761	2.172	1.029
β_3	0.00350	0.07532	0.00181	1.933	1.166

K_f

As initial model for the forward entry method, the regression equation with *HI* in its initial form and transformed form is evaluated. The best regression equation is presented when in the initial form *SAAR* is added. This relationship generates a value for r^2 of 35.3% and in table 8-7 corresponding statistical characteristics are shown. With respect to *SAAR* it can be interpreted as a feasible relationship. A positive relationships is generated which indicates that at wetter catchments, more precipitation will become quicker available for runoff. From the backward removal method another regression equation is derived. Concerning statistical characteristics are shown in table 8-8. As can be seen the PCCs *ELEVATION, HI* and *URBAN* are incorporated in the regression equation. In addition each regression coefficient generates a hydrological feasible relationship. Furthermore the equation is relatively strong since the r^2 generates a value of 55.5% and no strong correlation occurred between the PCCs. For K_f the latter equation is therefore the most feasible.

Table 8-7. Statistical characteristics for regression equation with K_f determined through forward entry method including HI and SAAR

Kf = β0 + β1 * HI + β2 * SAAR					
	Coefficients	*P value*	*Std Error*	*t Stat*	*VIF*
β_0	0.09316	0.108	0.05429	1.716	
β_1	-0.267	0.05331	0.127	-2.110	1.002
β_2	5.15704E-05	0.08263	2.75873E-05	1.869	1.002

Table 8-8. Statistical characteristics for regression equation with K_f determined through backward removal method including ELEVATION, HI and URBAN

Kf = β0 + β1 * ELEVATION + β2 * HI + β3 * URBAN					
	Coefficients	P value	Std Error	t Stat	VIF
β_0	0.05866	0.246	0.04833	1.214	
β_1	0.000347	0.01221	0.000119	2.908	1.277
β_2	-0.274	0.02654	0.110	-2.501	1.010
β_3	0.00775	0.02004	0.00292	2.649	1.287

K_s

For K_s it was not possible to perform the forward entry method since no initial model could be determined. With respect to the backward removal method a significant and strong relationships was determined which incorporated 8 PCCs and which rendered a value for r^2 of 84.9%. However, the same issue as addressed regarding model parameter *BETA* arose. All PCCs concerning to the PCC group land use were incorporated. Due to the high correlation of *ARABLE* with the other PCCs it was neglected and the backward removal method was repeated. In this case no significant regression equation was derived.

PERC

With respect to parameter *PERC* as the initial model for the forward entry method the relationship with *HI* was used. However no PCCs were added. Subsequently the backward removal method was executed. In this case the derived relationship with accompanying statistical characteristics is shown in table 8-9. A reasonable strong relationship was generated with a value for r^2 of 54.2%. As already described in paragraph 8.2.1 the positive relationship between *PERC* and *HI* could be confirmed. With respect to *ARABLE* also a positive relationship is determined which indicates that when allocating a larger part of the total area of the catchment to *ARABLE* an increase in *PERC* is estimated. From a hydrological point of view this relationship could not be confirmed. With respect to *HIGHP* a negative contribution to *PERC* is derived which from hydrological interpretation is not expected. Therefore, in total the regression equation is questioned.

Table 8-9. Statistical characteristics for regression equation with PERC including HI, ARABLE and HIGHP

$PERC = \beta_0 + \beta_1 * HI + \beta_2 * ARABLE + \beta_3 * HIGHP$					
		P value	*Std Error*	*t Stat*	*VIF*
β_0	-1.315	0.08548	0.706	-1.861	
β_1	6.684	0.00252	1.792	3.730	1.180
β_2	0.02700	0.07702	0.01406	1.920	3.741
β_3	-0.01815	0.09143	0.00996	-1.823	4.056

8.2.3. Conclusion

In the two previous paragraphs the results from the simple linear and multiple linear regression analysis are described. Several significant relationships between model parameters and PCCs could be determined. However, it is of importance that the relationships to be used for estimating concerning model parameters should also be sensible relationships from the hydrological point of view. This aspect is expounded at the same time in previous two paragraphs. After evaluating the significance and hydrological integrity of the relationships, for each model parameter the most sensible relationship is selected which is shown in table 8-10. As can be seen in the first column several model parameters are underlined. It means that concerning selected regression equations still are questioned from a hydrological point of view.

With respect to the regression equation of *FC* only a significant relationship could be determined when applying transformation of the model parameter values. The correlation with PCC *ARABLE* is interpreted to be hydrologically feasible but the correlation with *HIGHP* is not. Therefore this relationship is questioned from the hydrological point of view. In addition in the literature it is indicated that *FC* was positively correlated with *ELEVATION* (Merz and Blöschl, 2004). However in this study this correlation was very weak and in addition, it turned out to be negative.

With respect to *BETA* the most significant correlations could be demonstrated. However, after applying multiple linear regression analysis it turned out that two combinations resulted in a stronger relationship being almost equally strong. Based on hydrological interpretation the equation which incorporates the PCCs *ARABLE* and *URBAN* is selected. The reason that the other regression equation was rejected is based on the fact that it included a positive relationship with the PCC *SAAR.* This is underpinned by the fact that based on general understanding of runoff processes in different climates (see e.g. Goodrich et al., 1997) a negative relationship should occur. Furthermore several other studies indicated a relationship with *AREA* but in this study it could not be demonstrated.

Regarding *LP* the strongest simple correlation with the PCC *SAAR* was proved. During the multiple regression analysis no improvement of significance and strength could be generated. However, transformation of *LP* itself with respect to the simple regression equation resulted in an increase of strength but the hydrological feasibility of this relationship could not be confirmed and therefore this relationship still is questioned. In addition *LP* could also not be related to *ELEVATION* as addressed in another study (Merz and Blöschl, 2004). However this relationship resulted from the high correlation between *LP* and *FC.* In this study this relationship could not be demonstrated while a value for r of 0.075 was generated.

With respect to parameter *ALFA* at first after transformation a single regression equation with the PCC *HI* could be demonstrated. After performing multiple regression analysis it turned out that an inclusion of *ELEVATION* and *LOWP* resulted in an increase of significance and strength while the transformation was neglected. However, the total regression equation is questioned since the correlation between *ALFA* and *ELEVATION* as well as *HI* could not be confirmed.

Regarding K_f at first a significant relationship with *HI* could be proved which from the hydrological point of view was confirmed. After applying multiple regression analysis the PCCs

ELEVATION and *URBAN* are added which leads to the strongest established relationship with a value for r^2 of 55.5%. Hydrologically interpreted these added PCCs also could be confirmed.
For model parameter K_s no significant regression equation could be demonstrated. Although at first an equation was derived with 8 PCCs, it was decided to repeat the multiple linear regression analysis without the PCC *ARABLE* since it was very high correlated with the other PCCs. This finally led to no significant equation and therefore no relationship is selected.
With respect to model parameter *PERC* two significant equations could be demonstrated. One resulted from the simple linear regression analysis which included PCC *HI*. From the hydrological point of view this relationship was confirmed. In the second equation besides *HI* the PCCs *ARABLE* and *HIGHP* were added to generate a stronger relationship. However, the correlation with *HIGHP* could not be confirmed and therefore the single linear regression equation with the PCC *HI* is selected.

What is remarkable evaluating the selected regression equations is that in the regression equation for *ALFA* as well as K_f both the PCCs *ELEVATION* and *HI* are incorporated. Yet, it could be expected since these model parameters are both assigned to the quick runoff routine for calculating the contribution of the quick flow to the total runoff. Additionally can be remarked that the regression coefficients of these PCCs are of opposite sign in both equations. This probably results from the fact that the model parameters *ALFA* and *Kf* are highly negatively correlated. The correlation coefficient rendered a value of -0.710.
Furthermore in general the same PCCs are used for estimating the model parameter values. As can be seen from table 8-10 the PCC *HI* is incorporated three times. The PCCs *ARABLE, URBAN* and *ELEVATION* are two times used in estimating accompanying values. Therefore these four PCCs indicate to be the best descriptors for different hydrological processes. Concerning PCC *SHAPE* it was introduced since no data for the slope of the catchments could be derived. Since the slope of the catchment indicated to be a proper PCC for several rainfall-runoff processes as shown in several other studies, it was expected that *SHAPE* also would be a proper indicator. However, in none of the relationships it was incorporated and in general low correlation coefficients with model parameters were generated. Also with respect to *AREA* in the literature several relationships could be determined. However, in this study no significant relationships could be established. Thus, *AREA* also turned out not to be an appropriate PCC in this study.

Table 8-10. Statistical characteristics for the selected regression equations; underlined model parameters are questioned based on hydrological interpretation

Model parameter	**Regression equation**	**F-significance**	**Correlation**	**Strength**
FC	1/ FC = 0.0054 – 0.000105 * ARABLE + 0.0006685 * HIGHP	2.6 %	0.637	40.6 %
BETA	BETA = 3.244 – 0.02328 * ARABLE – 0.09863 * URBAN	1.5 %	0.673	45.3 %
LP	EXP (LP) = 1.568 + 0.000630 * SAAR	0.2 %	0.691	47.7 %
ALFA	ALFA = -0.06649 - 0.00155 * ELEVATION + 1.652 * HI + 0.00350 * LOWP	6.0 %	0.651	42.4 %
K_f	Kf = 0.05866 + 0.000347 * ELEVATION – 0.274 * HI + 0.00775 * URBAN	1.2 %	0.745	55.5 %
K_s	---	---	---	---
PERC	PERC = – 0.595 + 5.615 * HI	0.6 %	0.639	40.8 %

8.3. Results validation

In this paragraph the regional model is validated and evaluated. The validation approach is already described in paragraph 7.2. In the previous paragraph for each model parameter a regression equation is selected based on statistical significance and hydrological integrity. The regional model therefore incorporates these regression equations as shown in table 8-10. As can be seen for model parameter K_s no regression equation could be derived and to execute a model simulation, a value is required. For this model parameter therefore the default value as determined in paragraph 7.2 is used which has a value of 0.0315. When applying the PCC values and perform a model simulation, for each validation catchment SOF values are generated. After initial evaluation of regional model performance, it turned out that for two catchments infinitive values were calculated. This urged to apply more analysis which is executed in the form of evaluating the used PCC values and the generated model parameter values. This is described below.

8.3.1. Evaluation of physical catchment characteristic and model parameter space

At first it is evaluated if the values for the used PCCs are representative for the established regional model. The generated regression equations are based on the values of the PCCs belonging to the selected calibration catchments. If values belonging to the validation catchments are higher or lower than the values used for establishing the regression equations, it is not guaranteed that the regression equation is valid. Reason for this is the fact that the validation catchments are selected from the initial available 56 catchments. In addition, selection of these catchments is based on their diversity in climate and physiography which is described in paragraph 7.3.1. Eventually, just 17 catchments are used to establish the regression equations and therefore the initial PCC space which is determined through the absolute minimum and maximum value of all 56 catchments could be narrowed.

Furthermore, it is evaluated if the generated model parameter values are representative for the regional model. It may be that a specific combination of values of PCCs used in the regression equation result in a parameter value which lay outside the model parameter space used to derive the regression equations.

In order to overcome using values outside the PCC space and using generated parameter values outside the model parameter space as described above, it is chosen for to introduce two constraints which have to be assessed consecutively and which are stated as follows:

1. For PCC values outside the PCC space determined through the minimum and maximum value of the 17 catchments used for establishing the regression equations, the closest boundary value of the PCC space is used for calculating concerning model parameter value;
2. For generated model parameter values outside the model parameter space determined through the minimum and maximum value of the 17 catchments used for establishing the regression equations, the closest boundary value of the model parameter space is used for calculating the SOF values.

Both above stated constraints underpin the fact that the objective is not to assess the potential of the regional model to be applied in catchments in a different climate or with contrasting physiographic conditions. Although it is possible to optimize the regional model (e.g. by evaluating if default values for several model parameters instead of using the established regression equations result in better model performance) it is not the intention in this study.

In table 8-11 for each catchment the values of the PCCs before and after application of the constraints are shown. As can be seen also the PCC space determined by the calibration catchments are shown. When two values are presented, the first value represents the original PCC value and the second value represents the adjusted value imposed by the constraint. As shown, in total for three PCCs accompanying values lay outside the PCC space. For catchment 27034 *ELEVATION* exceeds the maximum with 6%. Regarding catchment 38029 the two other PCCs exceed the maximum. *HI* also exceeds the maximum boundary with 6% but the PCC *ARABLE* is exceeded with 26% which is considerably much. Besides presenting the PCC values, also the generated model parameter values are shown. As can be seen, in table 8-12 for each catchment concerning generated model parameter values are presented. In addition, for each model parameter the absolute minimum and maximum value of all 17 catchments used for establishing the regression equations are shown. Also for this table applies that when two values are generated, the first value represents the original model parameter value and the second value represents the adjusted value imposed by the constraint. Furthermore, the bold and underlined values are adjusted based on the first constraint i.e. due to adjustment of the PCC values. As can be seen in table 8-12, in total eleven values are adjusted from which four are adjusted due to the first constraint and seven are adjusted due to crossing of the model parameter space. Mainly model parameter *FC* experiences crossing the minimum value of the model parameter space for calibration. For four out of eight validation catchments very low values are generated. These values even lay outside the initially used model parameter space for calibration of all 48 catchments where a lower boundary of 125 was applied. What also turns out is the fact that model parameter K_f initially generates negative values for two catchments. Exactly those two catchments generate infinitive values with respect to the SOFs as addressed at the beginning of this paragraph.

Table 8-11. PCC values belonging to the validation catchments; min. and max. values of PCCs belonging to calibration catchments; first value is generated without the constraint, second value with the constraint

		Used physical catchment characteristics						
		ELEVATION	*HI*	*ARABLE*	*URBAN*	*HIGHP*	*LOWP*	*SAAR*
Cal.	*Max*	341.5	0.520	62.4	12.6	100	100	2055
	Min	38.5	0.21	0.4	0.4	0	0	620
Validation	*27034*	364.8 / 341.5	0.444	2.3	1.1	0	0	1342
	27056	166.4	0.520	26.1	2.4	0	30.3	828
	31010	112.8	0.391	51.2	3.0	28.3	71.1	640
	38029	118.0	0.555 / 0.520	78.9 / 62.4	1.8	100	0	625
	42008	120.9	0.392	50.2	3.2	100	0	889
	47008	162.7	0.378	15.1	1.9	0	100	1143
	53013	110.9	0.285	35.2	7.9	22.4	40.8	724
	60010	232.7	0.282	2.2	1.5	0	99.2	1534

Table 8-12. Estimated model parameter values for the validation catchments; min. and max. values belonging to the calibration catchments; first value is generated without the constraints, second value with the constraints, bold and underlined values are adjusted based on the constraint regarding the PCC space

		Derived model parameter values						
		FC [mm]	BETA [-]	LP [-]	ALFA [-]	Kf [day $^{-1}$]	Ks [day $^{-1}$]	PERC [mm day $^{-1}$]
Cal.	*Max*	705.3	3.76	0.99	1.10	0.1402	0.0914	2.48
	Min	138.8	1.16	0.41	0.15	0.0058	0.0134	0.31
Validation	*27034*	193.8	3.08	0.88	0.10 / 0.15	0.0721 / **0.0640**	0.0315	1.90
	27056	376.0	2.39	0.74	0.64	-0.0071 / 0.0058	0.0315	2.33
	31010	52.7 / 138.8	1.75	0.68	0.65	0.0139	0.0315	1.60
	38029	15.6 / 138.8	1.23 / **1.61**	0.67	0.67 / **0.61**	-0.0384 / 0.0058	0.0315	2.52 / **2.32**
	42008	14.9 / 138.8	1.76	0.76	0.39	0.0180	0.0315	1.60
	47008	262.2	2.71	0.83	0.66	0.0263	0.0315	1.53
	53013	59.9 / 138.8	1.65	0.71	0.37	0.0803	0.0315	1.00
	60010	193.4	3.08	0.93	0.38	0.0738	0.0315	0.99

Furthermore for catchment 27034 a value for *ALFA* is generated which crosses the minimum value of the model parameter space for calibration (i.e. a value of 0.15). With respect to adjustments imposed by the first constraint, in general minor adjustments are applied. Only model parameter *BETA* is adjusted considerably i.e. from 1.23 till 1.61, but when compared with the model parameter space this adjustment still is reasonably small for catchment 38029.

Concluding can be stated that the effect of the second constraint is larger than the first constraint. The first constraint in general leads to minor adjustments of the model parameter values. Especially when compared with the applied model parameter space. The second constraint on the contrary has a major influence on the used model parameter values for calculating the SOF values which is reflected in adjustment of model parameters *FC* and K_f. With respect to all eight validation catchments, for only two catchments no adjustments are carried out with respect to the model parameter values (i.e. catchment 47008 and 60010).

8.3.2. Evaluation of the performance of the regional model

With the definitive regional model accompanying SOF values are generated and these are presented in table 8-13. Also the values from the initial regional model are incorporated so it is able to evaluate the improvements of the definitive regional model i.e. including the two constraints. When two values are presented, the first value corresponds to the initial regional model and the second value to the definitive regional model. In addition, for each validation catchment the SOF values belonging to the optimum parameter set and the default values are calculated and presented. Moreover, the absolute maximum SOF values for each catchment are derived which are based on 10000 model simulations and those are also added to the table. As can be seen several values are presented in bold and are underlined. This is only the case for the initial and definitive regional model and it means that those SOF values are lower than the SOF values generated with the default parameter set. Thus, lower values indicate worse performance with the definitive regional model than the model performs with default parameter values.

With respect to catchment 27034, it can be seen that both the regional models perform worse than the default parameter set with respect to R^2, R_H^2 and RV_E. The difference concerning R^2 is reasonably small, but still it performs badly. Concerning R_H^2 the decrease is much bigger, while the difference between the optimum parameter set and the default parameter set is very small. Although RV_E performs worse than the default parameter set, it still performs well i.e. a value between -5 % and 5 %. With respect to R_L^2 the increase is substantial but still the performance is tremendously bad (i.e. a value of -56.117 for the definitive regional model). The differences between the initial regional model and the definitive model are in general very small. However, improvements have been made. As can be seen from table 8-12 only parameter *ALFA* and K_f are changed. These model parameters influences the peak discharge the most as described in paragraph 5.5, which is underpinned by the increase of R_H^2.

With respect to catchment 27056 it immediately stands out that for the initial regional model infinitive values are generated for all SOFs. It seems that the model is not able to execute a simulation at all and after evaluation of the model parameter values, it turns out that for model parameter *Kf* negative values have been generated. With respect to the SOF values generated with the definitive regional model it is remarkable that R^2 has higher values than the default values as well as the optimum parameter set. It is the only catchment where this occurs for R^2. However, the performance still is bad since a value of 0.081 is generated. In contrast to the maximum obtainable value it can be concluded that this catchments is hard to calibrate at all i.e. no value higher than 0.221 have been generated. With respect to the other three SOFs, the values are all slightly lower than have been generated with the default parameter set.

Concerning catchment 31010 it is shown that between the initial and the definitive regional model an increase for three out of four SOFs is obtained. This results solely from the adjusted model parameter value FC and is most effective for R_L^2 (i.e. an increase from -109.6351 to -12.406). With the definitive regional model a reasonable model performance is generated i.e. a value for R^2 higher than 0.6. Still, the performance is worse than the performance generated with the default parameter set. This applies for three SOFs whereas RV_E generates a better value.

Concerning catchment 38029 the same issue occurs as with catchment 27056. It means no SOF values have been generated with the initial regional model due to the negative value of K_f. However, after generating the values with the definitive regional model, still a bad model performance is obtained. Besides, for the SOFs R^2, R_H^2 and R_L^2 worse values have been generated than with the default parameter set. Only model performance with respect to the SOF RV_E increases, but still it performs badly i.e. a value of 112.121.

Catchment 42008 turns out to be the worst performing catchment for the initial regional model as well as the definitive regional model and the default parameter set. Although the definitive regional model increases considerably with respect to R^2, it still generates a value of -19.883.

Catchment 47008 on the contrary performs the best of all catchments. Besides, it is one of the two catchments for which no adjustments have been made with respect to the model parameter values. A value for R^2 of 0.832 has been generated which indicates to be a well performing regional model. Still, the default parameter set is able to perform better since a value of 0.844 is generated. In addition, the optimum parameter set generates a value of 0.845. With respect to the SOF R_H^2 also a decrease is obtained i.e. from -1.942 to -3.461. However, the default value performs better than the optimum parameter set does. With respect to R_L^2 a substantial increase has been obtained. Still, a value of -70.171 is generated which means this catchment performs extremely badly with respect to low flow conditions. RV_E on the contrary even performs better than the default parameter set as well as the optimum parameter set.

With respect to catchment 53013, most improvement is obtained when assessing the increase of model performance between the initial regional model and the definitive regional model. Each SOF value, with the exception of RV_E, increased significantly. With respect to R^2 an increase from 0.327 to 0.702 was obtained. Thus at first the model performed badly but after applying the constraints, the model performs reasonably. Furthermore R_L^2 also increased tremendously, but still performs badly. What stands out is the fact that these improvements are established by adjusting just one model parameter value i.e. FC from 59.9 to 138.8.

Concerning catchment 60010 it can be stated that it is the only catchment where the definitive regional model performs better than the default parameter set for all SOFs. However, the model still performs badly i.e. a value for R^2 of 0.448 is generated. In addition, SOF RV_E still is performing inadequate since it generates a value of 21.336.

From above described evaluation, it can be stated that the imposed constraints improved model performance of the initial regional model. In total 20 SOF values increased while 4 decreased. The remaining 8 SOF values stayed unchanged since no adjustments in model parameter values were generated. When evaluating total model performance of the definitive regional model in comparison to model performance using the default parameter set, it can be concluded that the regional model performs worse. In total just 13 SOFs generate higher values than the default parameter set while for 19 SOFs the default model parameter set performs better. In addition, with respect to the high flow SOF R_H^2 the default model parameter set even performs for 7 out of 8 validation catchments better than the regional model. However, it is difficult to point out which specific model parameter influences this particular aspect the most. What also is shown is that for some default parameter sets, higher values for SOFs are generated than with the optimum parameter set. This underpins the issue of a trade-off existing between the SOFs used jointly in the MOF.

Table 8-13. Values of SOFs concerning the three different model simulations including the absolute maximum value based on 10000 model runs; bold and underlined presented values are lower than the calculated default values.

		R^2 [-]	R_H^2 [-]	R_L^2 [-]	RV_E [%]
27034	*Absolute maximum value*	0.766	-0.097	0.490	0.003
	Optimum parameter set	0.747	-0.245	-3.311	-0.307
	Regional model	**0.532** / **0.553**	**-6.057** / **-5.100**	-55.980 /-56.117	**-1.483** / **-1.436**
	Default values	0.622	-0.301	-224.590	1.045
27056	*Absolute maximum value*	0.221	-1.994	0.507	0.006
	Optimum parameter set	-0.011	-2.797	-4.117	2.990
	Regional model	**Infinity** / 0.081	**Infinity** / **-3.278**	**Infinity** / **-13.122**	**Infinity** / **-12.294**
	Default values	-0.735	-2.607	-10.211	12.079
31010	*Absolute maximum value*	0.770	0.315	0.821	0.022
	Optimum parameter set	0.745	-0.636	-0.837	-4.875
	Regional model	**0.534** / **0.611**	**-2.705** / **-2.912**	**-109.351** / **-12.406**	**12.502** / -2.643
	Default values	0.718	-1.104	-8.353	3.227
38029	*Absolute maximum value*	0.649	0.793	0.042	0.005
	Optimum parameter set	0.646	0.270	-21.259	0.056
	Regional model	**Infinity** /**-0.042**	**Infinity** / **-0.137**	**Infinity** / **-336.461**	**Infinity** / 112.121
	Default values	0.254	-0.040	-201.183	119.356
42008	*Absolute maximum value*	0.552	0.101	-0.392	0.005
	Optimum parameter set	0.469	-4.917	-1.176	-0.493
	Regional model	-29.592 / -19.883	-307.321 / **-310.829**	**-880.613** / -124.873	**121.072** / **85.766**
	Default values	-36.590	-308.227	-139.454	85.657
47008	*Absolute maximum value*	0.864	-0.885	0.450	0.002
	Optimum parameter set	0.845	-2.189	-2.693	-1.863
	Regional model	**0.832**	**-3.461**	-70.171	-1.465
	Default values	0.844	-1.942	-142.418	6.943
53013	*Absolute maximum value*	0.820	0.641	0.366	0.076
	Optimum parameter set	0.716	-0.804	-10.396	-7.900
	Regional model	**0.327** / **0.702**	**-4.994** / **-1.771**	**-262.284** / **-50.234**	3.841 / -6.309
	Default values	0.787	-0.600	-20.986	-6.348
60010	*Absolute maximum value*	0.780	0.524	0.683	0.565
	Optimum parameter set	0.759	0.265	-0.689	11.118
	Regional model	0.448	-0.150	-1.410	21.336
	Default values	-0.464	-1.016	-1.976	22.107

8.3.3. Additional evaluation of the regional model applied at the calibration catchments

In previous paragraph 8.3.2 the performance of the regional model at the ungauged catchment is evaluated. Due to the generated results, the interest arose to evaluate the performance of the regional model at the calibration catchments which satisfied both stated conditions as addressed in paragraph 5.4.8. In this paragraph it is not the essence to quantitatively assess the change of model performance as is performed in the previous paragraph.

In table 8.14 the generated model parameter values due to the regional model used at the calibration catchments are shown. When two values are presented, the first value represents the generated model parameter value by the regional model and the second value represents an adjusted model parameter value. The adjustment of model parameter values are based on the same constraints as introduced in paragraph 8.3.1. Moreover, the first introduced constraint as described in paragraph 8.3.1 is not applicable to the calibration catchments since the defined PCC space is determined based on these calibration catchments. Therefore none of the values lay outside the defined PCC space and hence, only the second constraint is applicable to these calibration catchments. In addition, several catchment numbers are presented in bold and are underlined which means that for these catchments the model parameter values did not have to be adjusted by the constraint. As can be seen from table 8.14, this concerns for 7 out of 17 catchments. Furthermore it is shown that for the remaining 10 catchments, mainly model parameter *FC* experiences crossing the minimum value of the model parameter space. This corresponds with the adjustments made at the validation catchments as described in paragraph 8.3.1. Here also mainly *FC* crosses the model parameter space i.e. for 4 out of 8 catchments. In addition, what also corresponds is that for model parameter K_f negative values are generated. This concerns for two catchments which are 33019 and 60006. Moreover, for catchment 27035 the generated value of model parameter *ALFA* crosses the parameter space and for catchment 60006 the value for model parameter *LP* crosses the parameter space. Concluding it can be stated that the applied constraint concerning the generated model parameter values results in adjustment of rather many model parameter values and hence, this applies for many catchments.

Also the calculated SOF values of the regional model applied to the calibration catchments are presented. These are shown in table 8.15 and as can be seen, values are presented with and without application of the constraint. When the SOF values are shaded in grey it means that concerning catchment satisfies both conditions as stated in paragraph 5.4.8. In addition, with respect to the regional model with application of the constraint, several catchment numbers are presented in bold and are underlined. This means that for these catchments the model parameter values have not been adjusted due to the constraint.

When evaluating the SOF values of the regional model without the constraint, it turns out that from a total of 17 catchments just 4 catchments satisfy the two stated conditions which corresponds with 24%. As shown for catchment 33019 and 60006, infinitive SOF values are generated which result from the fact that negative values for K_f are generated. This also occurs for two validation catchments as described in paragraph 8.3.1. Moreover, all the catchments where model parameter *FC* crosses the minimum value of the model parameter space do not satisfy both stated conditions. Thus, it can be stated that the performance of concerning catchments decreases significantly.

When evaluating the regional model with application of the constraint, it is shown that 6 out of 17 catchments satisfy the two stated conditions which correspond with 35%. Catchment 60006 which without the constraint generated infinitive SOF values now satisfies both conditions. For catchment 33019 this however is not the case. Also catchment 27035 satisfies both conditions after application of the constraint. For this catchment model parameter *ALFA* has been adjusted. In addition, none of the catchments for which model parameter *FC* has been adjusted satisfies both conditions.

From above described evaluation, it can be stated that still many model parameter values lay outside the derived model parameter space and therefore are adjusted due to the constraint. Especially for model parameter *FC*, for which 7 out of 17 catchments concerning values are adjusted. Additionally, it can be stated that the performance of the regional model still is dissatisfying. Without application of the constraint just 4 catchments satisfy both conditions whereas application of the constraint results in 6 catchments satisfying both conditions. Thus, a significant decrease in performance of the regional model applied to the calibration catchments is demonstrated. This corresponds with the significant decrease in performance of the regional model applied at the validation catchments as described in previous paragraph 8.3.2.

Table 8-14. Estimated model parameter values for calibration catchments; min. and max. values belonging to the calibration catchments; first value is generated without the constraint, second value with the constraint; bold and underlined catchment numbers indicate that none of concerning model parameter values have been adjusted

		Derived model parameter values						
		FC [mm]	BETA [-]	LP [-]	ALFA [-]	Kf [day $^{-1}$]	Ks [day $^{-1}$]	PERC [mm day $^{-1}$]
Cal.	*Max*	705.3	3.76	0.99	1.1	0.1402	0.0914	2.48
	Min	138.8	1.16	0.41	0.15	0.0058	0.0134	0.31
Calibration catchments	*27035*	197.5	1.35	0.83	0.06 / 0.15	0.0896	0.315	1.03
	33019	15.2 / 138.8	2.30	0.67	0.64	-0.0205 / 0.0058	0.315	2.02
	41022	55.4 / 138.8	1.80	0.75	0.49	0.0502	0.315	0.81
	43006	32.5 / 138.8	1.71	0.75	0.40	0.0246	0.315	1.58
	45005	49.5 / 138.8	2.26	0.78	0.59	0.0416	0.315	1.91
	48003	316.1	1.87	0.85	0.67	0.0304	0.315	1.66
	48010	473.1	2.49	0.88	0.57	0.0681	0.315	1.21
	50001	330.4	1.93	0.83	0.34	0.0812	0.315	0.60
	52010	33.6 / 138.8	1.18	0.75	0.49	0.0292	0.315	1.31
	53009	44.5 / 138.8	1.90	0.79	0.60	0.0962	0.315	1.60
	54016	64.7 / 138.8	2.45	0.70	0.47	0.0531	0.315	0.84
	54029	342.2	3.02	0.73	0.48	0.0527	0.315	1.43
	55013	207.8	3.06	0.78	0.43	0.0560	0.315	1.77
	55014	211.5	2.03	0.78	0.30	0.0762	0.315	1.23
	57010	200.8	2.92	0.95	0.24	0.1116	0.315	1.35
	60006	202.5	3.19	0.95	0.85	-0.0010 / 0.0058	0.315	2.32
	66011	186.6	3.24	1.05 / 0.99	0.29	0.0928	0.315	1.21

Table 8-15. Values of SOFs concerning the regional model at the calibration catchments with and without the constraint; grey shade SOF values means the catchment satisfies both stated conditions as describe in paragraph 5.4.8; bold and underlined catchment numbers indicate that none of concerning model parameter values have been adjusted

Regional model - without constraint					**Regional model - with constraint**				
	R^2 [-]	R_H^2 [-]	R_L^2 [-]	RV_E [%]		R^2 [-]	R_H^2 [-]	R_L^2 [-]	RV_E [%]
27035	0.69	-4.017	-95.186	0.85	*27035*	0.775	-1.497	-93.691	1.101
33019	-Infinity	-Infinity	-Infinity	-Infinity	*33019*	0.706	-0.123	-11.977	-6.283
41022	0.519	-0.933	-1.713	30.003	*41022*	0.706	0.1	-6.109	16.699
43006	-0.95	-3.479	-954.011	27.867	*43006*	-0.102	-2.769	-188.39	12.158
45005	0.378	-2.396	-547.881	30.546	*45005*	0.56	-1.765	-623.357	19.782
48003	0.532	-0.563	-19.994	6.748	***48003***	0.532	-0.563	-19.994	6.748
48010	0.164	-1.525	-22.214	-7.037	***48010***	0.164	-1.525	-22.214	-7.037
50001	0.799	-2.894	-30.426	1.832	***50001***	0.799	-2.894	-30.426	1.832
52010	0.632	0.51	-874.316	19.359	*52010*	0.712	0.207	-137.539	6.105
53009	-1.52	-4.816	-61.263	9.244	*53009*	-0.53	-3.731	-44.937	-0.396
54016	-0.563	-12.817	-25.997	28.791	*54016*	0.262	-7.615	-32.309	13.767
54029	0.758	0.346	-0.774	-11.594	***54029***	0.758	0.346	-0.774	-11.594
55013	0.812	0.435	-5.003	2.436	***55013***	0.812	0.435	-5.003	2.436
55014	0.772	0.505	-5.25	0.031	***55014***	0.772	0.505	-5.25	0.031
57010	0.858	0.039	-1.75	-2.187	***57010***	0.858	0.039	-1.75	-2.187
60006	-Infinity	-Infinity	-Infinity	-Infinity	*60006*	0.886	0.315	0.728	-2.855
66011	0.737	-0.692	-1.667	-2.873	*66011*	0.734	-0.724	-0.034	-4.141

8.3.4. Conclusion

In paragraph 8.3.2 the performance of the regional model applied to the validation catchments is described. In addition, the interest arose to evaluate the performance of the regional model applied to calibration catchments which satisfy both stated conditions as described in paragraph 5.4.8. This is described in paragraph 8.3.3. From these evaluations the following can be stated.

Initial evaluation of the performance of the regional model applied at the validation catchments results in poor model performance. It turns out that PCC values are applied which lie outside the defined PCC space and that model parameter values are generated which lie outside the defined model parameter space. With the PCC space is meant the minimum and maximum PCC value of the 17 catchments used for establishing the regional model. Concerning the model parameter space, the minimum and maximum model parameter value of the 17 catchments used for establishing the regional model is meant. Especially parameter *FC* experiences crossing of the minimum value of the model parameter space. Moreover, model parameter K_f generates negative values for two catchments. To overcome applying model parameter values outside the model parameter space, it is chosen to introduce two constraints. These constraints concern the applicability of PCC values and the use of generated model parameter values. After application of these two constraints, the performance of the regional model applied at the validation catchments is evaluated. It turns out that the effect of the second constraint is larger than the first constraint and in general, the performance of the regional model increased considerably. However, when evaluating the performance of the regional model with the applied constraints in comparison to model performance using the default parameter set, it can be concluded that the model performance due to the regional model still is worse than when the default parameter set is applied. On a total of 32 generated SOF values, the regional model performs better merely for 13 SOFs than the default parameter set.

Additionally, the regional model is applied to the 17 calibration catchments from which the regional model has been established. Still, it turns out that for 10 out of 17 catchments concerning generated model parameter values lie outside the derived model parameter space. Again, especially model parameter *FC* experiences crossing of the model parameter space (i.e. for 7 out of 10 catchments) and therefore similar constraints are applied as has been used at the validation catchments. Moreover, the constraint concerning the PCC values is not applicable to the calibration catchments since the defined PCC space is determined based on these calibration catchments. Thus, no PCC values lie outside the PCC space. Still, the performance of the regional model with the applied constraint decreases significantly. Hence, application of the constraint resulted in 6 out of 17 catchments satisfying both conditions. Therefore, this additional evaluation confirms the demonstrated decrease in model performance by the regional model.

Concluding from these results, it can be stated that the regional model with application of the constraints performs not satisfactorily. In addition, it can be stated that using default parameter values at the ungauged catchments favours using the regional model.

9.

Conclusions, discussion and recommendations

In this chapter in paragraph 9.1 answers and conclusions regarding the research questions and the objective are drawn. Subsequently, a discussion has been raised which is described in paragraph 9.2. Eventually several recommendations are made and these are described in paragraph 9.3.

9.1. Conclusions

The main objective of this study is to contribute to reducing the uncertainty involved in predicting discharge at the ungauged catchment. Therefore in a structured way research has been executed through applying the classical approach of regionalisation which consists of three steps:

- First calibrating the hydrological model HBV against observed discharge for catchments in the United Kingdom in order to identify proper model parameter values.
- Subsequently establishing relationships between model parameters and climatic and physiographic data which all together merged in the HBV model is called the regional model.
- Finally estimate model parameter values at ungauged catchments using the regional model.

As the first step efficient and effective model parameters are selected which concern all the different aspects of the hydrograph. This due to the fact that in this study it is tried to establish a robust regional model which is able to adequately predict all the different aspects of the hydrograph such as total average flows, peak flows and low flows. Based on a profound evaluation of other studies where much experience is gained, in total 7 model parameters are selected which are: *FC, BETA, ALFA, LP,* K_f, K_s and *PERC*.

In addition for determining the optimum parameter set an approach is introduced which is based on application of Monte Carlo simulations using a composed multiple objective function (MOF). To be able to establish a robust regional model, four single objective functions (SOFs) are incorporated in the MOF each evaluating a particular aspect of the hydrograph. The four selected SOFs are the commonly used Nash-Sutcliffe coefficient (R^2), the relative volume error (RV_E), the Nash-Sutcliffe coefficient specifically adjusted for high flows (R_H^2) and the Nash-Sutcliffe coefficient specifically adjusted for low flows (R_L^2).

Subsequently, in order to establish relationships between model parameters and climatic and physiographic data appropriate so called physical catchment characteristics (PCCs) are selected which are expected to be of influence on generating catchment runoff. Selection of these PCCs is based on reviewing of studies at which 1) the HBV model has been regionalized at different geographical locations and 2) studies where other hydrological models have been regionalized at catchments throughout the United Kingdom. The selected appropriate PCCs eventually are evaluated based on availability of data. It resulted in selection of 14 different PCCs which are *AREA, ELEVATION, HI* (i.e. an altitude – area relationship), *SHAPE, SAAR* (i.e. the standard average annual rainfall), *5 types of soils* (i.e. *WOODLAND, ARABLE, GRASS, MOUNTAIN* and *URBAN*) and *4 classifications of hydrogeology* (i.e. *HIGHP, MODERATEP, LOWP* and *MIXEDP*).

Having calculated the optimum parameter set and accompanying SOF values, based on two conditions appropriate catchments are selected to be used for establishing the regional model. The conditions are based on the R^2 and RV_E and eventually 17 catchments satisfied both conditions. Together with the selected PCCs, it has been tried to establish a relationship for each model parameter. Through application of single linear regression analysis and also multiple linear regression analysis, in total for 6 out of 7 model parameters significant and relatively strong relationships are established. For model parameter K_s however no significant relationship could be determined and in order to be able to simulate at all, a default parameter value is used. In addition, out of the 6 established relationships still 3 are questioned from the hydrological point of view which are the relationships concerning model parameter *FC*, *LP* and *ALFA.*

Eventually the established relationships are validated using the ungauged catchment. Therefore a presupposition is made which states that 8 carefully selected well gauged catchments are interpreted as being ungauged. Hence, well observed discharge data are available and as a result it is possible to assess model performance of the regional model applied at the ungauged catchment. Model performance of the regional model is assessed with respect to model performance generated by the optimum parameter set as well as by a default parameter set. In this way it can be concluded how well the regional model performs instead of using the default parameter set which would have been used when there is no understanding about the hydrological processes occurring at the catchment.

Based on the applied methodology and the results, the following conclusions are drawn:

- Having assessed the performance of the regional model with respect to the optimum parameter set, it can be concluded that the established regional model performs not satisfactorily. At the start of this study it was expected that due to the regional model, the performance which is represented by R^2 would decrease, but within acceptable range. However, the decrease of R^2 turns out to be considerably for almost all 8 catchments. Additionally, the decrease of the other three SOFs varies from considerably up to very large, especially with respect to R_L^2.
- Having evaluated the performance of the regional model with respect to the default parameter set, it can be concluded that using default values at the ungauged catchment favours using the regional model. On a total of 32 generated SOF values, the regional model performs better merely for 13 SOFs than the default parameter set.
- The applicability of the classical approach of regionalisation of the hydrological model HBV with respect to adequately predicting all the aspects of the discharge regime at the ungauged catchment in general is questioned.

9.2. Discussion

In this study the process of regionalisation is applied in order to be able to predict discharge at the ungauged catchment. It was expected that the established regional model would reduce the uncertainty in parameter estimation at the ungauged catchments and therefore would result in an adequate prediction at the ungauged catchment. However, in this study it turns out that the concept of regionalisation with respect to the HBV model does not result in the expected reduction of uncertainty in predicting discharge at the ungauged catchment.

With respect to establishing the regional model, two main difficulties can be pointed out why regionalisation did not turn out to be successful. The first difficulty concerns the fact that the selected PCCs may not be sufficiently representative for the main driving characteristics in generation of the rainfall-runoff processes at the catchment. The second difficulty concerns the hard identification of proper model parameter values required for determining the regional model which is performed by model calibration. A commonly known problem which is called equifinality is that different parameter sets can be determined which lead to equally good simulation results and therefore it is almost impossible to determine a unique best model parameter set for each catchment. This may lead to generating optimum parameter sets which accidentally occurs and therefore the real present relationships between model parameter and physical catchment characteristics would be masked. On the contrary, significant relationships could be generated which in principal would not occur. In this study, this addressed weakness in model calibration is expected to be an important reason why regionalisation did not turn out to be successful. In addition, it is expected that due to this reason relationships are established which could not be confirmed from the hydrological point of view. Moreover, the additional evaluation as described in paragraph 8.3.3 underpins the assumption that statistical significant relationships could be generated which in principal would not occur.

For model parameter *FC* a significant statistical relationship with the PCCs *ARABLE* and *HIGHP* is determined, but it is questioned based on hydrological integrity. After application of the regional model at the validation catchments and at the calibration catchments, it turned out that for considerably many catchments very low parameter values are generated which indicate not to be realistic from the hydrological point of view. Thus, although the relationship turns out to be statistically significant, it generates for many catchments no realistic values what results in a disappointing performance of the regional model.

Furthermore, it can be stated that different sources of uncertainty underlie the stated problem of equifinality which are data limitations, overparameterisation of the model and structural deficiency of the model.

With respect to the data limitations it is not expected that qualitatively better data sets in temporal as well as spatial scale lead to a significant improvement of model calibration. Especially much effort has been put in deriving the required data sets at the appropriate temporal scale. Also the fact that all catchments are lumped represented in the HBV model is not expected to be a limitation for proper parameter identification. Especially since the sizes of the catchments are relatively small in comparison to other studies (e.g. Harlin and Kung (1992) and Bergström (1990)) and therefore it is not expected that subdividing the catchments into smaller units which supposed to be homogeneous result in significant improvements of deriving appropriate model parameter values.

Regarding the overparameterisation of the HBV model, which means that too many model parameters are applied to conceptualize the processes playing a role at the catchment, it is not expected that easily improvements could be made.

However, it is expected that partially a structural deficiency in the conceptual hydrological model HBV, which means that the conceptual hydrological model does not correctly conceptualize the real world hydrological processes, is a reason why no robust and adequate regional model could be derived. In what way this can be underpinned is described below.

It is expected that the main reason of dissatisfying results in proper model calibration and subsequently establishing the regional model results from the intention for the regional model. The method of regionalisation implies that with an optimum parameter set implemented in a hydrological model (i.e. the HBV model in this study) it is able to simulate all the different aspects of the hydrograph adequately. In this study it is tried to associate with this philosophy by incorporating all the aspects in the composed MOF particularly by letting them play a proportional role in identifying this optimum parameter set. It is expected that exactly this issue results in a bad identification of model parameter values which is underpinned by two observations. The first regards to the scatter plots shown in paragraph 8.1.2. Here it is tried to narrow the parameter space for all model parameters, but it turned out that not one parameter space could be well narrowed, and thus, not one of the model parameters is well-identifiable with respect to all the four incorporated SOFs. The second observation concerns the fact that particularly the slow flow SOF R_L^2 experienced much influence of the trade-off between the four SOFs. Concluding, the hydrological model HBV has difficulties with simulating adequately all the aspects of the hydrograph which can be stated to be a deficiency.

Another reason why in this study the problem of equifinality still occurs is the fact that the model parameters are dependent of each other. Main assumption for successful regionalisation is that the model parameters are not correlated. This also accounts for the PCCs. Especially the model parameters *ALFA* and K_f which both are incorporated in the quick flow routine render a large correlation coefficient of -0.710.

In addition, it is remarked that for 16 out of 17 calibration catchments which satisfy both stated conditions as described in paragraph 5.4.8, the PCC *SAAR* has values higher than 800 mm. This indicates that the HBV model has difficulty in properly identifying an optimum parameter set in catchments with a *SAAR* less than 800 mm when all aspects of the hydrograph are proportionally evaluated.

In this study, it is chosen for to apply two constraints due to the fact that the regional model generates model parameter values which lie outside the defined model parameter space. As described in paragraph 8.3.1, these constraints concern the applicability of PCC values and the use of generated model parameter values. However, when evaluating merely the catchments for which the generated model parameter values do not lay outside the model parameter space (i.e. they do not have to be adjusted), the following is remarked. Concerning the additional evaluation of the regional model at the calibration catchments, for 4 out of 7 catchments still the two stated conditions are satisfied which corresponds with 57%. Hence, this indicates that, in general, instead of applying constraints as has been chosen for in this study, it can also be considered not to apply the established regional model when adjustments should be made to the model parameter value. But, to apply a default parameter set.

9.3. Recommendations

Resulting from the conclusions and the discussion some recommendations can be made which are stated as follows:

- In order to deal with the problem of equifinality in other attempts of regionalising the HBV model, the concept of a unique best-fit model could be abandoned.
- Although application of MOFs contribute to dealing with the problem of equifinality, with respect to the HBV model one should address more weight with respect to the SOFs of which are thought to be the most important for the stated objective.
- When applying the HBV model in another regionalisation study, one of the model parameters *ALFA* and K_f can be neglected in the process of calibration due to high correlation.
- In order to determine which aspect of the hydrograph the HBV model has difficulty with in appropriately simulating, it is recommended to calibrate the HBV model separately for each SOF.
- The importance of establishing hydrologically feasible relationships between model parameters and PCCs should not be underrated and therefore these relationships should not be incorporated in the regional model in any case.

References

Abbott, M.B., Bathurst, J.C., Cunge, J.A., O'Connel, P.E. and Rasmussen, J.L., 1986. An introduction to the European hydrological system – Système Hydrologique Europeen, 'SHE'. 2. Structure of a physically-based, distributed modelling system. Journal of hydrology 87, pp. 61-77.

Arends, M., 2005. Low flow modelling of the Meuse: Recalibration of the existing HBV Meuse model. MSc thesis, University of Twente, Enschede.

BADC, 2006. http://badc.nerc.ac.uk. 25-05-2006.

Beck, M.B., 1991. Forecasting environmental change. Journal of forecasting 10, pp. 3-19.

Bergström, S., 1995. The HBV model. In: Singh, V.P., (Ed.), Computer models of watershed hydrology, Water resources publication, Littleton, CO, pp. 443-476.

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

Beven, K.J., 1993. Prophecy, reality and uncertainty in distributed hydrological modelling. Adv. Water Resour. 16, pp. 41-51.

Blöschl, G. and M. Sivapalan, 1995. Scale issues in hydrological modelling: a review, Hydrological Processes 9 (1995), pp. 251–290.

Booij, M.J., 2002. Appropriate modelling of climate change impacts on river flooding. PhD thesis, University of Twente, Enschede, ISBN: 90-365-1711-7

Booij, M.J., 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. Journal of hydrology 303, pp. 176-198.

CSI, 2006. http://www.ceh.ac.uk/data/nrfa/catchment_spatial_information.html. 08-05-2006.

Davis, J.C., 2002. Statistics and data analysis in geology. 3rd edition. Wiley, pp. 638.

Deckers, D.L.E.H., 2006. Literature study. The concept of regionalisation. University of Twente. Enschede.

Ellis, J.L., 2004. Statistiek voor de psychologie. Variantieanalyse. Boom, Amsterdam, pp. 253.

Encarta, 2006. http://encarta.msn.com. 12-07-2006.

Foppes, S., 2005. Regionalisation based on basin characteristics applied to flood forecasting in the Da river. MSc thesis, University of Twente, Enschede.

GNOCW, 2006. http://www.fao.org/geonetwork/srv/en/main.home. 17-07-2006.

Goodrich, D.C., Lane, L.J., Shillito, R.M., Miller, S.N., Syed, K.H., Woolhiser, D.A., 1997. Linearity of basin response as a function of scale in a semiarid watershed. Water Resource Research 33 (12), pp. 2951–2965.

Gupta, H.V., Sorooshian, S. and P.O. Yapo, 1998. Toward improved calibration of hydrological models: multiple and non commensurable measures of information. Water Resource Research 34 (4), pp. 751–763.

Gustard, A., Bullock, A., Dixon, J. M., 1992. Low flow estimation in the United Kingdom. Institute of Hydrology Report 108.

Haan, C., 2002. Statistical Methods in Hydrology, 2nd Edition. Blackwell, pp. 496.

Harlin, J., 1991. Development of a process oriented calibration scheme for the HBV hydrological model. Nordic Hydrology 22, pp. 15–36.

Harlin, J. and C. Kung, 1992. Parameter uncertainty and simulation of design floods in Sweden. Journal of hydrology 137, pp. 209-230.

Hundecha, Y., 2004. Regionalization of parameters of a conceptual rainfall-runoff model. PhD thesis, University Stuttgart, Stuttgart, ISBN: 3-933761-45-X.

Hundecha, Y. and A. Bárdossy, 2004. Modelling of the effect of land use change on the runoff generation of a river basin through parameter regionalization of a watershed model. Journal of hydrology 292, pp. 281-295.

Hunink, J., 2005. pre-estimation of baseflow model parameters out of catchment characteristics – a review. MSc thesis. University of Amsterdam. Amsterdam.

IHMS, 1997. Integrated hydrological modelling system, Manual version 4.5. Swedish meteorological and hydrological institute. Sweden.

Jakeman Al, and G.M. Hornberger, 1993. How much complexity is warranted in a rainfall-runoff model? Water Resources Research 29, pp. 2637-2649.

Klemeš, V., 1986. Operational testing of hydrological simulation models. Hydrological science journal 31, pp. 13-24.

Kokkonen, T.S., Jakeman, A.J., Young, P.C., Koivusalo, H.J., 2003. Predicting daily flows in ungauged catchments: model regionalisation from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. Hydrological Processes 17 (11), pp. 2219–2238.

Lidén, R. and J. Harlin, 2000. Analysis of conceptual rainfall-runoff modelling performance in different climates. Journal of hydrology 238, pp. 231-247.

Lifewater, 2006. www.lifewater.ca, 17-7-2006.

Littlewood, 2004. United kingdom hydrometric data, physical catchment descriptors and other hydroclimatic information available on the internet for PUB. NERC. Centre for Ecology and Hydrology. Wallingford. England.

Lindström, G., 1997. A simple automatic calibration routine for the HBV model. Nordic Hydrology 28, pp. 153-168.

Lindström, G., Johansson, B., Persson, M., Gardelin, M. and S. Bergström, 1997. Development and test of the distributed HBV-96 hydrological model. Journal of hydrology 201, pp. 272-288.

Madsen, H., 2000. Automatic calibration of a conceptual rainfall-runoff model using multiple objectives. Journal of hydrology 235, pp. 276-288.

Maidment, D., 1992. Handbook of Hydrology. McGraw Hill, New York, pp. 4-2

Merz, R. and G. Blöschl, 2004. Regionalisation of catchment model parameters. Journal of hydrology 287, pp. 95-123.

Nash, J.E., 1957. The form of instantaneous unit hydrograph. In: Proc. IASH Ass. G6n., Toronto, pp. 114-131.

Nash, J.E. and J.V. Sutcliffe, 1970. River flow forecasting through conceptual models. Part I – A discussion of principles. Journal of hydrology 10, pp. 282-290.

Parajka, P., R. Merz and G. Blöschl, 2005. A comparison of regionalisation methods for catchment model parameters. Hydrology and earth system sciences discussions 2, pp. 509-542.

Passchier, R.H., 1996. Evaluation hydrologic model packages. Technical report Q2044, WL/Delft Hydraulics, Delft (www.wldelft.nl).

Refsgaar, J.C. and J. Knudsen, 1996. Operational validation and intercomparison of different types of hydrological models. Water resource research 32 (7), pp. 2189-2202.

Rientjes, T.H.M., 2005. Modelling in hydrology. Lecture notes from: International institute for geo-information science and earth observation. Department of water resources. ITC.

Robinson, J.S. and Sivapalan, M., 1995. Catchment-scale runoff generation model by aggregation and similarity analyses. Hydrological Processes 9, pp. 555–574.

Sefton, C.E.M. and S.M. Howarth, 1998. Relationships between dynamic response characteristics and physical descriptors of catchments in England and Wales. Journal of hydrology 211, pp. 1-16.

Seibert J., 1999a. Conceptual runoff models - fiction or representation of reality? Dissertation. Acta University Uppsala, Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology, 436, Uppsala, Sweden.

Seibert, J., 1999b. Regionalisation of parameters for a conceptual rainfall-runoff model. Agricultural and forest meteorology 98-99, pp. 279-293.

Seibert, J., 2002. HBV light version 2. User's manual. Environmental assessment SLU. Uppsala University. Oregon.

Shaw, E.M., 1994. Hydrology in practice (third edition). Chapman & Hall, London, 569 pp.

Singh, V.P., (Ed.), 1995. Computer models of watershed hydrology. Water resources publication, Littleton, ISBN: 0-918334-91-8.

Sivapalan M., Takeuchi K., Franks S.W., Gupta V.K., Karambiri H., Lakshmi V., Liang X., McDonnell J.J., Mendiondo E.M., O'Connell P.E., Oki T., Pomeroy J.W., Schertzer D., Uhlenbrook S. & Zehe E., 2003. IAHS Decade on Predictions in Ungauged Basins (PUB), 2003-2012: Shaping an exciting future for the hydrological sciences. Hydrological Sciences Journal-Journal des Sciences Hydrologiques. Vol. 48(6), pp. 857-880.

Strahler, A.N., 1952. Hypsometric (area-altitude) analysis of erosional topography. Geological Society of America Bulletin 63, pp. 1117-1141.

Uni-Hamburg, 2006. www.uni-hamburg.de, 19-9-2006.

Uoregon, 2006. www.uoregon.edu/~robinh/outl.txt, 06-10-2006.

Van der Wal, K.U., 2001. Meuse model moulding: on the effect of spatial resolution. MSc thesis, University of Twente, Enschede.

Vandewiele, G.L., Elias, A., 1995. Monthly water balance of ungauged catchments obtained by geographical regionalization. Journal of hydrology 170, pp. 277–291.

Verstraeten, G., 2000. Modderoverlast, sedimentatie in wachtbekkens en begroting van de sedimentexport naar waterlopen in Midden-België. PhD Thesis, Katholic University of Leuven, Leuven.

Wagener, T., Wheater, H.S. and H.V. Gupta, 2004. Rainfall-runoff modelling in gauged and ungauged catchments. Imperial College Press, London, UK, 300 pp.

Ward, R.C. and M. Robinson, 1990. Principles of Hydrology. 3rd ed. McGraw-Hill, London: 365 pp.

Wheater, H.S., Jakeman, A.J. and K.J. Beven, 1993. Progress and directions in rainfall-runoff modelling, In: Jakeman, A.J., Beck, M.B. and M.J. McAleer (Eds), Modelling change in environmental systems, Wiley, pp. 101-132.

Zhang, X., and G. Lindström, 1997. Development of an automatic calibration scheme for the HBV hydrological model. Hydrological Processes 11, pp. 1671–1682.

Definitions

The terminology used in hydrological modelling is sometimes interpreted in different ways. To make sure the used interpretations are adopted as intended in this study, the definitions are outlined below.

Calibration:	The search for parameter values that provide the closest possible agreement between simulations and observations based on an objective function.
Equifinality:	Many different parameter combinations will produce similar good simulation results with respect to available calibration data and the objective function.
Identifiable model parameter:	A model parameter which can be well identified i.e. only for parameter values within a small parameter range the performance of the calibrated model is good.
Local model:	The ability to simulate rainfall-runoff from a gauged catchment through a model structure inherent in the HBV model based on the representation of the real world through equations, accompanying model parameters and input variables (i.e. rainfall data, air temperature and estimated potential evapotranspiration).
Objective function:	A quantitative measure to estimate the performance of a model based on similarity of observed and simulated discharge.
Optimum parameter set:	A set of parameter values belonging to the best value of the objective function.
Regionalisation:	The process of transferring information, through establishing relationships between model parameters and physical catchment characteristics based on well gauged catchments, to the catchment of interest in order to reduce model parameter uncertainty.
Regional model:	A model structure inherent in the HBV model based on the representation of the real world through input variables (i.e. rainfall data, air temperature and estimated potential evapotranspiration) and inherently equations using model parameters set up by functional relations which are using a set of physiographical and meteorological catchment characteristics.
Ungauged catchment:	Catchment where climatic and physiographic data are available, but no hydrometric data.
Validation:	Estimating the confidence in the ability of a model to perform with a certain quality for its intended purpose.

Validation catchments:	Selected catchments at which the established regional model is validated.

Glossary of abbreviations

ADT	Average daily temperature
ANOVA	Analysis of variance
BADC	British atmospheric data centre
BGS	British geological survey
CEH	Centre for ecology and hydrology
CSI	Catchment spatial information
GNOCW	Geonetwork opensource community website
HI	Hypsometric integral
IAHS	International association of hydrological sciences
IDHTM	Integrated hydrological digital terrain model
LCM2000	Land Cover Map 2000
MCS	Monte Carlo simulation
MOF	Multiple objective function
PCC	Physical catchment characteristic
PE	Potential evapotranspiration
PUB	Prediction in ungauged basins
RMSE	Root mean square error
SAAR	Standard annual average rainfall
SMHI	Swedish meteorological and hydrological institute
SOF	Single objective function
TDWG	Top down modelling working group

Symbols

A	area of a catchment
ALFA	parameter defining the non-linearity of the quick runoff reservoir in the HBV model
BETA	parameter in soil moisture routine in the HBV model
C'	lowest single objective function value for each model run
C_1	coefficient in routing routine in the HBV model
C_2	coefficient in routing routine in the HBV model
C_f	capillary flow returning from the quick runoff reservoir into the soil moisture routine in the HBV model
C_{opt}	decisive scaled value of the four single objective functions
C_s	scaled value of the single objective function
CEVPFO	correction factor for potential evapotranspiration in forest zones in the HBV model
CFLUX	parameter defining the maximum capillary flow in the HBV model
CFMAX	melting factor in the HBV model
CFR	refreezing factor in the HBV model
df	degrees of freedom
DAMP	parameter which attenuates the wave amplitude of discharge in the HBV model
DR	precipitation which becomes directly available for runoff generation in the HBV model
e_a	saturated vapour pressure at actual temperature
e_d	saturated vapour pressure at dew point temperature
E_a	actual evapotranspiration in the HBV model
E_{at}	evapotranspiration rate as function of wind speed and saturation deficit
E_p	measured potential evapotranspiration
ECALT	elevation correction factor for evapotranspiration in the HBV model
F	F-test value which indicates the significance level of the regression equation
FC	parameter defining the maximum soil moisture storage in the HBV model
FOCFMAX	factor that will be multiplied by *CFMAX* for forest zones in the HBV model
FOSFCF	factor that will be multiplied by *SFCF* for forest zoned in the HBV model
hq	parameter representing the high flow rate in the HBV model
H_0	hypothesis test
H_a	alternative hypothesis test
H_{max}	maximum altitude above sea level of concerning catchment
H_{mean}	average altitude above sea level of concerning catchment
H_{min}	minimum altitude above sea level of concerning catchment
H_T	available energy based on net radiation measurements
i	time step in the HBV model
j	specific catchment
khq	parameter representing a recession coefficient at a corresponding reservoir volume in the HBV model
K_f	parameter defining the recession coefficient in the quick runoff reservoir in the HBV model
K_s	parameter defining the recession coefficient in the base flow reservoir in the HBV model
LAG	delay parameter of routing routine in the HBV model
LP	parameter defining a limit where above the actual evapotranspiration reaches the measured potential evapotranspiration in the HBV model

LZ	storage in the base flow reservoir in the HBV model
IN	infiltration of precipitation through the soil layer in the HBV model
$m1000$	the thousandth best single objective function value
m	calibration run number
$mtot$	total number of calibration runs
$MAXBAS$	parameter distributing total discharge through filter technique in the HBV model
MS_{reg}	mean sums of squares of the regression equation
MS_{res}	mean sums of squares of the estimated error
n	measured sunshine duration
n_0	number of observations used in the dataset to be used for the regression equation
n_r	total number of time steps to be used in the HBV model
N	maximum possible sunshine duration fixed by latitude and longitude
p	number of regression coefficients used in the regression equation
P	precipitation
$PCALT$	elevation correction factor for precipitation in the HBV model
PE	potential evapotranspiration calculated through the Penman-Monteith equation
$PERC$	parameter defining the percolation of water from the quick runoff reservoir to the base flow reservoir in the HBV model
P_s	part of precipitation interpreted as snow in the HBV model
P_r	part of precipitation interpreted as rainfall in the HBV model
Q	total discharge by quick runoff and slow flow in the HBV
Q_0	quick runoff in the HBV model
Q_1	slow flow in the HBV model
Q_{in}	upstream total discharge in the HBV model
Q_{obs}	observed flow
$\overline{Q_{obs}}$	average observed flow
Q_{out}	downstream total discharge in the HBV model
Q_{sim}	simulated flow
$Q_{Threshold}$	threshold flow
r^2	proportion declared variance introduced by the regression equation
r	correlation coefficient
r_a	radius used for determining calculating mean of required variables for the Penman-Monteith equation
R^2	Nash-Sutcliffe efficiency coefficient
R	indirect discharge through the soil layer in the HBV model
R_a	solar radiation fixed by latitude and longitude
R_H^2	adjusted Nash-Sutcliffe efficiency coefficient for high flows
R_I	incoming radiation to be used for the Penman-Monteith equation
Ro	outgoing radiation to be used for the Penman-Monteith equation
R_L^2	adjusted Nash-Sutcliffe efficiency coefficient for low flows
Ro	outgoing radiation to be used for the Penman-Monteith equation
$RFCF$	rainfall correction factor in the HBV model
RV_E	relative volume error
SE	standard error presented by the ANOVA table
$SFCF$	snow fall correction factor in the HBV model
SM	soil moisture depth in the HBV model
SS_{reg}	sums of squares of the regression equation
SS_{res}	sums of squares of the estimated error
SS_{tot}	total sums of squares of the data set to be used for regression analysis
t_c	critical t value for testing the specific hypothesis

t_{crit}	critical t value for testing the significance of the correlation coefficients
t_{cor}	significance of correlation coefficients
T	air temperature in the HBV model
T_a	actual temperature
T_d	dew point temperature
$TCALT$	temperature laps in the HBV model
TT	threshold temperature defining precipitation as rainfall or snow in the HBV model
TTI	total length of a temperature interval in which the part of precipitation that is considered to be snow decreases linearly from 1.0 at the lower end of the interval to 0 at the upper end. The midpoint of the interval is defined by TT
u_2	wind speed at 2 meter above the surface
UZ	storage in the quick runoff reservoir in the HBV model
VAR_{res}	undeclared variance introduced by the residuals
WHC	water holding capacity of snow in the HBV model
X	independent variable
Y	observed values used in regression equation
Y'	estimated dependent variable through regression equation
$\overline{Y}$	average of observed values used in regression equation
Δ	slope of saturation vapour pressure against temperature
α	applied significance level to be used for regression analysis
β_0	intercept of the regression equation
β	the regression weight which assigns the effect of the independent variable on the dependent variable
γ	hygrometric constant
ε	estimated error term
λ	latent heat of vaporization of water
ρ	density of water
σ	Stefan-Boltzmann constant

Appendices

A. IAHS, PUB and TDWG

A.1. International Association of Hydrological Sciences

The field of hydrology as a science of the occurrence, movement and properties of water upon and beneath the land areas of the globe in relation to the global water originated in the 17e century. Until the second half of the 19th century little progress was made but due to enormous population growth and economic development the need arose for more knowledge. A modest beginning was made with hydrological inventories of river catchments including measurements of river stages and river discharges.

Until 1922 when the General Assembly of International Union of Geodesy and Geophysics was held, there was no international agreement of dealing with hydrology. Therefore a new initiative was originated called the International Branch of Scientific Hydrology which started with two commissions. In the 1930s the branch, which later became an Association, began to cover an increasing number of aspects of hydrology and many new commissions.

Throughout the years the Association did undergo several transformations in order to expand. Due to cooperation with UNESCO, the reorganization of the scientific framework of the Association and the influence of environmental changes the scope and spear points changed. Also the name changed in International Association of Hydrological Sciences (IAHS). Nowadays the IAHS encloses eight commissions and two working groups each dealing with a specific aspect of hydrology. One of the working groups is called the Prediction in Ungauged Basins working group (PUB) and gives rise to this assignment.

A.2. Prediction in Ungauged Basins

Drainage catchments in many parts of the word are ungauged or poorly gauged. The problem is compounded by the impacts of human-caused changes to the land surface and climate, occurring at local, regional and global scale. Predictions of these catchments under these conditions are highly uncertain. Therefore IAHS has launched this initiative.

The overall goal of PUB is to formulate and implement appropriate science programs to engage and encourage the scientific community, in a coordinated manner, towards achieving major advances in the capacity to make predictions in ungauged catchments. The PUB scientific program focuses on the estimation of predictive uncertainty, and its subsequent reduction, as its central theme.

Through the overall goal, main objectives which result in several key science questions, and the fact it is a time-bound research initiative two targets have been assembled:

1. Examine and improve existing models in terms of their ability to predict in ungauged catchments through appropriate measures of predictive uncertainty;
2. Develop new, innovative models to capture space-time variability of hydrological processes for making predictions in ungauged catchments, with an additional reduction of predictive uncertainty.

Eventually based on an assessment of the key science questions underpinning PUB and the two research targets, PUB has identified six Science Themes to serve as a framework for the organization of its research activities. To achieve these targets and the main goals these research programs will be carried out through a global network of underlying working groups comprising interested researchers in any area of prediction in ungauged catchments. They will be the “main engines of PUB research activities”.

This study is realized through the interest of such a working group, called the Top-Down modelling working group (TDWG).

A.3. Top Town modelling Working Group

Through a range of approaches the TDWG will focus on target 1 as mentioned in the previous section which is:

- *Examine and improve existing models in terms of their ability to predict in ungauged catchments through appropriate measures of predictive uncertainty.*

As said, PUB has identified six Science Themes. Two of them the TDWG will address which are:

- *Develop new approaches for hydrological interpretation from existing data archives: data rescue and re-analysis, catchment inter-comparisons and global hydrology.*
- *Advance learning from the application of existing models, through uncertainty analysis and model diagnostics.*

To manage these two science themes the TDWG will focus on three aspects:

- *evaluation of existing models with a view to developing better models;*
- *exploration of data to develop new modelling approaches;*
- *development of new models.*

In order to find support for these aspects, the TDWG released a free-of-charge well gauged dataset of daily rainfall and stream flow for 61 catchments throughout England and Wales. By applying this dataset on revised or new modelling techniques, results can be compared with any previous published work that used the same data. In this way, the hydrological research community can assess different modelling techniques in the context of reducing predictive uncertainty.

B. Catchments in the study area

In table B-1 the 56 catchments to be used in this study are presented.

Table B-1. 56 selected catchments

#	**River**	**Location**
22001	Coquet	Morwick
22006	Blyth	Hartford Bridge
23006	South Tyne	Featherstone
24004	Bedburn Beck	Bedburn
25005	Leven	Leven Bridge
25006	Greta	Rutherford Bridge
27034	Ure	Kilgram Bridge
27035	Aire	Kildwick Bridge
27042	Dove	Kirkby Mills
27056	Pickering Beck	Ings Bridge
27058	Riccal	Crook House Farm
28008	Dove	Rocester Weir
28066	Cole	Coleshill
29003	Lud	Louth
30015	Cringle Brook	Stoke Rochford
31010	Chater	Fosters Bridge
31025	Gwash South Arm	Manton
32004	Ise Brook	Harrowden Old Mill
32006	Nene/Kislingbury	Upton
33019	Thet	Melford Bridge
33029	Stringside	Whitebridge
36003	Box	Polstead
37005	Colne	Lexden
38003	Mimram	Panshanger Park
38029	Quin	Griggs Bridge
39006	Windrush	Newbridge
39015	Whitewater	Lodge Farm
39020	Coln	Bibury
39028	Dun	Hungerford
39029	Tillingbourne	Shalford
41022	Lod	Halfway Bridge
42008	Cheriton Stream	Sewards Bridge
42012	Anton	Fullerton
43006	Nadder	Wilton
44006	Sydling Water	Sydling St Nicholas
45005	Otter	Dotton
47008	Thrushel	Tinhay
48003	Fal	Tregony
48010	Seaton	Trebrownbridge
49002	Hayle	St Erth
50001	Taw	Umberleigh
52010	Brue	Lovington
53009	Wellow Brook	Wellow

#	**River**	**Location**
53013	Marden	Stanley
53017	Boyd	Bitton
54016	Roden	Rodington
54029	Teme	Knightsford Bridge
55012	Irfon	Cilmery
55013	Arrow	Titley Mill
55014	Lugg	Byton
57010	Ely	Lanelay
60006	Gwili	Glangwili
60010	Tywi	Nantgaredig
62001	Teifi	Glan Teifi
66011	Conwy	Cwm Llanerch
67018	Dee	New Inn

C. Calculation potential evapotranspiration

C.1. Penman-Monteith

In order to calculate the potential evapotranspiration, the formula of Penman-Monteith (Shaw, 1994) is used; see equation [C-1].

$$PE = \frac{(\Delta / \gamma)H_T + E_{at}}{(\Delta / \gamma) + 1} \qquad \text{[C-1]}$$

With:

Δ = slope of the saturation vapour pressure against temperature, [$kPa\ {}^0C^{-1}$]
γ = hygrometric constant, 66 [$Pa\ {}^0C^{-1}$]
H_T = $R_I - R_O$ [$mm\ day^{-1}$]
E_{at} = $0.35\ (1 + u_2 / 100)(e_a - e_d)$ [$mm\ day^{-1}$]

With:

R_I = $0.75R_a(0.18 + 0.55\ n/N)$
R_o = $0.95\sigma T_a^4(0.56 - 0.092\ \sqrt{e_d})(0.10 + 0.90\ n/N)$
u_2 = mean wind speed at 2 m above surface, [$miles\ day^{-1}$]
e_a = actual saturated vapour pressure at actual temperature T_a, [$mm\ of\ mercury$]

With:

R_a = the solar radiation fixed by latitude and season, [$mm\ day^{-1}$]
n = bright sunshine, [$h\ day^{-1}$]
N = length of day fixed by latitude and season, [h]
σ = Stefan-Boltzmann constant, $5.67 \cdot 10^{-8}$ [$Wm^{-2}K^{-4}$]
T_a = actual temperature, [K]
e_d = saturated vapour pressure at dew point temperature T_d, [$mm\ of\ mercury$]

C.2. Calculation potential evapotranspiration

Calculation of the average areal PE is performed based on the formula of Penman-Monteith; see equation C-1, appendix C.1. In advance it should be noticed that great care is required in using the correct units. Requirements for this formula are the following four variables:

T_a = actual temperature [${}^0C$]
e_d = vapour pressure [$mm\ of\ mercury$]
n = bright sunshine [$h\ day^{-1}$]
u_2 = wind speed at 2 meter above the surface [$miles\ day^{-1}$]

Besides these variables, several other parameters are needed. These are:

Δ = slope of the saturation vapour pressure against temperature shown in figure C-1 [$kPa\ {}^0C^{-1}$]
R_a = solar radiation fixed by latitude and season shown in table C-1 [$mm\ day^{-1}$]
N = length of day fixed by latitude and season shown in table C-3 [h]
T_d = dew point temperature from which e_d is calculated is shown in figure C-2 [${}^0C$]

Derivations of these parameters are expounded underneath.

Slope of saturation vapour pressure, Δ

In figure C-1 the slope of saturation vapour pressure against temperature is shown. It is compounded with credit to my supervisor M.J. Booij. Unfortunately the range of *Δ* went from 0 to 39 degrees. Since in England and Wales temperatures beneath 0 ^{0}C can occur, a trend line is added from which a formula is derived. From this formula accompanying results for temperatures below 0 ^{0}C are determined. The formula is shown in equation C-2.

$$\Delta = 9 \cdot 10^{-9} * T_a^{\ 4} + 2 \cdot 10^{-6} * T_a^{\ 3} + 7 \cdot 10^{-5} * T_a^{\ 2} + 0.003 T_a + 0.0442 \qquad [C-2]$$

With:

T_a = actual temperature [^0C]

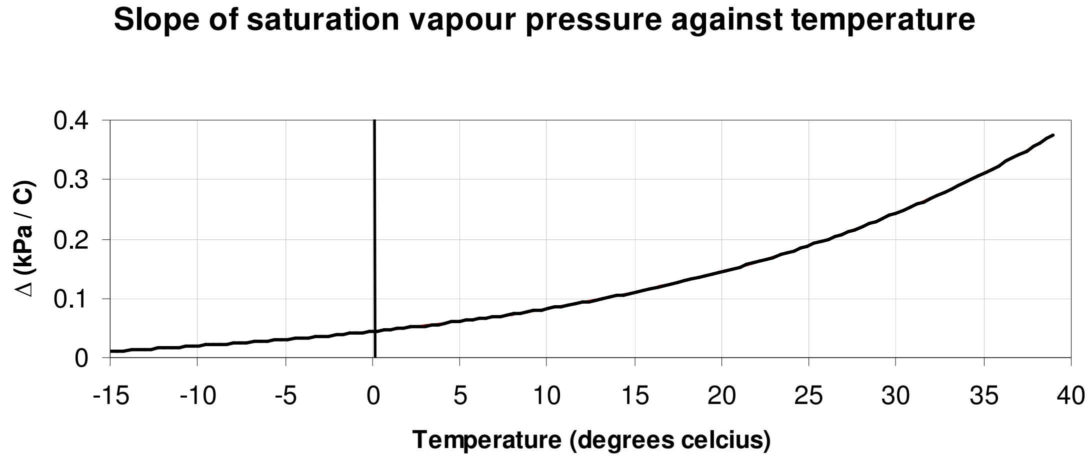


Figure C-1. Slope of saturation vapour pressure against temperature

Solar radiation, R_a

In table C-1 the values required for 0.75 * R_a are given fixed by latitude and season. For the observation stations used in this study, the latitudes are determined and accompanying values are determined. These values are linear interpolated up to 1 decimal since the latitudes of the observation stations are also presented up to 1 decimal. The three observation stations used, respectively one for the bright sunshine n and two for calculating the mean of the other three variables, T_a, T_d and u_2 are shown in table C-2. In total 19 observation stations are used at which the variable n is available. With respect to the three remaining variables 32 different observation stations are used. This brings in total of 39 different datasets out of 56 possible different datasets for the applied catchments.

Table C-1. 0.75 * Solar radiation fixed by latitude and season in [_mm_/day]

	Latitude ^{0}N			
Month	**50**	**52**	**54**	**56**
January	2.73	2.38	2.04	1.69
February	4.48	4.13	3.76	3.38
March	6.91	6.58	6.24	5.89
April	9.51	9.30	9.06	8.81
May	11.47	11.35	11.25	11.14
June	12.30	12.26	12.22	12.18
July	12.00	11.92	11.83	11.73
August	10.20	10.02	9.84	9.64
September	7.71	7.44	7.13	6.83
October	5.15	4.80	4.46	4.11
November	3.13	2.80	2.45	2.10
December	2.32	1.98	1.64	1.31

Table C-2. Combinations of observation stations used for the applied catchments

#	***Observation station*** **(n)**	**Observation station 1 (T_a, T_d, u_2)**	**Observation station 2 (T_a, T_d, u_2)**
22001	Boulmer	Boulmer	Tynemouth
22006	Boulmer	New castle	Tynemouth
23006	Aspatria	New castle	Eskdalemuir
24004	Boulmer	New castle	Tynemouth
25005	Leeming	Leeming	New castle
25006	Leeming	Leeming	New castle
27034	Leeming	Leeming	Bingley Samos
27035	Leeming	Leeming	Bingley Samos
27042	Leeming	Leeming	Bingley Samos
27056	Leeming	Leeming	Finningley
27058	Leeming	Leeming	Bingley Samos
28008	Nottingham	Nottingham	Ringway
28066	Elmdon	Elmdon	Nottingham
54016	Shawbury	Shawbury	Elmdon
54029	Elmdon	Elmdon	Shawbury
29003	Nottingham	Coningsby	Waddington
30015	Nottingham	Waddington	Coningsby
31010	Nottingham	Coningsby	Waddington
31025	Nottingham	Nottingham	Waddington
32004	Woburn	Elmdon	Stansted
32006	Woburn	Elmdon	Stansted
33019	Honington	Marham	Coltishall
33029	Honington	Marham	Coltishall
36003	Wattisham	Stansted	Marham
37005	Cavendish	Stansted	Manston
38003	London weather	Stansted	London weather
38029	Woburn	Stansted	London weather
39006	Bracknell	Heathrow	Elmdon
39015	Bracknell	Heathrow	Gatwick
39020	Bristol	Bristol	Elmdon

#	*Observation station* (*n*)	**Observation station 1** (T_a, T_d, u_2)	**Observation station 2** (T_a, T_d, u_2)
39028	Bracknell	Bristol	Heathrow
39029	Bracknell	Gatwick	Heathrow
41022	Gatwick	Gatwick	Heathrow
42008	Bracknell	Heathrow	Gatwick
42012	Hurn	Heathrow	Yeovilton
43006	Hurn	Yeovilton	Bristol
44006	Hurn	Yeovilton	Exeter
45005	Plymouth	Exeter	Yeovilton
47008	Plymouth	Plymouth	St Mawgam
48003	St Mawgam	St Mawgam	Culdrose
48010	Plymouth	Plymouth	St Mawgam
49002	Camborne	Culdrose	St Mawgam
50001	Plymouth	Exeter	Rhoose
52010	Bristol	Yeovilton	Bristol
53009	Bristol	Bristol	Yeovilton
53013	Bristol	Bristol	Yeovilton
53017	Bristol	Bristol	Yeovilton
55012	Shawbury	Cilfynnydd	Rhoose
55013	Shawbury	Shawbury	Cilfynnydd
55014	Shawbury	Shawbury	Cilfynnydd
57010	Bristol	Cilfynnydd	Rhoose
60006	Bristol	Milford Have	Brawdy
60010	Bristol	Milford Have	Brawdy
62001	Valley	Brawdy	Milford Have
66011	Valley	Valley	Aughton
67018	Shawbury	Shawbury	Valley

Length of days, N

In table C-3 the values required for *N* are shown fixed by latitude and season. For the catchments used in this study, the latitudes are determined and accompanying values are determined. These values are linear interpolated up to 1 decimal since the latitudes of the catchments are also presented up to 1 decimal.

Table C-3. Length of day fixed by latitude and season in [*h*]

	Latitude ^{0}N			
Month	**50**	**52**	**54**	**56**
January	8.6	8.3	8.0	7.6
February	10.0	9.9	9.7	9.5
March	11.8	11.8	11.8	11.8
April	13.7	13.8	14.0	14.1
May	15.4	15.6	15.9	16.2
June	16.3	16.6	17.0	17.4
July	15.9	16.1	16.5	16.9
August	14.4	14.6	14.8	15.0
September	12.6	12.7	12.7	12.8
October	10.7	10.6	10.5	10.4
November	9.0	8.8	8.6	8.3
December	8.1	7.8	7.4	7.0

Saturation vapour pressure

In figure C-2 the saturation vapour pressure against dew point temperature is shown. It is compounded with credit to my supervisor M.J. Booij. Unfortunately the range of *e* went from 0 to 39 degrees. Since in England and Wales temperatures beneath 0 ^{0}C can occur, a trend line is added from which a formula is derived. From this formula accompanying results for temperature below 0 ^{0}C are determined. The formula is shown in equation C-3.

$$e = -4\cdot 10^{-10} * T_a^{\,6} + 8\cdot 10^{-8} * T_a^{\,5} - 5\cdot 10^{-7} * T_a^{\,4} + 0.0003 * T_a^{\,3} + 0.0102 * T_a^{\,2} + 0.3361 * T_a + 4.5937 \qquad [C\text{-}3]$$

With:

T_a = actual temperature [^0C]

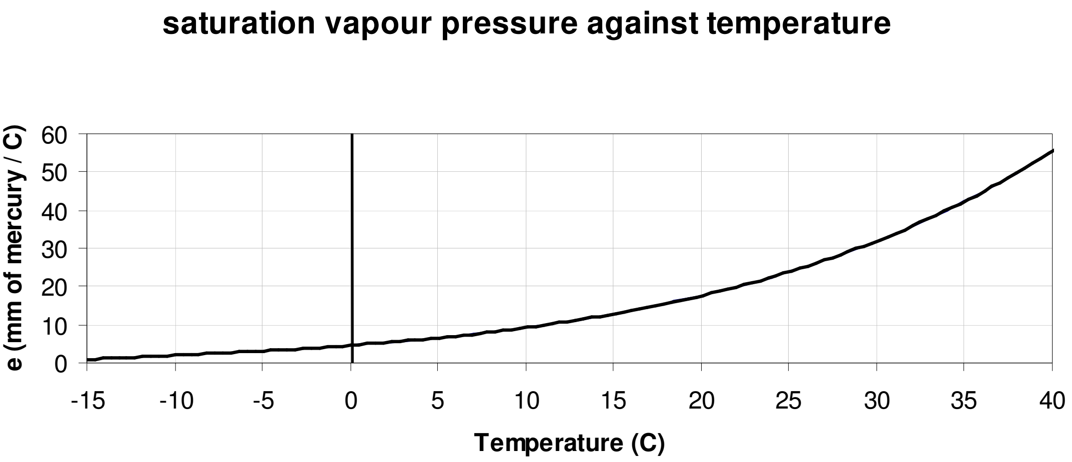


Figure C-2. Saturation vapour pressure against temperature

After having determined the datasets of the four required variables, calculation of average areal PE can be carried out. During calculation still one difficulty should be reckoned with. One of them regards converting σT_a^4 from W*m^{-2} to mm*day^{-1} which is required in calculating the parameter R_0. σT_a^4 stands for the theoretical black body radiation at a specific temperature. In order to attain the appropriate unity, σT_a^4 should be divided by the density of water, ρ as well as the latent heat of vaporization, λ. The unity of ρ should be expressed in [$kg\ m^{-3}$] and λ in [$MJ\ kg^{-1}$] which is shown in equation [C-4] (Maidment, 1992):

$$\lambda = 2.501 - 0.002361 \cdot T_a \qquad [C\text{-}4]$$

With:

T_a = actual temperature [^0C]

After dividing, the unity results in [$m\ s^{-1}$]. In order to attain [$mm\ day^{-1}$] this result is multiplied times 10^3 and 86400 respectively to convert from [*mm*] to [*m*] and to convert from [*s*] to [*day*]. In this way the appropriate unity is rendered.

D. Data assimilation

Data for the four variables are extracted from the British Atmospheric Data Centre (BADC, 2006). As already stated, for each catchment three observation stations are used in order to determine the PE. In table C.2 from appendix C the used observation stations and accompanying different datasets are given. Eventually, for each catchment one dataset with average areal PE based on a time step of one day is needed. How these data input are build and which problems are encountered, is expounded beneath.

The data available in the British Atmospheric Data Centre (BADC) are stored for each observation station, split up in years. For each observation station and for each variable the required years from 01-01-1983 till 31-12-1990 are obtained. All single files are merged in order to get one file for each variable. Since all the merged data files have a temporal scale of hourly measurements, these measurements are converted to daily averages. Several problems were encountered.

D.1. Wind speed, actual temperature and dew point temperature

With respect to wind speed, the unity which is required as input for the formula of Penman-Monteith is [*miles day*$^{-1}$]. Since hourly measurements are available, simple aggregation should be sufficient for obtaining the appropriate format. Nonetheless, the measurements were expressed in the unity of [*knots*] and not every observation measurement used the same format to reflect the measurement. With respect to the unity of the measurements a conversion factor was applied which corresponds as follows:

- Wind speed in [*knots per hour*] * 1.1508 = [*miles per hour*].

With respect to the format used for the wind speed, the following difficulty occurred:

- Although as has been reported, not for every observation station continuous hourly measurements were available. For some observation stations 24 measurements per day were available. Some other stations only had values each 3 hours and other observation stations each 8 hours. In order to get the wind speed in unity of [*miles day*$^{-1}$], these values are multiplied respectively times 8 or times 4.
- Besides multiplying available values in order to obtain the right format, several stations contained a mixture of above described temporal distribution. Not just between the different years this format varied, also between different months within one year this format varied. Forth, to obtain daily average wind speed in [*miles day*$^{-1}$] for each catchment every year is checked manually.

After multiplied from [*knots*] to [*miles*], multiplied the required values and checked all observation stations, the values are aggregated in order to obtain daily values.

With respect to the actual and dew point temperature the same difficulties regarding the format occurred since these three variables all are stored in one file. However, instead of aggregating the values, the average is determined.

D.2. Bright sunshine

With respect to the bright sunshine the unity requires for the formula of Penman-Monteith is [*h*]. Two kinds of difficulties occurred when the generated datasets were analyzed. One regards the unity in which the values are presented and one regards the format used. With respect to the unity the following can be said:

- Two different unities are used in presenting the measurements. Several observation stations presented their measurements in minutes per hour of sunshine whereas other observation stations presented their measurements in values scales between 0 and 10. Thus, when a value of 5 is presented, 30 minutes of sunshine occurred.

With respect to the format two difficulties occurred, which are:

- Not every day the same amount of measurements are presented in the datasets. Since it is not possible that at midnight the sun shines, no measurement is done. Thus per day a specific amount of measurements are carried out, for instance 10 measurements in January 1983. Since the length of days in the summer is bigger than in the winter, the start and end measurement per day differs per month. So in September 1983 16 measurements are done.
- Besides the non-continuity of measurements described above, between different years in one observation station the amount also differs. Thus, for instance in January 1983 per day 10 measurements are presented whereas in January 1984 per day 12 measurements are made. Forth, to obtain daily average bright sunshine in [h] for each catchment every year is checked manually.

After having checked the datasets of every observation station, for each day the values are aggregated to obtain daily values in [h].

D.3. Data quality

After having established the datasets for the four variables, these datasets are analyzed concerning the quality. The datasets are analyzed on two conditions which are incorrect values and missing values. The difficulties occurred are outlined underneath.

Incorrect values

Under incorrect values are those measurements understood where one to four out of the four variables do have a record in the dataset, but where the value "NaN" is generated. When calculating the PE no value can be produced. This is solved through linear interpolation between previous and consecutive correct value. In general incorrect values of one to three consecutive time steps occurred, thus not rendering a significant decrease of the quality of the data. However, three stations did comprehend a significant amount of consecutive, incorrect values. This is presented in table D-1 where for each observation station the amount of incorrect values are presented. The number of incorrect values stands for the number of measurements with incorrect hourly values which are interpolated. Only incorrect values in the observation stations with the variables T_a, T_d and u_2 occurred. The dataset with the variable n did not hold any incorrect value. The four stations with consecutive incorrect values are expounded underneath:

- Bingley Samos did not hold values for the variable T_a and T_d from 20th of June 1984 till 30th of June 1984. Furthermore it did not hold values for u_2 from 1st of October 1985 till 17th of October 1985.
- Marham did not hold values for the variable u_2 from 6th of December 1983 till 5th of January 1984.
- New Castle did not hold values for all the three variable T_a, T_d, and u_2 from 29th of October 1990 till 30th of November 1990.
- Yeovilton did not hold values for all the three variable T_a, T_d, and u_2 from 27th of July 1990 till 19th of August 1990.

The difficulties for the four above stated observation stations are solved by applying the average of accompanying time steps from the other available years.

Table D-1. Observation stations with incorrect and missing values for Ta, Td and u2

Observation station	**Incorrect values**	**Missing values**
Aughton	*2*	
Bingley Samos	*299*	
Boulmer	*0*	
Brawdy	*1*	*January 1984*
Bristol	*1*	*January 1984 and January1990*
Cilfynnydd	*124*	
Coltishall	*3*	
Coningsby	*2*	
Culdrose	*0*	*January 1984*
Elmdon	*3*	
Eskdalemuir	*2*	
Exeter	*0*	*January 1984*
Finningley	*0*	
Gatwick	*0*	
Heathrow	*0*	
Leeming	*3*	
London	*2*	
Manston	*1*	
Marham	*744*	
Milford Haven	*12*	*January 1984*
New castle	*6*	
Nottingham	*0*	
Plymouth	*0*	*January 1984*
Rhoose	*16*	
Ringway	*0*	*July 1990*
Shawbury	*0*	*July 1990*
St Mawgam	*0*	*January 1984*
Stansted	*0*	
Tynemouth	*63*	
Valley	*0*	
Waddington	*1*	
Yeovilton	*27*	

Missing values

All of the aggregated datasets for the variables T_a, T_d and u_2 contained missing values, except for one. Under missing values is understood that no record is present in the dataset which is extracted from the BADC. All stations did not have any records for the month of July. Only for the year 1989 a record for the month of July is available. Just one observation station which is Boulmer, has records for all days, thus for every month of July. In order to fill up the missing values regarding the variables T_a, T_d and u_2 equation [D-1] is used, which is:

$$Value_{j,i} = \left(\frac{Average_{j,1989}}{Average_{Boulmer,1989}} \right) \bullet Boulmer_i \qquad [D\text{-}1]$$

With:

$Value_{j,i}$ = value for catchment j and model time step i

$Average_{j,i}$ = average of all values for the month of July 1989 for catchment j

$Average_{Boulmer,1989}$ = average of all values for the month of July 1989 for catchment Boulmer

$Boulmer_i$ = daily values for catchment Boulmer for the months of July of the period 1983 – 1990 with the exception of 1989

Besides missing values for every month of July for the variables T_a, T_d and u_2, 7 observation stations were missing records for the month of January 1984, 2 observation stations for records for the month of July 1990 and one observation station for the month of January 1990. This problem is solved by using the mean from the other 7 available years of the same observation station. The observation stations which did not contain the records are presented in table D-1.

With respect to the variable n only for one observation station missing values were obtained. Shawbury was missing values for the whole month of August 1983. This is solved at the same way as describes above.

E. Evaluating potential evapotranspiration

The map in figure E-1 is build based on a dataset provided by the GeoNetwork opensource Community website (GNOCW, 2006). The map holds values of long term average annual potential evapotranspiration over the period 1961 – 1990.

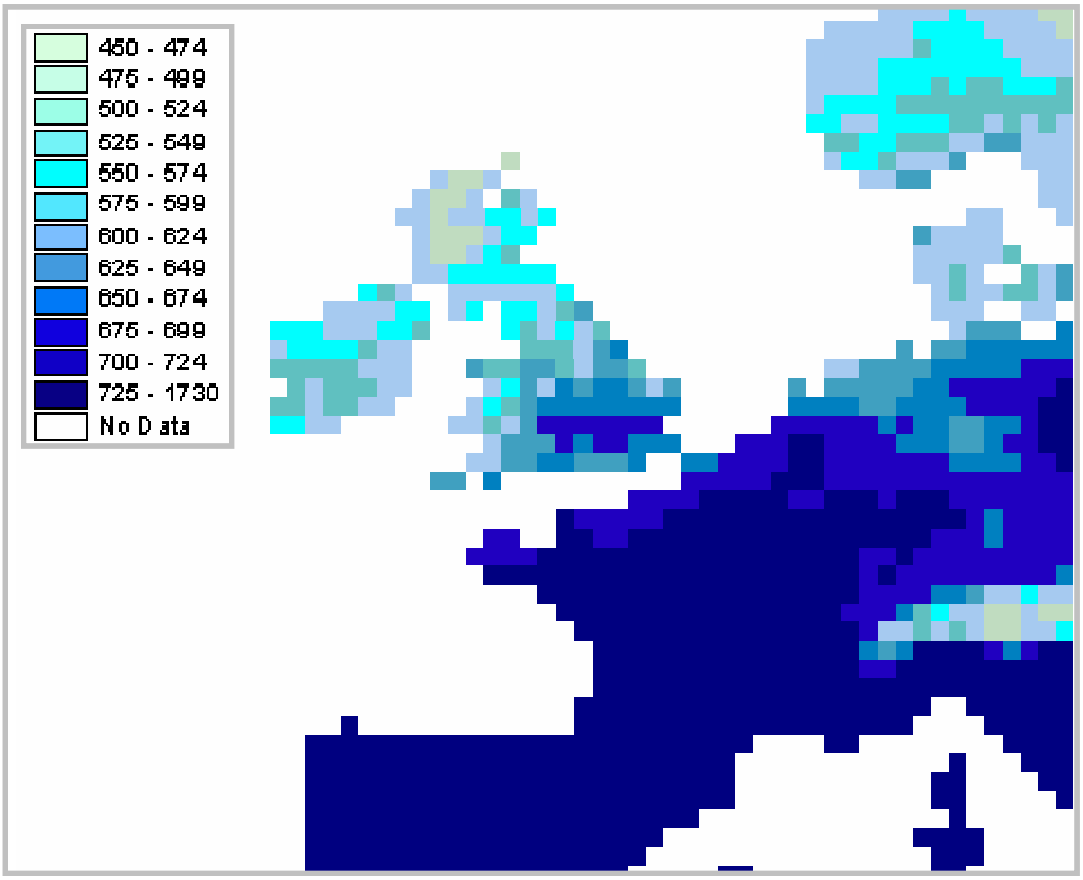


Figure E-1. Long term average annual potential evapotranspiration over the period 1961 - 1990

F. Values for the required model parameters

In this appendix the values of the model parameters which are required to simulate with the HBV model are shown. These are shown in table F-1. The model parameters which are selected for establishing the relationships with the PCCs are not presented.

Figure F-1. Values for the required model parameters

Model parameter	Value	Unity
CEVPFO	1.15	[-]
CFLUX	1.0	[mm day^{-1}]
CFMAX	3.5	[mm ^{o}C^{-1} day^{-1}]
CFR	0.05	[-]
ECALT	0.1	[-]
FOCFMAX	0.6	[-]
FOSFCF	1.0	[-]
PCALT	0.1	[-]
RFCF	1.0	[-]
SFCF	1.0	[-]
TCALT	6.0	[^{o}C km^{-1}]
TT	-0.5	[^{o}C]
TTI	2.0	[^{o}C]
WHC	0.1	[-]

G. Brief description sensitivity model parameters

In this appendix it is shown in what way the hydrograph changes when one of the seven model parameters is changed. Hence, for each model parameters an indication is given for which part of the hydrograph a specific model parameter is most sensitive. This is based on visual interpretation of the differences between two figures. For each model parameter at first one is generated based on the optimum parameter set derived for one of the validation catchments. The second figure shows the hydrograph with a contrasting parameter value.

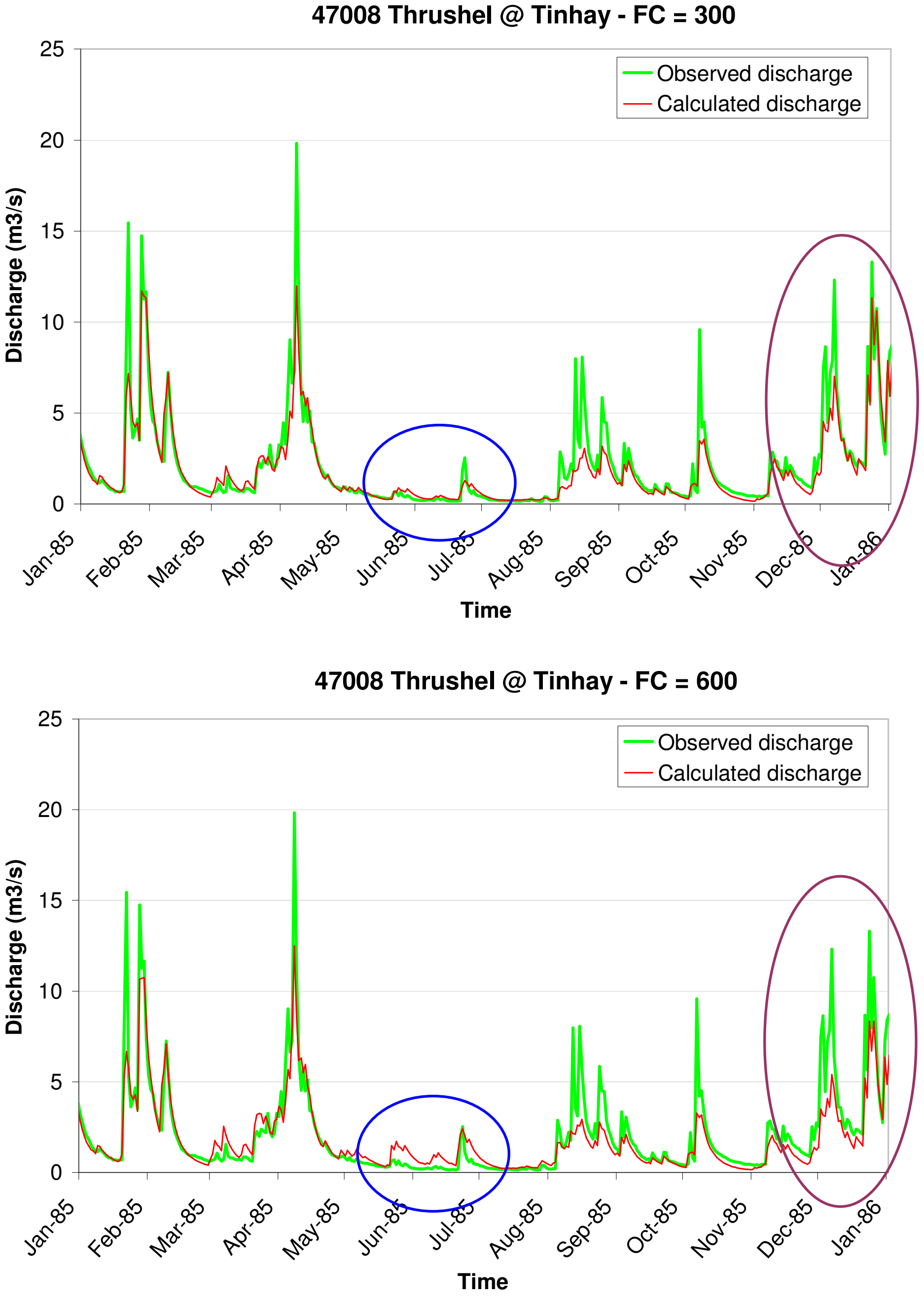


Figure G-1. Optimum parameter value for FC of 300 and a contrasting value of 600

As can be seen from figure G-1, larger values of *FC* result in a more responsive catchment when the system reaches its steady state. This can be seen indicated by the blue circles. However, higher values also results in less higher peaks at high discharge as indicated by the purple circles. When assessing another time period of the hydrograph such as the whole year of 1987, the latter difference is being confirmed and this difference is larger than is shown in figure G-1. Concluding, it seems that *FC* is a relative sensitive model parameter.

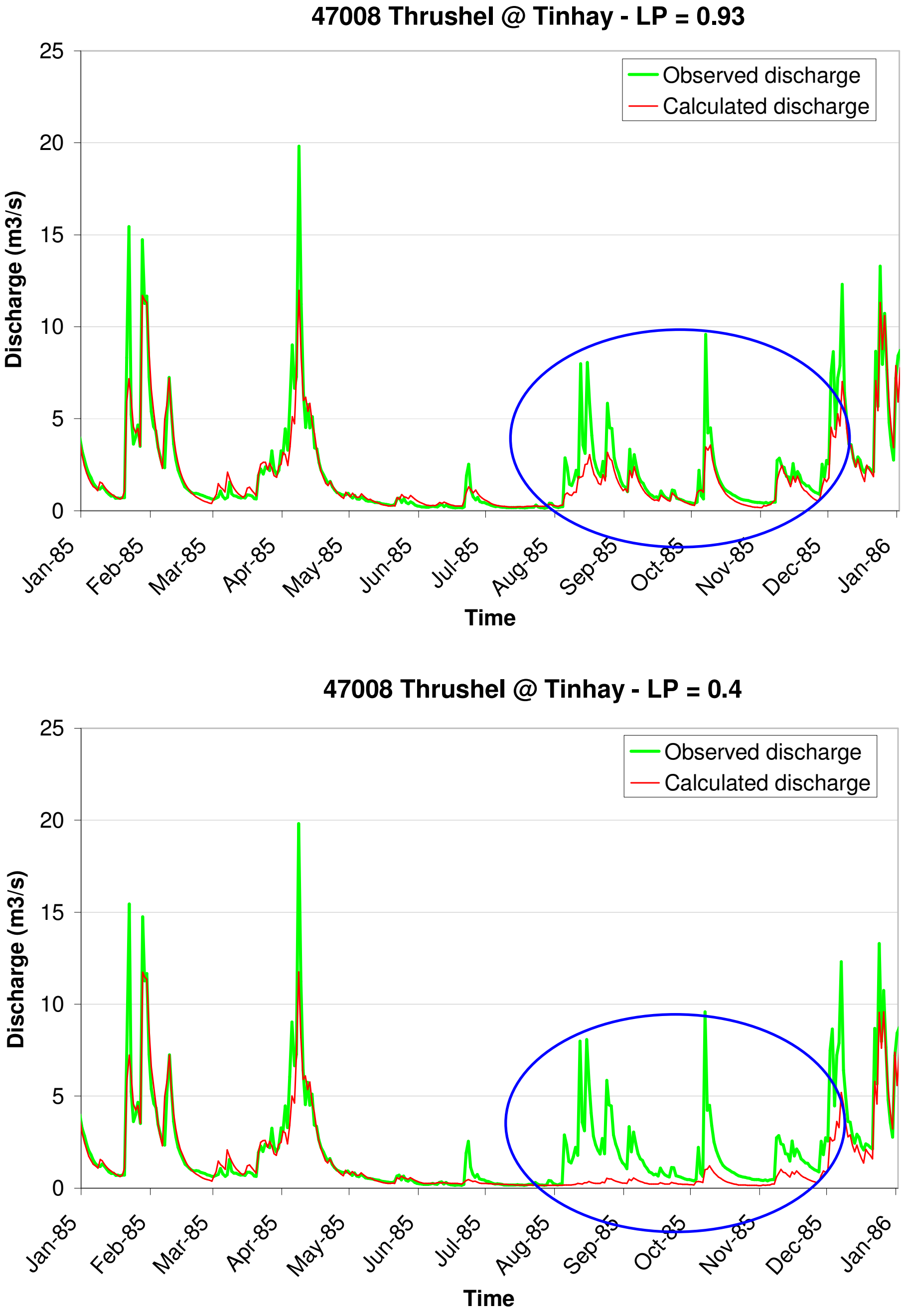
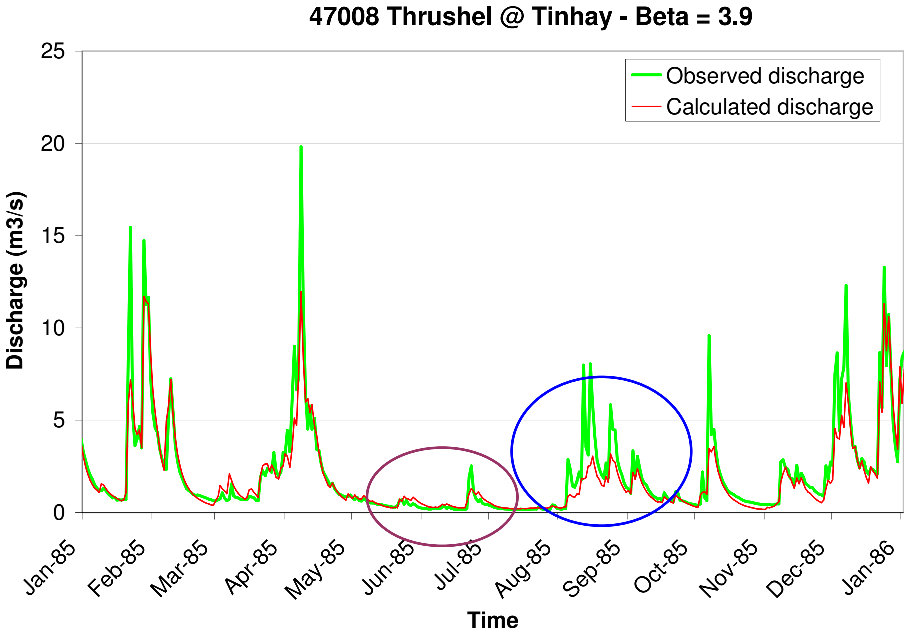


Figure G-2. Optimum parameter value for LP of 0.45 and a contrasting value of 0.9

As can be seen in figure G-2, lower values of *LP* can result in less discharge. This due to the fact that *LP* is a limit where above the evapotranspiration reaches its potential value. Hence, at a low amount of the soil moisture state the evapotranspiration reaches its potential value and in total more precipitation will evapotranspiration. In this case, as indicated in the blue circle the amount of potential evapotranspiration causes the soil moisture reservoir not to be able to fill up since the amount of evapotranspiration is larger than could be generated by the indirect discharge. The problem only occurs during summer but it persists through to the beginning of the next year. Therefore it can be stated that *LP* influences both quick and slow flow and is a very sensitive model parameter.



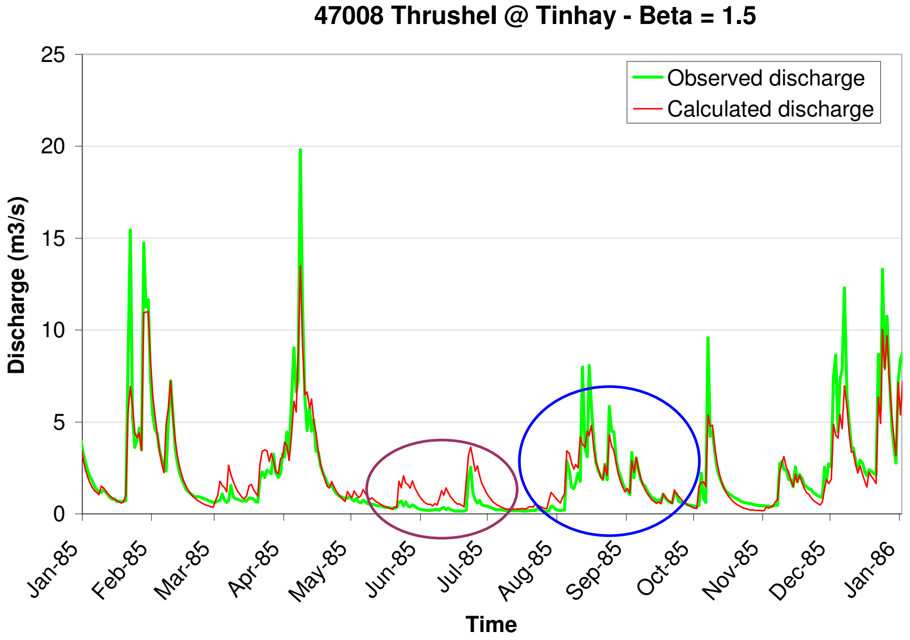


Figure G-3. Optimum parameter value for BETA of 3.9 and a contrasting value of 1.5

Smaller values of *BETA* result in more infiltration from the soil moisture state to the quick runoff reservoir. In this case, the system's potential for more discharge is higher. This is shown in figure G-3 by for instance the blue circle. In contrast to *FC* this also applies to the slow flow condition as indicated by the purple circles. Concluding, it appears that *BETA* is equal sensitive as *FC*.

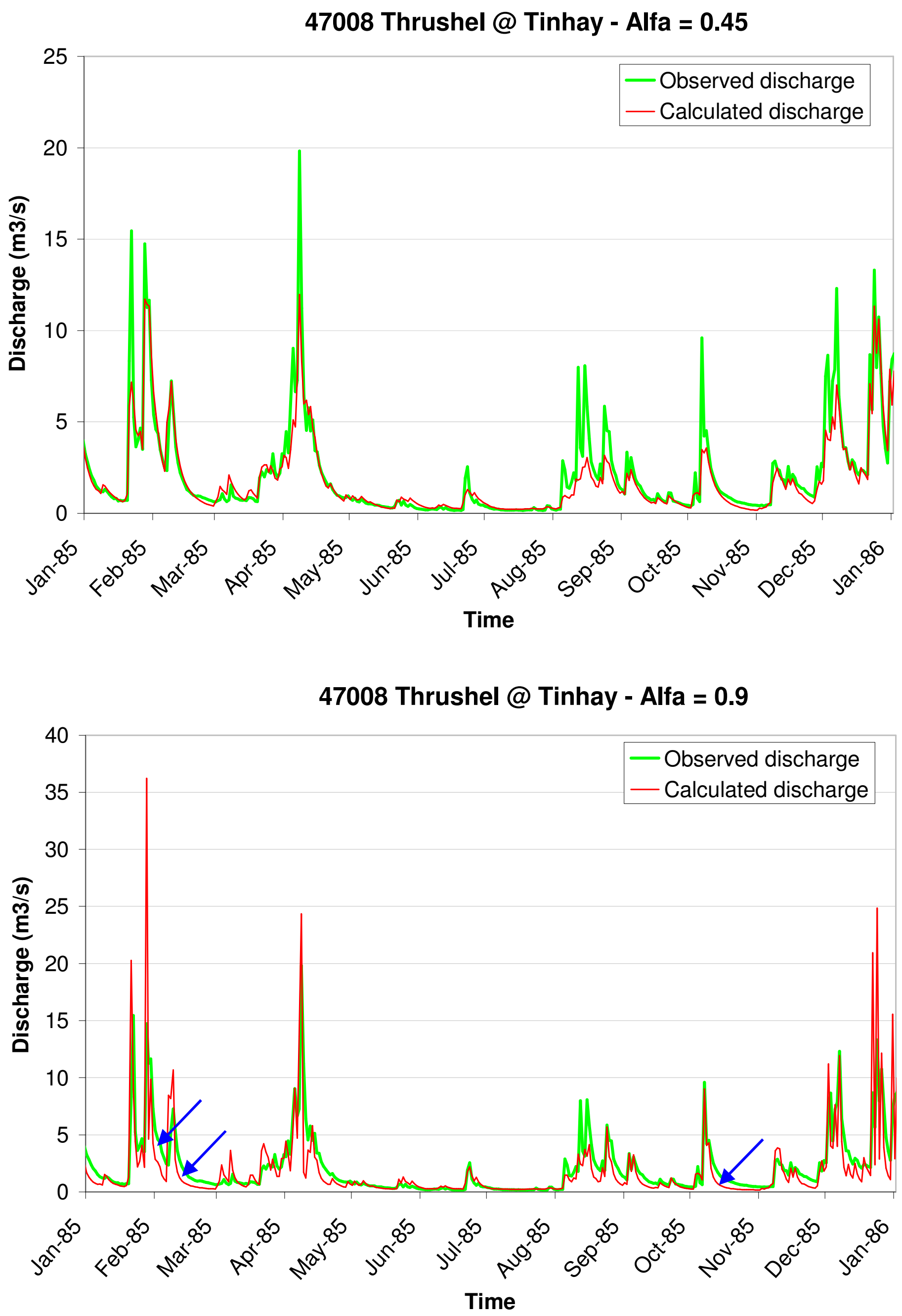


Figure G-4. Optimum parameter value for ALFA of 0.45 and a contrasting value of 0.9

As can be seen from figure G-4, higher values of *ALFA* result in extremer differences with respect to the amount of discharge as well as the slope of the rising and declining limb of the hydrograph. The model parameter *ALFA* is responsible for the behaviour of the quick runoff of the total discharge. Hence, higher values of *ALFA* result in a more non-linear behaviour, thus more discharge at concerning time step. This applies to the quick flow as well as the slow flow. However, when *ALFA* has a large value, the amount of precipitation available in the quick runoff reservoir also decreases more rapidly. This can be seen indicated by the blue arrow since quick runoff is eliminated considerably fast from the total discharge. Concluding, it is clear that *ALFA* is a very sensitive model parameter.

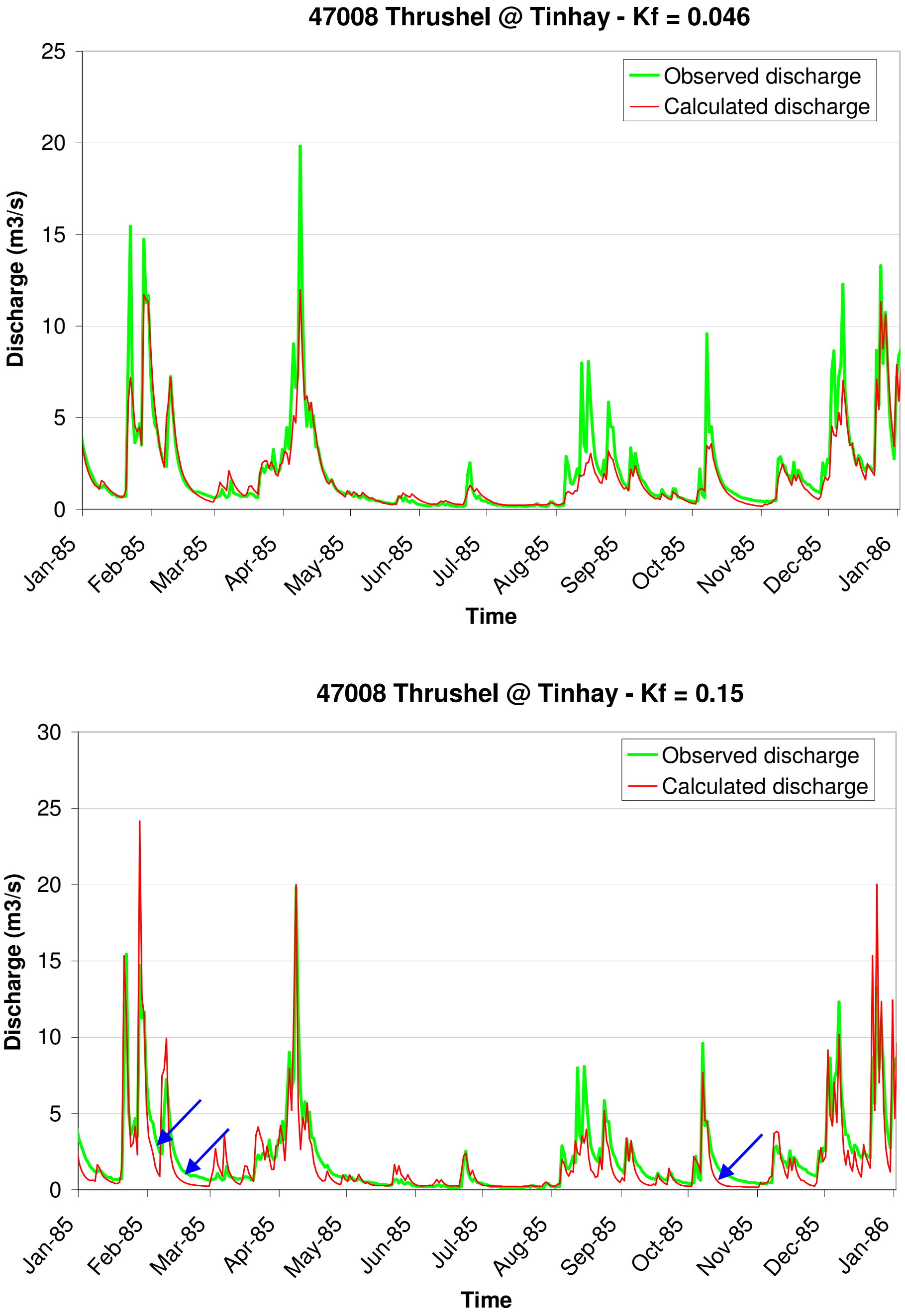


Figure G-5. Optimum parameter value for Kf of 0.046 and a contrasting value of 0.15

As can be seen from figure G-5, higher values of K_f result in more discharge at a given time step. In principal the same appearance occurs as is presented in figure G-4, which shows the results of differences of *ALFA*. However, the differences with respect to model parameter K_f are slightly smaller than model parameter *ALFA*. Concluding, it can be stated that K_f is also a very sensitive model parameter.

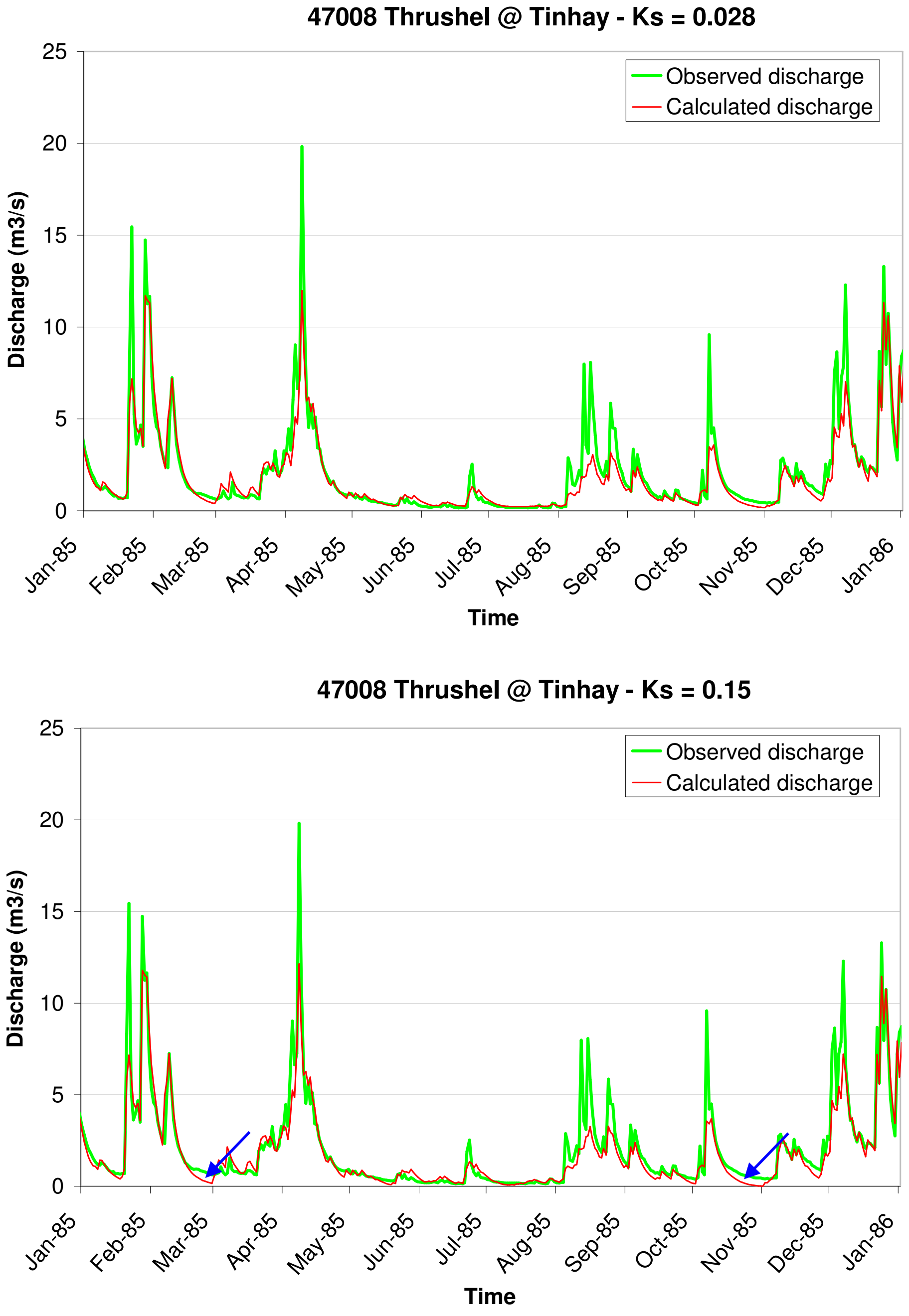


Figure G-6. Optimum parameter value for Ks of 0.028 and a contrasting value of 0.15

As can be seen from figure G-6 at first it looks no differences occur between the two hydrographs. K_s is a model parameter which indicates how much discharge is released from the base flow reservoir. Large values of K_s indicate much discharge. It can be concluded that K_s is a relative low sensitive model parameter since the only difference occurring is indicated by the blue arrows. The falling limb after a storm event keeps on declines than when a high value for K_s is used.

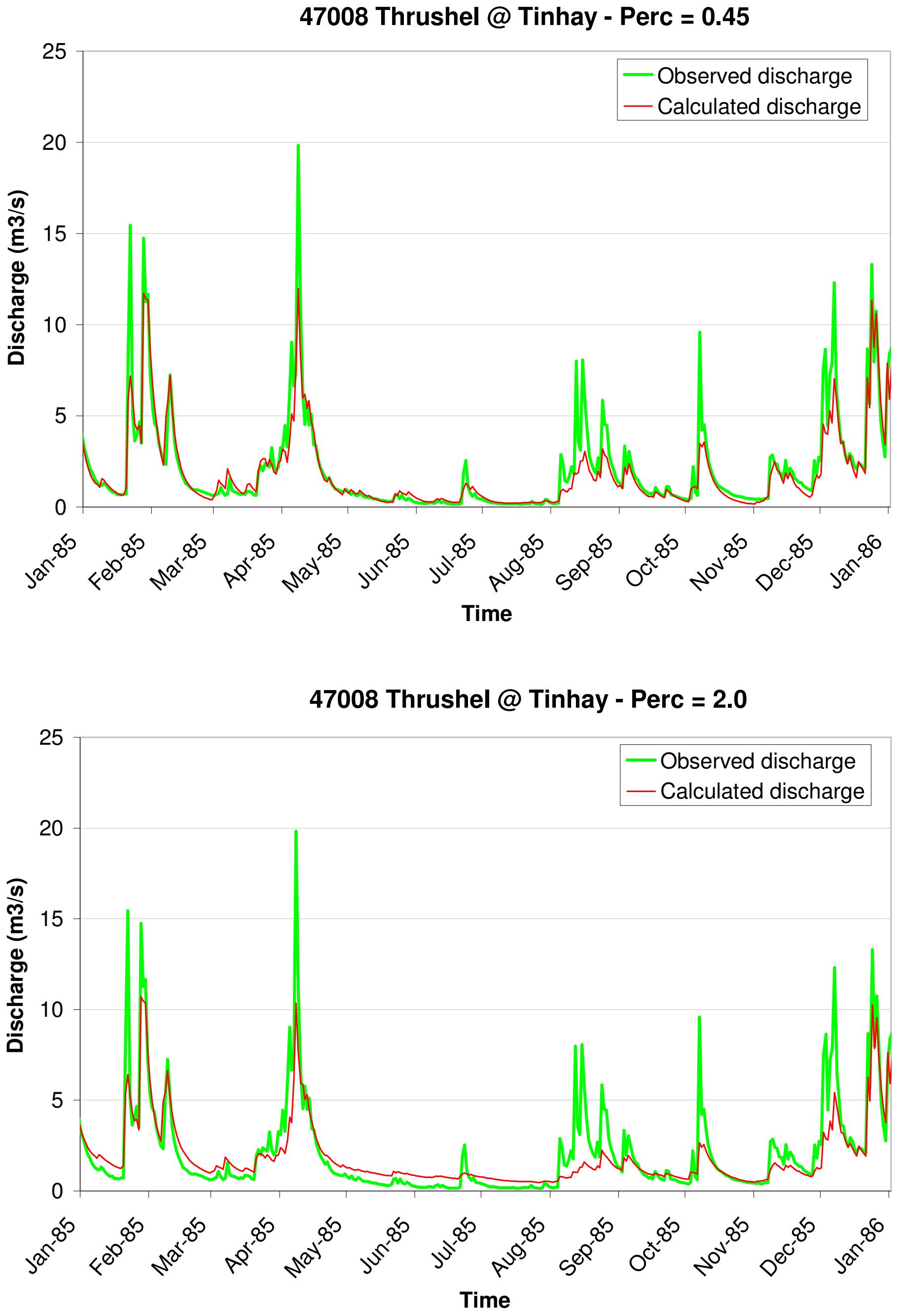


Figure G-7. Optimum parameter value for PERC of 0.45 and a contrasting value of 2.0

As can be seen from figure G-7, model parameter *PERC* is of great influence on the behaviour of the hydrograph. When high values are used, the high discharge is levelled off while during low discharge the flow is overestimated. The reason for this is that *PERC* is the only parameter which fills the base flow and when a high value is used, in respectively a short time the quick runoff reservoir is emptied into the base flow reservoir. Thus, in this case respectively quick only the base flow contributes to the total discharge. It can be concluded that *PERC* is a very sensitive model parameter.

H. Benchmarked physical catchment characteristics

In table H-1 the PCCs used in the evaluated studies are presented.

Table H-1. Evaluated studies with accompanying PCCs

	Study			
Model	**HBV**	**HBV**	**HBV**	**IHACRES**
Type of PCC	**Merz and Blöschl (2004)**	**Hundecha & Bárdossy (2004)**	**Seibert (1999b)**	**Sefton and Howarth (1998)**
Dimension of catchment	Catchment area [km2]	Catchment area [km2]	Catchment area [km2]	Catchment area [km2]
Shape		Catchment shape [-]		
Topographic	Mean catchment elevation [m]			Mean catchment elevation [m]
	Mean slope [m/km]	Mean slope [%]		Mean slope [m/km]
	Topographic wetness index [-]			
Stream network structure	River network density [km/km2]			Stream frequency [junctions/km2]
				Channel slope [m/km]
Geology and soils	Two classes of soil types [%]	Six classes of soil types		Five classes of soil types [%]
	Areal portion with porous			
	Three classes of geologic units [%]			
Land use	Two classes of land use [%]	Three classes of land use [%]	Two classes of land use [%]	Eight classes of land use [%]
Climatic	Mean annual precipitation [mm]			Standard annual average rainfall
	Mean long term maximum annual			Annual relative humidity [%]
				January/July relative humidity
				Mean monthly sunshine [h]
				January/July sunshine [h]

I. Summarized physical catchment characteristics

In table I-1 the selected PCCs with accompanying values are shown. The grey shaded catchments are selected for validation.

Table I-1. Selected PCC with accompanying values

		Dimension	***Topography***		***Shape***	***Land use***					***Geology and soils***				***Climatic***
Region	*#*	*AREA*	*ELEVATION*	*HI*	*SHAPE*	*WOODLAND*	*ARABLE*	*GRASS*	*MOUNTAIN*	*URBAN*	*HIGHP*	*MODERATEP*	*LOWP*	*MIXEDP*	*SAAR*
North-East	22001	569.8	224.9	0.286	16.99	16	17.8	52.8	12.5	0.8	0	52.1	26.2	21.7	850
	22006	269.4	117.2	0.385	9.27	7.1	47	42.3	0.9	2.7	0	74.9	0	25.1	696
	23006	321.9	430.6	0.394	38.06	5.3	0.8	63	30.6	0.3	0	100	0	0	1331
	24004	74.9	315.5	0.487	33.20	25.6	2.7	30.8	40.7	0.2	0	82.3	0	17.7	894
	25005	196.3	127.2	0.277	18.24	13.1	42.6	32.9	7	4.4	4.2	8.4	87.4	0	725
	25006	86.1	402.6	0.490	14.46	1.2	0.7	34.1	63.6	0.4	0	100	0	0	1128
	27034	510.2	364.8	0.444	19.44	5.5	2.3	70.9	20.1	1.1	0	100	0	0	1342
	27035	282.3	231.1	0.290	18.81	6.2	3.2	81	5.4	3.9	0	98.9	1.1	0	1151
	27042	59.2	231.5	0.493	41.24	11.1	7.9	40.9	38.3	1.8	0	53.3	46.7	0	906
	27056	68.6	166.4	0.520	24.09	24.9	26.1	30.3	16.3	2.4	0	69.7	30.3	0	828
	27058	57.6	198.4	0.424	39.28	17.6	22.3	23.4	35.1	1.6	0	78.7	21.3	0	856
Midlands	28008	399.0	268.3	0.402	13.53	6	7.7	80.9	2.2	2.4	8.7	90.4	0.9	0	1021
	28066	130.0	126.5	0.384	6.91	7.6	7.3	21.8	1.8	61.3	0	0	100	0	722
	54016	259.0	89.6	0.256	3.43	5.7	39.4	48.8	1.5	4.3	21.2	0	73.2	5.6	693
	54029	1480.0	212.3	0.361	8.63	12	23.6	58.6	2.9	2.5	0	0.5	80.2	19.3	818
Anglian	29003	55.2	90.8	0.542	13.06	5.9	80	9.8	0	4.3	100	0	0	0	699
	30015	50.5	128.9	0.682	7.60	8.7	63.1	25.5	0.2	2.5	89	0	11	0	656
	31010	68.9	112.8	0.391	13.82	14	51.2	31.6	0.2	3	28.3	0.6	71.1	0	640
	31025	24.5	146.0	0.485	18.20	9.1	35.5	49.6	0.1	5.7	0	0	100	0	663
	32004	194.0	108.3	0.410	6.49	9.2	51.4	27.8	0.4	11	0	55.5	44.5	0	635
	32006	223.0	124.4	0.389	6.04	8.6	49.3	34.6	0.2	6.9	0	12.8	87.2	0	651
	33019	316.0	38.5	0.465	1.99	15.7	62.4	17.3	0	4.5	100	0	0	0	620
	33029	98.8	25.3	0.241	5.73	12.5	69.4	14	0	4	92.3	0	7.7	0	629
	36003	53.9	59.7	0.637	5.52	5.2	75.1	14.9	1.1	3.7	44.3	0	45.1	10.6	566
	37005	238.2	66.0	0.540	4.20	7.5	73.5	13.7	0.4	4.9	18.8	0	73.3	7.8	566
Thames	38003	133.9	120.8	0.503	7.47	12.7	56.4	18.2	0	12.7	97	0	0	3	656
	38029	50.4	118.0	0.555	7.47	5.6	78.9	13.7	0	1.8	100	0	0	0	625
	39006	362.6	177.9	0.449	9.76	8.7	0.9	16.3	0	74	73.8	0	26.2	0	743
	39015	44.6	132.4	0.387	14.82	12.1	42.1	29.3	1.8	14.7	96.9	0	1	2.1	777
	39020	106.7	197.4	0.425	13.81	16.2	40.7	39.8	0.3	2.9	87.6	0	12.4	0	820
	39028	101.3	157.3	0.326	6.91	24.9	48.9	21.9	1.7	2.6	81.7	8.4	0	9.9	786
	39029	59.0	132.6	0.386	23.02	49.1	17.8	23.1	0.3	9.7	90.4	0	9.6	0	809

		Dimension	***Topography***		***Shape***	***Land use***					***Geology and soils***				***Climatic***
Region	*#*	*AREA*	*ELEVATION*	*HI*	*SHAPE*	*WOODLAND*	*ARABLE*	*GRASS*	*MOUNTAIN*	*URBAN*	*HIGHP*	*MODERATEP*	*LOWP*	*MIXEDP*	*SAAR*
South	41022	52.0	82.0	0.251	19.05	41.6	23	30.5	0.7	4.1	22.5	0	77.5	0	858
	42008	75.1	120.9	0.392	12.28	13.3	50.2	29.6	3.7	3.2	100	0	0	0	889
	42012	185.0	113.4	0.345	9.27	14.5	42.2	30.9	5.3	7.1	100	0	0	0	773
South-West	43006	220.6	138.3	0.387	8.44	15.9	48.7	29.9	2.2	3.1	45.5	41.3	13.2	0	875
	44006	124.4	187.9	0.509	11.12	7	54	34.5	3.5	1	100	0	0	0	1032
	45005	202.5	143.8	0.445	14.46	12.8	35.7	42.6	1.8	7.1	27.7	31.7	40.6	0	976
	47008	112.7	162.7	0.378	14.53	14.6	15.1	65.8	0.1	1.9	0	0	100	0	1143
	48003	87.0	126.5	0.402	20.07	16.3	21.3	41.6	15.8	4.9	0	0	76.9	23.1	1210
	48010	39.1	135.5	0.321	35.82	6.9	31.3	54.6	0.7	6.5	0	0	90.5	9.5	1328
	49002	47.6	80.1	0.374	17.09	8.9	40.6	44	0.4	6.1	0	0	79.3	20.7	1077
	50001	826.2	181.8	0.213	8.97	12.9	22.6	60.3	1.9	2.3	0	2.8	95.4	1.8	1155
	52010	135.2	104.5	0.339	12.81	7	41.5	47.1	0.8	3.5	42.9	12.8	44.3	0	867
	53009	72.6	135.5	0.391	13.29	11.2	35.2	40.4	0.6	12.6	31	0	64.9	4.1	998
	53013	99.2	110.9	0.285	10.72	10.9	35.2	45	0.9	7.9	22.4	36.7	40.8	0	724
	53017	47.9	111.9	0.441	22.06	8.7	28.3	56.5	0.3	6.2	11.7	4.3	84.1	0	808
Wales	55012	244.2	333.3	0.386	22.40	25	0.8	62.2	11.1	0.9	0	0	100	0	1628
	55013	126.4	302.3	0.421	26.04	10.6	5.6	70.7	12.1	1	0	0	75.9	24.1	962
	55014	203.3	298.0	0.325	25.16	11.7	6.4	73.3	8.2	0.4	0	0	83.7	16.3	978
	57010	39.4	172.0	0.347	35.73	18.2	4	64.3	2.1	11.4	0	94.1	0	5.9	1620
	60006	129.5	188.2	0.518	18.41	18.8	4.4	73.8	0.8	2.2	0	0	100	0	1602
	60010	1090.4	232.7	0.282	12.34	21.4	2.2	72	2.7	1.5	0	0.8	99.2	0	1534
	62001	893.6	209.2	0.349	10.96	12	4.7	79	1.9	2.3	0	0	100	0	1382
	66011	344.5	341.5	0.322	21.45	17.1	0.4	65.3	16.2	0.5	0	0	100	0	2055
	67018	53.9	384.5	0.327	50.47	24.3	0.1	57.9	17.3	0.3	0	0	100	0	2020

J. Extended description of relationships

In this appendix the demonstrated dependent relationships between model parameters and PCCs are shown. In table J-1 these relationships are shown and if a brief description was given, it is added. In addition, the relationships addressed in the literature based on hydrological reasoning and visual interpretation of calibrated parameter values are also described. Since Hundecha and Bárdossy (2004) introduced a-priori relationships and these are based on hydrological reasoning, this study is not expounded in the table. Furthermore, the relationships addressed in Sefton and Howarth (1998) are not described in this table since the IHACRES model is used.

Table J-1. Dependent relationships addressed in the literature

Study	**Expected relationships**			**Description**
	Parameter	*Sign*	*Physical catchment characteristic*	
Booij (2005)	BETA	+	1/AREA	A measure of heterogeneity. In large catchments more heterogeneity will occur and runoff is gradually generated. Small catchments have more homogeneity and therefore runoff is simultaneously generated, thus *BETA* having a high value.
	ALFA	+	Slope	Catchments with steep hills generate a more non-linear behaviour and increase the quick flow.
	K_f	+	Slope	Catchments with steep hills generate faster discharge response with respect to the quick flow.
Merz and Blöschl (2004)	BETA	-	ELEVATION	Large *BETA* values stand for low runoff coefficients and non-linear runoff generation behaviour which prevail in lowland catchments.
	K_f	+	ELEVATION	More responsive surface runoff occurs in high altitude catchments.
	PERC	-	River network density	In catchments with few streams a larger portion of water penetrates deep into the subsurface.
	FC	+	% porous aquifers	Porous aquifers intend to increase the storage capacity of the catchment.
Seibert (1999b)	K_f	-	% lake	
	BETA	+	AREA	
	FC	+	% lake	
	K_s	+	% forest	

J.1. Merz and Blöschl (2004)

The following expected relationships are addressed in the study of Merz and Blöschl (2004).

- Smaller values of the maximum soil moisture storage *FC* are found in higher alpine catchments. This implies that shallow hydrologically active soil depths are present, which is a realistic implication since in higher catchments in general more bare rock covers are present.
- The limit for potential evapotranspiration, LP, has a similar pattern as for *FC*. Thus, in higher catchments, smaller values occur.

- Wetter catchments imply a relatively linear rainfall-runoff relationship, which indicates that *BETA* has a low value. Furthermore, non-linear rainfall-runoff relationships are related to dryer catchments which indicate that *BETA* has a relatively high value.
- From process based reasoning it is expected that relationships between the fast storage coefficient as well as the slow storage coefficient and PCCs such as land use or soil type could be determined, which however was not the case.
- Smaller catchments tend to produce surface runoff more easily than large catchments.

J.2. Hundecha and Bárdossy (2004)

In table J-2 the a-priori established relationships between catchment characteristics and model parameters are shown. Furthermore, they executed a sensitivity analysis which is also shown in the same table. This study however determined these a-priori relationships based on experience gathered from physically-based models.

Table J-2. Physical catchment characteristics used in a-priori determined relationship and the degree of sensitivity.

Parameter	**Physical catchment characteristic**	**Sensitivity**
FC	Soil type, land use	+++
LP	Soil type	-
BETA	Soil type, land use	+
ALFA	Soil type, land use	+++
K_f	Soil type, land use, area, slope, shape	+++
K_s	Soil type, land use, area, slope, shape	+
PERC	Area, slope, shape	+++

J.3. Sefton and Howarth (1998)

Sefton and Howarth (1998) at first considered what dependencies they expected for the IHACRES parameters. Although these dependencies are not of interest for the HBV model used in this study, it gives insight in hydrological reasoning. However, the only interesting expected dependencies for this study concern the routing module. With respect to recession coefficients, as the HBV model also incorporates, they stated that these would be affected by topography and soils and geology. In addition, geology is expected to be the most dominant with respect to volumetric separation between components of the hydrograph. With respect to this study this can be related to the parameter *PERC* since this parameter differs between the base flow and the quick runoff reservoir.

K. Adjusted parameter space

In table K-1 the adjusted parameter space against the initial selected parameter space is shown.

Table K-1. Adjusted against initial parameter space

	FC				BETA				LP				ALFA				Kf				Ks				PERC			
	Initial		**Adjusted**		**Initial**		**Adjusted**		**Initial**		**Adjusted**		**Initial**		**Adjusted**		**Initial**		**Adjusted**		**Initial**		**Adjusted**		**Initial**		**Adjusted**	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*	*Min*	*Max*
22001	125	800	125.3	797.8	1	4	1.003	4	0.1	1	0.2152	0.9995	0.1	3	0.1025	2.104	0.0005	0.15	0.0005	0.1494	0.0005	0.15	0.0007	0.1499	0.1	2.5	0.1026	2.498
22006	125	800	126.3	799.3	1	4	1.002	4	0.1	1	0.1866	0.9993	0.1	3	0.1049	2.804	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1158	2.498
23006	125	800	126.6	796.7	1	4	1.002	3.999	0.1	1	0.115	0.9956	0.1	3	0.1045	1.426	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1142	2.499
24004	125	800	125.3	797.8	1	4	1.003	3.996	0.1	1	0.3598	0.9998	0.1	3	0.1026	2.267	0.0005	0.15	0.0005	0.1493	0.0005	0.15	0.0007	0.1497	0.1	2.5	0.1026	2.491
25005	125	800	125.3	798.4	1	4	1.002	4	0.1	1	0.3017	0.9995	0.1	3	0.104	2.748	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0006	0.1499	0.1	2.5	0.1026	2.498
25006	125	800	125.3	799.1	1	4	1.002	4	0.1	1	0.1256	0.9994	0.1	3	0.1025	1.732	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0007	0.1499	0.1	2.5	0.1026	2.494
27035	125	800	125.3	797.8	1	4	1.002	4	0.1	1	0.2982	0.9996	0.1	3	0.1025	2.074	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0007	0.1499	0.1	2.5	0.1026	2.497
27042	125	800	125.3	798.3	1	4	1.003	3.996	0.1	1	0.3743	0.9997	0.1	3	0.1059	2.324	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1494	0.1	2.5	0.1026	2.494
27058	125	800	387.4	799.9	1	4	1	4	0.1	1	0.1006	0.6144	0.1	3	0.1022	1.834	0.0005	0.15	0.0005	0.1492	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1922	2.492
28008	125	800	126.4	799.1	1	4	1.003	4	0.1	1	0.3867	0.9996	0.1	3	0.1049	2.074	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.498
28066	125	800	NaN	NaN	1	4	NaN	NaN	0.1	1	NaN	NaN	0.1	3	NaN	NaN	0.0005	0.15	NaN	NaN	0.0005	0.15	NaN	NaN	0.1	2.5	NaN	NaN
29003	125	800	125.3	795.9	1	4	1.002	4	0.1	1	0.3943	0.9996	0.1	3	0.1022	2.192	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.1026	2.499
30015	125	800	125.8	799.3	1	4	1.002	3.999	0.1	1	0.1372	0.9983	0.1	3	0.1049	2.674	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.1066	2.495
31025	125	800	126.4	794.4	1	4	1.002	4	0.1	1	0.1266	0.9993	0.1	3	0.1105	2.788	0.0005	0.15	0.0005	0.1498	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1158	2.498
32004	125	800	125.3	797.9	1	4	1.002	4	0.1	1	0.2119	0.9993	0.1	3	0.104	2.812	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0007	0.15	0.1	2.5	0.1026	2.499
32006	125	800	126.4	795.9	1	4	1.002	4	0.1	1	0.1266	0.9994	0.1	3	0.107	2.804	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1112	2.499
33019	125	800	125.3	797.8	1	4	1.002	4	0.1	1	0.2916	0.9995	0.1	3	0.1046	2.674	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0006	0.1499	0.1	2.5	0.1026	2.499
33029	125	800	125.6	799.5	1	4	1.003	3.999	0.1	1	0.1015	0.9868	0.1	3	0.1054	2.799	0.0005	0.15	0.0006	0.1497	0.0005	0.15	0.0006	0.1499	0.1	2.5	0.1216	2.497
36003	125	800	126.8	799.3	1	4	1.005	3.996	0.1	1	0.1265	0.9983	0.1	3	0.1047	2.817	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0005	0.15	0.1	2.5	0.1099	2.496
37005	125	800	126.4	799.3	1	4	1.002	4	0.1	1	0.1266	0.9993	0.1	3	0.1063	2.817	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.1222	2.495
38003	125	800	127.4	799.6	1	4	1.002	4	0.1	1	0.1356	0.9994	0.1	3	0.104	2.783	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.2375	2.499
39006	125	800	132.1	797.8	1	4	1.002	4	0.1	1	0.1112	0.9994	0.1	3	0.1063	2.373	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1085	2.499
39015	125	800	141.3	799.7	1	4	1.002	4	0.1	1	0.1384	0.9983	0.1	3	0.1013	1.133	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1497	0.1	2.5	0.1307	2.491
39020	125	800	125.3	794	1	4	1.002	3.996	0.1	1	0.2014	0.9996	0.1	3	0.1015	1.777	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1114	2.499
39028	125	800	196.7	799.8	1	4	1.003	4	0.1	1	0.12	0.9993	0.1	3	0.1047	2.698	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0006	0.1498	0.1	2.5	0.1273	2.499
39029	125	800	128.4	799.5	1	4	1.002	4	0.1	1	0.1411	0.999	0.1	3	0.1023	2.698	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.145	2.496
41022	125	800	125.4	798.3	1	4	1.002	4	0.1	1	0.1015	0.9993	0.1	3	0.1068	2.267	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1497	0.1	2.5	0.1026	2.499
42012	125	800	191.4	799.5	1	4	1.003	4	0.1	1	0.2827	0.9996	0.1	3	0.1023	1.432	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1497	0.1	2.5	0.1126	2.499
43006	125	800	127.4	797.8	1	4	1.002	4	0.1	1	0.1665	0.9994	0.1	3	0.1049	2.14	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.1087	2.499
44006	125	800	418.7	799.9	1	4	1	4	0.1	1	0.1007	0.6689	0.1	3	0.1007	1.476	0.0005	0.15	0.0005	0.1499	0.0005	0.15	0.0005	0.1496	0.1	2.5	0.1035	2.492
45005	125	800	140.8	799.3	1	4	1.013	4	0.1	1	0.1694	0.9994	0.1	3	0.1046	2.353	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.1267	2.499
48003	125	800	127.4	799.2	1	4	1.013	4	0.1	1	0.1173	0.9994	0.1	3	0.1038	1.757	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.15	0.1	2.5	0.1085	2.499
48010	125	800	126.6	799.1	1	4	1.002	4	0.1	1	0.2845	0.9994	0.1	3	0.1046	1.768	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.499
49002	125	800	126.4	793.1	1	4	1.001	3.996	0.1	1	0.3516	0.9996	0.1	3	0.1061	1.789	0.0005	0.15	0.0005	0.1497	0.0005	0.15	0.0005	0.1498	0.1	2.5	0.1026	2.498
50001	125	800	125.3	796.4	1	4	1.002	4	0.1	1	0.1185	0.9994	0.1	3	0.1064	1.77	0.0005	0.15	0.0005	0.1498	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.499
52010	125	800	125.3	797.8	1	4	1.002	4	0.1	1	0.257	0.9997	0.1	3	0.1026	2.521	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0005	0.1497	0.1	2.5	0.1026	2.498
53009	125	800	126.4	799.1	1	4	1.002	3.996	0.1	1	0.2273	0.9996	0.1	3	0.1047	1.974	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.499
53017	125	800	125.3	797.8	1	4	1.002	3.996	0.1	1	0.2315	0.9994	0.1	3	0.1025	2.322	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0007	0.1497	0.1	2.5	0.1026	2.498
54016	125	800	126.4	796.8	1	4	1.002	4	0.1	1	0.1266	0.9994	0.1	3	0.1057	2.376	0.0005	0.15	0.0005	0.1498	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1099	2.498
54029	125	800	125.3	795.6	1	4	1.002	4	0.1	1	0.1266	0.9994	0.1	3	0.1062	1.907	0.0005	0.15	0.0005	0.1498	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.499
55012	125	800	125.4	797.2	1	4	1.002	3.996	0.1	1	0.4949	0.9997	0.1	3	0.1022	1.845	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0006	0.1499	0.1	2.5	0.1026	2.492
55013	125	800	125.4	788.6	1	4	1.002	3.995	0.1	1	0.1228	0.9994	0.1	3	0.1058	1.703	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.499
55014	125	800	125.3	774.7	1	4	1.002	4	0.1	1	0.2126	0.9995	0.1	3	0.1024	1.657	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.499
57010	125	800	125.4	797.2	1	4	1.003	3.996	0.1	1	0.5222	0.9997	0.1	3	0.1024	1.791	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.493
60006	125	800	125.4	797.2	1	4	1.003	3.996	0.1	1	0.4398	0.9995	0.1	3	0.1024	1.701	0.0005	0.15	0.0005	0.1495	0.0005	0.15	0.0005	0.1499	0.1	2.5	0.1026	2.493
62001	125	800	125.4	798	1	4	1.002	3.996	0.1	1	0.4815	0.9997	0.1	3	0.1025	2.132	0.0005	0.15	0.0005	0.15	0.0005	0.15	0.0005	0.1493	0.1	2.5	0.1026	2.498
66011	125	800	125.4	798.1	1	4	1.003	3.996	0.1	1	0.451	0.9996	0.1	3	0.1019	1.478	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0006	0.1498	0.1	2.5	0.1069	2.497
67018	125	800	125.4	798.1	1	4	1.002	3.996	0.1	1	0.518	0.9997	0.1	3	0.1022	1.422	0.0005	0.15	0.0005	0.1496	0.0005	0.15	0.0006	0.1498	0.1	2.5	0.1069	2.497

L. Optimum parameter set

In table L-1 the optimum parameter sets regarding the catchments that satisfy both conditions are shown.

Table L-1. Optimum parameter set for the 17 selected catchments

	FC	BETA	LP	ALFA	Kf	Ks	PERC
27035	162.8	2.334	0.8533	0.1516	0.1028	0.08215	0.3519
33019	169.5	1.755	0.7537	0.4899	0.01016	0.03951	1.588
41022	255.7	1.404	0.605	0.6951	0.02582	0.08165	0.6824
43006	358.2	1.366	0.733	0.1615	0.05009	0.02318	2.421
45005	705.3	1.156	0.7169	1.098	0.007404	0.01342	1.899
48003	627.2	2.694	0.9099	0.7949	0.00579	0.01506	1.877
48010	370.2	1.249	0.8371	0.3363	0.01827	0.01644	1.557
50001	319.8	3.716	0.8888	0.1787	0.1402	0.02461	0.4819
52010	181.6	2.644	0.843	0.48	0.06828	0.02201	1.08
53009	292.1	1.302	0.8083	0.1602	0.1283	0.02179	1.624
54016	309.4	1.704	0.7056	0.6708	0.01313	0.07437	0.7084
54029	227.1	2.132	0.6679	0.4708	0.02798	0.04921	2.082
55013	138.8	1.839	0.4133	0.2776	0.04698	0.03851	1.2
55014	323.2	3.632	0.9755	0.3142	0.05003	0.03054	2.475
57010	168.6	2.456	0.9979	0.3065	0.1175	0.03994	1.404
60006	229.6	3.757	0.9957	0.9586	0.006535	0.04011	2.139
66011	243.7	3.125	0.9924	0.3681	0.1129	0.09135	0.3069

M. Correlation matrix between physical catchment characteristics

In table M-1 the correlation matrix between PCCs is presented. The significant relationships are presented in bold.

Table M-1. Correlation matrix between PCCs

	AREA	ELEVATION	HI	SHAPE	SAAR	WOOD	ARABLE	GRASS	MOUNTAIN	URBAN	HIGHP	MODERATEP	LOWP	MIXEDP
AREA	1,000													
ELEVATION	0,186	1,000												
HI	-0,189	-0,046	1,000											
SHAPE	**-0,435**	**0,425**	-0,026	1,000										
SAAR	-0,173	**0,537**	0,042	**0,598**	1,000									
WOOD	-0,149	-0,183	-0,039	0,081	0,093	1,000								
ARABLE	0,018	**-0,794**	0,126	**-0,643**	**-0,684**	-0,105	1,000							
GRASS	0,125	**0,791**	-0,137	**0,501**	**0,529**	-0,340	**-0,863**	1,000						
MOUNTAIN	-0,055	**0,655**	0,026	0,304	**0,429**	-0,036	**-0,535**	0,340	1,000					
URBAN	-0,327	**-0,465**	0,101	0,181	0,005	-0,013	0,234	-0,299	-0,411	1,000				
HIGHP	-0,131	**-0,652**	0,304	**-0,603**	**-0,563**	0,067	**0,845**	**-0,799**	**-0,435**	0,158	1,000			
MODERATEP	-0,150	0,064	-0,093	0,268	0,191	-0,111	-0,246	0,272	-0,117	0,351	-0,109	1,000		
LOWP	0,186	0,346	-0,168	0,135	0,277	0,097	-0,341	0,291	0,299	-0,392	**-0,544**	**-0,750**	1,000	
MIXEDP	0,193	0,343	0,101	0,306	-0,116	-0,195	-0,283	0,252	**0,536**	-0,171	**-0,433**	-0,276	0,329	1,000