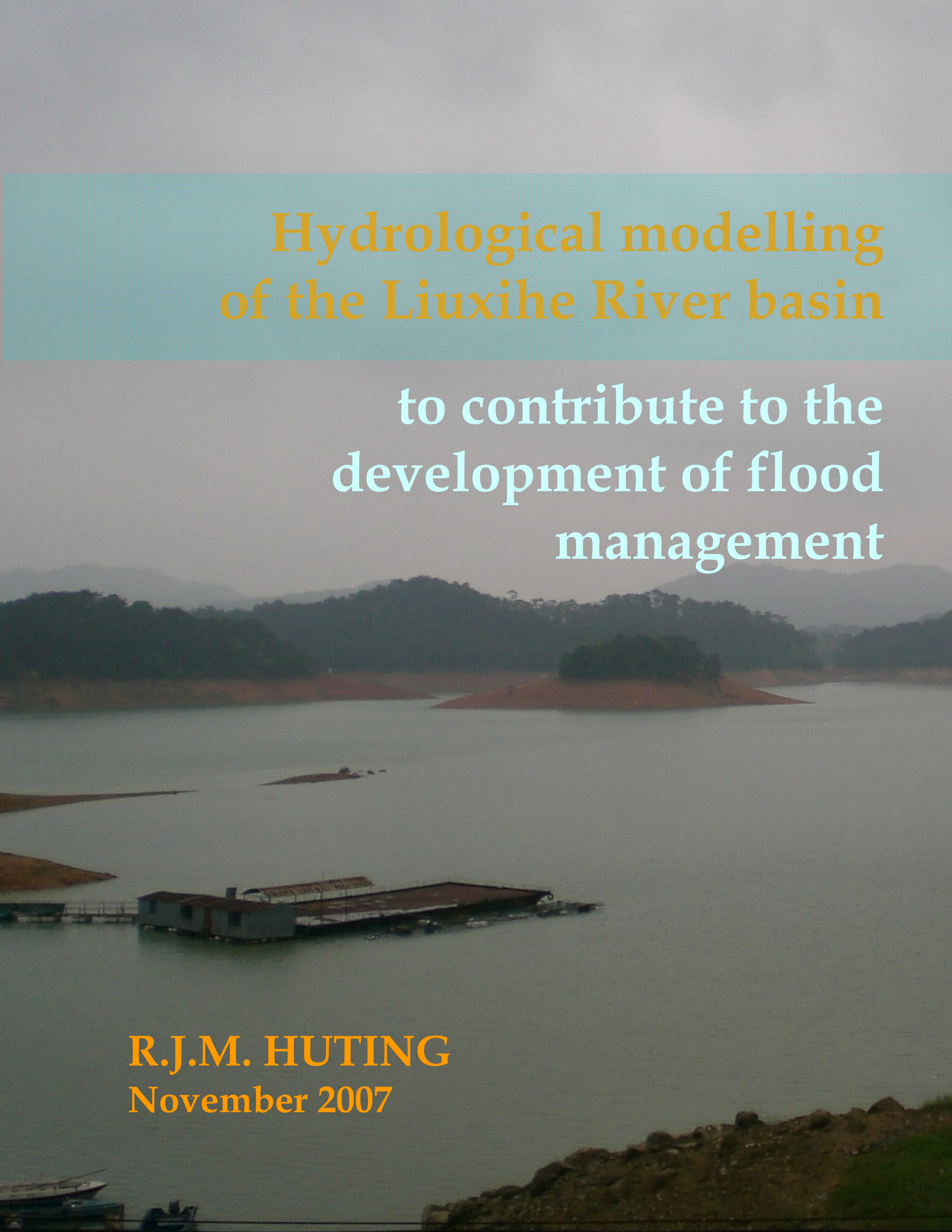

Hydrological modelling of the Liuxihe River basin

to contribute to the development of flood management

R.J.M. HUTING

November 2007

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Preface

Ni hao!

“A journey of a thousand miles begins with a single step”, Confucius already mentioned wisely about 2500 years ago. Early September 2006 I stepped into Martijn’s office for a chat about the possibility of working on a graduation project under his supervision. As soon as I left his office again, I realized that I was at the beginning of something very exciting and challenging: within a few months I would be at the other side of the world, doing research and working on my thesis.

The time at Sun Yat-sen University in Guangzhou was wonderful and sometimes I blamed myself for having planned my stay to last only for 10 weeks. Although I often worked 6 days a week, it still felt a bit as if being on holiday, which actually was the case when I traveled back to The Netherlands by train at the end of May. I never felt bored the past 27 years but this has definitely been the biggest experience of my life. Nevertheless I liked being back home again! I did not expect at that time that it would last until November before I would finish my studies. Probably Ferry and Willeke did not have a clue either when they offered me a bedroom in their flat for as long as my project would last.

I would like to thank Yangbo Chen for giving me the opportunity to work on my thesis at Sun Yat-sen University in China and for offering me a place in his lab among his own students. I never felt alone because my Chinese colleagues were so kind and took me into the city, played football or basketball, went for a swim or for dinner somewhere. And they helped me with finding information and collecting data, and learned me how to eat with chop-sticks. They really are nice friends!

Suzanne and Martijn I would like to thank for their supervision and their involvement with my project, especially when I returned from China and did not really know what had to be done. I hardly ever found a closed door when I went to Martijn’s office with some questions and these visits were never fruitless.

I would like to thank my former housemates of Huize La Strada for keeping in touch while I was in China. I have had a great time during my studies because of our cosy home.

CSD, I am not sure if I will be able to keep on playing with you, but I am sure that next weeks' party will be great fun!

I was very lucky with the 3 physiotherapists who cracked my back when I felt really bad because of spending too much time sitting in front of my computer!

Thijs, I hope you don't mind that this years' cycling will be on Tenerife instead of in the Czech Republic? Thanks for the distraction by doing triathlons, cycling and running together.

Ferry and Willeke, my apologies that it took so long before I knitted an end to this project. Hopefully, my presence in your flat did not bother you too much. On my side I enjoyed living with you at your place for this period, and I am grateful that you gave me shelter.

Michiel, Patrick, Judith and Sterre, I am very lucky that you are my family :-D

Pa & Ma, I think you never really understood why studying had to last this long, but nevertheless you kept on supporting without hesitation. Feel relieved, this definitely was my last course. I love you and hope I will have the opportunity to be there for you in the future!

Enschede, November 2007,

Ric

Summary

The Liuxihe River basin in Guangdong Province, South China, is frequently affected by floods. In order to reduce future losses due to floods, effective flood management is an absolute necessity. The HBV-model, developed at the Swedish Meteorological and Hydrological Bureau, has been successfully applied in many countries all over the world for different purposes. Therefore, the objective of this study is: "The simulation of discharges for the Liuxihe River in South China to contribute to the development of effective operational and strategic flood management by setting up and testing a HBV-model for the Liuxihe River basin."

The HBV-model is a semi-distributed conceptual hydrological model. It uses simplifications of fundamental physical laws, containing non-measurable parameters whose values have to be determined by means of calibration. Model input consists of precipitation, potential evapotranpiration and temperature. For calibration and validation, also observed discharge is a necessary model input. The main model output is the simulated discharge.

Model scale is an important issue in hydrological modelling. Scale refers to both time and space and a distinction can be made between process, observation and modelling scale. For observation scale and modelling scale a scale triplet can be identified, consisting of spacing, extent and support.

Calibration of the HBV-Liuxihe was carried out by means of Monte Carlo simulation, since this method is not very time-consuming and does not require a very skilled hydrologist. Unfortunately, model validation was not possible due to the small temporal extent of the available data. A combined criterion of Nash-Sutcliffe Efficiency E and relative volume error RVE – $ERVE$ – was introduced as criterion to assess performance of the HBV-model during calibration, because this criterion maximizes E while at the same time minimizes RVE.

The available hydrological data for the Liuxihe River basin was of poor quality and quantity. Precipitation data was available for a period of 2 year (2005 – 2006) and contained some errors and had missing values. Potential evapotranspiration data were not available at all, as was the case for temperature. However, the latter was not necessary as model input since temperatures in Guangdong Province do not drop below 0 °C. Observed discharge data were available for a period of 2 years (2005 – 2006), however, only for the most upstream sub-basin: Huanglong Dai Reservoir sub-basin. These data contain missing and unrealistic values.

Because of quality only precipitation data over 2005 were used. For the same period potential evapotranspiration values were derived from literature and the observed discharge data series for these periods were treated with 4 methods. This treatment enabled the use of the observed discharge series since all methods removed negative values from the data series. Eight model calibrations were executed, for the 'zero-based values method' and the 'sequence-based values method', varying temporal resolution and extent of the input data.

Water balances could be set up with the 4 'repaired' observed discharge data series. The outlet of the Huanglong Dai Reservoir sub-basin is formed by a hydro-power reservoir, and balances were made for both the sub-basin and the reservoir. These balances showed the existence of a residual term, which implies that not all water entering or leaving the system is captured by measurements. The existence of this residual term strengthens the idea that the observed discharge data series – as well before as after the four methods were applied to it – are incorrect. Also, the amount of water available for evapotranspiration is small according to the potential evapotranspiration. The 2 extremes of observed discharge data series are used to calibrate the HBV-Liuxihe. Model performance is poor according to the efficiency criterion ERVE (0.18 – 0.34). The best results are obtained with daily temporal resolution, which is contrary to the general idea that an increase in temporal resolution leads to an increase in model performance. However, model performance is too low to classify one of the observed discharge data series as more representative than the others. It is remarkable that about 40 % of the observed runoff occurs after the wet season when only 15 % of the annual precipitation is measured. None of the calibrated models simulates this flow.

Lowest model performance during calibration was obtained with the data series with hourly temporal resolution (*ERVE*: 0.18 – 0.20), with higher performance with the data series with daily temporal resolution (*ERVE*: 0.24 – 0.34). The model calibrations with the data series with the shortest extent – March to December – tend to lead to better results than the model calibrations with the discharge data series for the period January to December 2005. However, this is only the case for the data series with a daily temporal resolution. The model calibrations with the data series obtained with the sequence-based values method are slightly better than the calibrations obtained with the zero-based values method. Despite these differences in model performance according the criterion *ERVE* it is not realistic to argue that one of the eight observed discharge data series is more reliable than the others.

The simulated actual evapotranspiration was much higher than the amount of water available for evapotranspiration.

The set up of an automated gauging system of hydrological variables would be an important step to enable the set up of hydrological models in the future, at least for a part of the Liuxihe River basin. The optimal number of gauges in relation to the natural variability can be determined. The gauging system can later be extended over the whole river basin.

Further research should focus on the constant flow that appears after the wet season. Possibly this flow can be captured by the model by adding an extra storage box to the model. Model calibration with a multi-objective criterion that puts emphasis on both low and high flows could possibly improve model performance. Maybe it is possible to derive different parameter sets for the wet and the dry seasons.

However, although these suggestions may sound interesting, it remains difficult to carry out any kind of research with such a limited amount of data available.

Samenvatting (Dutch)

Het stroomgebied van de Liuxihe Rivier in de provincie Guangdong in Zuid-China wordt veelvuldig getroffen door overstromingen. Om toekomstige overstromingsschade te verminderen is effectief overstromingsbeheer een absolute noodzaak. Het HBV-model, ontwikkeld op het Zweeds Meteorologisch en Hydrologisch Bureau, is succesvol toegepast in veel landen over de gehele wereld voor verschillende doeleinden. Daarom is het doel van deze studie: "De simulatie van afvoeren voor de Liuxihe Rivier in Zuid-China om bij te dragen aan de ontwikkeling van effectief operationeel en strategisch overstromingsbeheer, door een HBV-model voor het stroomgebied van de Liuxihe Rivier op te zetten en te testen."

Het HBV-model is een semi-gedistribueerd conceptueel hydrologisch model. Het maakt gebruik van vereenvoudigde fundamentele natuurkundige wetten en bevat niet-meetbare parameters waarvan de waarden dienen te worden bepaald door middel van calibratie. De modelinvoer bestaat uit neerslag, potentiële evapotranspiratie en temperatuur. De voornaamste modeluitvoer is de gesimuleerde afvoer.

Modelschaal is een belangrijk punt bij hydrologisch modelleren. Schaal heeft betrekking op zowel tijd als ruimte en onderscheid kan worden gemaakt tussen proces-, observatie- en modelleerschaal. Voor de observatieschaal en de modelleerschaal kan een drietal onderdelen worden onderscheiden: afstand, lengte en ondersteuning.

Calibratie van het HBV-Liuxihe model is uitgevoerd door middel van Monte Carlo simulatie, omdat voor deze methode niet veel tijd benodigd is en men geen zeer ervaren hydroloog hoeft te zijn. Model validatie was helaas niet mogelijk vanwege een te korte periode aan beschikbare data. Een gecombineerd criterium van Nash-Sutcliffe efficiëntie E en relatieve volume fout RVE was ingevoerd – $ERVE$ – als criterium om de modelprestatie tijdens de calibratie te beoordelen, omdat dit criterium E maximaliseert en tegelijkertijd RVE minimaliseert.

De beschikbare hydrologische data voor het stroomgebied van de Liuxihe Rivier was van magere kwaliteit en kwantiteit. Neerslagdata zijn beschikbaar over een periode van 2 jaar (2005 – 2006) en bevatten fouten en er ontbreken waarden. Potentiële evapotranspiratiedata waren in zijn geheel niet beschikbaar, net zoals temperatuurgegevens. Deze laatste waren echter ook niet meer noodzakelijk als invoer, omdat in de provincie Guangdong de temperatuur niet daalt tot beneden 0 °C. De waargenomen afvoerdata waren beschikbaar over een periode van 2 jaar (2005 – 2006), echter, alleen voor het meest bovenstroomse deelstroomgebied: het Huanglong Dai reservoir deelstroomgebied. Deze data bevatten zowel ontbrekende als onrealistische waarden.

Om kwaliteitsredenen zijn alleen de neerslagdata uit 2005 gebruikt. Voor dezelfde periode zijn potentiële evapotranspiratie waarden bepaald op basis van literatuurwaarden en de waargenomen afvoerdata zijn gerepareerd met 4 verschillende methoden. Door deze operaties werd het mogelijk de afvoerdata te gebruiken omdat alle negatieve waarden ermee verwijderd werden. Er zijn 8 calibraties uitgevoerd. Hierbij werd ook de tijdsresolutie en lengte van de data aangepast.

Met de 4 gerepareerde waargenomen afvoer datasets zijn water balansen gemaakt voor het Huanglong Dai reservoir en het gelijknamige deelstroomgebied. Dit reservoir ligt achter een waterkrachtcentrale en vormt het uitstroompunt van het deelstroomgebied. De waterbalansen bevatten een restterm. Dit betekent dat niet de gehele waterstroom in het deelstroomgebied door de metingen vastgelegd wordt. Het bestaan van deze restterm versterkt het idee dat de waargenomen afvoerdata - zowel behandeld als onbehandeld – niet correct zijn. Ook is de beschikbare hoeveelheid voor evapotranspiratie klein in vergelijking met de potentiële evapotranspiratie. De 2 uitersten van de waargenomen afvoer datasets zijn gebruikt voor calibratie van het HBV-Liuxihe model. Dit betrof de data sets verkregen met de 0-waarden methode en de reeksgebaseerde waarden methode. De modelprestatie is laag volgens het gecombineerde criterium *ERVE* (0.18 – 0.34). De beste resultaten worden verkregen met de data met dagelijkse tijdstappen, wat tegengesteld is aan de algemeen geldende opvatting dat een vergroting van de tijdsresolutie leidt tot betere modelprestaties. Echter, de modelprestaties zijn te laag om 1 van de afvoer datasets als meest representatief te classificeren. Het is opvallend dat 40 % van de afvoer is gemeten na het regenseizoen als nog maar 15 % van de jaarlijkse neerslag valt. Geen van de 8 gecalibreerde modellen simuleert deze afvoer.

De laagste modelprestatie tijdens calibratie is verkregen met de afvoerdata met een tijdsresolutie van een uur (*ERVE*: 0.18 – 0.20). De prestaties tijdens calibratie met de data met een dagelijkse tijdsresolutie waren hoger (*ERVE*: 0.24 – 0.34). De model calibraties met de datasets met de kortste lengte – maart tot en met december – leiden tot betere resultaten dan calibratie met de datasets van januari tot en met december 2005. Dit is echter alleen het geval voor de dataseries met een tijdsresolutie van een dag. De modelprestaties tijdens calibratie zijn beter voor de reeksgebaseerde data dan voor de 0-gebaseerde data.. Ondanks de verschillen in waarden van *ERVE* is het onredelijk om te betogen dat een van de 8 datasets meer representatief is. De gesimuleerde actuele evapotranspiratie was veel hoger dan het volgens de waterbalans beschikbare water.

Het opzetten van een automatisch meetsysteem voor hydrologische variabelen (HBV-invoer) zou een belangrijke stap zijn om nieuwe hydrologische modellen voor het stroomgebied van de Liuxihe Rivier mogelijk te maken. Een begin kan worden gemaakt door 1 deelstroomgebied volledig te bemeten en zo de optimale hoeveelheid meetstations te bepalen in relatie tot de natuurlijke variabiliteit van het stroomgebied. Dit meetnetwerk kan bij goed functioneren eenvoudig uitgebreid worden. Verder onderzoek zou zich moeten richten op de constante afvoer de gemten wordt na het regenseizoen. Misschien dat deze stroom gesimuleerd kan worden door een extra opslagbak met afvoer aan het HBV-model toe te voegen. Calibratie met behulp van een meervoudige doelfunctie die de nadruk legt op zowel hoge als lage afvoeren zou de modelprestatie mogelijkerwijs kunnen verbeteren. Er zouden zelfs parametersets bepaald kunnen worden voor het natte en het droge seizoen.

Echter, ook al klinken deze suggesties misschien interessant; het blijft moeilijk om enige vorm van onderzoek te doen met zulk een beperkte hoeveelheid beschikbare data.

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Abbreviations

CWRE	Centre of Water Resources and Environment
DHI	Danish Hydrological Institute
EL	Eastern longitude
HBV	Hydrologiska Byråns Vattenbalansavdelning
	Hydrological Bureau Water balance section
IHMS	Integrated Hydrological Modelling System
MCS	Monte Carlo simulation
NL	North latitude
SAR	Special administrative region
SCE	shuffled complex evolution
SEZ	Special economic zone
SHE	European Hydrological System
SMHI	Swedish Meteorological and Hydrological Institute
SYU	Sun Yat-sen University

Symbols

A	total area
a_i	area represented per gauge
ALFA	coefficient for non-linearity fast flow
CEVPFO	forest correction factor potential evapotranspiration
CFLUX	capillary flux
DEE	elevation correction factor for potential evapotranspiration
DEP	elevation correction factor for precipitation
DET	elevation correction factor for temperature
E	Nash-Sutcliffe efficiency
EA	actual evapotranspiration
ECALT	elevation difference between gauges from which potential evapotranspiration is determined indirectly and average basin level
EI	evaporation interception
E_{ow}	open water evaporation
ERVE	Combined criterion of E and RVE
ET_0	reference evapotranspiration
ET_{act}	actual evapotranspiration
ET_{pot}	potential evapotranspiration
FC	maximum soil moisture storage
FFI	fraction field
FFO	fraction forest
FOSFCF	forest snow fall correction factor
h	reservoir water level
hf	reservoir water level factor
IN	infiltration
K	recession coefficient fast flow
K_4	recession coefficient slow flow
k_f	recession coefficient fast flow

k_s	recession coefficient slow flow
k_w	correction factor
LP	limit for potential evapotranspiration
LZ	ground water storage
MAXBAS	transformation parameter
n	time step
P	precipitation
PCALT	elevation difference between precipitation gauge and average basin level
PERC	percolation
Q	discharge
Q_0	slow runoff
Q_1	fast runoff
Q_c	capillary rise
Q_f	fast runoff
Q_{in}	reservoir inflow
Q_{in}^*	corrected reservoir inflow
Q_{out}	reservoir outflow
Q_{PERC}	percolation
Q_s	slow runoff
R	recharge
R	rain fall
R_d	direct recharge
RF	rain fall
RFCF	rain fall correction factor
R_i	measured precipitation (Thiessen method)
R_{in}	indirect recharge
RT	residual term waterbalance Huanglong Dai reservoir
RVE	Relative volume error
S	storage
S	snow fall
SF	snow fall

SFCF	snow fall correction factor
sgw	storage ground water
SM	soil moisture storage
S_r	storage reservoir
S_{sb}	storage sub-basin
ssm	storage soil moisture
ssw	storage surface water
T	temperature
TCALT	elevation difference between temperature gauge and average basin level
TT	threshold temperature
TTI	threshold temperature interval
UZ	surface water storage

List of tables and figures

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Chapter 1

Introduction

1.1 Project background

The Liuxihe River basin is frequently affected by floods. In order to reduce future losses due to floods, effective operational and strategic flood management are an absolute necessity. Operational flood management refers to the short term river basin management. Flood forecasting in real time sense is an important issue for operational flood management, with the aim of a possibly early warning concerning an expected river water rise, defining its size as well as its course. Actions based on these warnings are e.g. the raising of water barrages along the river, evacuation or the regulation of discharge at a hydropower dam.

Strategic flood management refers to the long term river basin management. The research on the impact of future changes on a river basin is the main purpose of strategic flood management. The study on the impact of climate change on river discharge and the study on the way the river basin (management) should be adjusted to face up to this impact are part of strategic river basin management.

Hydrological models are a useful tool for both operational and strategic flood management. At the Centre of Water Resources and Environment (CWRE) at Sun Yat-sen University in Guangzhou research has been done on flow prediction in the Liuxihe River basin on behalf of the Guangdong Hydrology Bureau. A variety of models has been applied, ranging from simple water balance models to more complex physically-based distributed models. Among these models were the Chinese conceptual Xinanjiang model and the distributed physically-based MIKE-SHE model (Chen and Zhu, 2005). However, the latter has a relatively high data demand, which is especially difficult in a data-poor area as the Liuxihe River basin.

The HBV-model, developed at the Swedish Meteorological and Hydrological Institute, has been successfully applied in many countries all over the world for different purposes, e.g. for the purpose of discharge forecasting and impact studies of climate and land-use changes. The HBV-model is a semi-distributed conceptual model and has a relatively low data demand, compared with for example physically-based models. This characteristic, together with the availability of the model, makes it attractive to apply the model also in data-poor areas like the Liuxihe River basin.

An important issue in hydrological modelling and also for the HBV model is scale. The concept of scale refers to both a spatial and a temporal aspect. The HBV model has been applied successfully over a wide range of spatial scales. Concerning temporal model scale, the HBV uses daily time steps as default. The availability of hourly measured hydrologic data enables variations in temporal model scale. It is therefore worth studying model performance with different temporal scales.

1.2 Objective and research questions

1.2.1 Objective

The objective of this study is:
"The simulation of discharges for the Liuxihe River in South China to contribute to the development of effective operational and strategic flood management by setting up and testing a HBV-model for the Liuxihe River Basin."

1.2.2 Research questions

In order to support the accomplishment of the objective three research questions are formulated:

- ***How is the HBV-Liuxihe model built up?***
- ***What are proper values for the free HBV-model parameters?***
- ***What is the influence of changing temporal scale on model performance?***

1.3 Report outline

Chapter 2 gives an introduction to the Liuxihe River basin and consists of four paragraphs dealing subsequently with a general introduction, hydraulic information, physiography and geography and climate.
Chapter 3 is about the HBV-model. This chapter starts with an explanation of the choice for the HBV-model as hydrological model for the Liuxihe River basin, followed by a detailed description of the HBV-model. Thereafter, scale issues in hydrological modelling in general and for HBV-Liuxihe are discussed.
Chapter 4 deals with model calibration and validation. A deliberation of calibration methods is given, followed by a description of the applied assessment criterion.
Chapter 5 discusses the data available for the Liuxihe River basin. The shortcomings are highlighted and also the way these shortcomings are dealt with.
In chapter 6 the results of this study are presented. Discussion of these results can also be found in this chapter.
Finally, in chapter 7 conclusions and recommendations are given.

Chapter 2

The Liuxihe River basin

2.1 Introduction

The Liuxihe River basin is a small river basin situated in the province of Guangdong in South China. The Liuxihe River is a major tributary river of the Pearl River or Zhu Jiang. This river is the 3rd largest river of China after the Yangtze and Yellow River. Originally the name Pearl River only defined the river segment from Guangzhou to the estuary downstream, but nowadays this name has been adapted over the whole drainage area that stretches across six provinces: Yunnan, Guizhou, Guangxi, Guangdong, Hunan and Jiangxi.

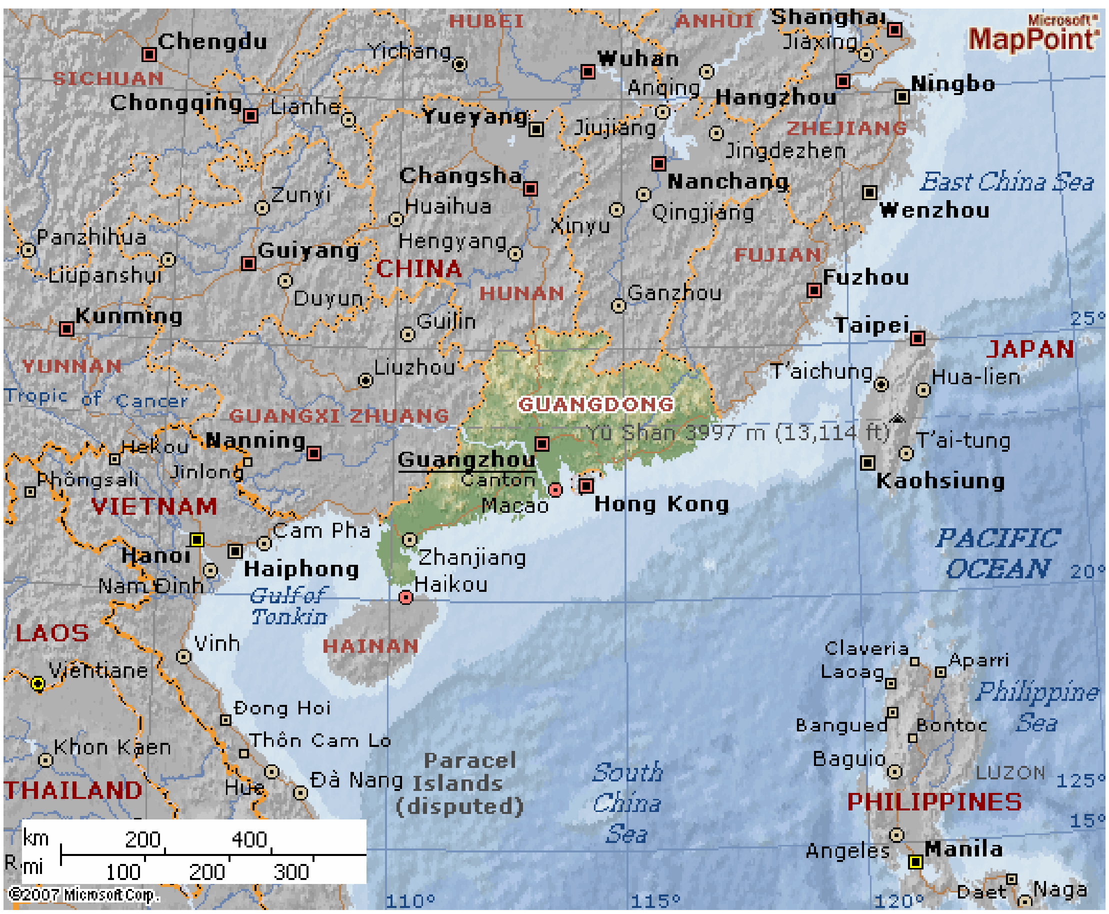


Figure 2.1: *The location of the Chinese province of Guangdong in south-east China* (Encarta, 2007)

The total length of the main trunk and branches is about 11,000 km, with a total drainage area of 452,600 km². The Pearl River flows into the South Chinese Sea in Guangdong province and has formed a large delta in this province over time.
Guangdong is located around the Tropic of Cancer and covers an area of about 180,000 km². In the year 2000 the estimated population was about 86.4 million people. The capital city of Guangdong is Guangzhou and is located in the centre of the Pearl River Delta. The cities of Macau and Hong Kong lie at the base of this delta (China Culture, 2007). A map of South China is shown in figure 2.1.

Figure 2.2: *The location of the Pearl River delta in Guangdong province and the Liuxihe River basin (purple) (JoHomaps, 2007). The picture right below shows the location of the Liuxihe River basin (purple) and the city of Guangzhou (yellow)* (CWRE, 2007).

The Liuxihe River originates from a mountainous area in the Northern part of the river basin. The river is regulated to a high degree, since discharge generated in the most upstream part of the river basin is controlled by the Huanglong Dai and Liuxihe (see figure 2.3) Reservoirs. The river flows almost continuously in a southwesterly direction before it flows into the Zhu Jiang just north of the city Guangzhou. The length of the main stream is about 156 km and the total drainage area measures about 2300 km^2 (Chen and Zhu, 2005).

Already in early history the Pearl River Delta was a prosperous region, because of the fertile delta soil, the excellent waterways and its location close to the sea. Nowadays, it is the most important region of South China and sometimes referred to as Chinas Southern Gate. After the reunion with Hong Kong in 1997 and Macau in 1999 Special Administrative Regions (SAR) were installed in both cities and as a kind of transition zone Special Economic Zones (SEZ) were installed in the regions of Shenzhen, Zhuhai and Shantou, all bordering either Hong Kong or Macau. As one of the locations of China's Special Economic Zones, and bordering Hong Kong and Macao, Guangdong has marked advantages in utilizing overseas capital and technology and carrying out foreign economic and technical cooperation. This makes the area especially valuable to China and the Chinese economy.

Figure 2.3: *The Liuxihe Reservoir in the most upstream part of the Liuxihe River basin*

It is in this area with a large pressure on the available water resources by the large and still increasing population and the many economic activities that the Liuxihe River basin is located. The location of the Liuxihe River basin with respect to the Pearl River basin in the province of Guangdong is shown in figure 2.2. The Guangdong Hydrology Bureau is responsible for the river basin management. The Liuxihe River is primarily used for the generation of hydro power – by Guangdong Hydro Power – and for the drinking water supply. Also small scale fisheries occur on the river. The Liuxihe River is not suitable for navigation and therefore not used for that purpose.
The next paragraphs subsequently discuss the hydraulics, the physiography and geography and the climate of the Liuxihe River basin.

2.2 Hydraulic information

The Liuxihe River is strongly influenced by human interventions. Since the late 50´s of the 20th century the river has been highly regulated. Altogether 3 steps of regulation were carried out, consisting of the construction of dams and river bend cutting.

Table 2.1: *Overview of reservoirs and dams in the Liuxihe River.*

	name	river reach	controlling area [km^2]	controlling reach [km]
1	Liuxihe reservoir	upper reach	539,0	-
2	Huanglong Dai reservoir	upper reach	92,3	-
3	Liangkou dam	upper reach	68,7	8,7
4	Qingnian dam	middle reach	50,0	2,9
5	Shengli dam	middle reach	60,0	4,0
6	Weidong dam	middle reach	74,0	6,1
7	Wenquan dam	middle reach	41,0	7,6
8	Jiekou dam	middle reach	24,0	13,3
9	Da Ao dam	middle reach	497,6	6,4
10	Li Xi dam	lower reach	483,4	42,0
11	Ren He dam	lower reach	170,0	13,0

Nowadays, 2 hydro power dams can be found in the upper reach. In the middle and the lower reaches altogether 9 dams are located, which deprived the river of its natural character. In table 2.1 the dams and reservoirs that are located in the Liuxihe River are listed. In figure 2.4, the location of the dams mentioned in table 2.1 is shown in a map that also shows the position of the different sub-basins. As can be seen, most dams are located in the upper reach of the Liuxihe River.

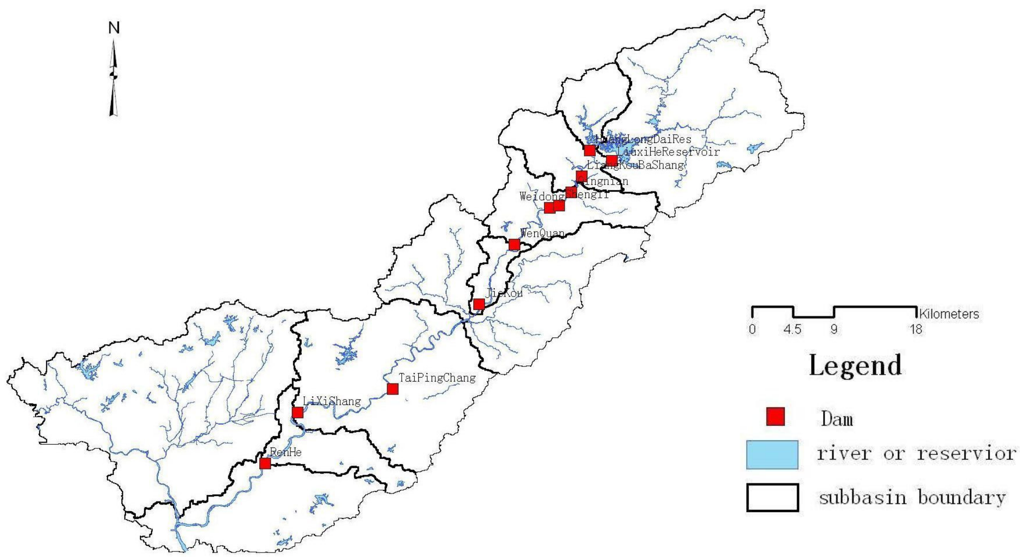


Figure 2.4: *The location of the (hydro power) dams in Liuxihe River* (CWRE, 2007)

2.3 Physiography and geography

The Liuxhe River basin is mountainous in the upstream part and rather flat in the downstream part. The downstream part is highly urbanized and is characterized by much human activity, which makes the area vulnerable to flash flooding. Flash floods occur due to periods of intense rainfall in the mountainous area where runoff is quickly generated. Figure 2.5 is a 3-D visual map of the Liuxihe River basin. The reservoirs in the upstream part of the basin, the mountainous upstream part and the rather flat downstream part can be distinguished clearly. The maximum basin elevation amounts 1057 m.a.s.l. while the minimum basin elevation amounts 10 m.a.s.l..

Figure 2.5: *3-D visual map of Liuxihe River basin* (U.S. Geological Survey, 2007)

Figure 2.6 is an overview map of the land-use of the Liuxihe River basin. Large parts of the upstream part of the basin are covered with different types of forest. Mean potential evapotranspiration values are higher in forested areas. The downstream part is largely covered with fields.

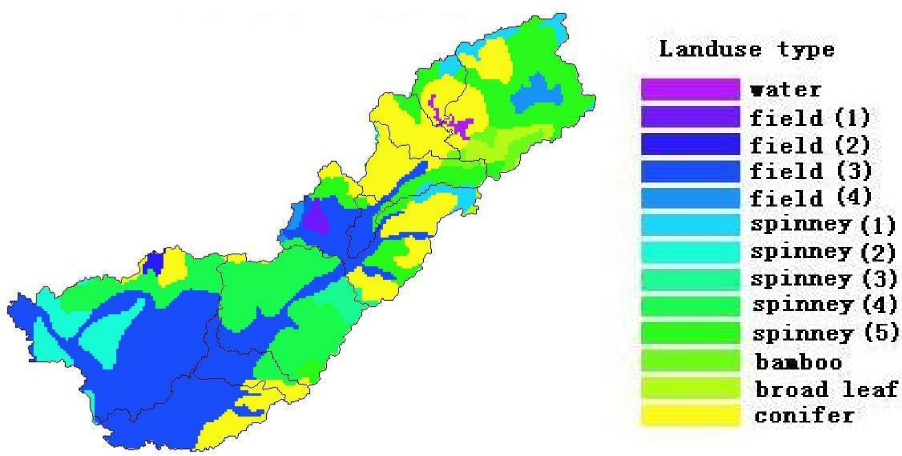


Figure 2.6: *Overview map of the land-use of the Liuxihe River basin. Field 1 to 4 are equal types of land-use, although their colour differs. This is the same with spinney 1 to 5* (U.S. Geological Survey, 2007).

2.4 Climate

The Liuxihe River basin is located just north of the Tropic of Cancer, which implies that it is situated in the subtropical zone. The average temperature ranges from 19 ˚C in the winter to 26 ˚C in the summer. The mean annual precipitation is about 1824 mm. The mountainous area in the upstream part of the river basin causes orographic rainfall. The raining season lasts from April to September and is determined by the Southeast Asia Summer Monsoon. This is a sub-system of the Asian Summer Monsoon and stretches over the south of China and the South Chinese Sea (Chan et al., 2004).

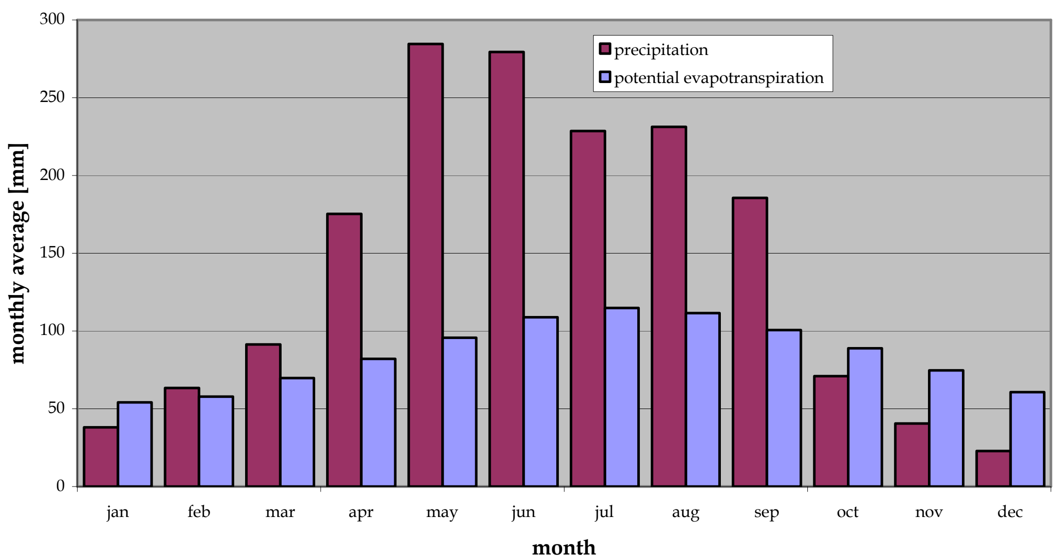


Figure 2.7: *Average monthly precipitation* (FWCC, 2007) *and potential evapotranspiration* (Gao et al., 2006*) in Guangzhou.*

"Monsoons are weather patterns of seasonal nature caused by widespread changes in atmospheric pressure" (Shaw, 1994). Monsoons are determined by 3 physical mechanisms: differential heating between the land and oceans, Coriolis forces due to the rotation of the Earth and the role of water which stores and releases energy as it changes from liquid to vapour and back (latent heat). The combined effect of these three mechanisms produces the monsoon's characteristic reversals of high winds and precipitation. In South China during the rainy season the land mass is heated up much faster than the neighbouring South Chinese Sea. This causes the air above the land to heat up, expand and rise. As the air rises, cooler, moister, and heavier air from over the South Chinese Sea will replace it. During the dry season the winds blows from the northern cold land mass of the Asian continent. The Himalayas act as a kind of barrier and prevent the cold and moist air from reaching South China. Therefore the winters in South China are warm and dry.

Figure 2.7 is used to illustrate the monthly averages of precipitation (period 1951 – 1988) and potential evapotranspiration in Guangzhou. This graph shows the main part of the precipitation falls during the spring and summer months, the monsoon rains.

Chapter 3
The HBV-Liuxihe model

3.1 Introduction

This chapter is about the HBV-Liuxihe model. In the following paragraph (3.2) an explanation is given for the choice to use the HBV-model for simulating discharges for the Liuxihe River. Paragraph 3.3 contains a description of the HBV-model and attention is paid to model structure and model input. Paragraph 3.4 is about model scale and also discusses scale in hydrological modelling in general.

3.2 Model choice

3.2.1 Introduction

The hydrological model that is used for the modelling of the Liuxihe River basin is the HBV-model, developed by the Swedish Hydrological and Meteorological Institute (SMHI) in the early seventies of the last century (Bergström and Forsman, 1973). This paragraph is therefore not a deliberation between different hydrological models, as the paragraph head might suggest, but rather an explanation of the choice for the use of the HBV-model.

Although the choice for the model that is to be used for the modelling of the Liuxihe River basin is already clear, this paragraph starts with a general overview of types of hydrological models and the way they are classified, followed by an explanation for the use of the HBV-model.

3.2.2 Categorisation of hydrological models

Dooge (1992, in: Leavesley, 1994) stated about hydrological modelling that: "Hydrologic modelling is concerned with the accurate prediction of the partitioning of water among the various pathways of the hydrological cycle". Figure 3.1 is a schematisation of this hydrological cycle and gives a glance of the dominant water storages and fluxes on earth.

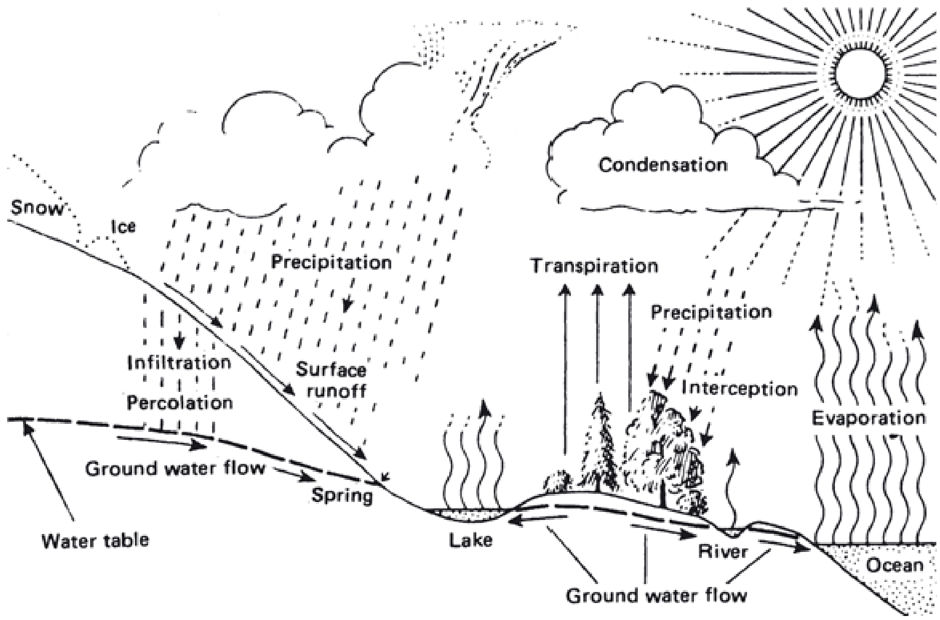


Figure 3.1: *The hydrological cycle* (Shaw, 1994)

A large variety of models has been developed to simulate this partitioning of water, from simple lumped black box models to complex distributed process-based models with high spatial and temporal resolution. Although these differences exist, most models are based on the same fundamental principle, i.e. the water balance equation, which is given by equation 3.1:

(3.1) $$Q = P - ET \pm \Delta S$$

Q	runoff
P	precipitation
ET	evapotranspiration
ΔS	change in storage

The unit of the variables is either $m^3 s^{-1}$ or mm per time step. Hydrological modellers sometimes refer to bookkeeping when explaining the way their models operate, since the models compare the amount of water that comes into a system with the amount of water that goes out and determine the net gain or loss of water in the system per time step.

Hydrological models can be categorized with different classification criteria, e.g. the *purpose of model application* (e.g. real-time application, process understanding), *model structure* (e.g. physically-based, conceptual), *spatial discretisation* (e.g. lumped, (semi-)distributed), *temporal scale* (e.g. daily, annually) and *spatial scale* i.e. the scope of the model (e.g. point, basin, global), (Leavesley, 1994). Of these criteria model structure is the most commonly used criterion to classify a model, since it is the only criterion for which hydrological models have a unique result, i.e. many models have different forms according to the other criteria e.g. many types of the HBV-model exist but all of these models are conceptual.

Durand *et al*. (2002) discern four main categories concerning model structure. In order of increasing complexity, these categories are: the *empirical* or *black box* hydrological models, the *conceptual* hydrological models, the *physically-based* hydrological models and the *process-based* hydrological models. Leavesley (1994) brings forward *water balance models* as a fifth model category– based on model complexity – which is situated in-between the empirical and the conceptual models. The borders between these categories are rather vague, since hybrid forms of some of the models exist.

Empirical model

An empirical hydrological model describes the relationship between input and output based on a long series of observations. Model output is based on a function of model input. Since no governing physical laws or involved processes are considered, empirical hydrological models are only representative for the climate and basin conditions for which the model was developed and extension of the model for changed climate and/or basin conditions is questionable. For example, an empirical model was developed by Langbein *et al.* (1949).

Water balance model

A water balance model is basically a book keeping procedure that accounts for the movement of water from the time it enters a basin as precipitation to the time it leaves the basin as either runoff or evapotranspiration. Guo *et al*. (2002) developed a water balance model to assess the impact of climatic change on hydrological cycle and water resources planning for several semi-dry and humid river basins in China. Most water balance models account for direct runoff from rainfall and lagged runoff from basin storage in the computation of total runoff. Evapotranspiration is often computed as some function of potential evapotranspiration and the water available in storage. Temporal scales can vary from daily to annual (Leavesley, 1994).

Lumped parameter conceptual model

A lumped parameter conceptual hydrological model uses simplifications of fundamental physical laws, containing non-measurable parameters whose values have to be determined by means of calibration. River (sub-) basins are the primary units for which one set of model parameters is determined. As with water balance models, conceptual models attempt to account for the movement of water from the time it enters the basin until it leaves either as runoff or evapotranspiration. The difference, however, is the much greater detail of flow paths and residence times, and temporal resolution is in the order of hours or days (Leavesley, 1994). Crawford and Linsley (1966) introduced the conceptual hydrological model with the development of the Stanford Watershed model. The HBV-model also belongs to this category of hydrological models, although it can be semi-distributed instead of having a lumped parameter set.

Semi-distributed physically based models

A physically based model uses physical equations to compute water fluxes. The equations are simplified by some assumptions and can be solved analytically or by means of calibration. River basins are divided into functional subparts which can be areas that are homogeneous with respect to one or more characteristics. The TOPMODEL is considered to be a physically based model, as its parameters – theoretically – can be measured in the field (Beven and Kirkby, 1979, Beven *et al*., 1984).

Distributed process-based models

Distributed process-based models use a grid that spatially distributes the river basin. The fluxes between the grids are computed using partial differential equations of the physics of porous media and hydraulics, solved by a numerical scheme. Since all parameters in this kind of model have a physical meaning they should be measurable and therefore calibration should not be required, which implies however a high data-demand. The MIKE-SHE, developed at the Danish Hydrological Institute (DHI) by Refsgaard and Storm (1996) belongs to this category of models.

3.2.3 Hydrological model for the Liuxihe River basin

Whether to choose between a simple or more complex model seems to depend on a combination of available data and the purpose of the model, as was recognized by Leavesley (1994): "Model choice is normally a function of problem objectives, data constraints, and the spatial and temporal scales of application." Empirical models and water balance models do not require many data and have little parameters that need calibration, but these models do not incorporate the physical meaning of the modelled process, which makes them less reliable than the conceptual, physically-based and process-based models.

Process-based models usually have numerous parameters. Developers of this model type claimed that this model type does not require calibration since the parameters have a physical meaning and therefore can be measured. Beven (1989, in: Durand *et al*., 2002) demonstrated that this is not the case. The equations of process-based models are determined on a small scale for homogeneous systems and there is no proof that the same equations with the same parameters can be applied at grid scale.

Even if the equations are valid on the grid scale, effective parameters for every grid-cell should be determined, which is in practice impossible to do for each grid square. And since the process-based models still need calibration, the physical meaning of the many parameters is partially lost. In addition, the amount of parameters makes calibration even more difficult, e.g. because of parameter interdependence.

Neither conceptual models nor the physically-based models have the excessive data demand like process-based models have and they are physically sounder than empirical models and water balance models. Validation tests according to the scheme proposed by Klemes (1986, in: Ewen and Parkin, 1996) are available to test the ability of both model types to be climatically and geographically transferable as well.

A physically-based model for the Liuxihe River basin was developed by Chen and Zhu (2005). They concluded that their results were promising, but an important problem was the lack of sufficient data. The development of a conceptual model could possibly solve this problem, since this kind of model has a lower data demand.

The HBV-model was proven to perform well under different climate conditions and in small river basins, e.g. the Yassidere River basin that has an area of only 41 km^2 (Lidén and Harlin, 2000). Furthermore, the HBV-model has been used for flash flood forecasting by Kobold and Brilly (2006). Essential for flash flood forecasting is the high temporal resolution of the model needed to catch the important processes. Kobold and Brilly used hourly data. Hourly data is available for the Liuxihe River basin that is threatened by flash floods too. It is therefore worth testing and studying the performance of the HBV-model applied to the Liuxihe River basin.

3.3 The HBV-model

(SMHI, 2007, Bergström, 1995, IHMS, 1999)

3.3.1 Introduction

The HBV-model is a semi-distributed conceptual rainfall-runoff model, developed in the early seventies of the last century by the former Hydrological Bureau Water balance section – after which the model was named, since the Swedish name of the section was **H**ydrologiska **B**yråns **V**attenbalansavdelning – at the Swedish Hydrological and Meteorological Institute (Bergström and Forsman, 1973).
The original purpose of the model was runoff simulation and hydrological forecasting. However, until now a diversity of HBV-applications has been developed in many different countries (Bergström, 1995), with aims varying from climate and land-use change impact studies (e.g. Booij, 2005; Menzel et al., 2006; Wilk et al., 2001), flash-flood forecasting (Kobold and Brilly, 2006) and the simulation of alluvial sediment transport (Lidén *et al*., 2001). Although many modifications to the model have been made over the years since its development the basic modelling philosophy remained unchanged. In 1996 the model was evaluated and the latest version of the HBV-model was finished: HBV-96 (Lindström *et al*., 1997). The HBV-96 proved to be physically sounder and model performance during calibration with an automatic calibration routine was improved by the development of a new assessment criterion.

For the purpose of this study a version of the HBV-96 model programmed in FORTRAN by Booij (e.g. Booij *et al*., 2006) was used instead of the original program with user interface developed at the SMHI. The advantage of the FORTRAN version is that modifications can easily be made and since the model code is visible clear insight in its functioning can be obtained.
The next paragraph deals with model input followed by a paragraph about the structure of the HBV-model. Only model parts used in this study are discussed. The snow routine and the routing routine and transformation function are out of the scope of this study.

3.3.2 Model input

3.3.2.1 Introduction

The necessary input for the HBV-model consists of observations of temperature, precipitation and potential evapotranspiration. For calibration and validation also discharge observations are needed. Together with the difference in basin storage these data form the components of the simple water balance given by equation 3.1, although temperature is only indirectly represented in the water balance, since it influences precipitation and evapotranspiration. The next paragraphs deal subsequently with precipitation, temperature and potential evapotranspiration.

3.3.2.2 Precipitation

Precipitation may occur as either snowfall or rainfall. The amount of precipitation is based on data measured by precipitation gauges, with a correction for the elevation difference between the precipitation gauge and the average elevation of the basin, according to equation 3.2:

(3.2) $$P = P_{obs} \cdot \left(1 + PCALT \cdot DEP\right)$$

P	corrected precipitation [mm]
P_{obs}	observed precipitation [mm]
$PCALT$	elevation difference between precipitation gauge and average basin level [100 m]
DEP	elevation correction factor for precipitation [-/100 m]

In order to have representative precipitation series for each (sub-) basin the areal average precipitation has to be determined. Different methods for determining this areal average precipitation exist. The simplest method is the use of the *arithmetic mean* of the available precipitation series. This method involves all precipitation gauges located in the (sub-) basin, with equal weights. A simple method that takes into account the actual influence of each precipitation gauge on the areal average precipitation is the *Thiessen Method*. Other methods to derive areal average precipitation series are e.g. the *isohyetal method*, which is based on the drawing of isohyets – lines of equal rainfall – in each (sub-) basin, the *hypsometric method*, which takes into account the topography of the (sub-) basin and the *multiquadric method*, that integrates the volume of precipitation under a surface fitted with multiquadratics to the measurements by different precipitation gauges. *Kriging* and *inverse distances* are also often used methods to derive areal average precipitation.

3.3.2.3 Temperature

The corrected temperature is determined with equation 3.3 and depends on the observed temperature T_{obs} and a correction factor for the elevation difference between the temperature gauge and the average basin elevation level.

(3.3) $$T = T_{obs} - TCALT \cdot DET$$

T	corrected temperature [˚C]
T_{obs}	observed temperature [˚C]
$TCALT$	elevation difference between temperature gauge and average basin level [100 m]
DET	elevation correction factor for temperature [˚C/100 m]

3.3.2.4 Potential evapotranspiration

The potential evapotranspiration input is used to determine actual evapotranspiration. The latter also depends on the amount of soil moisture available. "Potential evapotranspiration is the amount of evaporation and transpiration that would take place given an unlimited supply of moisture" (Shaw, 1994). Evaporation can be defined as the process by which liquid water is converted into a gaseous state and transpiration as the process of water loss from plants which are both passive processes largely controlled by the humidity of the atmosphere and the moisture content of the soil, and by temperature, wind speed and solar radiation. The potential evapotranspiration is corrected like temperature and precipitation for the difference in elevation between the gauges from which potential evapotranspiration is determined indirectly and average basin level, according to equation 3.4:

$$ET_{pot} = ET_{pot;obs} \cdot (FFO \cdot CEVPFO + FFI) \cdot (1 - ECALT \cdot DEE) \tag{3.4}$$

ET_{pot}	corrected potential evapotranspiration [mm]
$ET_{pot;obs}$	observed potential evapotranspiration [mm]
FFO	fraction forest [-]
FFI	fraction field [-]
CEVPFO	forest correction factor potential evapotranspiration [-]
ECALT	elevation difference between gauges from which potential evapotranspiration is determined indirectly and average basin level [100 m]
DEE	elevation correction factor for potential evapotranspiration [-/100 m]

3.3.3 Model structure

3.3.3.1 Introduction

The HBV-model consists of three storage boxes and a set of numerical equations that describe the fluxes between these boxes and the model output in relation to model input. The three boxes are from top to bottom the *soil moisture storage box*, the *surface water storage box* from which the fast flow is generated and the *ground water storage box* from which the slow flow is generated. If snow is present, the snow pack can be regarded as a fourth storage box, placed on top of the three other boxes. Figure 3.2 is a conceptual visualisation of the model, with a clear distinction between the storage boxes and the different water fluxes and the generation of model output. The abbreviations that appear in figure 3.2 are listed in table 3.1, with the meaning of the abbreviations and their function in the model.

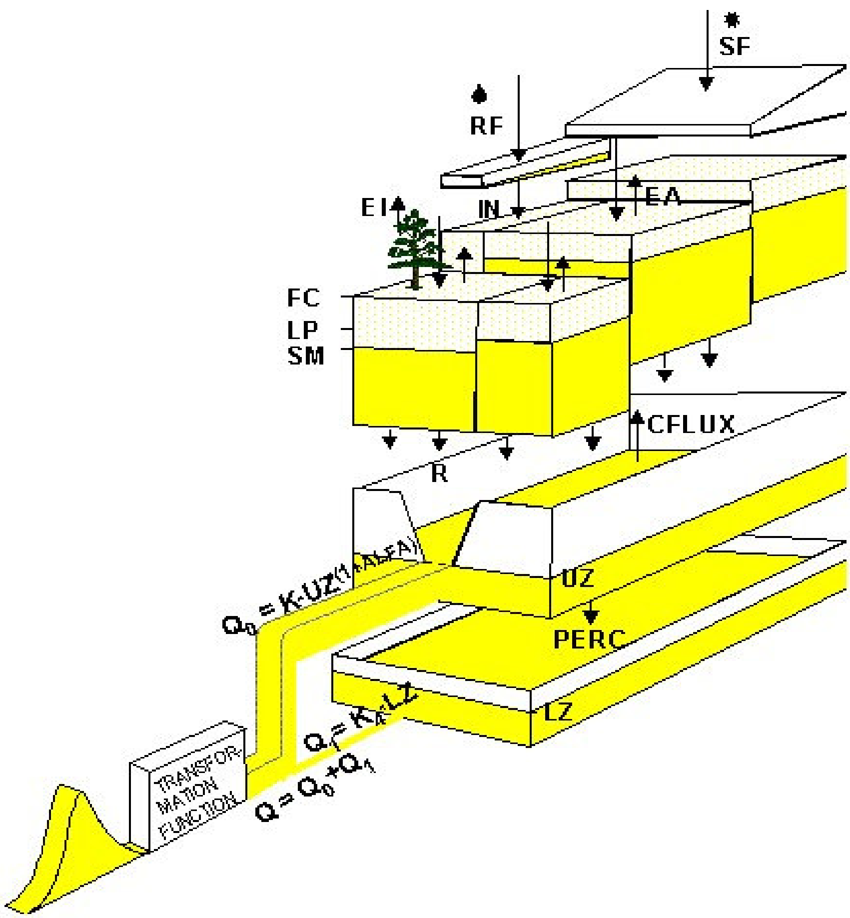


Figure 3.2: *Conceptual visualisation of the HBV-model. Yellow represents water, the white areas represent available water storage and the yellow dots represent water storage that has a limited capacity in the HBV-model* (SMHI, 2007).

Paragraph 3.3.3.2 is about the precipitation routine, paragraph 3.3.3.3 discusses the soil moisture routine and the related potential evapotranspiration determination. The paragraphs 3.3.3.4 and 3.3.3.5 deal respectively with the fast and the slow runoff routine. In paragraph 3.3.3.6 the transformation function MAXBAS is explained and the last paragraph deals with the flood routing in the river network.

Table 3.1: *Clarification of the abbreviations in figure 3.2*

SF	snow fall	input
RF	rain fall	input
EA	actual evapotranspiration	flux
EI	evaporation interception	flux
IN	infiltration	flux
FC	maximum soil moisture storage	parameter
LP	limit for potential evapotranspiration	parameter
SM	soil moisture storage	state variable
R	recharge	flux
CFLUX	capillary flux	parameter
UZ	surface water storage	state variable
α	coefficient for non-linearity fast flow	parameter
PERC	percolation	parameter
LZ	ground water storage	state variable
K, (k_f)	recession coefficient fast flow	parameter
K4, (k_s)	recession coefficient slow flow	parameter
Q_0	fast runoff	output
Q_1	slow runoff	output
Q	total runoff	output

3.3.3.2 Precipitation routine

Precipitation occurs as either rainfall or snowfall. Whether precipitation occurs as snowfall or rainfall is determined by the corrected temperature *T*, the threshold temperature *TT* and the threshold temperature interval TTI. The threshold temperature interval TTI is a range around TT between which precipitation occurs as a combination of snowfall and rain. When the corrected temperature exceeds the value of the upper boundary of TT + ½TTI, precipitation occurs as rainfall. When the corrected temperature lies within the interval TTI ± ½TTI, precipitation occurs as a combination of rainfall and snowfall, e.g. 50% rainfall when the temperature equals the threshold temperature. The division between both rainfall and snowfall is linear related to the position of the corrected temperature between the interval boundaries.

If the value of the corrected temperature does not exceed TT - ½TTI, precipitation occurs only as snowfall. Rainfall and snowfall are given by equations 3.5 and 3.6:

(3.5) $$R = P \cdot RFCF$$

(3.6) $$S = P \cdot \left(FFO \cdot FOSFCF + FFI \right) \cdot SFCF$$

R	rainfall [mm]
P	corrected precipitation [mm]
RFCF	rainfall correction factor [-]
S	snowfall [mm]
FOSFCF	forest snowfall correction factor [-]
SFCF	snowfall correction factor [-]

Both rainfall and snowfall are corrected by a correction factor. This correction can be necessary when the network of precipitation gauges is not representative enough to determine areal average precipitation which may lead to systematic errors in rainfall and snowfall. Snowfall is also corrected for forested areas, by multiplying the fraction of the forested area of the basin with the forest snowfall correction factor.

3.3.3.3 Soil moisture routine

The soil moisture routine includes the four water fluxes in the soil moisture storage box. These are actual evapotranspiration (EA or ET_{act}), recharge (R) of the surface water storage box consisting of a direct component R_d and an indirect component R_{in} and capillary rise (Q_c). The relation between the four fluxes is given in figure 3.3 and the corresponding equation 3.7 and 3.8.

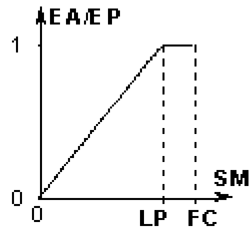


Figure 3.3: *relation actual evapotranspiration and soil moisture* (SMHI, 2007)

(3.7) $EA = \frac{SM}{LP \cdot FC} \cdot EP\, ,\, SM < LP \cdot FC$

(3.8) $EA = EP\, ,\, SM \geq LP \cdot FC$

EA actual evapotranspiration [mm Δt^{-1}]

SM storage soil moisture [mm]

LP limit for potential evapotranspiration [-]

EP potential evapotranspiration [mm Δt^{-1}]

The division of the recharge of the surface water storage box into a direct and an indirect component is based on the infiltration capacity of the ground, according to equation 3.9:

(3.9) $R_d = \max\left(IN + SM - FC, 0\right)$

R_d Direct recharge [mm]

IN Infiltration of rainfall and possibly snow melt and stored melted water [mm]

FC Maximum soil moisture storage [mm]

As long as the sum of infiltration and soil moisture storage does not exceed the maximum soil moisture storage there is no direct recharge. The infiltrated water will leave the soil moisture storage box as indirect discharge, according to equation 3.10:

(3.10) $R_{in} = IN \cdot \left(\frac{SM}{FC}\right)^{BETA}$

R_{in} indirect recharge [mm]

BETA soil parameter [-]

Equation 3.10 is graphically illustrated by figure 3.4.

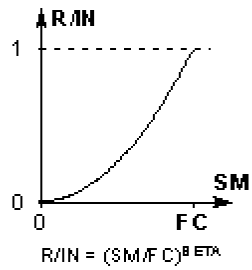


Figure 3.4: *The influence of parameters FC and BETA* (SMHI, 2007).

The parameter BETA controls the contribution to the response function or the increase in soil moisture storage from each millimeter of rainfall or snow melt. Large values for BETA result in a small value of indirect recharge R_{in}.

The capillary rise (Q_c) is determined by the soil moisture storage, the maximum soil moisture storage and the parameter CFLUX, according to equation 3.11:

$$(3.11) \quad Q_C = CFLUX \cdot \left(\frac{FC - SM}{FC} \right)$$

Q_c capillary rise [mm Δt^{-1}]

CFLUX capillary flux parameter [mm Δt^{-1}]

If the soil moisture storage box is ´fully saturated´ no capillary rise occurs. The capillary rise is limited by the available space in the soil moisture storage box. The capillary rise is also limited by the amount of water available in the surface water storage box (see section 3.3.3.4). The mass balance for the soil moisture storage box is given in equation 3.12:

$$(3.12) \quad \Delta SM = IN - R_d - R_{in} + Q_c - EA$$

3.3.3.4 Fast runoff routine

The fast runoff routine generates runoff from the surface water storage box. This runoff is non-linear and depends on the water level (UZ) in the surface water storage box and the flow recession coefficients k_f and ALFA, according to equation 3.13. The parameter ALFA introduces non linearity in the relation between Q_f and UZ.

(3.13) $$Q_f = k_f \cdot UZ^{(1+ALFA)}$$

Q_f	fast runoff [mm]
k_f	recession parameter [-]
UZ	water level surface water storage box [mm]
ALFA	coefficient of non-linearity of fast runoff [-]

Besides fast runoff two more water fluxes appear in the surface water storage box. These are capillary rise to the soil moisture storage box and percolation to the ground water storage box. The percolation is given by the parameter PERC. If little water is available in the surface water storage box this water is divided first to percolation up to its maximum value, then to the fast runoff routine and the remaining water is available for capillary rise and storage in the upper ground water storage box. The mass balance for the surface water storage box is given in equation 3.14:

(3.14) $$\Delta UZ = R_d + R_{in} - Q_f - Q_c - PERC$$

3.3.3.5 Slow runoff routine

The slow runoff routine generates runoff from the lower ground water storage. Only two water fluxes are applied on the lower ground water storage box: inflow from the upper ground water storage box and the slow runoff. The slow runoff is determined by equation 3.15:

(3.15) $Q_s = k_s \cdot LZ$

If the sum of direct and indirect recharge of the surface water storage box exceeds the parameter PERC the latter determines the inflow of water from the surface water storage box. Otherwise this inflow equals the sum of direct and indirect recharge. The maximum storage in the ground water storage box is given by the quotient of the parameters PERC and k_s, because in this case inflow and outflow are equal according to equation 3.15 and the mass balance in equation 3.16:

(3.16) $\Delta LZ = Q_{PERC} - Q_s$

Q_{PERC} percolation from surface to ground water storage box {mm Δt^{-1}]

It is a physical sound property that the ground water storage box in the HBV-model has a maximum capacity, since real ground water storages also have a limited capacity.

3.4 Model scale

3.4.1 Introduction

Model scale is an important issue in hydrological modelling. Shaw (1994) stated about hydrologists that their prime interests are “the quantitative aspects of the subject (hydrology) in finding answers to engineering problems with limited data”. The limited availability has a large influence on hydrological model scale. And if data availability is not limited there is no consensus amongst hydrologists how many data should be incorporated in a model, because complex models with excessive data demand do not always lead to better results than the simpler models.

The next paragraph is an introduction into scales in hydrology. Besides model scale the process and observation scale are distinguished. Paragraph 3.4.2 discusses the spatial model scale, paragraph 3.4.3 deals with the temporal model scale.

3.4.2 Scales in hydrology

In general, researchers do not seem to have agreed on the definition of scale. The literal meaning of 'to scale' means 'to zoom' or 'to reduce/increase in size'. Blöschl and Sivapalan (1995) utilize the following definition of scale: "The term scale refers to a characteristic time (or length) of a process, observation or model". A distinction is thus made between three different scales: the process scale, the observation scale and the modelling scale. These three scale types are applicable in both space and time.

The transfer of information across these scales is called scaling; problems associated with it are scale issues. Two important scaling procedures can be discerned: upscaling, which is the transfer of information from a given scale to a larger scale, and downscaling, which is the transfer of information from a given scale to a smaller scale. The ratio between spatial and temporal scale for a certain process tends to be relatively invariant over a range of scales for a certain process. This ratio is termed the characteristic velocity. Because of the relationship between length and time scales it is often implicitly assumed that the scale of a process relates to both length and time. For both measurement and modelling scale a feature called scale triplet can be identified.

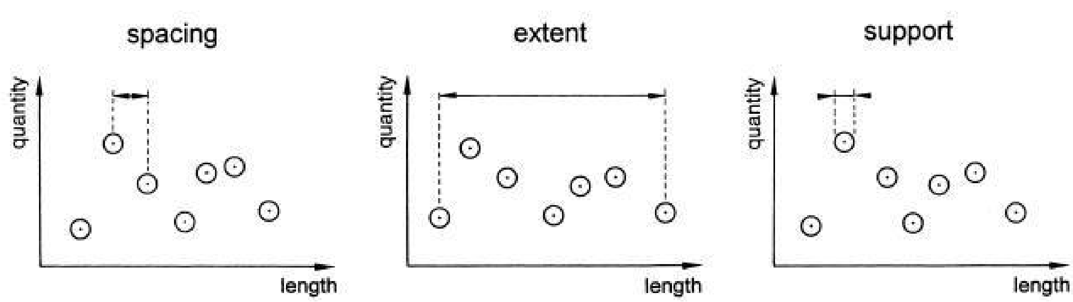


Figure 3.5: *Definition of the scale triplet: spacing, extent and support* (Blöschl and Sivapalan, 1995)

This triplet is shown in figure 3.5 and consists of: spacing, extent and support. A short description of the three different scales is given below, also addressing the scale triplet.

Process scale

The process scale is the scale natural phenomena exhibit. With scale both temporal scale and spatial scale are addressed. Three definitions exist for both characteristic temporal and spatial scales. These definitions are: extent, period and correlation length. Extent can be regarded as lifetime when referring to the temporal scale and as length in space when addressing to the spatial scale. Period is an indication for periodic processes and correlation length points out to a span within a process over which some correlation exists. (Blöschl and Sivapalan, 1995).

Observation scale

According to the scale triplet in figure 3.5, Blöschl and Sivapalan (1995) mention three definitions for observation scale: spacing, extent and support. With spacing the resolution of a data set is meant, e.g. the distance between the individual points of a grid. The extent of a data set points to the coverage of the data set: the 'distance' between the data values that are on the limits of the data set. The support points to the integration volume (time) of a sample, which can be regarded as the 'size' of a sample.

Modelling scale

The modelling or working scale refers to the model size, i.e. the scale is determined by the size of the object of modelling. As for the observation scale, the scale triplet can also be applied on the modelling scale. Important factors in determining modelling scale are spatial and temporal variability and heterogeneity. "Natural catchments exhibit a stunning degree of heterogeneity and variability in both space and time", (Blöschl and Sivapalan, 1995). Heterogeneity is associated with media properties that vary in space. In hydrological modelling these properties are called parameters. Variability is associated with fluxes or state variables that can vary in space and time. In hydrological modelling these fluxes and state variables are called variables.

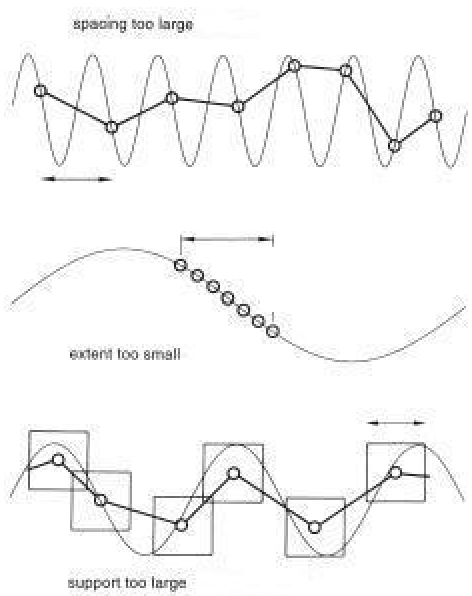


Figure 3.6: *The effect of sampling for measurement scales not commensurate with the process scale* (Blöschl and Grayson, 2000).

In hydrological modelling, the different scales (process, observation and modelling scale) hardly ever correspond. This was recognized by Blöschl and Sivapalan: "Unfortunately, more often than not, the modelling scale is much larger or much smaller than the observation scale. To bridge that gap, scaling is needed" (Blöschl, 1996). It seldom happens that processes are observed at the scale on which they occur. This is schematically shown in figure 3.6. The first figure shows a too large spacing, in this case the spacing is almost equal to the period of the process. The reproduced modeled process based on the measurement shows hardly any similarity with the original process. A denser observation scale is needed. The second figure shows a too small extent for both the observation and modelling scale. Obviously, by choosing an extent that is not appropriate for the process measured and/or modelled a trend can be found that however does not represent the process under study. The third figure shows the influence of support (or sample 'size') of observation scale on the obtained modelled process. Because the support is perhaps too large, the measured data is less representative for the process under study

3.4.3 Spatial scale

Conceptual hydrological models can be divided into three categories according to spatial model scale: the lumped models, the distributed models and in-between the semi-distributed models. The support of the spatial modelling scale is the largest in a lumped model, which treats a whole area of study as one catchment. The semi-distributed and distributed model split up this area of study. In a semi-distributed model this split up is based on spatial variability. Areas with low heterogeneity and variability are treated as one sub-catchment. In a distributed model the split up is often grid based, i.e. the individual sub-areas can have comparable properties, but the division is based on an a priori made decision of the modelling resolution. The spacing or resolution in space of a model is closely related to the support scale, e.g. in a grid-based distributed model the support and spacing are both equal to the size of the grid.

The HBV-model is an example of a semi-distributed hydrological model. However, it can be used as a lumped model too, as was done by Dong *et al*. (2005). Requisites for treating a study area as one catchment in a lumped model are: low spatial variability, heterogeneity and of course the availability of data.

Amongst hydrologists no consensus exists about the appropriate model scale. The aim is, as ever, a 'realistic' representation of the hydrology of a catchment that will be useful in making predictions in situations that have not yet occurred or where measurements have yet to be made. Supporters of distributed hydrologic modelling argue that the use of distributed modelling in hydrology might be more 'realistic' than simpler models that are calibrated to historical data (Beven, 2001). In a distributed hydrological model e.g. it is possible to apply flow paths and residence times of runoff according to the flow paths, which a lumped model does not take into account.

However, hydrologists who support more lumped modelling argued that for catchments with high spatial variability and poor data coverage distributed modelling is an unfeasible job. The developers of the HBV-model, who belong to this group of hydrologists stated that: "It was soon realised that a rather crude distributed approach based on variability parameters was the only practical approach to the problem of soil moisture accounting in basins with as high variability and as poor data coverage as in northern Sweden" (Bergström and Graham, 1998).

Booij (2005) studied the impact of climate change on flooding in the river Meuse with different spatial model resolutions, in order to see the effect of model resolution on the results. Three models were set up, with respectively 1, 15 and 118 sub-basins. A conclusion of this study was that all three models reproduced well the average and extreme discharge behaviour at the catchment outlet, but the results became somewhat better with increasing model resolution. So the use of a smaller spatial scale can improve model performance, but it should be considered if it outweighs the increasing data demand.

HBV-models have been set up over a range of extents of spatial modelling scales. For example, the Yassidere River catchment in Turkey modelled with HBV by Lidén and Harlin (2000) measures about 41 km^2, while Bergström and Carlson (1994) set up a HBV-model for the entire Baltic Sea region, measuring about 1.6 10^6 km^2.

3.4.4 Temporal scale

The spacing of the temporal modelling scale depends on the temporal observation scale and on the temporal variability of the process under study. The temporal observation scale is one of the major difficulties for the developers of hydrological models, since the availability of historical discharge time series is a prerequisite for a hydrological model that needs to be validated and possibly calibrated too. The spacing of the temporal modelling scale is often equal to the spacing of the temporal observation scale, because hydrologists try to use as much of the available data as possible.

The standard HBV model originally used daily time steps for input and output values. Lindström *et al*. (1997) studied temporal model resolution for the realization of the HBV-96 model. They concluded that the standard daily time step in the HBV-model could cause errors in the discrimination of snow and rain which, in turn, may result in errors in the simulation of runoff. Test runs were made with time steps of 12 hours but did not lead to significant improvements.

However, for catchments with unsteady climate patterns, the use of daily time steps can lead to a loss of data information e.g. when hourly data are available. When a catchment has a very rapid rainfall – runoff response the hydrological model will underestimate the generated runoff when daily time steps are used as a result of too large temporal spacing. This was already shown in figure 3.2. An example of a short hydrological process is a flash flood. Kobold and Brilly (2006) showed that for the Savinja catchment in Slovenia it was necessary to have an increased temporal model resolution: instead of using a HBV-model with daily time steps they proposed to apply hourly time steps.

The extent of the temporal modelling scale depends on the temporal scale of the hydrological process under study. If the assessment of the impact of climate change is part of this study, the extent of the temporal modelling scale will be larger than the extent of the temporal modelling scale of a model that is only used for forecasting. The support of the temporal modelling scale considers the length in time over which a measurement is valid. As for the spatial modelling scale, temporal support is closely related to temporal spacing.

Chapter 4
Model calibration

4.1 Introduction

Important phases of the set up of a hydrological model are, for example, the creation of a model structure that represents the area subject to study, model calibration, during which the model parameters are tuned by fitting model output to historical data and validation of the calibrated model. After validation one can draw conclusions about the applicability of the model and what changes possibly have to be made in the model structure in order to create a more reliable model. This chapter discusses subsequently calibration, validation and assessment criteria for model performance during calibration and validation.

4.2 Calibration

4.2.1 Introduction

The HBV-model is a conceptual model. Although the model parameters may have a physical meaning, they cannot be measured directly. This is in contrast to the parameters of a physically-based model which – theoretically – can be measured in the field. However, even physically-based model often need calibration. To determine the values of the parameters of the HBV-model, calibration of these parameters is necessary. Calibration literally means: “to ensure accuracy of something”. Harlin (1991) described calibration of a hydrological model as: “to obtain a unique and conceptually realistic parameter set so that the model becomes specific to the system it simulates and performs well”, Yapo *et al*. (1998) mention that: “To calibrate a hydrologic model, the hydrologist must specify values for its "parameters" in such a way that the model's behaviour closely matches that of the real system it represents” and Wagener *et al*. (2003) state about calibration:

"Calibration is a process of parameter adjustment (automatic or manual), until observed and calculated output time-series show a sufficiently high degree of similarity". Though Wagener *et al*. speak of output time-series calibration can also concern spatial patterns. With calibration model parameters are thus tuned by fitting model output to historical or spatial data. According to the definitions of Harlin and Wagener the process of calibration will lead to an optimal set of parameter values whose values lie within the conceptually realistic range. With this set a certain level of model performance is obtained. This level of model performance is determined by an objective function, e.g. Nash-Sutcliffe efficiency (see section 4.4.2).

However, Beven stated that: "It does not follow, of course, that invalid physical descriptions of real world processes are not useful to the hydrologist" (Beven, 1996). This is due to the principle of *equifinality*, which means that in open systems a given end state can be reached by many potential means. Or, in case of hydrological modelling, many combinations of parameter values provide equally good model fits to the observed data. Beven concluded that given the limited measurements available in any given distributed hydrological model it will not be possible to find one 'optimal' model. The modeller has to accept that there will be many different model structures and parameter sets that acceptably simulate the available data (Beven, 1993). This contradicts with the definition of calibration given by Harlin which suggests that a unique parameter set can be obtained by means of model calibration. In his definition of calibration Harlin also mentions that the parameter set obtained by model calibration should be conceptually realistic. However, this largely depends on the hydrologist who determines the starting values and the calibration range of the parameters involved in the calibration.

Therefore it is important to investigate the ranges of parameter values from other HBV-models to get an overview of realistic values of parameters, but it is difficult to attribute certain properties to the area under study based on the parameter values that are determined with model calibration.

4.2.2 Involved parameters

This section describes which parameters of the HBV-model will be involved in the calibration of HBV-Liuxihe. According to Booij (2005), "The most important and uncertain parameters occur in the soil moisture and fast flow routine." Seibert (1999) also included the slow flow routine in model calibration. Due to the climate of the Liuxihe River basin all parameters concerning snowfall are out of the scope of this study.

With the soil moisture routine and both flow routines involved in model calibration, the following parameters will be calibrated:

FC	[mm]	Maximum soil moisture storage
LP	[-]	Limit for potential evapotranspiration
BETA	[-]	Soil parameter, determining the relative contribution to runoff from a millimeter of precipitation at a given soil moisture deficit
CFLUX	[mm d^{-1}]	Capillary flux parameter
ALFA	[-]	Measure of non-linearity for fast flow
k_f	[-]	Recession parameter fast flow
k_s	[-]	Recession parameter slow flow
PERC	[mm d^{-1}]	Percolation parameter

Another parameter that is involved in the flow routine is the MAXBAS parameter, which smoothens the hydrograph generated by the model. However, since the basin is relatively small it is supposed that all generated runoff leaves the basin within a single time step, i.e. it is supposed that all runoff is generated at least within one hour. Therefore, the parameter MAXBAS does not have to be integrated in the HBV-Liuxihe, because its value will be constantly one.

For the eight parameters involved in calibration a parameter space has to be determined. This parameter space is the preset range where the values of all parameters have to lie within. Although the parameters do not have a real physical meaning they still can have unrealistic values. Therefore, a feasible range is determined in advance.

Booij (2005) evaluated several studies concerning the HBV model and an overview of his findings is shown in table 4.1. The ranges for the parameters CFLUX and PERC were not investigated by Booij, but are listed in table 4.1 too.

Table 4.1: *Parameter ranges HBV studies* (Booij, 2005)

Reference	**Region**	**FC**	**BETA**	**LP**	**ALFA**	**k_f**	**k_s**	**CFLUX**	**PERC**
		[mm]	[-]	[-]	[-]	[day^{-1}]	[day^{-1}]	[mm day^{-1}]	[mm day^{-1}]
Bergström (1990)	Sweden	100 - 300	1.0 - 4.0	0.50 - 1.0	-	-	-	-	-
Booij (2005)	Meuse	100 - 660	1.0 - 3.0	0.2 - 0.8	0.1 - 1.9	0.06 - 0.17	-	-	-
Default HBV-96, SMHI (1997)	-	200	2.0	0.9	1.0	0.17	-	1.0	-
Diermanse (2001)	Mosel, Germany	0 - 580	3.0	0.80	-	-	0.01	-	0.6
Harlin and Kung (1992)	Sweden	50 - 274	1.0 - 5.9	0.73 - 1.0	-	-	0.08 - 0.05	-	0.6 - 2.1
Killingtveit and Sælthun (1995)	Various	75 - 300	1.0 - 4.0	0.7 - 1.0	-	-	0.0005 - 0.002	-	0.6 - 1.0
Lidén and Harlin (2000)	Various	400 - 800	1.0 - 6.0	0.50 - 1.0	0 - 3.0	-	0.0005 - 0.1	0.1 - 1.0	0.2 - 5
Seibert (1999)	Sweden	50 - 500	1.0 - 6.0	0.30 - 1.0	-	-	0.001 - 0.15	-	0.0 - 6.0
Velner (2000)	Ourthe, Belgium	180	1.8	0.66	1.1	-	0.023	-	0.4
Deckers (2006)	UK	125 - 800	1.0 - 4.0	0.1 - 1.0	0.1 - 3.0	0.0005 - 0.15	0.0005 - 0.15	-	0.1 - 2.5

The initial parameter space for the HBV-Liuxihe is determined based on table 4.1, by taking the minimum and maximum values of each parameter, and by taking into account the position of the HBV default values between these minima and maxima, i.e. if the default parameter value equals either the minimum or maximum parameter value, the range is set wider. The results are shown in table 4.2.

Table 4.2: *Initial parameter space for HBV-Liuxihe*

	FC	**BETA**	**LP**	**ALFA**	**k_f**	**k_s**	**PERC**	**CFLUX**
	[mm]	[-]	[-]	[-]	[day^{-1}]	[day^{-1}]	[mm day^{-1}]	[mm day^{-1}]
Minimum	125	1.0	0.1	0.1	0.0005	0.0005	0.1	0.1
Maximum	800	4.0	1	3.0	0.17	0.15	2.5	1.9

The parameter FC has a minimal value of 125 mm. It should be taken into account that this value can conflict with the initial soil moisture storage. The latter cannot exceed the maximum soil moisture storage, because this is physically impossible.

Table 4.3: *Initial parameter space for HBV-Liuxihe, with hourly temporal resolution*

k_f	k_s	PERC	CFLUX
[hourly^{-1}]	[hourly^{-1}]	[mm hour^{-1}]	[mm hour^{-1}]
0.000021	0.000021	0.004	0.004
0.0077	0.0067	0.10	0.08

The time-dependent parameters are adapted to the hourly resolution and are shown in table 4.3. The hourly PERC and CFLUX parameter are just one twenty-fourth of their daily value. The hourly values for k_f and k_s are determined according to equation 4.1:

(4.1) $$k_{Hourly} = 1 - \sqrt[24]{\left(1 - k_{Daily}\right)}$$

4.2.3 Calibration methods

Model calibration can be carried out in different ways. Lidén and Harlin (2000) used manual calibration, automatic calibration and Monte Carlo simulation (MCS) for calibration of the HBV-model in their study on model performance in different climates. Within these three categories of model calibration a variety of calibration methods has been developed by different modellers. These methods are often model-specific, i.e. for the HBV-model the calibration method is based on the modelling purpose, the characteristics of the hydrological system and the available data.

Manual calibration

Manual calibration is usually considered the most realistic way to find the optimal set of parameter values. However, this calibration method is very extensive and the modeller needs to have good insight in the model structure and parameters. When a hydrological model is manually calibrated by different hydrologists, chances are low that similar parameter sets will be obtained, because the quality of the calibration is often closely related to the skill and knowledge of the hydrologist (Zhang and Lindstrom, 1997). The problem of subjectivity of the modeller who carries out the model calibration was also recognized by Lindstrom (1997): "A disadvantage of manual calibration is that the results depend on the experience and opinion of the hydrologist who is doing the calibration".

Automatic calibration

To overcome the disadvantages of manual calibration automatic calibration routines have been developed. An automatic calibration procedure for the HBV model has been developed by Harlin (1991). This automatic calibration procedure was improved by Lindstrom (1997). According to the latter, automatic calibration roughly consists of four steps: determination of the parameter range, the selection of an objective function, the selection of a search method and a termination criterion. Lindström (1997) used parabolic interpolation as search method. This method ignores the fact that it might optimize the objective function for a local optimum. To overcome this problem, global search methods have been developed, such as the shuffled complex evolution (SCE) method by Duan et al. (1992).

Monte Carlo simulation

Monte Carlo Simulation (MCS) is a technique in which numerous model simulations – in the order of thousands – are made with different parameter sets. The values of the parameters involved in model calibration are uncertain. Therefore, not a single value for these parameters is given, but a range of possible values has to be determined. During the simulation randomly chosen possible combinations of parameter values are tested against an objective function. In this way the most acceptable fitting parameter set can be determined.

4.2.4 Selected calibration method for HBV-Liuxihe

Based on their descriptions in paragraph 4.2.3 the 3 calibration methods can be compared in order to decide which method will be used for calibration of the HBV-Liuxihe. There seems to be consensus amongst hydrologists that manual calibration of a hydrological model is the most realistic way of calibration. However, it is far too time consuming and requires a high degree of experience. Besides, manual calibration is not an objective method.

With automatic calibration the problem of subjectivity has disappeared and automatic calibration itself is not time consuming. However, an automatic calibration routine is often case-specific and therefore not always available. The design of the method and the writing of the script is time consuming.

Monte Carlo simulation does not necessary have to be time consuming and does not require an experienced modeller to carry out the calibration. Attention has to be paid to the boundary values of the parameters involved in the calibration, especially during subsequent calibration rounds in which the parameter ranges have to be adjusted.

Because Monte Carlo simulation does not require an experienced hydrologist, does not have to be very time consuming and is not subject to subjectivity of the modeller this method will be used for the calibration of the HBV-Liuxihe.

4.3 Assessment criteria

4.4.1 Introduction

Assessment criteria are used in hydrological modelling as a tool to judge model performance. The next section introduces the assessment criteria Nash-Sutcliffe efficiency (E) and relative volume error (RVE). Section 4.4.3 discusses the combined criterion $ERVE$ – based on E and RVE - that will be used to assess the performance of HBV-Liuxihe during calibration and gives a description of these criteria and their specifications.

4.4.2 Assessment criteria

Assessment or efficiency criteria are measures used to assess the performance of a model during calibration and validation. According to Krause et al. (2005): "The process of assessing the performance of a hydrologic model requires the hydrologist to make subjective and/or objective estimates of the "closeness" of the simulated behaviour of the model to observations (typically of stream flow) made within the watershed." This subjective estimate is often based on visual inspection of the fit of the simulated hydrograph. However, it is difficult to express such a subjective estimate. Especially when two hydrographs are compared which look quite equal on first sight. Therefore objective estimates are necessary that can be expressed with a certain value and by which comparison with other model results can be made.
Beven (2001) defined efficiency criteria as "mathematical measures of how well a model simulation fits the available observations". Many efficiency criteria contain a summation of a squared or absolute – to avoid canceling of errors of opposite sign - error term. This results in emphasis lying on the capture of the peak flows, since errors in low flows tend to be smaller.
However, there are also criteria developed that put emphasis on low flows too. A modeller often chooses an assessment criterion after it has been determined what the purpose of the modelling is.

Besides the single objective criteria, multi objective criteria have been developed: "An approach that has the flexibility of emphasizing different portions of the model residuals according to one's preference is multi-objective optimization. The advantage of a multi-objective approach is to explicitly focus attention on the model performance/uncertainty trade-offs that are inevitable during model calibration." (Yapo et al., 1996) With multi-objective functions the modeller can make a bargain between the different objectives of a model and emphasis does not necessarily have to be put on one single objective. With the use of weighing factors it is possible to attribute different levels of importance to these multiple objectives.

Nash Sutcliffe efficiency (E)

For the assessment of the HBV-model performance during calibration and validation originally the efficiency criterion *E* according to Nash and Sutcliffe (1970) was used (see equation 4.2).

(4.2) $$E = 1 - \frac{\sum_{t=1}^{n} \left(Q_{obs}(i) - Q_{sim}(i)\right)^2}{\sum_{t=1}^{n} \left(Q_{obs}(i) - \overline{Q}_{obs}\right)^2}$$, with (4.2) $$\overline{Q}_{obs} = \frac{1}{n} \sum_{t=1}^{n} Q_{obs}(i)$$

With:

Q_{sim} Simulated discharge

Q_{obs} Observed discharge

$\overline{Q}_{obs}$ Mean observed discharge

The Nash-Sutcliffe efficiency ranges between 1 en -∞. In case the efficiency criterion reaches values close to 1 the simulated discharge equals observed discharge. On the other hand, low values for *E* prove that there is no similarity between simulated and observed discharge.

The main disadvantage of the Nash-Sutcliffe efficiency is the fact that squared differences between observed and simulated discharges are used. As a result larger discharge values have a stronger influence on the model performance. This problem can be reduced by using logarithmic runoff values, which flattens the peak flows and leaves the low flows more or less the same.

It is also optional to determine Nash-Sutcliffe efficiency for model output when observed discharge is above or below a certain threshold, as was done by Arends (2005) who investigated low flows in the river Meuse.

Relative volume error (RVE)

The relative volume error criterion RVE is a criterion based on the degree of similarity in the water balances of the simulated and the observed runoff. The differences between simulated and observed runoff relative to the observed runoff for each time step are added (see equation 4.3).

(4.3) $$RVE = \frac{\sum_{i=1}^{n} \left(Q_{sim}(i) - Q_{obs}(i)\right)}{\sum_{i=1}^{n} Q_{obs}(i)}$$

A disadvantage of this criterion is the canceling of errors of the opposite sign in the numerator. This can result in good scores according to the RVE criterion with a correct water balance over the whole period, but with completely wrong water balances on the smaller time scale. Therefore, the RVE criterion is seldom used alone. Combination with another criterion is almost indispensable. Lindström (1997) developed a criterion (see equation 4.4) for his automatic calibration routine that combines the RVE criterion with the Nash-Sutcliffe efficiency E, because "a maximization of E alone can lead to a significant, often negative, volume error."

(4.4) $$E_{RVE} = E - w\left|RVE\right|$$

As follows from equation 4.4, the Nash-Sutcliffe efficiency is corrected for a relative volume error. The parameter w is a weighing factor, its standard value is 0.1, recommended by Lindstrom (1997) who obtained optimal results with this value. Equation 4.4 is an example of a multi-objective criterion.

4.4.3 Assessment criterion for calibration

Since the development of the HBV model the Nash-Sutcliffe criterion has been its main assessment criterion (Bergström, 1995). It was already shown in paragraph 4.4.2 that optimisation with only Nash-Sutcliffe efficiency is not sufficient. Therefore, a multi-objective function similar to the one introduced by Lindström (1997) is used. The criterion E_{RVE} was developed especially for Lindström's automatic calibration routine for fine tuning of the model parameters. Around the optimum of the Nash-Sutcliffe criterion RVE is often already low and therefore the contribution of RVE to E_{RVE} is relatively small.

The HBV-Liuxihe will be calibrated with Monte Carlo Simulation. Although easier to use it is more difficult to catch the optimal parameter set. A combined criterion is introduced that attributes more weight to RVE, given by equation 4.5:

(4.5) $$ERVE = \frac{E}{\left(1 + \left|RVE\right|\right)}$$

The criterion *ERVE* ranges between -∞ and 1, like the criterion *E*. Only for small values of *RVE* the *ERVE*-criterion does not differ much from *E*. Any remaining relative volume error leads to a decrease of the *ERVE* criterion, even if *E* is close to 1.

Chapter 5
Liuxihe River basin data

5.1 Introduction

The most important model inputs for the HBV model are – as was pointed out in chapter 3 – the measured data series of the components of the general water balance: precipitation, potential evapotranspiration and – during model calibration – runoff.
The next paragraph discusses these input data for the Liuxihe River basin. The next paragraph reveals the problems that occurred with the precipitation, potential evapotranspiration and discharge data. Paragraph 5.3 gives a detailed description what could and what is done to improve the data series and to make them suitable as input for HBV-Liuxihe. Paragraph 5.4 reveals in which way the data series are applied in HBV-Liuxihe.

5.2 Data issues

This paragraph subsequently discusses the problems related to the data series mentioned in paragraph 5.1 as most eminent input for the HBV model.

Precipitation
Precipitation gauges are located abundantly in the Liuxihe River basin, although they are not equally spread. There are 20 precipitation gauges divided over the 8 sub-basins. The most downstream Ren He sub-basin has – with 6 gauges – the largest amount of precipitation gauges, while in the midstream Wenquan sub-basin there are no precipitation gauges located at all.
Hourly measurements were available made from January 5 2005 till December 31 2006. However, these data series contain many gaps, ranging from a single missing measurement to a range of missing measurements over a period of more than a day. Extreme cases are found in January and February of both years. Hardly any

measurement was made in these periods that seem to coincide with the Chinese New Year Holidays. In contrast to for example water level and runoff it is difficult to determine precipitation values based on adjacent measurements. Not in time, because rainfall is not a continuous process and not in space, because of spatial variability.

Potential evapotranspiration

Potential evapotranspiration data series were not available for the Liuxihe River basin. It is not clear whether the parameters, needed to derive potential evapotranspiration, are not measured in the basin at all. Studies on hydrological modelling at the Centre of Water Resources and Environment (CWRE) concentrate on short term forecasting rather than on long term simulations. In short term forecasting evapotranspiration has only a marginal role and is therefore often omitted.

Discharge

Three discharge gauges are located in the Liuxihe River: one measures the outflow of the Huanglong Dai Reservoir sub-basin into the Liangkou sub-basin, another gauge measures the outflow of the Da Ao sub-basin into the Li Xi sub-basin and the third one measures the outflow of the Li Xi sub-basin into the Ren He sub-basin, see figure 3.9. for the location of the sub-basins. In theory, these gauges would allow the hydrological modelling of the Huanglong Dai Reservoir sub-basin and the Li Xi sub-basin. However, the validity of the measurements at the Li Xi sub-basin can be doubted, since the inflow from the Da Ao is often higher than the outflow to the Ren He sub-basin without adequate information on water subtraction in the Li Xi sub-basin itself.

In case of the Huanglong Dai Reservoir sub-basin, the outflow is controlled by a hydro power dam. This sub-basin also lacks a single main course of the Liuxihe River, many small water courses exist which all flow into the reservoir. To determine the inflow an algorithm is used based on the reservoir outflow and the water level in the reservoir, according to equation 5.1:

(5.1) $$Q_{in}(n) = \frac{\left(Q_{out}(n-1) + Q_{out(n)}\right)}{2} + 100 \cdot hf \cdot \left(h(n) - h(n-1)\right)$$

Q_{in} reservoir inflow [$m^3\ s^{-1}$]

Q_{out} reservoir outflow [$m^3\ s^{-1}$]

hf reservoir water level factor [$m^2\ s^{-1}$]

h reservoir water level [m.a.s.l.]

n time step

The accuracy of the water level measurements is 10^{-2} m. Small values of reservoir inflow are therefore not measured in this way. A drop of 1 cm in the reservoir water level corresponds to a reservoir outflow of about 10 $m^3\ s^{-1}$ at a reservoir water level of 168 m.a.s.l., and values smaller than 10 $m^3\ s^{-1}$ are therefore not measured. Their contribution is only visible over more than one time step. For example, after 5 hours of a reservoir outflow of 2 $m^3\ s^{-1}$ the reservoir water level drops with 1 cm and a reservoir outflow of 10 $m^3\ s^{-1}$ is calculated. This makes the inflow look discontinuous. Hourly measurements of water level and reservoir outflow were available for the period January 5 2005 till December 4 2006. However, these data series contain gaps. Some water level measurements show unrealistic values, i.e. a water level drop of many meters in just one hour followed shortly by a rise of the water level of the same proportion. These unlikely water level values are found easily by looking at the reservoir inflow determined by equation 5.1: two large reservoir inflows of about the same magnitude are found close to each other and one of them has a negative value. The missing reservoir outflow values are marked by a value of -1 m3 s-1. This automatically leads to a negative reservoir inflow value.

The reservoir water level factor *hf* changes with the water level, which is quite obvious on first sight. The factor *hf* is not related linearly with the water level, but has a certain value for intervals of the reservoir water level. Sometimes the value of the factor *hf* decreases with increasing water level. This appears to be rather unnatural, since it implicates that the reservoir sides get closer to each other at a higher level. According to the factor *hf* the mountain reservoir would have an unnatural geometry. Because the factor also differs in a single interval the accuracy of this factor can be doubted since the existence of multiple values of *hf* for the same water level would imply that the storage capacity of the reservoir changes over time. Due to the inflow of sediments into the reservoir it is theoretically possible that the reservoir storage capacity alters, but not at the temporal scale of one hour.

5.3 Solutions

This paragraph explains which measures were taken in order to prepare the available hydrological data of the Liuxihe River basin suitable as input for the HBV-Liuxihe.

Precipitation

The precipitation data series contains many gaps. Interpolation of precipitation values is not a useful tool to fix these gaps since the process is discontinuous, in contrast to for example a water level where neighbouring measurements are related to each other if the temporal scale is not too large. For example, one can measure subsequently 4, 0 and 8 mm of precipitation with a temporal interval of 1 hour. If the second measurement is missing, it is not possible to interpolate between the neighbouring measurements. Only in long dry periods one can cautiously suppose that a missing precipitation value might be 0 as well.

The precipitation data series for the Huanglong Dai Reservoir sub-basin are determined with the measurements of 3 precipitation gauges: the Feng Mulang gauge, the Huanglong Dai Reservoir gauge and the Lian Xing gauge. Areal average precipitation is determined with the Thiessen method, already mentioned on page 20. When applying the Thiessen method, precipitation gauges do not necessarily have to lie within the (sub-) basin. The influence of each precipitation gauge is determined by the drawing of *Thiessen polygons*, lines that are equidistant between pairs of adjacent gauges. This results in a network of ´areas-of-influence´ for each gauge. The quotients of these areas and the total basin area are called *Thiessen coefficients*. By summing the product of gauge output with its corresponding

Thiessen coefficient an areal average precipitation series is determined, which is shown with equation 3.18:

$$(5.2) \qquad \sum_{i=1}^{n} \frac{R_i \cdot a_i}{A}$$

n	number of gauges involved [-]
R_i	measured precipitation [mm]
a_i	area represented per gauge [m²]
A	total area (sub-) basin [m²]

Figure 5.1 shows the grid obtained by the drawing of the Thiessen polygons. The grid was made using all stations in and near the Liuxihe River basin.

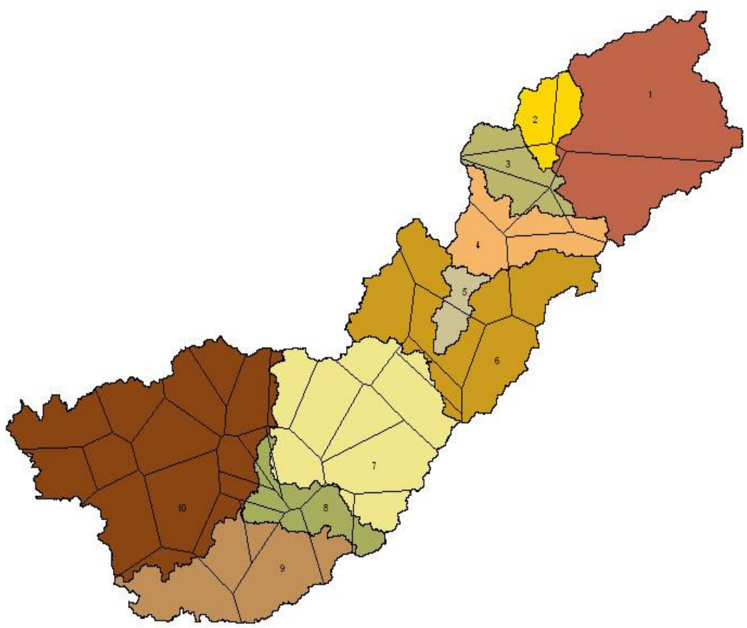


Figure 5.1: *The Liuxihe River basin with its division in sub-basins and the Thiessen polygons.*

A method for fixing the gaps in the precipitation data series for the Huanglong Dai Reservoir sub-basin could have been to use only the precipitation gauges for which measurements are available and to alter the Thiessen coefficients correspondingly.

Unfortunately, the gaps in the precipitation series coincide with gaps in the precipitation measurements of all 3 gauges involved, which excludes this method as a way of bridging the gaps.

Analysis of the available precipitation data series points out that the longest uninterrupted period of measurements lasts from March 22 2005 till December 31 2005. In this time interval only 9 measurements are missing, on a total of 6840 measurements. These 9 missing measurements are all found in the middle of dry periods and are therefore supposed to have the value of 0 mm as well.

The available data in the periods after this interval have more missing values which makes them not reliable as input for a hydrological model. The available data in the period before this interval – January 4 till March 22 2005 – is almost complete, but the quality of these data was doubted at the Centre of Water Resources and Environment.

Potential evapotranspiration

Measurements of potential evapotranspiration in the Liuxihe River basin were not available at all. Therefore literature was studied to search for indicative values. Gao et al. (2006) investigated the change in potential evapotranspiration in China over the period 1956 – 2000. They divided China into 10 regions based on major river basins and used climatic data and the Penman-Monteith formula to derive general potential evapotranspiration values for the 10 regions. These values are given for the different seasons in table 5.1 for the Pearl River basin region.

Table 5.1: *Seasonal potential evapotranspiration Pearl River basin, based on the period 1956 - 2000* (Gao et al., 2006)

season	months	EPO [mm]
spring	mam	246
summer	jja	345
autumn	son	267
winter	djf	163
annual		1020

These seasonal values have to be downscaled to daily and hourly values to be useful as input for the HBV-model. This is realized with three steps. First, the seasonal values are divided over three months, which results into monthly values. Then by means of interpolation between summer maximum and winter minimum values the monthly values are altered. The newly obtained values are smoothened by changing every monthly value with the average of these values and the values of the month before and the month thereafter: a 3-month moving average. The meaning of this step is that during the summer months potential evapotranspiration values increase and decrease (during winter months it is the other way around). During spring and autumn these values only increase, respectively decrease. Therefore the differences between the summer months should be lower – as for the winter months – than the differences between the spring or autumn months.

Figure 5.2 shows the monthly values for potential evapotranspiration for every alteration step.

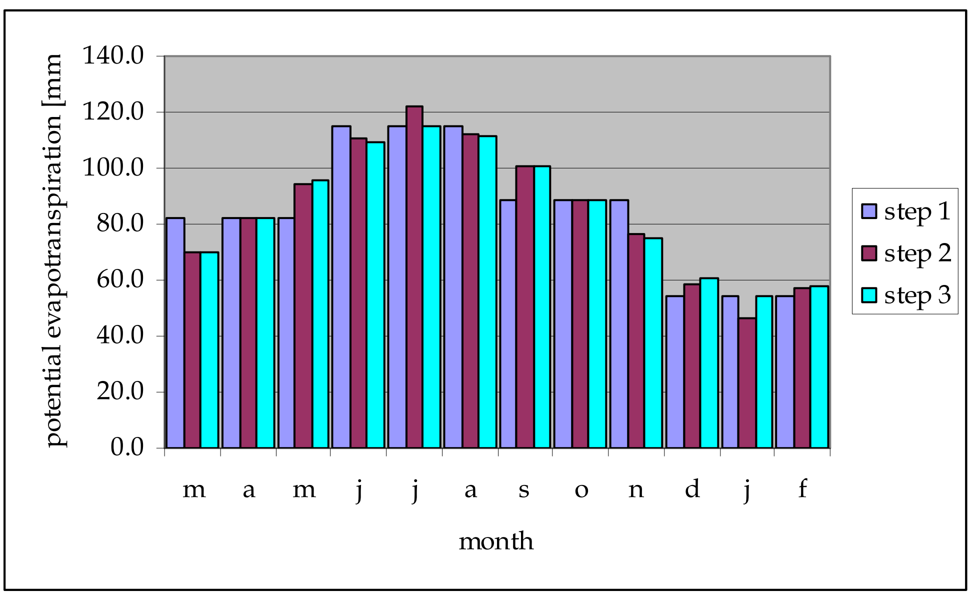


Figure 5.2: *Monthly values for potential evapotranspiration based on table 5.1. The blue bars indicate third fractions of the seasonal values, the red bars indicate interpolated values and the magenta bar indicate the three-month averaged values..*

Discharge

To determine reservoir inflow of the Huanglong Dai Reservoir, two variables are measured: the reservoir water level and the reservoir outflow. These measurements are used as input for equation 5.1. Many measurements in the reservoir water level data series are missing. However, it is not difficult to determine these values manually in the case of single missing events.

In case of more than one event missing linear interpolation is used to derive reservoir water level values. Reservoir outflow values and precipitation data have to be taken into account to check if no precipitation events or outflow events occurred in these periods. These events could have influenced the course of the reservoir water level, different from the course derived by linear interpolation.

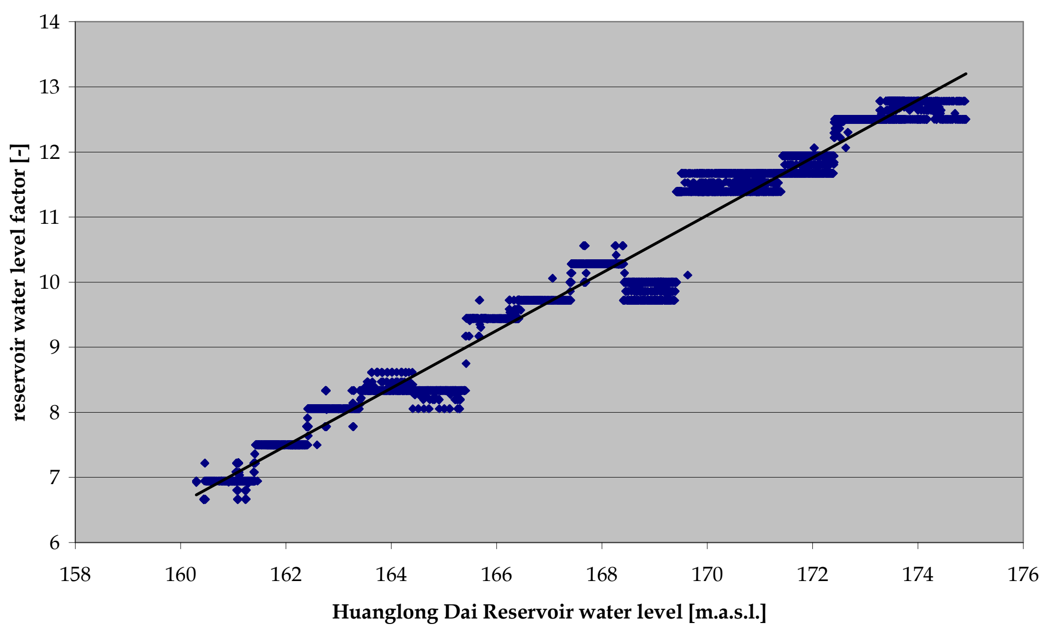


Figure 5.3: *Relation between the water level in Huanglong Dai Reservoir and the water level factor hf.*

Figure 5.3 shows the relation between the water level in Huanglong Dai Reservoir and the reservoir water level factor *hf*. The values of *hf* are determined by using equation 5.1 with the original – as determined by the CWRE – reservoir inflow as input. As mentioned in the preceding paragraph it is strange that different values for *hf* exist within a single interval. For water levels around 169 and 171 m.a.s.l. at least 3 different values for *hf* are found. These different values are used almost at the same time, i.e. not one single value for a period where a certain water level is maintained.

To overcome the problem of the discontinuous relationship between *hf* and the reservoir water level and multiple values of *hf* for the same water level a new relationship has to be determined. Based on the dispersal of the data one might suppose a linear relation. Based on linear regression analysis a trend line was drawn through the data. The R^2 value of 0.97 corresponding to the trend line shown in figure 5.2 indicates that the trend line fits well. The equation for this trend line is given in equation 5.2:

(5.2) $$hf = 0.44 \cdot h - 64.2$$

With the use of equation 5.2 a unique water level factor *hf* can be determined for every water level. Further, a new series of reservoir inflow data can be determined with the newly obtained values of *hf*. Only the reservoir outflow Q_{out} remains an obstacle for successful recalculation of the reservoir inflow Q_{in}, since it contains errors: in case of a measurement missing the generated reservoir outflow is -1 $m^3\ s^{-1}$. It is difficult to determine values for these data errors.

Therefore, instead of a single method, 4 different methods to fix the reservoir outflow data series are used and their results are compared. These methods are:

- Zero values
- Reservoir water level based values
- 12 hourly averaged values
- Sequence based values

The use of *zero values* means that all missing values in the reservoir outflow data series are regarded to be 0 $m^3\ s^{-1}$. The *reservoir water level based values* are based on drops in the reservoir water level. If a missing value of reservoir outflow coincides with a drop of the reservoir water level the missing value will be replaced with a value based on the reservoir water level factor *hf*. The *12 hourly averaged values* are averaged values of 12 subsequent reservoir outflow values: a 12-hour moving average. The *sequence based values* are based on the reservoir outflow values that surround missing value(s), e.g. if a missing data point is situated in a series of 10 m^3 s^{-1} it is regarded to be 10 m^3 s^{-1} too and if it is situated between data points with different values the missing data point is regarded to be 0 m^3 s^{-1}.

5.4 Method

Based on the preceding paragraphs a method is proposed for calibration of HBV-Liuxihe. Table 5.2 shows an overview of the necessary input data for HBV-Liuxihe available for the Liuxihe River basin. The 20 precipitation gauges measured data over about the same period and the data coverage, i.e. real measurements, is on average 75 %. If the data from 2006 are not concerned, this percentage is considerably higher. For the 3 discharge gauges this data coverage is smaller.

Table 5.2: *Overview available data.*

data	# gauges	period		% available
P	20	5-01-05 0:00	24-12-06 8:00	75
ET_{pot}	0			
Q	3	1-05-05 0:00	30-07-05 22:00	34
		1-05-05 0:00	30-07-05 22:00	25
		5-01-05 0:00	4-12-06 22:00	68

Discharges will be simulated only for the Huanglong Dai Reservoir sub-basin, because of the lack of data for the other sub-basins. The extent of the available data however is too short to carry out calibration and validation, and therefore only calibration runs will be done with the HBV-Liuxihe model.

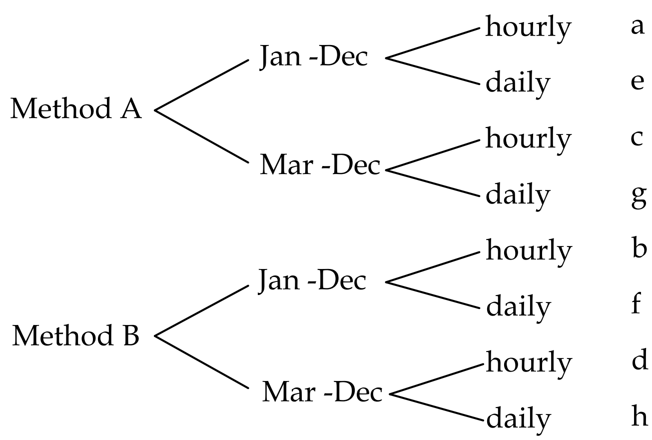


Figure 5.4: *Calibration scheme HBV-Liuxihe model.*

The model will be calibrated with 8 different observed discharge series, according to the scheme given in figure 5.4. The data series thus vary in temporal resolution, temporal extent and applied 'repair' method. Which 2 of the 4 methods will be used as method A and B will be based on the water balances obtained with these methods. This will be further explained in the next chapter.

Chapter 6

Results & Discussion

6.1 Introduction

This chapter discusses the results of the simulation of discharges with the HBV-Liuxihe model. Paragraph 6.2 is about the water balances for both the Huanglong Dai Reservoir and the Huanglong Dai Reservoir sub-basin. Four of these balances are set up, based on the four newly obtained discharge series. Two discharge series are used to calibrate the HBV-Liuxihe. This calibration is discussed in paragraph 6.3

6.2 Water balances

As was described in chapter 5, the Huanglong Dai Reservoir inflow was determined based on the reservoir outflow and water level. For this purpose the erroneous reservoir outflow data are transformed with the four different methods described in paragraph 5.3.

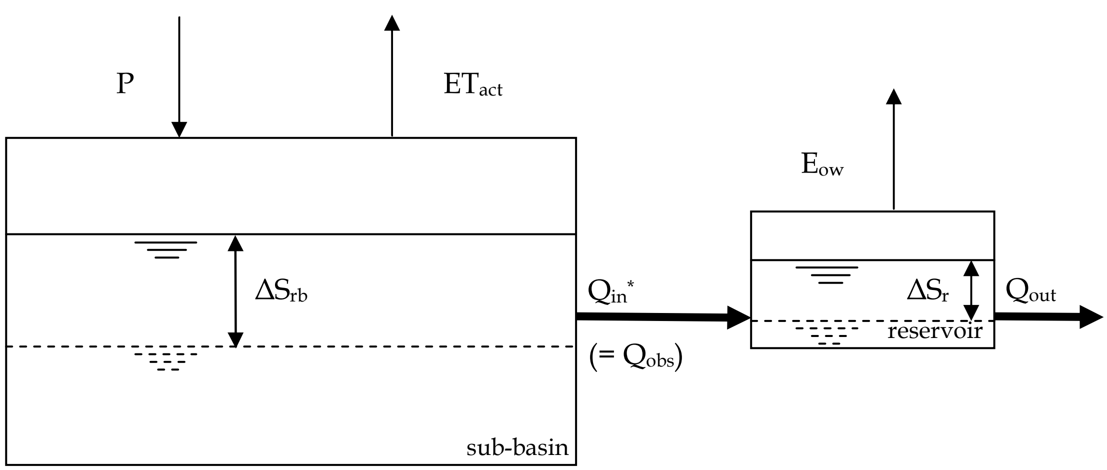


Figure 6.1: *Schematic representation of the water flows of the Huanglong Dai Reservoir sub-basin and the Huanglong Dai Reservoir and the relation between the two.*

The used reservoir outflow data were measured between January 5, 2005 and December 31, 2005. This enabled the set up of a reasonable water balance for the Huanglong Dai Reservoir over the year 2005, given the fact that the four missing days in January are ahead of a long interval of no precipitation and reservoir inflow, which strengthens the presumption that January 1, 2, 3 and 4 did not have any contribution to the water balance.

Figure 6.1 is a schematic representation of the water flows in Huanglong Dai Reservoir sub-basin and in the Huanglong Dai Reservoir. The corrected reservoir inflow Q_{in}^* is the same variable as the observed discharge Q_{obs} that is used for the calibration of the HBV-model. The water balance for the Huanglong Dai sub-basin is given by equation 6.1:

$$(6.1) \qquad P - Q_{in}^* - ET_{act} - \Delta S_{sb} = 0$$

The change in storage ΔS_{sb} in the sub-basin is supposed to be 0 mm over a full hydrological year, if no changes in the sub-basin take place. The precipitation P and corrected reservoir inflow Q_{in}^* are measured, so the annual actual evapotranspiration E_{act} is equal to the difference between annual precipitation and annual reservoir inflow. The water balances for the Huanglong Dai Reservoir sub-basin according to the four different methods are shown in table 6.1.

Table 6.1: *Water balances of 2005 for Huanglong Dai Reservoir sub-basin, based on the discharge series modified with four different methods. The values are given in both $m^3\ s^{-1}$ and $mm\ y^{-1}$.*

	zero		***level***		***averaged***		***sequence***	
	[$m^3\ s^{-1}$]	[mm]	[$m^3\ s^{-1}$]	[mm]	[$m^3\ s^{-1}$]	[mm]	[$m^3\ s^{-1}$]	[mm]
P	6.78	2317	6.78	2317	6.78	2317	6.78	2317
$\mathbf{Q_{in}^*}$	5.43	1855	5.61	1917	5.43	1855	6.05	2067
$\mathbf{\Delta S_{rb}}$	0.00	0	0.00	0	0.00	0	0.00	0
$\mathbf{ET_{act}}$	1.35	462	1.17	400	1.35	462	0.73	250

The reservoir inflow Q_{in}^* is a modification of the reservoir inflow Q_{in} based on Q_{out} and the measured changes in the reservoir's water level according to the algorithms discussed in chapter 5. Due to drops in the reservoir water level that did not coincide with corresponding reservoir outflows the newly obtained reservoir inflow series of Q_{in} still contained a large amount of negative values. The corrected reservoir inflow data series were derived by treating all negative reservoir inflow values as 0 m^3 s^{-1}, which lead to an increase of the annual average reservoir inflow for all the four methods. The correction of the reservoir inflow also influenced the water balance of the Huanglong Dai Reservoir. The water balance for the reservoir is given by equation 6.2:

(6.2) $$Q_{in}^{*} - Q_{out} - E_{ow} - \Delta S_r = RT$$

The reservoir outflow Q_{out} is measured at the hydropower dam. The difference in reservoir storage ΔS_r is based on the difference between reservoir inflow and outflow. A small part of the water that is stored in the reservoir will leave the system through evaporation. The residual term RT should be close to 0 mm or 0 m^3 s^{-1}, but in all four cases RT contained a considerable amount of water that can not only be assigned to evaporation. It is difficult to estimate the amount of water that evaporates, because only values for potential evapotranspiration are available from literature. Besides, these values are only seasonal averages. This makes the determination of the open water evaporation E_{ow} a difficult procedure.
According to Hoogeveen (1999) open water evaporation E_{ow} can be derived from the Penman Monteith reference evapotranspiration by means of the relation given by equation 6.3.

(6.3) $$E_{ow} = k_w \cdot ET_0$$

The parameter k_w is a dimensionless correction factor and is supposed to have a value of 1.3 under 'average circumstances'. Only to show that the evaporation of water from the reservoir has no significant contribution to the water balance of the reservoir an attempt is made to quantify the open water evaporation with the poor available means. Since no Penman Monteith reference values were available the potential evapotranspiration values from literature were used in equation 6.3, which results in an open water evaporation E_{ow} of 1326 mm per year. The average reservoir surface was estimated at about 2.5 km^2, which means that approximately 0.11 m^3 s^{-1} of water evaporates from the reservoir. The resulting water balance for Huanglong Dai Reservoir is given in table 6.2.

Table 6.2: *Water balances of 2005 for Huanglong Dai Reservoir, based on the discharge series modified with four different methods. The values are given in both m^3 s^{-1} and mm y^{-1}.*

	zero		***level***		***averaged***		***sequence***	
	[m^3 s^{-1}]	[mm]	[m^3 s^{-1}]	[mm]	[m^3 s^{-1}]	[mm]	[m^3 s^{-1}]	[mm]
Q_{in}	5.43	68496	5.61	70767	5.43	68496	6.05	76317
Q_{out}	3.75	47304	4.34	54746	3.75	47304	4.55	57396
ΔS_r	0.72	9082	0.72	9082	0.72	9082	0.72	9082
E_{ow}	0.11	1326	0.11	1326	0.11	1326	0.11	1326
RT	0.85	10784	0.44	5612	0.85	10784	0.67	8513

Because the rest term RT is different for the four methods it is obvious that the existence of this term is not caused by one or more unknown water extractions only. However, the differences in the RT value can easily be explained. The zero and averaged value methods have the same water balance on a yearly basis. The level based value method links drops in the reservoir water level to reservoir outflow. Drops in the reservoir water level without measured reservoir outflow lead to negative reservoir inflow values, according to equation 5.1. The level based value method wipes out these negative reservoir inflow values for all combinations of reservoir water level drops and missing reservoir outflow data, leading to a decrease of 0.41 m^3 s^{-1} of the annual average corrected reservoir inflow.

However, the annual average reservoir outflow increases, leading to an increase of 0.59 m^3 s^{-1} of the annual average corrected reservoir inflow. This is shown in table 6.3 where the differences in reservoir outflow, residual term and corrected reservoir inflow between the four methods are given.

The sequence based value method only accidentally links drops in the reservoir water level with reservoir outflow. Therefore the decrease of the annual average corrected reservoir inflow amounts only 0.18 m^3 s^{-1}, a smaller decrease than the decrease caused by the level-based values method. The sequence based value method leads to an increase of the annual average reservoir outflow of 0.80 $m^3\ s^{-1}$. This method also attributes water to reservoir outflow without a drop in the reservoir water level, what implicates that there must have been a reservoir inflow event at the same time.

Table 6.3: *Differences in reservoir outflow, residual term and corrected reservoir inflow of the water balances of 2005 for Huanglong Dai Reservoir.*

	zero		***level***		***averaged***		***sequence***	
	[$m^3\ s^{-1}$]	[mm]	[$m^3\ s^{-1}$]	[mm]	[$m^3\ s^{-1}$]	[mm]	[$m^3\ s^{-1}$]	[mm]
ΔQ_{out}	0,00	0	0,59	7442	0,00	0	0,80	10092
ΔRT	0,00	0	-0,41	-5172	0,00	0	-0,18	-2271
ΔQ_{in}^*	0,00	0	0,18	2271	0,00	0	0,62	7821

The effect of the increasing value of the corrected annual average reservoir inflow on the water balance of the Huanglong Dai Reservoir sub-basin is visible in table 6.1. The method with the largest increase of Q_{in}^* has the smallest value of actual evapotranspiration ET_{act}, which is actually the rest term in the balance. Both the level based values method and the sequence based values method lead to an increase of Q_{in}^*, and the first method also has a very small residual term in the reservoir water balance. However, it can be questioned whether it is reliable to suggest that reservoir outflow events should coincide with drops in the reservoir water level in case of no reservoir inflow, since the reservoir outflow data series contain many drops in the reservoir water level with 0 $m^3\ s^{-1}$ of reservoir outflow.

6.3 Simulations with HBV-Liuxihe

The derived corrected reservoir inflow data series can be used in the HBV-Liuxihe model as equivalent for the observed discharge Q_{obs}. The observed discharge is used in the HBV-model to assess the simulated discharge Q_{sim} during model calibration and validation, as described in chapter 4. In fact, the length of the observed discharge data series is too short to carry out calibration, let alone both calibration and validation, because 10 years of daily data are normally used for calibration

(Bergström, 1995) and Kobold and Brilly (2006) used 1 year of hourly data to calibrate their HBV-model for the Savinja catchment. However an attempt was made to calibrate HBV-Liuxihe with the observed discharge series obtained with the zero and sequence based values method.

The choice for these two methods is based on their diverging values for the actual evapotranspiration in the Huanglong Dai Reservoir sub-basin, according to table 6.1, which amounts respectively 462 and 250 mm y^{-1}. In fact, these two data series are the two extremes. The extremes are chosen because it is not clear whether a low value for actual evapotranspiration in the water balance of the sub-basin is more realistic than a high value or not.

Table 6.4: *Overview of calibrations of the HBV-Liuxihe model for 8 data series obtained with either the zero or the sequence based values method. The simulations were made with hourly and daily temporal resolution and for the periods between January 5 to December 31 2005 and between March 22 and December 31 2005.*

name	**method**	**temporal resolution**	**period**
	ZB/SB	H/D	
a	zero based	hourly	5-1 to 31-12
b	sequence based	hourly	5-1 to 31-12
c	zero based	hourly	22-3 to 31-12
d	sequence based	hourly	22-3 to 31-12
e	zero based	daily	5-1 to 31-12
f	sequence based	daily	5-1 to 31-12
g	zero based	daily	22-3 to 31-12
h	sequence based	daily	22-3 to 31-12

An overview of the different simulations with HBV-Liuxihe is given in table 6.4. The two data series were both varied concerning temporal resolution and the length of the data series. The temporal resolution was varied in order to study the effect of this resolution on model performance. The applied resolutions were daily and hourly time steps. The length of the data series was either from January 5 - December 31 2005 or March 22 – December 31 2005. It was more or less guaranteed that the data for the period March 22 – December 31 2005 were complete, while in the period before March 22 2005 the quality of the measured precipitation series was doubted, although data were available for this period. The annual precipitation over 2005 in the Huanglong Dai Reservoir sub-basin amounts 2317 mm. Over 2006, this annual precipitation amounts about 2890 mm. That is a difference of 572 mm of which about 164 mm was measured in the first three months of 2006, although the annual precipitation over 2006 can be an outlier regarding the average annual precipitation. For this reason the model output for the two different periods is compared.

Table 6.5: *Values for precipitation P, observed discharge Q_{obs}, simulated discharge Q_{sim}, actual evapotranspiration ET_{act} and storage S resulting from calibration of the HBV-Liuxihe.*

name	**P**	**Q_{obs}**	**Q_{sim}**	**E_{act}**	**S**
	[mm]	[mm]	[mm]	[mm]	[mm]
a	2317	1836	1391	798	277
b	2317	2043	1520	744	202
c	2145	1649	1218	902	173
d	2145	1855	1396	675	222
e	2318	1836	1645	742	82
f	2318	2044	1684	721	63
g	2145	1649	1209	791	250
h	2145	1855	1488	660	103

The calibration was carried out in three rounds of 10000 Monte Carlo simulations. Starting with the parameter ranges according to table 4.2 and narrowing the parameter ranges after every round based on the range of the parameters of the fifty simulations with the highest value of the combined criterion ERVE. The initial conditions for the storage boxes of soil moisture, surface water and ground water were respectively 125, 12.5 and 12.5 mm, according to Deckers (2006). The value of 125 mm is the upper limit for the soil moisture storage since the lower boundary for the maximum soil moisture storage parameter FC is 125 mm in the first calibration round.

The results of the eight calibrations of the HBV-Liuxihe model for different situations are shown in table 6.5. The difference between observed Q_{obs} and simulated discharge Q_{sim} and the corresponding large values for the actual evapotranspiration ET_{act} immediately catches the eye. The added values of the three storage boxes do not differ extremely from the initial conditions, they range between about half and double values of the initial values.

Table 6.6: *The initial conditions for the storage boxes concerning soil moisture (ssm), surface water (ssw) and ground water (sgw) and their values (i.v.) on December 31, 2005.*

name	ssm	ssw	sgw
	[mm]	[mm]	[mm]
i.v.	*125*	*13*	*13*
a	274	2	1
b	196	2	4
c	171	1	1
d	219	3	0
e	45	36	1
f	46	7	10
g	240	0	10
h	91	0	11

Table 6.6 shows how the storage is composed over the three different boxes. Most of the water is located in the soil moisture storage box, as it is under the supposed initial condition.

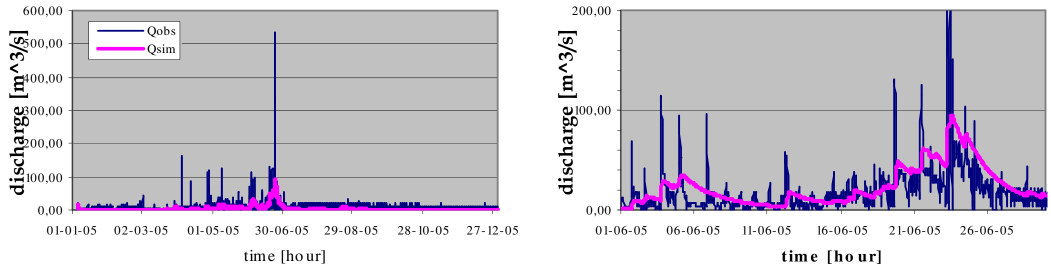
Table 6.7: *Optimal parameter sets for 8 different model calibrations.*

name	FC	BETA	LP	ALFA	k_f	k_s	PERC	CFLUX
	[mm]	[-]	[-]	[-]	$[d^{-1}]$ / $[h^{-1}]$	$[d^{-1}]$ / $[h^{-1}]$	$[mm\ d^{-1}]$ / $[mm\ h^{-1}]$	$[mm\ d^{-1}]$ / $[mm\ h^{-1}]$
a	701	1.19	0.79	0.64	0.00045	0.0030	0.065	0.0060
b	536	1.11	0.88	0.68	0.00032	0.00070	0.080	0.0074
c	690	1.23	0.43	0.71	0.00032	0.0016	0.072	0.0053
d	574	1.13	0.88	0.61	0.00032	0.0021	0.044	0.0070
e	191	1.29	0.89	0.11	0.0093	0.098	2.2	0.24
f	187	1.14	0.90	0.14	0.012	0.017	1.6	0.30
g	719	1.11	0.64	0.48	0.012	0.018	1.8	0.20
h	337	1.11	0.85	0.41	0.010	0.018	2.2	0.25

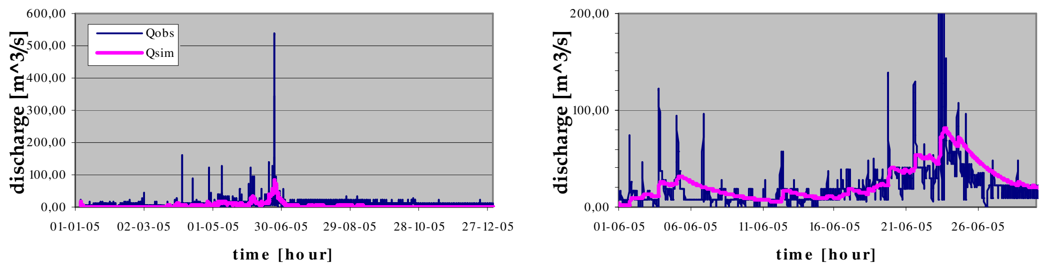
The actual evapotranspiration according to the balance given in table 6.1 is in all cases smaller than the simulated values shown in table 6.5. This could imply that ET_{act} is consequently overestimated by the HBV-Liuxihe. However, the values for the parameter LP that governs the amount of actual evapotranspiration are not small, as can be concluded from table 6.7 that shows the optimal parameter sets obtained with calibration of the HBV-Liuxihe. Small values of LP cause the actual evaporation to equal the potential evapotranspiration as long as enough soil moisture is available. Large values of LP lead on average to a lower amount of actual evapotranspiration. The parameter BETA that governs the flow through the ground does not show odd values, but higher values of this parameter would lead to a faster generation of runoff: more direct runoff instead of indirect runoff. The remaining processes that could lead to overestimation of ET_{act} are the potential evapotranspiration - which values are based on literature and are not measured in the basin itself - and the storage in the soil moisture, governed by the parameter FC. The values for this parameter are high especially for the calibrations with the data series with a hourly temporal resolution - and it can be doubted whether it can occur that the soil reaches this maximum storage, since the terrain is mountainous and it can be expected that a large part of the precipitation will reach the surface water as overland flow. The differences in the parameter FC are remarkable: the largest value is 719 mm (g), while the smallest value is 187 mm (f). The latter (f) calibration also resulted in a high parameter LP, which caused the smallest value of E_{act} of all calibrations. The influence of LP is clear in calibration (c): this calibration resulted in the highest value of E_{act}.

Table 6.8: *Model performance according to three assessment criterions: Nash-Sutcliffe efficiency E, Relative volume error RVE and the combined criterion ERVE.*

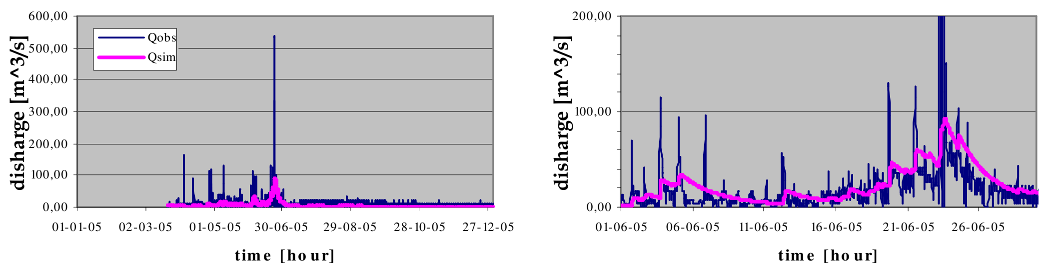
name	**E**	**RVE**	**ERVE**
	[-]	[%]	[-]
a	0.22	-24.3	0.18
b	0.25	-25.6	0.20
c	0.24	-26.1	0.19
d	0.25	-24.7	0.20
e	0.27	-10.4	0.24
f	0.33	-17.6	0.28
g	0.41	-26.7	0.32
h	0.40	-19.8	0.34



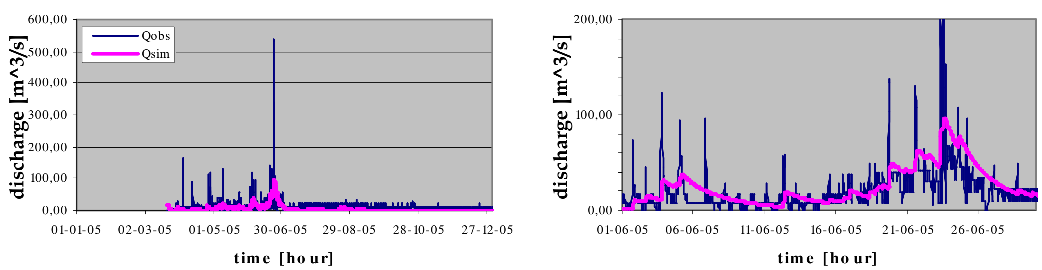
a) 05-01/31-12, *hourly, zero-based, with enlarged view of the month June*



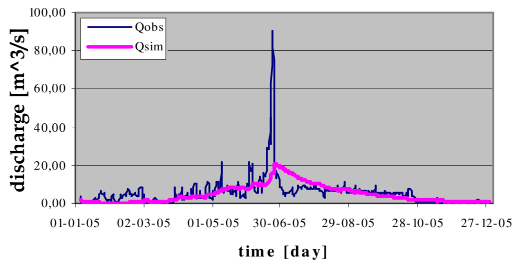
b) *05-01/31-12, hourly, sequence-based, with enlarged view of the month June*



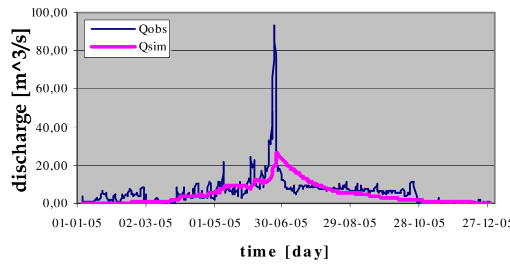
c) *22-03/31-12, hourly, zero-based, with enlarged view of the month June*



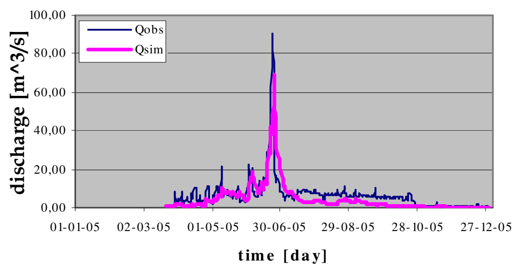
d) *22-03/31-12, hourly, sequence-based, with enlarged view of the month June*



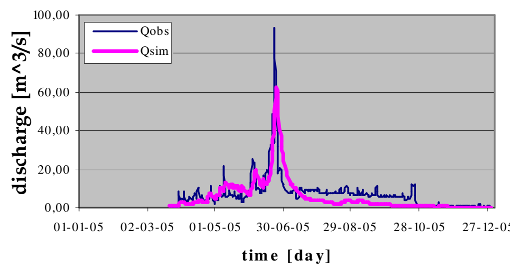
e) *05-01/31-12, daily, zero-based*



f) *05-01/31-12, daily, sequence-based*



g) *22-03/31-12, daily, zero-based*



h) *22-03/31-12, daily, sequence-based*

Figure 6.2: *Observed and simulated hydrographs for Huanglong Dai Reservoir sub-basin, with varying temporal temporal resolution (hourly/daily), temporal extent (Jan – Dec 2005/Mar – Dec 2005) and applied data repair method (sequence-based/zero-based).*

Model performance during the eight calibrations was assessed with the ERVE criterion, as described in chapter 4. Comparing the values of table 6.8 with figures 6.2a to 6.2h shows that the hydrographs simulated with the HBV-Liuxihe model have a poor fit. The performance according to the assessment criterion E is poor, since the values for E obtained by calibration are even far from the value of 0.8 mentioned in the IHMS user manual. Figures 6.2a and 6.2b seem to have a better fit then figure 6.2c and 6.2d, but their values for E and RVE are only slightly higher. The relative volume error in the figures 6.2a and 6.2b is even larger, but this can be caused by the cancelling of errors the opposite sign. Although the values for the efficiency criteria are poor they can be used for comparison. The zero and sequence based values method over the period between March 22 and December 31 2005 on a daily time scale have the highest ERVE values and of all figures, figure 6.2g and 6.2h have the best fit. Generally, the efficiency criterion values obtained with the models with daily time steps are better.

The data with a hourly temporal resolution are more fickle and alter between extreme values. While extremes with a duration shorter than one day are spread out in case of a daily model resolution, these extremes are visible when using hourly time steps. During times of low runoff the course of the discharge can be caused by the sensitivity of the measurements, as was explained in the last chapter. After some steps of low discharge this discharge is summed and attributed to the time step when changes in the reservoir water level are measured. Runoff is not generated as fast with the HBV-Liuxihe as in the Huanglong Dai Reservoir sub-basin, and therefore the peaks are not captured. The model is not capable to catch this alternation. The simulated peaks are lower and wider. Enlarged views of the month June for the calibrations with the HBV-Liuxihe models with hourly time steps are added to give a better understanding of the functioning of the model with a hourly temporal resolution.

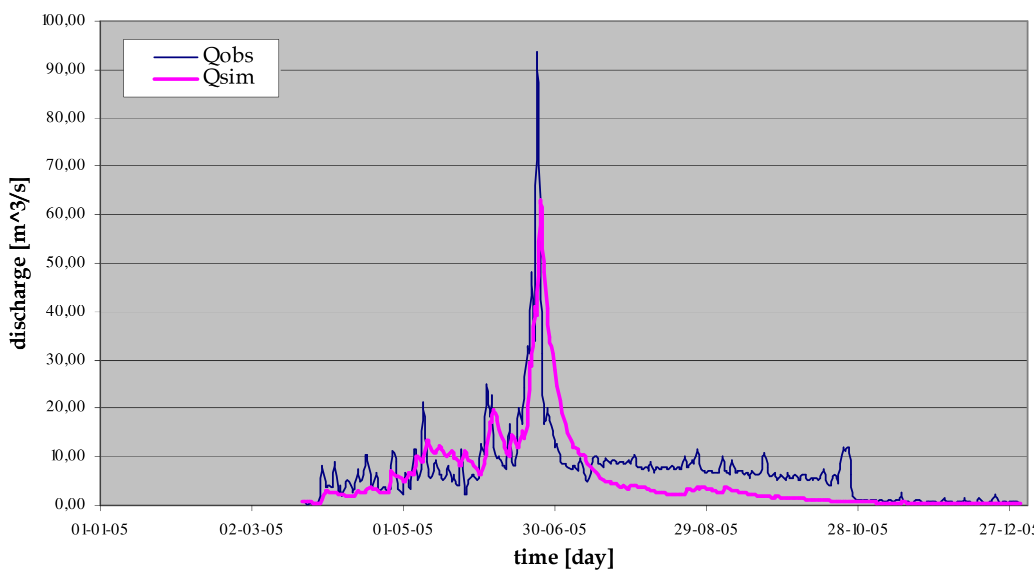


Figure 6.3: *Enlarged view of figure 6.2h, the observed and simulated hydrograph for Huanglong Dai Reservoir sub-basin, period 22-03 to 31-12-2005, daily time steps, sequence -based values method.*

Although June is in the middle of the rainy season, there are no records of precipitation events for 74 % of the precipitation measurements. The response time of the system is rapid and the base flow only small, so that without a precipitation event the observed discharge is only small, in contrast to the model that responses less rapid. The precipitation data with a daily temporal resolution show precipitation events for 90 % of the measurements. The observed discharge with a daily temporal resolution is therefore less fickly and shows more similarity with the simulated discharge.

When using daily time steps, the data series starting on March 22 show better results than the data series starting on January 5. Although for every calibration with the sequence based values method data series the performance criteria are equal or higher than for calibration with the zero based values method data series it is difficult to state that the sequence based values method data series is a better representation of the observed discharge than the zero based values data series. The differences between the performance criteria are small and do not make really sense if one concerns also the uncertainty in the model and the data.

Figure 6.3 gives an enlarged view of figure 6.2h. Of all simulations this figure shows the best fit between observed and simulated discharge. As for the simulations with hourly time steps the model does not catch the peaks on the full scale.

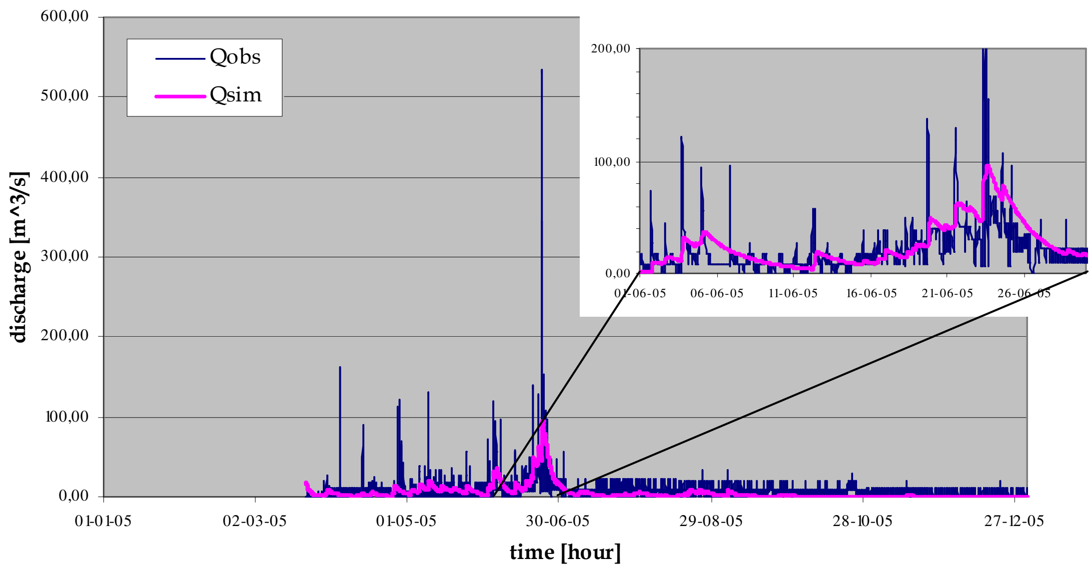


Figure 6.4: *Enlarged view of figure 6.2d, the observed and simulated hydrograph for Huanglong Dai Reservoir sub-basin, period 22-03 to 31-12-2005, hourly time steps, sequence-based values method.*

The simulated peaks are lower and wider, and often with one day delay with respect to the observed peaks. Also remarkable is the difference between observed and simulated discharge from July till the end of October. This difference is also clear in figure 6.4, but most striking in this figure is the difference between the maximum observed discharge of over 500 $m^3\ s^{-1}$ and the maximum simulated discharge of about 100 $m^3\ s^{-1}$.

Remarkable is the fact that in the second half of 2005 only 15 % of the annual precipitation is measured, while the observed discharge in this period consists of about 40 % of the annual observed discharge. This seems to contradict with the earlier finding that the response time of the system is very short, which implies that water leaves the system as runoff very soon after it enters the system as precipitation. Precipitation is in some way stored that over the period from July to November a quite constant outflow is measured, that surprisingly is not witnessed anymore after the month October. The type of flow shows similarity with ground water flow. However, if this would be the case this flow should be captured by the model's simulated slow runoff.

Chapter 7
Conclusions & recommendations

7.1 Introduction

This chapter presents the conclusions of the study about hydrological modelling of the Liuxihe River basin with the HBV-model. These conclusions are given in the next paragraph, which starts with answering the research questions of section 1.2.2. The last paragraph (7.3) gives recommendations, for instance about further research.

7.2 Conclusions

The objective of this study is: "The simulation of discharges for the Liuxihe River in South China to contribute to the development of effective operational and strategic flood management by setting up and testing a HBV-model for the Liuxihe River Basin." The 3 research questions formulated in section 1.2.2 are answered in this paragraph.

How is the HBV-Liuxihe model built up?

A HBV-model – HBV-Liuxihe – could not be set up for the entire Liuxihe River basin, because the Liuxihe River proved to be highly regulated and normalized. Due to the river regulation and normalisation the course of the river discharge appears to be less natural and the necessary extra observed discharge series were not available. The HBV-Liuxihe model therefore includes only one of the two most upstream sub-basins: the Huanglong Dai Reservoir sub-basin, since this is the only sub-basin within which the river discharge is not influenced by man. This sub-basin measures 92.6 km^2 and is covered with for over about 90% of the area. Although the model only a part of the Liuxihe River basin, it is still called HBV-Liuxihe for convenience reasons.

The Huanglong Dai Reservoir sub-basin is mountainous and therefore has a high spatial variability. Average precipitation is determined with the Thiessen-method, based on the measurements over 1 year (2005) of 3 gauges. This number is possibly a bit small to catch the variability in precipitation. Discharge is measured only at the outlet of the sub-basin over a period of about 1 year.

What are proper values for the free HBV-model parameters?

Eight model parameters were involved in the calibration of HBV-Liuxihe. These were FC, BETA, LP, ALFA, k_f, k_s, PERC and CFLUX. The parameter ranges were based on parameter values found in other HBV-studies. By means of Monte Carlo simulation (MSC) the optimal parameter values were determined. In total 8 calibrations were carried out with different data sets. The calibration results were assessed with the relative volume error *RVE*, the Nash-Sutcliffe efficiency *E* and the newly introduced combined criterion *ERVE*. According to these criteria HBV-Liuxihe performed poor. However, a visual check confirms that the large peak in the rainy season is simulated by the model.

The calibrations did not result in a single optimal parameter set, but each calibration resulted in its own optimal parameter set. Especially the parameter FC has various values, as shown in table 6.7. Also the parameter ALFA varies over a part of the preset parameter range. However, none of the parameters showed values close to on side of the parameter range. The optimal parameter values for HBV-Liuxihe consequently lie within the limits based on literature.

What is the influence of changing temporal scale on model performance?

HBV-Liuxihe was calibrated with 8 different observed discharge data sets. These data sets were determined with 2 different repair methods; the zero based values and sequence based values method. Both the temporal extent and the temporal resolution were varied, to investigate the influence of a change in temporal scale on model performance.

The calibration of the HBV-Liuxihe model was not successful according to the assessment criteria. The simulated hydrographs only poorly fitted with the observed hydrograph, i.e. the hydrographs show similarity in their contours. According to the combined criterion of Nash-Sutcliffe efficiency E and relative volume error RVE – ERVE – small differences in model performance were obtained with the 8 data series of observed discharge. Lowest performance was obtained with the data series with hourly temporal resolution (ERVE: 0.18 – 0.20), with higher performance with the data series with daily temporal resolution (ERVE: 0.24 – 0.34). Hydrologist speak of a 'good' fit when Nash-Sutcliffe efficiency is at least 0.8 and relative volume error is only small. In this case ERVE is also close to 0.8. Kobold and Brilly (2006) argued that an increase in temporal resolution should improve model performance, especially in basins with a high spatial variability, where flash floods can occur. These are caused by extreme precipitation events in a short period in the order of 1 or a couple of hours. When this precipitation is averaged over a whole day the obtained discharges are not as high as they should be. Although flash floods occur in the Liuxihe River basin (Chen and Zhu, 2005) the increase in temporal resolution does not lead to an increase of model performance. The performance is even better with daily temporal resolution.

The model calibrations with the data series with the shortest extent – March to December – tend to lead to better results than the model calibrations with the discharge data series for the period January to December 2005. However, this is only the case for the data series with a daily temporal resolution. Normally, a larger extent should improve model calibration. In this case, the quality of the observed discharge data for the period January – March is doubted, which can be the cause for the lower model performance with the data with the longest extent.

Although the calibrations with the data series with a daily temporal resolution showed better model performance than the calibrations with the data series with a hourly temporal resolution one may not conclude that daily temporal resolution can be preferred above hourly temporal resolution because of better model performance. The difference in model performance for different model resolutions depends in this case on the method used to derive the observed discharge data series. Because of the translation from reservoir water level and reservoir outflow to reservoir inflow – and thus sub-basin outflow – especially during low flows it is impossible to simulate the observed discharge correctly, since it shows a discontinuous course due to the sensitivity of the measurements: small reservoir inflows are only measured after more than 1 time step.

Unfortunately the observed discharge series for the Huanglong Dai Reservoir sub-basin – necessary for calibration and validation of the HBV-Liuxihe – were incomplete and contained unrealistic values. The four methods applied to the data – zero based, level based, 12-hour average and sequence based values – all improved the observed discharge data series by removing the negative values. Table 6.2 and table 6.3 show that the level-based values method and the sequence-based values method improved the water balance for the Huanglong Dai Reservoir, i.e. the residual term RT decreased. The existence of this residual term strengthens the idea that the observed discharge data series – before as well after the four methods were applied to them – are incorrect. The existence of the residual term implies that water has disappeared from the reservoir by means other than reservoir outflow, but no records of extractions of water other than reservoir outflow were available. The lowest residual term obtained with the sequence-based values method supports the idea that this method gives the best resulting observed discharge series. However, regarding table 6.1, the amount of water left for actual evapotranspiration E_{act} is only about a quarter of the estimated potential evapotranspiration. It is therefore not possible to conclude which of the four applied methods gives the most representative observed discharge data series based on the water balances for the Huanglong Dai Reservoir and the homonymous sub-basin.

The model calibrations with the data series obtained with the sequence-based values method are slightly better than the calibrations obtained with the zero-based values method. Despite of the differences in model performance according to the criterion ERVE it is not realistic to argue that one of the eight observed discharge data series is more reliable than the others. The ERVE values are just too low. Unfortunately there are many possible causes for the obtained model performances. The parameter sets obtained with the calibrations already vary for the 8 different calibrations. Therefore, and also bearing in mind the principle of equifinality explained in chapter 4, no conclusion can be drawn about a parameter set or range that typically represents the Liuxihe River basin.

The simulated actual evapotranspiration with the HBV-Liuxihe was much higher than the amount of water available for evapotranspiration according to table 6.1, resulting in large relative volume errors and corresponding low values for ERVE. The potential evapotranspiration values applied in the model were found generally valid for the Pearl River basin. This may cause some errors when applying these values to the Liuxihe River basin, but a difference of 75 % - ET_{pot} according to Gao et al. (2006) amounts 1020 mm annually and with the sequence based method only 250 mm of water is available for evapotranspiration – is just too high.

7.3 Recommendations

The main problem concerning the successful set up for a hydrological model for the Liuxihe River basin is the lack of data available. The regulation and normalisation of the Liuxihe River are not problematic, as long as discharge measurements at for example weirs are available. Therefore, the set up of a gauging system of hydrological variables is an important step to enable the set up of hydrological models in the future. If possible, a gauging system should be installed for the entire Liuxihe River basin. But a first attempt can be made on a smaller scale. Attention should be paid to the number of gauges. The number of precipitation gauges for example should be high enough to deal with the spatial variability. By investigating this optimal number of gauges for a part of the Liuxihe River basin first, the set up of a gauging system for the entire basin will be simplified.

In case of the HBV-model, measurements should start as soon as possible regarding the length of the data series needed for calibration and validation. As Kobold and Brilly (2006) stated that one year of hourly input data for the HBV-model is sufficient for successful calibration, an attempt to calibrate HBV-Liuxihe can be made as soon as 1 year of data is collected.

Evapotranspiration values typical for the Liuxihe River basin or even areas with a smaller scale are not available. For successful calibration of HBV-Liuxihe realistic values of evapotranspiration are a necessity. The parameters that determine potential evapotranspiration should thus be measured, preferably with hourly resolution too.
The determination of reservoir inflow in the Huanglong Dai reservoir is not very strong. If possible, discharge gauges should be installed in the main streams that mouth into the reservoir. By measuring the reservoir inflow, it can be checked whether the calculated reservoir inflow based on water level and reservoir outflow is reliable.
It is preferred to install automatic gauges, since the available manual records often show gaps. It is not a coincidence that for 2005 and 2006 no values for all variables are available for the period of the Chinese New Year holiday.

HBV-Liuxihe had difficulties with simulating the relatively constant observed discharge that occurred after the rainy season, which contained about 40 % of the total observed discharge. It is not clear what process causes this flow, but it could be regarded as a reservoir emptying slowly and at an almost constant rate. Research should be carried out on this process and perhaps it is possible to apply an extra storage box to HBV-Liuxihe to catch this outflow.

Attention should also be paid to the multi-objective assessment of performance of the HBV-Liuxihe. Especially because of the typical monsoon climate with a wet and a dry season, a multi-objective criterion that puts emphasis on both high and low flows could enhance model calibration and validation. Possibly, different criterions can be used during the wet and the dry season, or maybe it is even possible to obtain different parameter sets for the wet and the dry season. However, although these suggestions may sound interesting, it remains difficult to carry out any kind of research with such a limited amount of data available.

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