JRC Scientific and Technical Reports

The impact of retention polders, dyke-shifts and reservoirs on discharge in the Elbe river

Hydrological modelling study in the framework of the Action Plan for the Flood Protection in the Elbe River Basin of the International Commission for the Protection of the Elbe River (ICPER)

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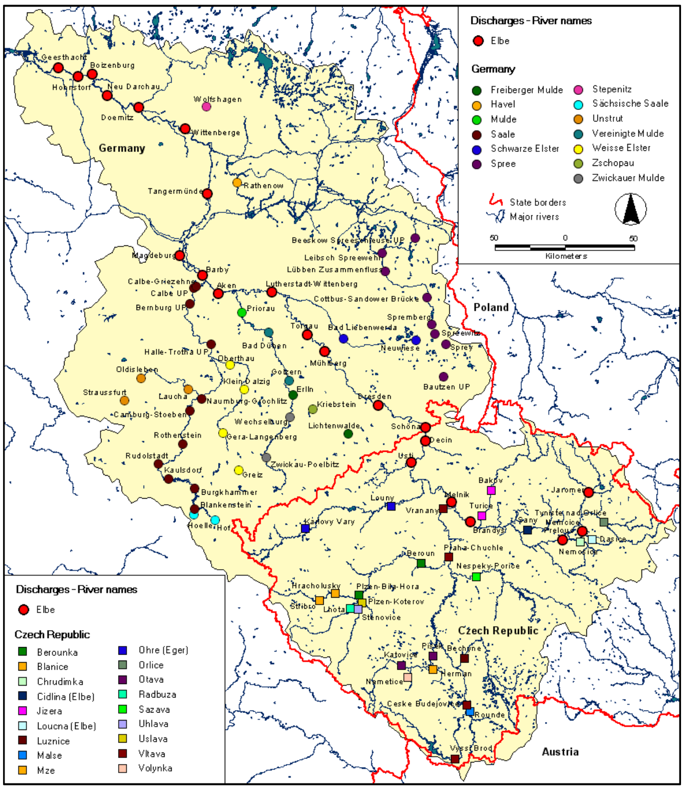

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Executive Summary

A hydrological model simulation study has been carried out in the Elbe basin using detailed data obtained from the relevant Czech and German institutes. The LISFLOOD model has been calibrated for the Elbe river basin using these data. Using this calibrated model setup, two studies have been carried out in the framework of the Action Plan for Flood Protection of the International Commission for the Protection of the Elbe River (ICPER).

The 2002 flood without dyke-breaks

The first part of the simulation study was a simulation of the 2002 summer flood without dyke-breaks. It has been estimated here that without dyke-breaks, the discharge in the lower part of the Elbe river would have been 2.6 – 9.1 % higher (117-384 m^3/s). Waterlevels would have between 18 and 54 cm higher.

Reservoir Study

The planned scenario for Saale reservoir steering investigated here does not have any significant influence on the discharge of the Elbe. The influence of changing the flood storage in the Bleiloch and Hohenwarte reservoirs in winter from 40 to 55 Mm^3 and in summer from 25 to 35 Mm^3 on river discharge has been assessed. The scenario results have shown that this planned scenario for reservoir steering in the Saale cascade does not have a significant influence on the discharge of the river Elbe, for the investigated flood events in 1994, 2002 und 2003 at gauging station Calbe-Griezehne (lower Saale). Also the influence on the discharge in the river Elbe is marginal: changes in peak discharge downstream the Saale-confluence are in the order of 0.2% (difference in discharge 4-8 m^3/s).

Furthermore, the influence of the Vltava reservoir cascade was investigated using two datasets provided by the Czech Hydro-Meteorological Institute (CHMI): one dataset with the actual situation and steering of the Vltava cascade, and a scenario without the Vltava cascade. For floods with a magnitude such as in August 2002, the difference between the scenario with and without the Vltava cascade is between 1.6 and 3.7% (84-171 m^3/s) in the German part of the Elbe river.

Polder and Dyke-shift Study

The potential effects of 5 polders and 20 dyke-shifts on discharge in the river Elbe have been estimated. The main outcomes are the following:

The 20 planned dyke-shifts reduce the peak discharge of the 2002 summer flood with 1.3-4.6% (58-202 m^3/s). Waterlevels would have been 10-31cm lower. For the 2006 flood the results are similar in character, but lower in magnitude. The measures reduce the peak discharge of the 2006 spring flood with 0.4-1.3% (10-48 m^3/s). Waterlevels would have been 3-10cm lower.

The 5 planned polders and 20 planned dyke-shifts simulated here, reduce the peak discharge of the 2002 summer flood with 3.9-10.8% (178-469 m^3/s). Waterlevels would have been 23-74cm lower. For the 2006 flood, the results are again lower: the measures reduce the peak discharge of the 2006 spring flood with 1.2-3.3% (31-121 m^3/s). Waterlevels would have been 8-21cm lower.

Zusammenfassung (DE)

Eine hydrologische Simulation für das Flusseinzugsgebiet der Elbe wurde mit den detaillierten Daten der jeweiligen tschechischen und deutschen Instituten erstellt. Das hydrologische Modell LISFLOOD wurde anhand dieser Daten kalibriert und zwei Studien wurden mit dem kalibrierten Modell im Rahmen des IKSE „Aktionsplans Hochwasserschutz Elbe“ durchgeführt.

Simulation Hochwasser 2002 ohne Deichbrüche

Gegenüber den Beobachtungswerten weisen die Berechnungsergebnisse für das Hochwasser 2002 ohne Deichbrüche ein Erhöhung der Scheitelabflüsse um 2,6 bis 9,1 % und der Wasserstände um ca. 18 bis 54 cm auf.

Studie zur Reaktivierung ehemaliger Überschwemmungsflächen und zur Schaffung zusätzlicher Retentionsräume

In dieser Studie wurde der Einfluss von fünf Poldern und 20 Deichrückverlegungen, die an der Elbe geplant sind, auf den Hochwasserverlauf in der Elbe untersucht.

Gegenüber den Beobachtungswerten weisen die Berechnungsergebnisse der einzelnen Szenarien für das Hochwasser 2002 folgende Änderungen der Scheitelabflüsse auf:

- unter Berücksichtigung der 20 geplanten Deichrückverlegungen – Reduzierung der Scheitelabflüsse um 1,3 bis 4,6 % und der Wasserstände um ca. 10 bis 31 cm.
- unter Berücksichtigung der geplanten fünf Polder und 20 Deichrückverlegungen – Reduzierung der Scheitelabflüsse um 3,9 bis 10,8 % und der Wasserstände um ca. 23 bis 74 cm.

Gegenüber den Beobachtungswerten weisen die Berechnungsergebnisse der einzelnen Szenarien für das Hochwasser 2006 folgende Änderungen der Scheitelabflüsse auf:

- unter Berücksichtigung der 20 geplanten Deichrückverlegungen – Reduzierung der Scheitelabflüsse um 0,4 bis 1,3 % und der Wasserstände um ca. 3 bis 10 cm.
- unter Berücksichtigung der geplanten fünf Polder und 20 Deichrückverlegungen – Reduzierung der Scheitelabflüsse um 1,2 bis 3,3 % und der Wasserstände um ca. 8 bis 21 cm.

Studie zur Wirkung der großen Talsperren in der Moldau, Eger und Saale auf den Hochwasserverlauf der Elbe

Aus den Ergebnissen der Saale-Studie geht hervor, dass die im Szenario vorgesehene Änderung des gewöhnlichen Hochwasserrückhalteraums in den Talsperren Bleiloch und Hohenwarte (im Winter von 40 auf 55 und im Sommer von 25 auf 35 Mio. m^3) keinen wesentlichen Einfluss auf den Verlauf der untersuchten Hochwasser 1994, 2002 und 2003 am Pegel Calbe-Griezehne unterhalb der Saalemündung in die Elbe hätte und damit auch keinen bedeutenden Einfluss auf den Verlauf dieser Hochwasser in der Elbe (Reduzierung der Scheitelabflüsse um max. 0,2 % beim Hochwasser 2002).

Wir untersuchten unter Nutzung von Daten der Tschechischen Republik die Wirkung der großen Talsperren in der Moldau, Eger und Saale auf den Verlauf des Hochwassers 2002 im deutschen Elbeabschnitt. In der Tschechischen Republik wurden ein Szenario mit dem Ist-Zustand der Moldaukaskade und ein Szenario ohne Moldaukaskade berechnet. Für Hochwasserereignisse der Größenordnung des Hochwassers 2002 ergaben sich im Szenario ohne Moldaukaskade am deutschen Elbeabschnitt um ca. 1,6 bis 3,7 % erhöhte Scheitelabflüsse. Die Ergebnisse entsprechen den Resultaten für den tschechischen Teil der Studie, die zeigten, dass die Wirkung der Moldaukaskade im absoluten Maßstab im Bereich von Hochwassern mit einem Wiederkehrintervall von 10 bis 20 Jahren am stärksten ausgeprägt ist.

Shrnutí (CZ)

Hydrologické simulace byly provedeny na základě detailních dat, která byla pro účely této studie poskytnuta českými a německými institucemi. Pomocí těchto dat byla provedena kalibrace hydrologického modelu LISFLOOD pro povodí Labe. Poté byly s jeho využitím zpracovány dvě studie v rámci Akčního plánu povodňové ochrany v povodí Labe MKOL.

Povodeň 2002 bez protržení ochranných hrází

Byl simulován průběh povodně v roce 2002 bez protržení ochranných hrází. Výsledky výpočtů ukazují zvýšení kulminačních průtoků o 2,6 – 9,1 % (117 – 384 m3/s) a zvýšení vodních stavů o 18 až 54 cm oproti pozorovaným hodnotám.

Studie o vlivu velkých údolních nádrží na Vltavě, Ohři a Sále na průběh povodní na Labi

Z výsledků studie na Sále vyplývá, že ve scénáři uvažovaná změna ovladatelného ochranného objemu u vodních děl Bleiloch a Hohenwarte (v zimě z 40 na 55 a v létě z 25 na 35 mil. m3) neměla významný vliv na průběh posuzovaných povodní 1994, 2002 a 2003 ve stanici Calbe-Griezehne před zaústěním Sály do Labe a tudíž neměla ani významný vliv na průběh těchto povodní na Labi (snížení kulminačních průtoků max. o 0,2 % při povodni v roce 2002).

S využitím dat z ČR byl posouzen vliv velkých údolních nádrží na Vltavě, Ohři a Sále na průběh povodně 2002 na německém úseku Labe. V ČR byly posuzovány scénáře pro stávající stav s Vltavskou kaskádou a bez Vltavské kaskády. Dle scénáře bez Vltavské kaskády by na německém úseku Labe došlo při extrémních povodních na úrovni povodně 2002 ke zvýšení kulminačních průtoků o cca 1,6 až 3,7 %. Tyto výsledky korespondují s výsledky české části studie, které ukázaly, že v absolutním měřítku se vliv Vltavské kaskády nejvíce projevuje v oblasti povodní s dobou opakování 10 až 20 let.

Studie k obnově bývalých záplavových ploch a k vytvoření dalších retenčních prostor

V této studii byl posuzován vliv plánovaných 5 manipulovatelných odlehčovacích poldrů na Labi a 20 oddálení ochranných hrází na průběh povodní na Labi.

Výsledky výpočtů dle jednotlivých scénářů pro povodeň 2002 ukazují následující změny kulminačních průtoků oproti pozorovaným hodnotám:

- se zohledněním plánovaných 20 oddálení ochranných hrází - snížení kulminačních průtoků o 1,3 až 4,6 % a vodních stavů o cca 10-31 cm
- se zohledněním plánovaných 5 manipulovatelných odlehčovacích poldrů a 20 oddálení ochranných hrází - snížení kulminačních průtoků o 3,9 až 10,8 % a vodních stavů o cca 23-74 cm

Výsledky výpočtů dle jednotlivých scénářů pro povodeň 2006 ukazují následující změny kulminačních průtoků oproti pozorovaným hodnotám:

- se zohledněním plánovaných 20 oddálení ochranných hrází - snížení kulminačních průtoků o 0,4 až 1,3 % a vodních stavů o cca 3-10 cm
- se zohledněním plánovaných 5 manipulovatelných odlehčovacích poldrů a 20 oddálení ochranných hrází - snížení kulminačních průtoků o 1,2 až 3,3 % a vodních stavů o cca 8-21 cm

1 Introduction

Following the disastrous floods in the Elbe and Danube river basin in August 2002, the Directorate General (DG) Joint Research Centre (JRC) of the European Commission (EC) offered to carry out two flood scenario studies in the Elbe river in support of the Action Plan for the Flood Protection in the Elbe River Basin of the International Commission for Protection of the Elbe River (ICPER).

The aims of the studies, as defined in the Action Plan, are:

- Estimation of the changes in peak water level, the time of the flood peak, and the flood wave in the Elbe, as a consequence of a series of planned retention polders and dyke-shifts in the German part of the Elbe river basin;
- Provide technical basic information for the planning and execution of the retention polders and dyke-shifts
- The assessment of the impact of large dam reservoirs (located on the Vltava, the Ohre, and the Saale rivers) on the Elbe River flood development

This report describes the two studies that have been carried out, the methods used, and the results obtained.

The study solely describes the quantitative hydrological modelling results, and does not include a cost-benefit analysis, nor descriptions on advantages and disadvantages of the planned measures.

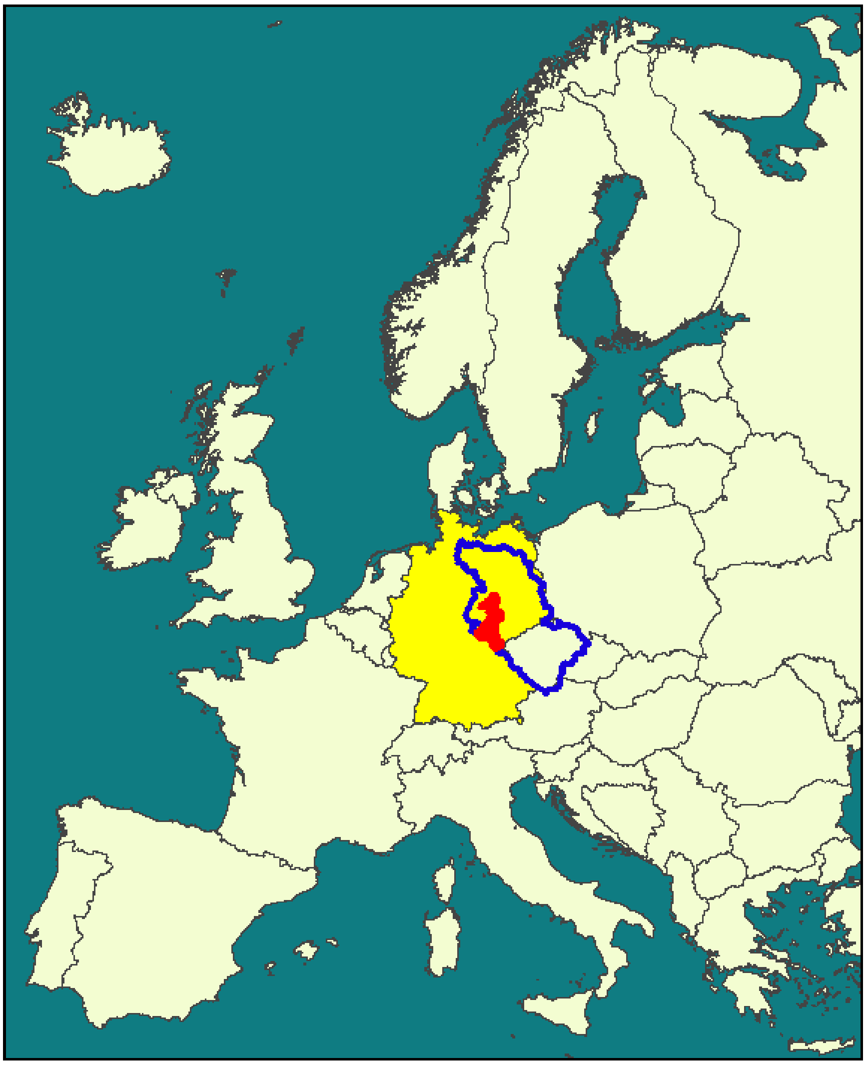


Figure 1.1 The Elbe and Saale River Basins

1.1 Study on the influence of Saale reservoirs on Saale and Elbe discharge

The first study consists of an evaluation of the influence of German reservoirs (Saale-cascade) on the discharge in the river Saale and Elbe.

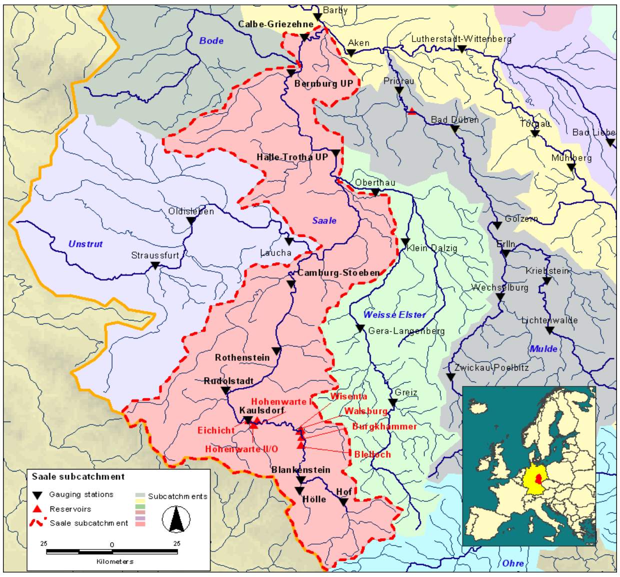


Figure 1.2 *Reservoir cascade within the Saale River*

This study aims to investigate the impact of the reservoir cascade in the Saale River on the discharge behaviour in the main Elbe river, while using two different reservoir steering scenarios: the current steering of the reservoirs, and a scenario with a changed reservoir operation.

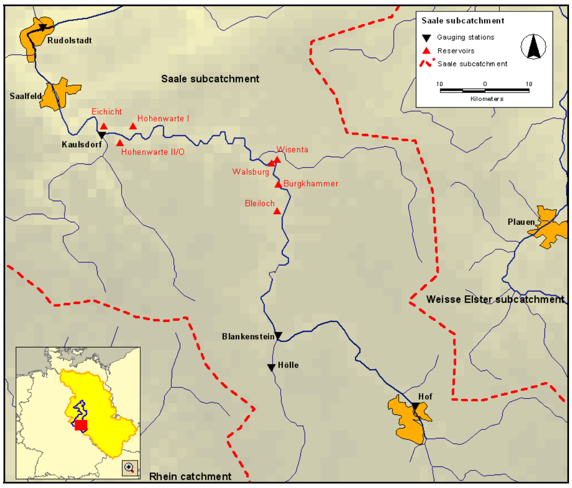


Figure 1.3 *Saale reservoir cascade*

1.2 Study on reactivation of former flood plains and the creation of additional retention polder areas along the German Elbe

The second study aims to evaluate scenarios to reactivate former flood plains and the creation of additional retention polders along the German Elbe. This study evaluates possibilities of constructing flood retention polders to temporarily store water from the Elbe during flood events (Figures 1.4, 1.5 and 1.6). Furthermore, the effects of several dyke-shifts are studied. The effects of these measures on maximum discharge, time of peak discharge and water level have been studied. Furthermore, the downstream effects on discharge of upstream planned measures have been studied. Finally, also the integrated effect off all measures (dyke-shifts, reservoirs, flood retention polders) has been studied.

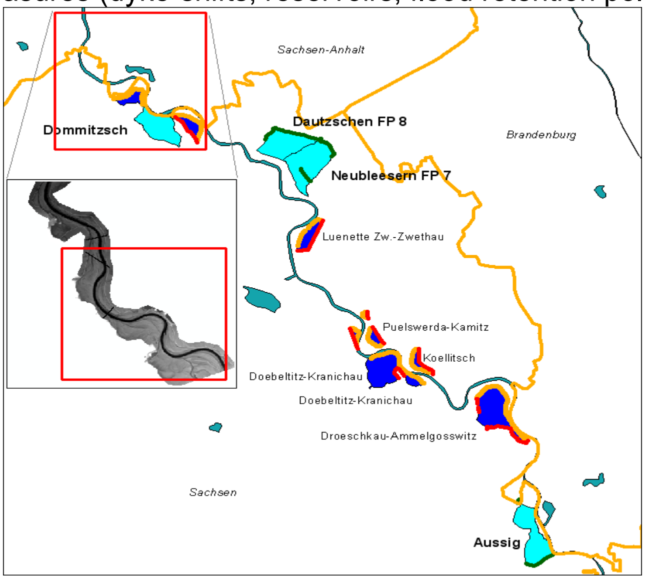


***Figure 1.4** Example of planned retention polders in the Elbe River*

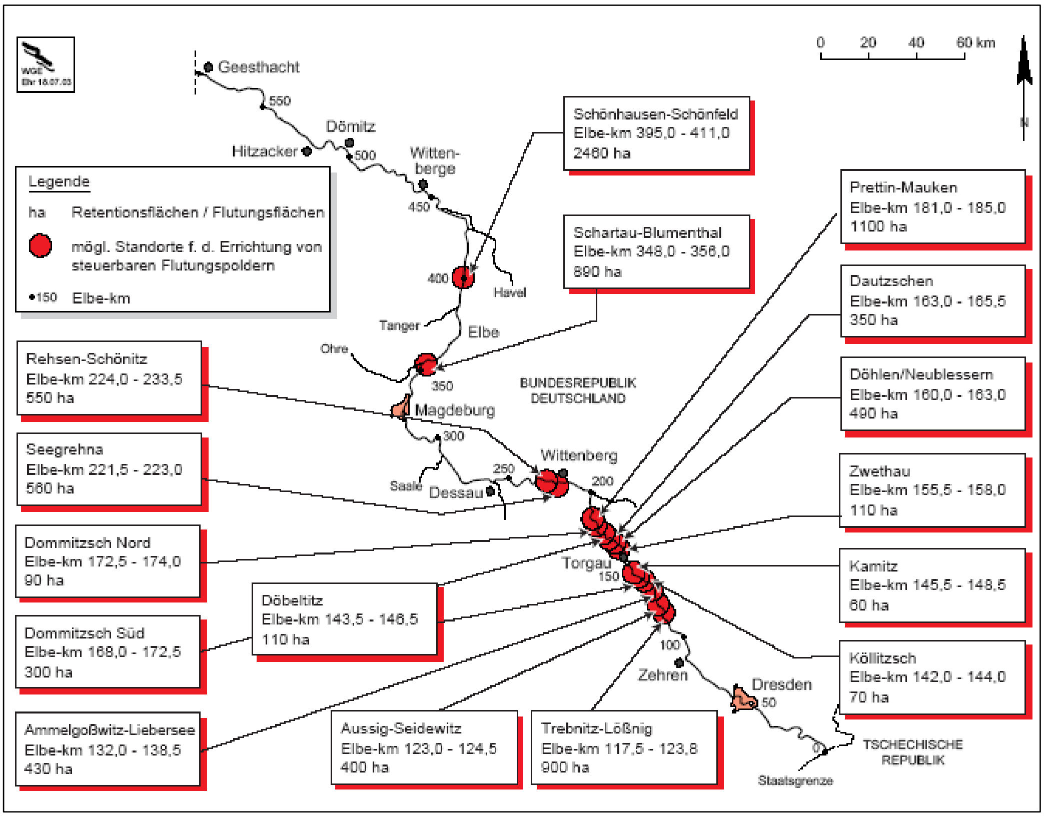


***Figure 1.5** Possible locations for construction of regulated flooding polder areas along the German Elbe [Action Plan for Flood Protection Elbe – ICPER, 2003]*

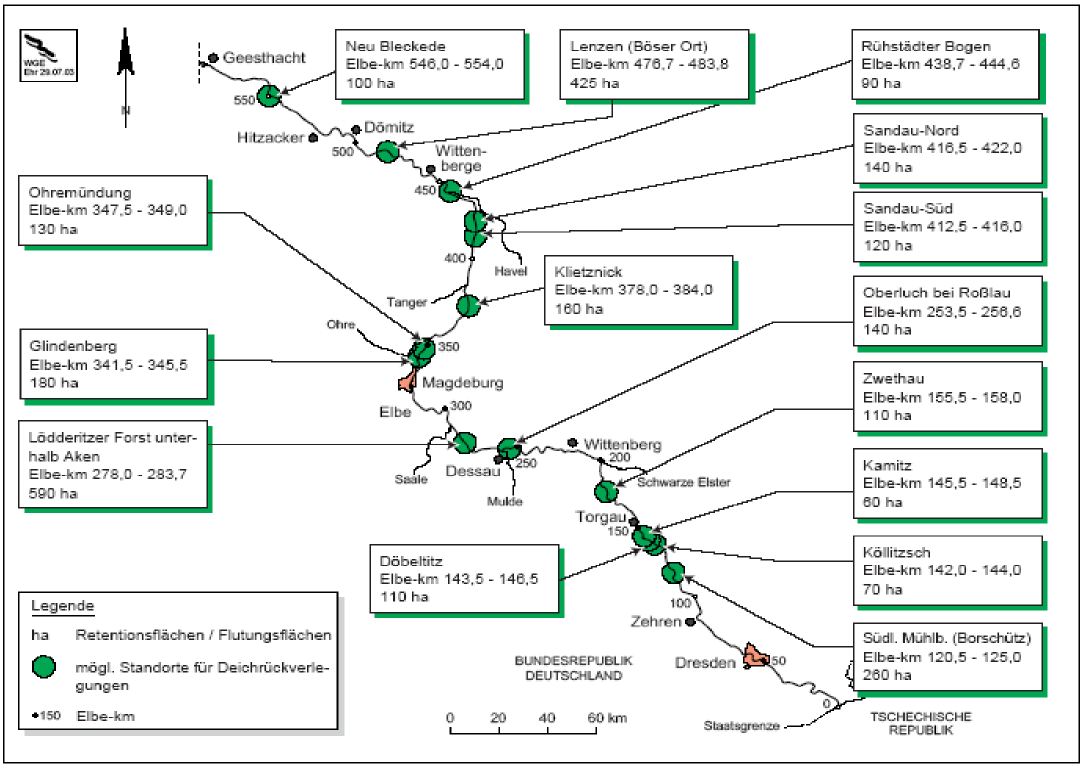


Figure 1.6 *Possible locations for dyke enlargements along the German Elbe [Action Plan for Flood Protection Elbe – ICPER, 2003]*

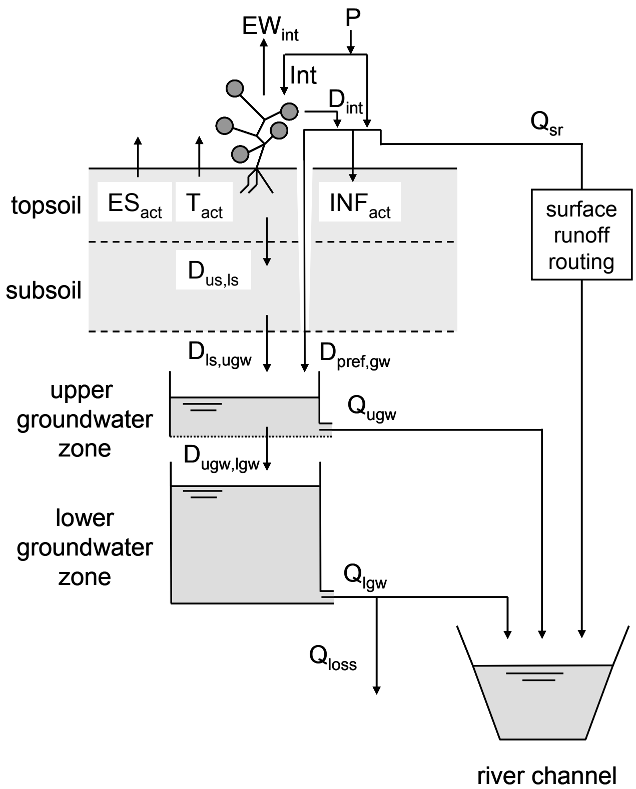
During discussions and meetings in later stages of these two studies, the list of polders and dyke-shifts has been updated (see Chapter 7).

2. The LISFLOOD modelling system

2.1 The processes simulated in LISFLOOD

The hydrological model LISFLOOD has been developed explicitly for the simulation of floods in large European drainage basins. LISFLOOD is a spatially distributed combined rainfall-runoff and 1-dimensional hydrodynamic model. It is capable of simulating large river basins, while still maintaining a relatively high spatial resolution, advanced flood routing methods and as much as possible physical process descriptions. The model theory is described in detail in various publications from De Roo [*De Roo,* 1999; *De Roo et al.*, 2000; *De Roo,* 2001]. The description of the present version can be found in Van der Knijff et al. (2006). Here only basic model processes are summarised to give a main overview.

LISFLOOD is embedded in the PCRaster GIS [*Wesseling et al.*, 1995] and is using readily available European datasets, such as Corine Land Cover [*EC*, 1993] and the European Soils Database [*King et al.*, 1995 and *Heineke et al.*, 1998]. LISFLOOD *(Figure 2.1)* takes into account the hydrological processes at the surface, in the soil, and in the river channel network on a regular horizontal grid. Basically, a total of four different layers are considered: two soil layers and two groundwater layers. For each grid point a value is calculated at every time step.



Abbreviations:
P = precipitation; Int = interception;
EW_{int} = evaporation of intercepted water;
D_{int} = leaf drainage;
ES_{act} = evaporation from soil surface;
T_{act} = transpiration (water uptake by plant roots);
INF_{act} = infiltration;
Q_{rs} = surface runoff;
$D_{us,ls}$ = drainage from upper to lower soil zone;
$D_{ls,ugw}$ = drainage from lower soil zone to upper groundwater zone;
$D_{pref,gw}$ = preferential flow to upper groundwater zone;
$D_{ugw,lgw}$ = drainage from upper to lower groundwater zone;
Q_{ugw} = outflow from upper groundwater zone;
Q_{lgw} = outflow from lower groundwater zone;
Q_{loss} = loss from lower groundwater zone. Note that snowmelt is not included in the Figure, even though it is simulated by the model).

Figure 2.1 *Schematic overview of the LISFLOOD Model*

Processes simulated are interception, soil freezing, snowmelt, evapotranspiration, infiltration, preferential flow, percolation, groundwater flow and surface runoff. Overland flow is simulated using a kinematic wave approximation.

Channel flow is simulated using either a kinematic wave for upstream rivers or using dynamic wave approximation for low gradient river sections, depending on river channel bed gradient and the occurrence of backwater effects. The cross section of the river and associated floodplain is taken into account by using series of water-level, wetted perimeter, and hydraulic radius values for locations for which river geometry is available. The user can define which sections of the river to simulate with a kinematic wave, and which sections with a dynamic wave. The current implementation of the dynamic wave function in PCRaster is a partially dynamic wave formulation according to the Saint Venant equations described in Chow (1988). The implementation consists of the friction force term, the gravity force term and the pressure force term. Actually, it should be characterised as a diffusion wave formulation. The equations are solved as an explicit, finite forward difference scheme. A straightforward iteration using an Euler solution scheme is used to solve these equations.

The user also can choose both the spatial and temporal resolution of the model. The grid-size used for the Elbe river basin is 1x1km, whereas the time-step is 1 hr for the flood and scenario simulations, and 1 day for water balance and initial conditions simulations. LISFLOOD can operate as a water balance model with a daily time step and as a flood simulation model with an hourly time step. The results of the daily water balance run can be either stand alone or serve to provide the initial conditions for the flood simulation model in an hourly time step.

Particular structures such as water reservoirs and retention polders can be simulated by taking their location, various storage capacities (conservative, normal, flood and total storage volume), outflow boundary conditions (minimum, normal, non-damaging, flood and spill-way outflow) and reservoir or polder steering rules, respectively.

2.2 Simulating reservoirs

Within the model the locations of water reservoirs are considered as points with given various storage capacities (conservative, normal, flood and total storage volume), outflow boundary conditions (minimum, normal, non-damaging, flood and spill-way outflow) as well as reservoir steering rules. Depending on the fraction of the reservoir filled, the calculated outflow is based on user defined minimum, normal and non-damaging outflow in m^3/s.

2.3 Simulating polders

Like reservoirs also polders are treated as points with a user defined storage capacity. In case the water level of the river reaches a user-defined threshold, the polder starts to be active until it is filled. If the river water level decreases to a user-defined level, the polder then empties gradually. A more detailed description is given in the chapter on polder scenarios (Chapter 7).

2.4 Model INPUT data

The main inputs to the model are meteorological data which can be given as point data from meteorological gauging stations or as grid data, e.g. from radar measurements. Other input data needed are topography (elevation), slope gradient, land use type and cover, total soil depth, soil texture (upper layer and lower layer), and rooting depth. Moreover, the river network, river gradient, river geometry (cross sections) as well as the river roughness (manning coefficient) are needed for simulations. In general it is observed that the better the quality and density of the input data the better the obtained results.

2.5 Model OUTPUT data

The LISFLOOD model output can be any internal variable calculated by the model, either as time-series, summary maps or as stacked maps. Examples of outputs are discharge hydrographs, water level graphs user-defined locations, graphs of the reservoir filling & outflow, soil moisture at user-defined locations. Summary maps of precipitation, temperature, evapotranspiration, groundwater recharge can be generated, as well as a timeserie stack of soil moisture maps.

2.6 Model limitations

Hydrological models are developed for specific purposes and scales. LISFLOOD is developed for simulating medium and large river basins. Good results are obtained in basins of a few thousand km^2 until the size of the entire Danube basin. However, the grid size should correspond to the data availability. The model runs either with a daily or an hourly time step.

Since a one-dimensional dynamic wave approach is used in the channel calculations, waterlevel simulations may be less accurate than the discharge simulations. If detailed and accurate waterlevel simulations are aimed for, other river routing models such as Sobek, Mike21 or Wavos should be selected. Examples of linking LISFLOOD and Wavos are carried out in other projects (Elbe-VERIS).

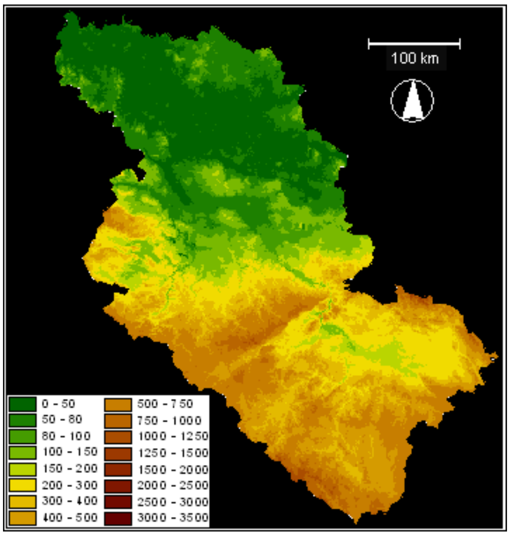
A major limitation for obtaining good and accurate results is often the data availability, for example the number and distribution of meteorological stations. Hourly data are ideally needed for simulating flood events, but often not available. Furthermore, the number and quality of river cross section data is essential for using the dynamic wave approach and obtain accurate water levels. Detailed data for reservoirs and polders are needed as well.

3. Data used in the study

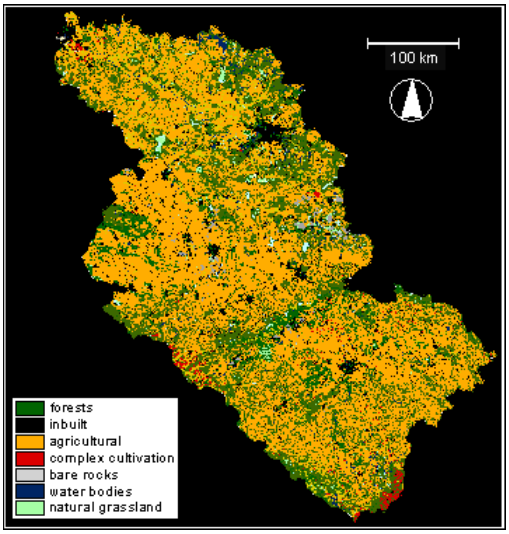
3.1 European data base

Physically-based spatially distributed models require a vast amount of data to represent the spatial distribution of meteorological and hydrological characteristics in large river basins. A rigorous parameterisation procedure is crucial to avoid methodological problems during model calibration. Spatial patterns of the parameter values have to be specified so that parameters reflect only significant and systematic spatial variations inherent in the available data. As such, the parameterisation process can effectively reduce the number of free parameters to be adjusted during calibration [*Refsgaard*, 1997]. The relevant spatial parameters needed for flood simulation modelling at European scale are: meteorological data, topography, soil data, land use data, river cross sections, reservoirs, lakes and if relevant retention areas. River discharge stations are needed for calibration and validation

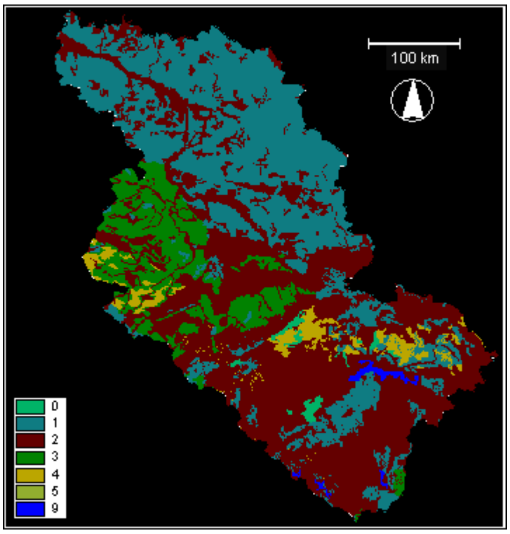
To avoid problems of over-parameterisation and to reduce the dimensionality of the model calibration, input parameters and variables of LISFLOOD are estimated a priori from available data bases as much as possible. For example, soil physical properties are derived from the European Soil Geographical Database [*King et al*., 1994]. The HYPRES database [*Wösten et al*., 1999] is used to estimate porosity, saturated hydraulic conductivity and moisture retention properties for each texture class. Vegetation and land use information are obtained from the CORINE land cover database [*EEA*, 2000]. Digital elevation data are obtained from the Catchment Information System, which has a spatial resolution of 1 km [*Hiederer and De Roo*, 2003]. Meteorological parameters are typically derived from high resolution networks of station observations where available. For areas, which are not sufficiently covered by high resolution observations, missing meteorological parameters are extracted from the **M**eteorological **A**rchiving and **R**etrieving **S**ystem **MARS** Meteorological Database [*EC*, 1998].



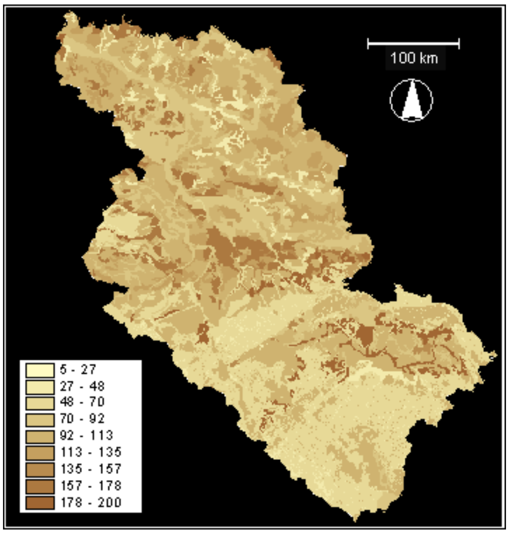
Elevation



Land use



Soil texture



Soil depth

Figure 3.1.1 Used GIS maps of the European data base for the Elbe River Basin

3.2 Gathering of national data

Since the beginning of 2003 the JRC has contacted the responsible Meteorological Services as well as Water Authorities of Germany and the Czech Republic in order to obtain necessary high resolution national data for the model calibration and validation as well as for the planned scenario analysis in the framework of the Working Group "Flood Protection" of the International Commission for the Protection of the Elbe River (ICPER). Such data are: historical high resolution precipitation and temperature data, hydrological data (observed daily and/or hourly discharge and water level data), river-geometry data (i.e. high resolution cross sections data), data about reservoirs and retention polders (steering rules, inflow/outflow data). Furthermore, the JRC has also obtained data about large lakes, because of the possible buffer function, and river bed enlargement information, i.e. planned dyke movements or floodplain enlargements, which are needed for the two studies which have to be carried out for the ICPER.

The JRC has gathered all data over a period of more than two years, between 2003 and 2005. The data collection by JRC has been stopped in April 2005. In case necessary model input data were not available or not provided, estimations were made by the JRC.

3.3 Summary of data availability

The following table *(Table 3.3.1)* presents the number of available station data for the whole Elbe catchment in summarized overview.

Type of data	Germany number	Czech Republic number	Comments
Stations			
Precipitation	713	492	National data set
Temperature	139	157	National data set
Potential Evapotranspiration	65	30	MARS
Actual Evapotranspiration	0	0	MARS
Discharge (daily)	42	31	National data set
Discharge (hourly	22	31	National data set
Water Stage (daily)	21	0	National data set
Water Stage (hourly)	33	0	National data set
Cross Sections			
- Elbe	4278	-	National data set
- Saale	2207	-	National data set
- Havel	667	-	National data set
- Mulde	385	-	National data set
- Bode	500	-	National data set
Reservoirs	28	-	National data set
Polders	7	-	National data set
Dyke Breaks	22	-	National data set
Dyke Enlargement	(1)	-	National data set
Flood plains	from 3 German states	-	National data set
Lakes	from1 German states	-	National data set
Geology	from 4 German states	-	National data set
Soil	from 4 German states	-	National data set
Hydrogeology	from 4 German states	-	National data set

Table 3.3.1 *Available data within the Elbe River Basin - Germany and Czech Republic*

The following maps *(Figure 3.3.1 - 3.3.5)* show the spatial distribution of available data sets within the Elbe River basin.

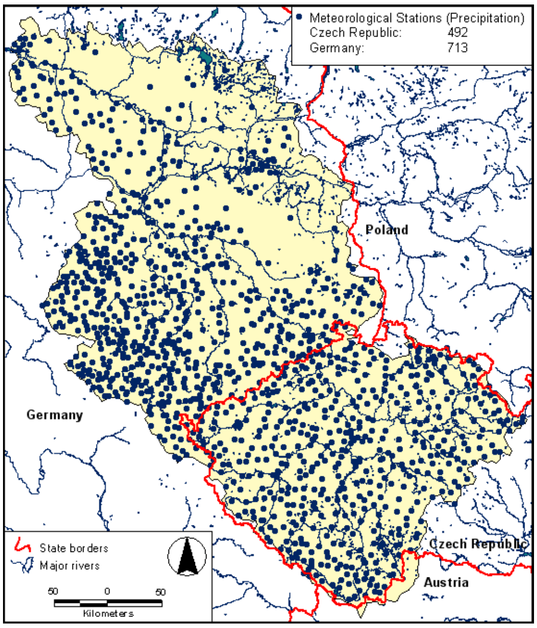


Figure 3.3.1 Available meteorological stations with precipitation data within the Elbe River Basin

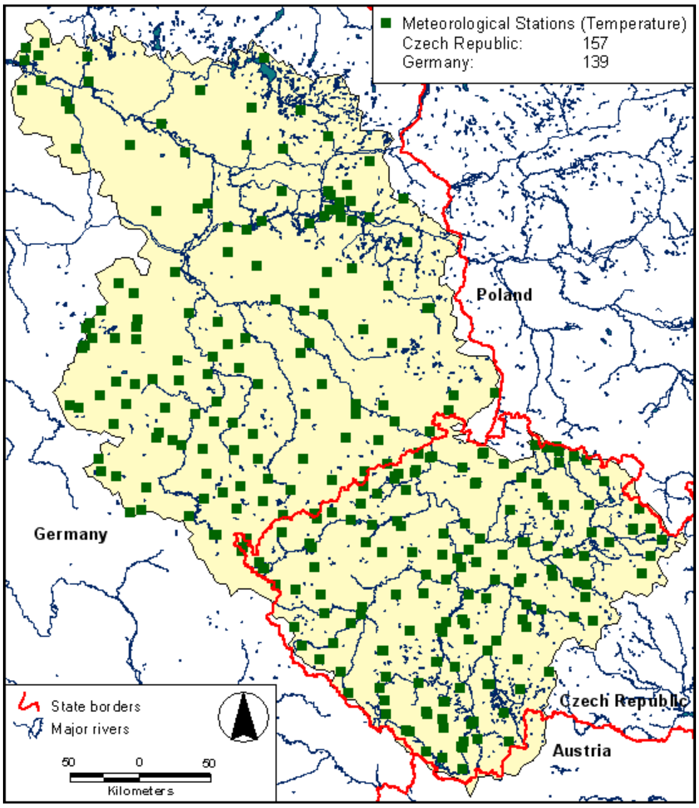


Figure 3.3.2 *Available meteorological stations with temperature data within the Elbe River Basin*

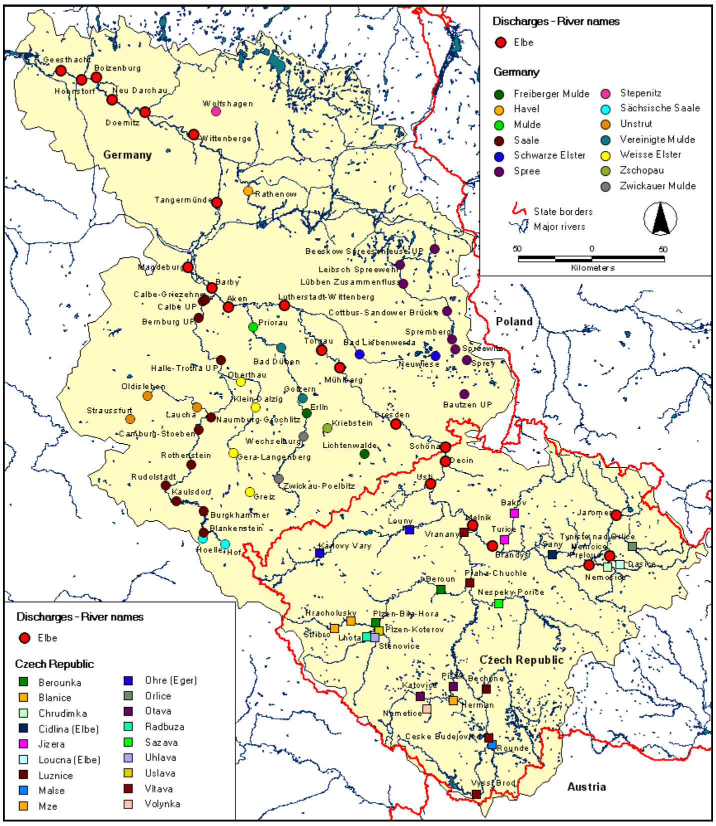


Figure 3.3.3 *Available stream gauging stations with observed discharge and measured water level data for the time period 1993/1994 until 2002/2003 in the Elbe catchment*

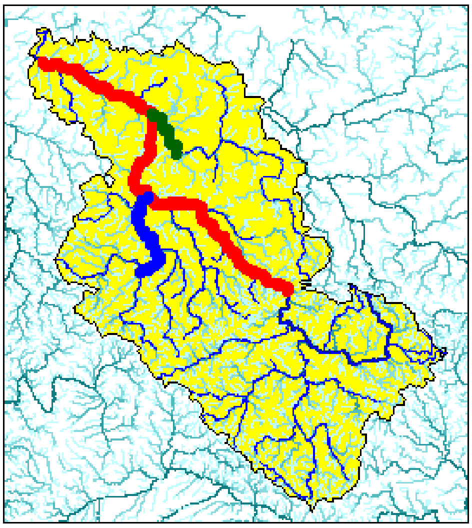


Figure 3.3.4 Elbe River cross section data

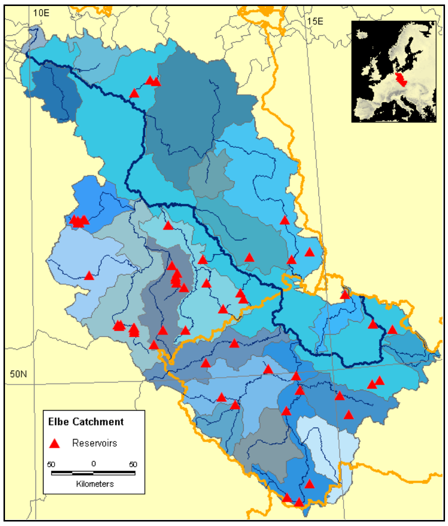


Figure 3.3.5 Reservoirs within the Elbe river basin

In Figures 3.3.6 up to 3.3.13 samples of different data sets and their editing are shown.

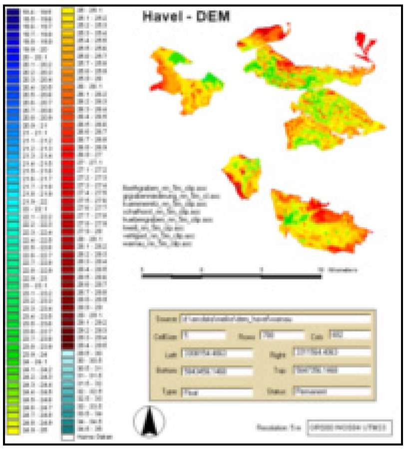


Figure 3.3.6 Visualisation of a high resolution DEM for the Havel River (Brandenburg)

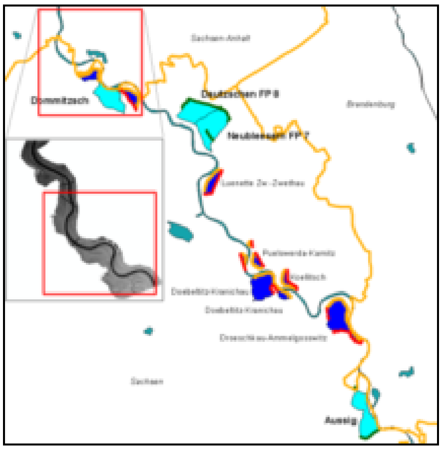


Figure 3.3.7 Visualisation of potential retention polder (Saxony)

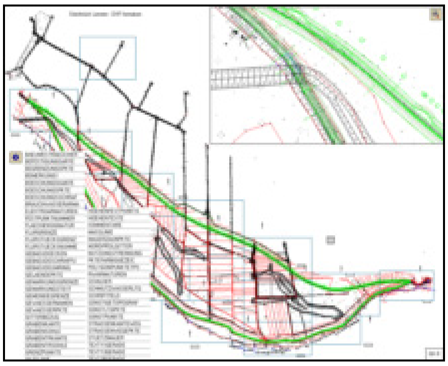


Figure 3.3.8 Visualisation of the dyke enlargement at Lenzen (Brandenburg)

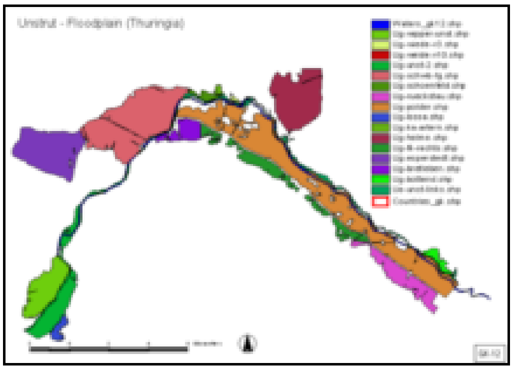


Figure 3.3.9 Visualisation of flood plains at the Unstrut River (Thuringia)

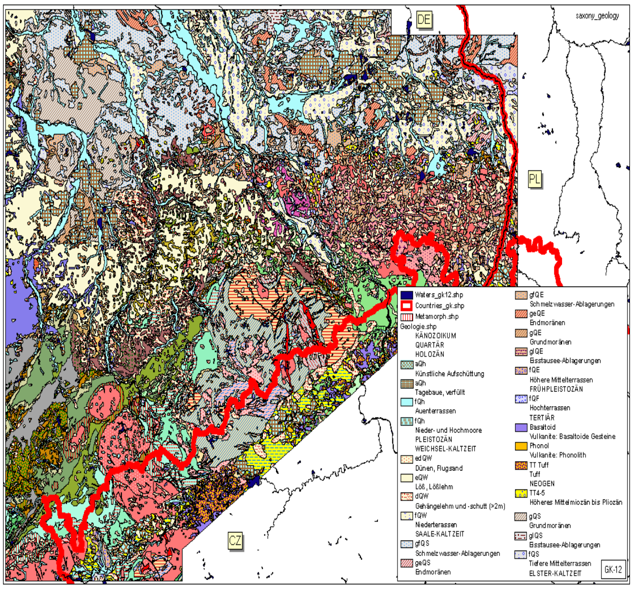


Figure 3.3.10 Visualisation of geological data (Saxony)

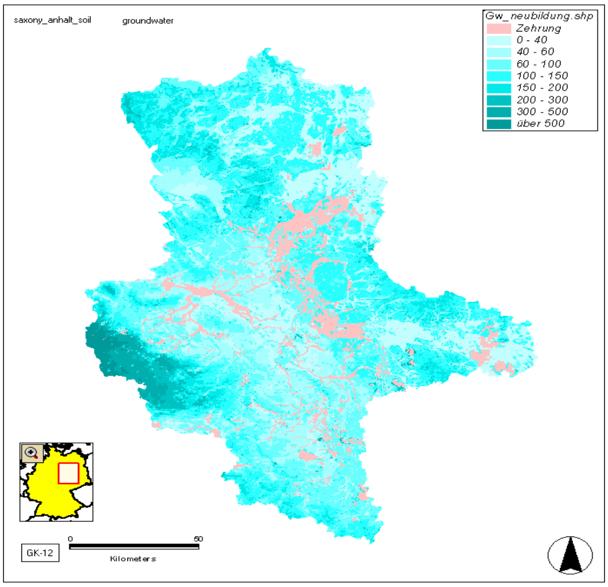


Figure 3.3.11 Visualisation of groundwater recharge (Saxony-Anhalt)

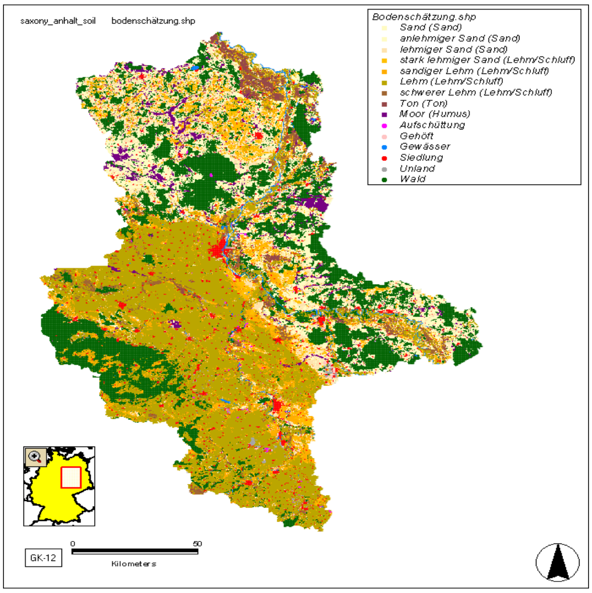


Figure 3.3.12 Visualisation of soil data (Saxony-Anhalt)

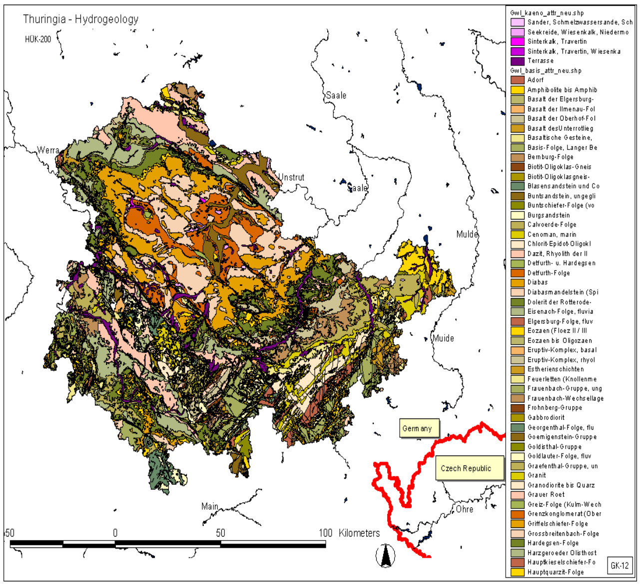


Figure 3.3.13 Visualisation of hydrogeology (Thuringia)

4. Data preparation and pre-processing of high resolution national data

4.1 Integration of georeference systems

The majority of hydrological and meteorological phenomena is spatial related i.e. data are given by their geographical location (gauging stations, polders, reservoirs, cross-section geometry). The additional descriptive geographical datasets, like topographical relations, land use, soils, river network, etc. have spatial attributes as well, which are usually given by precisely-defined parameters of projection and coordinate systems.

Since our modelled area extends over several administrative regions and countries it was required to specify a common reference system, which is also corresponding to the European standards [*A. Annoni et al.*, 2001].

Based on available data and map projections at JRC, the so-called GISCO Lambert Azimuthal Equal Area Coordinate Reference System [*GISCO*, 2001] has been selected as a common reference system *(Table 4.1.1).*

Table 4.1.1 The parameters of GISCO Lambert Azimuthal Equal Area (LAEA) system

```
/* GISCO Lambert Azimuthal Equal-Area (LAEA), 09,48,6378388,sphere

projection lambert_azimuthal  /* Lambert Azimuthal Equal-Area, Zenithal Equal-Area
units meters                  /* Units of the coordinates
spheroid sphere               /* Reference-surface is a sphere
parameters
6378388              /* Radius of reference sphere
009 00 00            /* Longitude of centre of projection
048 00 00            /* Latitude of centre of projection
0                    /* False easting
0                    /* False northing
```

The original reference systems of the collected data were very different since they arrived in national reference grid systems provided by the responsible national institute. In a few cases we had technical difficulties, because the meta-data of the delivered data was not sufficient or was missing.

The most usual input formats were the meter-based Transverse Mercator projection on Bessel or Krasovsky ellipsoid with different central meridians and false easting according to the geographical location or geographic coordinates given in decimal degrees or degrees, minutes and seconds on WGS 1984 ellipsoid and “datum”.

All the incoming data were transformed into GISCO LAEA applying projection scripts of Arc/Info Workstation 9.1.

4.1.1 Gauging stations

The master data containing geographical locations of incoming data records arrived in various file formats, mostly in tabularized structure and numerous projection systems as mentioned above. After the necessary coordinate transformations the hydrological and meteorological gauging stations are defined as point data in GIS layers (ArcGIS shape). Every object has a unique ID which is the key to the corresponding data records.

4.1.2 Reservoirs

The spatial attributes of reservoirs arrived as a point and polygon GIS layers in national projection systems. Due to the coordinate transformation method the area of the original shapes could be kept in the results. The bordering dams were on separated GIS layers as line objects with some essential descriptive attributes. Based on a quick analysis we could see that the numerical attributes like “length” of the constructions were not inserted as a technical parameter but were calculated only based on the digital object of the shape file. To accept these values we had to assume that they were digitized extremely accurately.

4.1.3 Cross sections

The purpose of using cross-section data is to acquire more detailed information about the riverbeds and its corresponding discharge properties.

4.1.3.1 General characteristics of the source data

The incoming cross-section data formats were various, the location information as well as the descriptive geometrical data. After the preparation we could distinguish between two main types of sources:

a) Separated location file(s) and corresponding data file(s) by cross-sections

In these types of data the link between the location and the attribute information was given in very different ways (similar or same file names, corresponding registry in the data file referring to the location file, an ID number or codes, river kilometres, etc.) There were two main methods for description of the profile geometry: coordinates for each point or distances from the appointed starting point (zero point) of the profile. The situation was not clearer in the case of geographical reference systems. The original coordinate system was not always given, or it was confusing. One data provider used different systems (sometimes the same coordinate systems, but a different ellipsoid) even within the same dataset without further information *(Figure 4.1.1).*

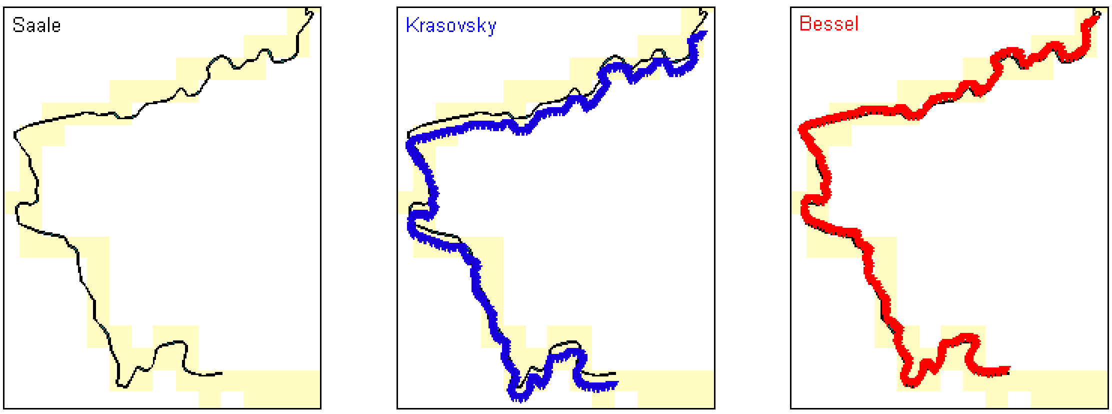


Figure 4.1.1 Result of application of a not properly defined base-ellipsoid

b) List of all the points with coordinates

In these types of data every point was responsible for the shape of the profile. There were no appointed zero-points defined, but since we needed one for calculation the distances between the points we agreed to select the most left point of each profile.
There was one advantage of this data structure: since the points were stored in tables the numerous mistyping or data duplication were discovered easily. Since for the data preparation and integration we used GIS applications there was an excellent visual possibility (maps) to observe geometrical errors that would had been very difficult using only numerical methods.

4.1.3.2 Geometrical inconsistency

GIS datasets were created from the processed cross-section points. These maps provided a quality overview of the source data as well. Some examples *(Figures 4.1.2)* of the occurred geometrical problems:

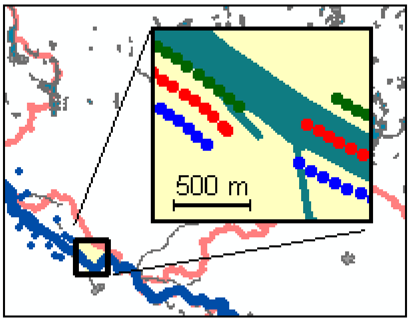


Figure 4.1.2a
Elbe
The same river, same institute.
The most left, most right and middle points are given.
The two adjacent segments are shifted.

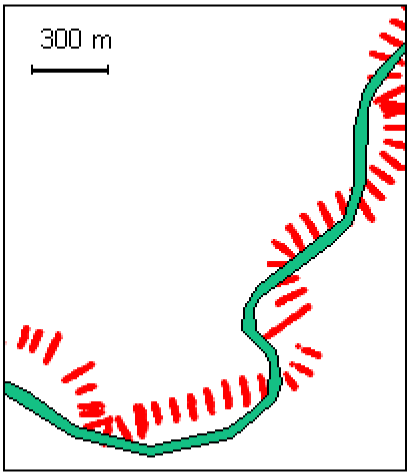


Figure 4.1.2b
Saale, Saxony-Anhalt
All the cross-sections points are given by coordinates.
The pattern of points departs from the reference river map.

4.1.3.3 Definition of a matrix of selected rivers

In order to insert the high resolution (sequential sampling distance is 100 m, within a profile 1-2 m) cross-section information into the model river network (1 km grid) we had to elaborate a projection algorithm between the cross-section points and the cell-based river network.

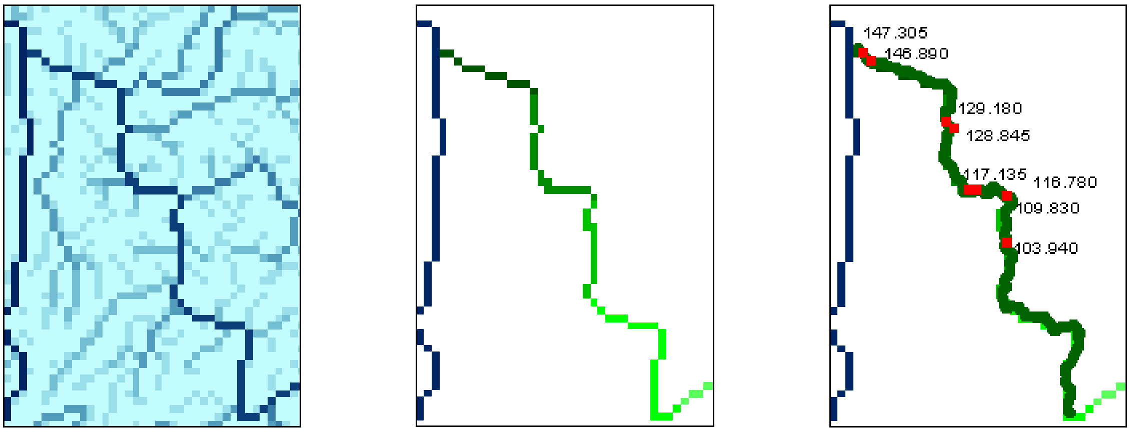
Each profile shaped by cross-section points should belong to one pixel, but since the model river is not exactly overlapping the course of cross-sections and the river lengths could not be the same in the modelled and the real network the applied projection is not linear along the entire river. For the more realistic operation we split the rivers into segments defining a few fix points based on those discharge gauging stations where the LEAE coordinates were known and their position in river kilometres were given too.

For the preparation of assignment process three matrixes of selected rivers (Elbe, Saale, Havel) network were created by the followings:

Inputs:
ups_elbe.map – the cells contain the upstream area cell by cell
ldd_elbe.map – deterministic 8 (D8) flow direction

1) The cell-based values of upstream area can be used as an identifier of each pixel, since it should be unique within one river, so the IDs of each pixel of rivers were derived from the map of upstream areas.
2) The Strahler order values help to separate the main river segments from side flows and tributaries (Elbe is order 8; Havel and Saale are order 7).

3) A polygon shape was defined as a convex hull of the river segments having cross-section information (analysis extent).
4) A raster mask containing only the selected river segments was derived based on corresponding Strahler order and the analysis extent.
5) The reference points were based on gauging stations with known coordinates in the model river network and their real position given by river kilometres as well.
6) Map algebra calculation was applied for assignment the unique IDs of river cells to the corresponding reference points (Figure 5.1.3).
7) The result is a matrix containing the unique IDs of pixels AND the fixed positions of known river length.



Map of Strahler order | Unique IDs of pixels derived from upstream area | Corresponding river kilometres

Figure 4.1.3 *Preparation of assignment process between cross-sections and river network*

The pre-processing provided a matrix containing the unique ID of each pixel, the coordinates, another key value derived from the pair of coordinates and the corresponding river kilometres where they were available.

4.1.3.4 Development of an allocator routine

For the purpose of precise assignment between the cross-section points and the river pixels a script had been written in an interpreted, interactive, object-oriented programming language (Python) using the content of the matrix as input variables. Applying the river kilometres in the cross section files, which are always available and the reference points of those stations that are already mapped into the river network, it is possible to calculate approximately the limits of each pixel.

The elaborated script determines the distances in kilometres between each pair of nearest reference points and calculates the number of pixels between them. In the next step the script computes the theoretical river length in kilometre that belongs to each pixel. In this way the river segments together the set of cross-sections that belong to a pixel can be defined.

4.2 Improving static data in the European Data Base using global and national information

New sources of different topographic information (high resolution Digital Elevation Model, processed cross-section data, Image2000 dataset, corrected vector maps of European rivers) gave the possibility to improve the static basic inputs applied by the LISFLOOD model.

4.2.1 Digital Elevation Model

In the previous phases of the project the GTOPO30-based [1] global digital elevation model (DEM) was processed (projection, resampling to 1km and 5 km resolutions) and expanded by available higher resolution DEMs from a few regions of Europe. This dataset contained visible errors and artifacts (e.g.: edges of maps, terrain stairs) but it provided a more or less uniform coverage of the continent. This topographical basic data was changed to an SRTM-based DEM [2] that was prepared (format conversion, void filling, projection, resampling) within the Institute for Environment and Sustainability of the Joint Research Centre.

4.2.2 Updating of the gradient map

The previously applied surface gradient map inherited the errors from the source GTOPO30 DEM. In spite of the gradient values of some areas were replaced by gradient values based on the more precise national data *(Figure 4.2.1)* it did not provide a consistent European coverage.

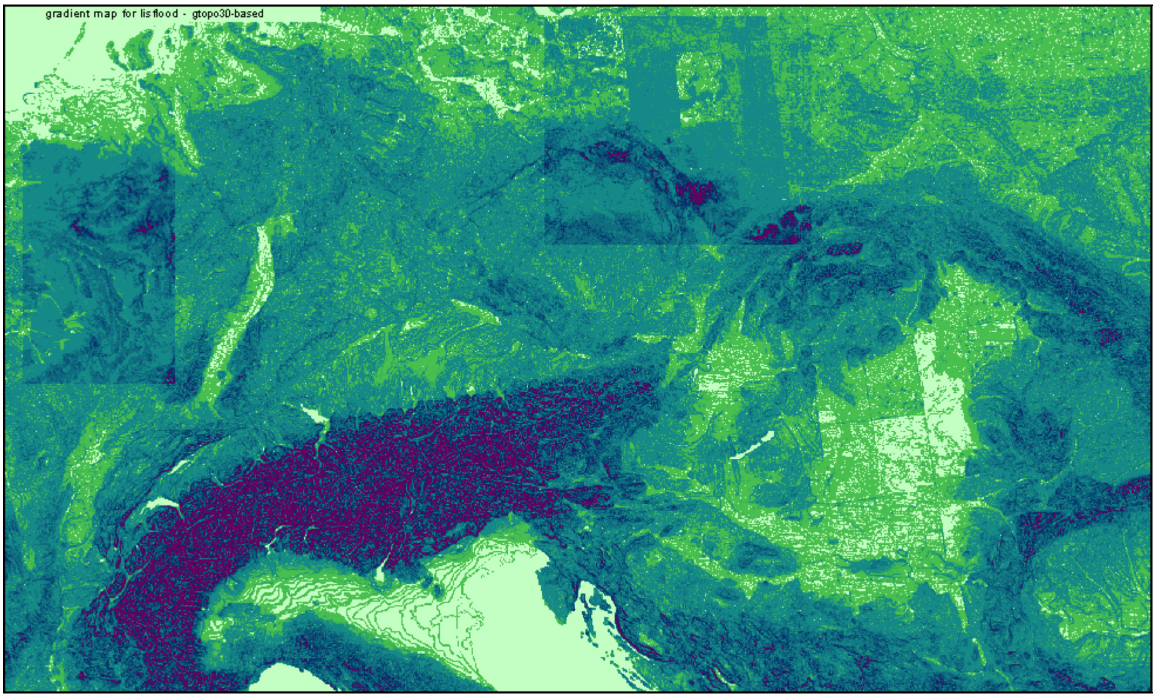


Figure 4.2.1 *The previously applied surface gradient map as a derivative of GTOPO30 and national DEMs*

In a later stage the gradient map was based on the 100 m Digital Elevation Model which was derived from the SRTM (Shuttle Radar Topography Mission) [1] data. The preprocessing (filling voids and missing values, projection, re-sampling, coastline correction, etc.) of the raw SRTM grids was done in the second term of the Catchment Characterisation and Modelling (CCM) project (Vogt, 2003).

The new gradient map was done in two main phases with several steps in each:

a) Channel gradient map based on the model river network and drainage directions

The river network and the related local drainage direction (LDD) maps are significant components of the input data of hydrological modelling. Since the current model river network (in 1 km and 5 km resolution) applied by the LISFLOOD model is independent of the topographic data – consequently the river pixels are not necessarily at the bottom of the valleys – it was not possible to calculate the new channel gradient values of river pixels using only neighbourhood operators or inbuilt GIS functions on the elevation model.

Assuming that the riverbeds are located at the bottom of the valleys following the lowest points of their closer surroundings the elevations of starting (upstream, highest) and ending (downstream, lowest) points were computed for each river segment based on the local minimum values (aggregate function, the searching block was 1 and 5 square kilometre) of the nodes (sources and inflows).

Technical comments: Section identification and node selection
Based on the river network and the related flow direction maps a unique ID can be assigned to each section of a raster linear network between intersections (from-points, to-points). The STREAMLINK (<net_grid>, <dir_grid>) function can be applied within the Arc/Info Grid module, where the <net_grid> is the grid representing a raster linear network and the <dir_grid> is the one showing direction of flow out of each cell. Since the structure of the network (nodes and edges in between, no loops) is a directed acyclic graph the from-points can be selected by the lowest upstream area (UPS) values within one river section and similarly the inflow points downstream have the highest UPS value within a section.

Linear interpolation has been done within the river sections between the elevation values of nodes *(Figure 4.2.2).* The result is the calculated ideal elevation model of the channel network where the pixels with greater UPS have lower or equal altitude within one segment, the river is consistently descending.

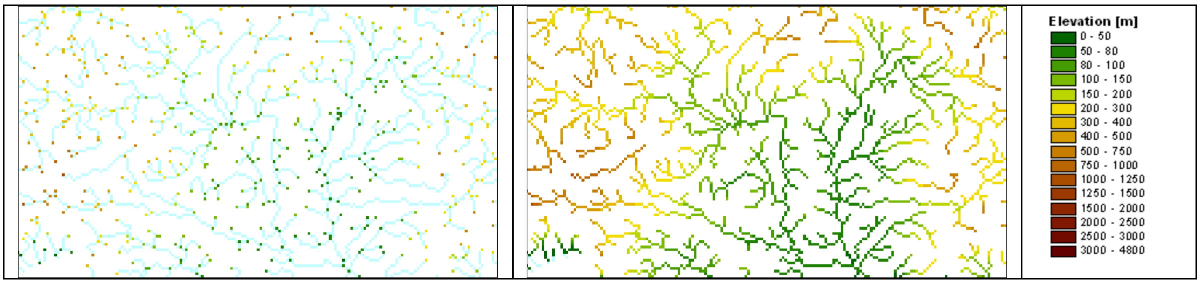
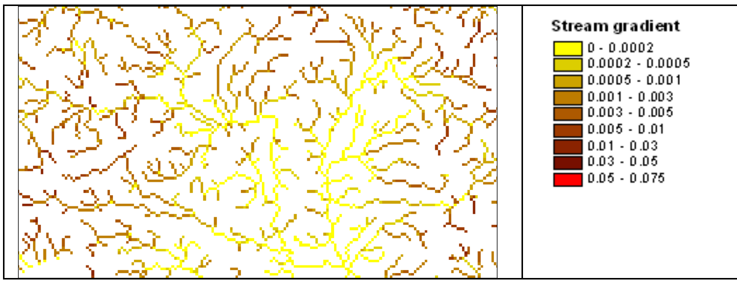


***Figure 4.2.2** Nodes of river network with associated elevation values and interpolated channel elevation model*

Since the general slope functions apply a third-order finite difference method based on the 3x3 neighbourhood using the average maximum technique they are not suitable in a situation where only the upstream and downstream values are available (1Dimension). In order to calculate the gradient the whole system was shifted with one cell-value downstream along the LDD, so the cells got the value of the adjacent downstream cell. The simple difference of the interpolated and shifted channel DEM results a map containing the differences in elevation between the neighbouring channel pixels.
In the next step the flow length was calculated based on LDD. The flow length in the orthogonal directions was equal to the cell size (1000 and 5000 metres), and in the diagonal directions was equal to the diagonal of the cell (sqrt2 * cell size, 1414.2135 and 7071.0678 metres). This geometrical estimation of the river length can be modified using the methods explained in the chapter 4.2.3.

The channel gradient can be calculated using the two right-angle sides of the slope:
Stream gradient = TANGENT of the slope angle = (Grid with differences in elevation) / (Grid with flow length)

The result map contains the calculated stream gradient values *(Figure 4.2.3)* based on the elevation model.



This SRTM-based general map was refined by additional information from national hydrological institutes. The gradient values of Danube River were corrected based on descriptive data from the responsible national water authorities.

Figure 4.2.3 *Stream gradient map*

The German part of the main Elbe River was corrected by the provided cross-section data. Since the density of cross-sections is higher (about 100 m) than the resolution of the raster river network (1 and 5 km) in this case the average value of the absolute minimum altitudes within one pixel provided the input data for the gradient calculation. The cross-section data gives the most detailed description of the riverbed geometry and the phenomenon (absolute minimum altitude of a point upstream is lower than downstream) mentioned above was eliminated by averaging longer distances and the differences were smoothed by this operation.

An experimental comparison between the surveyed and processed national cross-section data and the generally applied SRTM-based digital elevation model also has been done. There is an obvious absolute difference between the surveyed mean of bottom values and the remote sensed surface DEM. The relative differences in elevation and the derived gradient values are close to those values that are acceptable by experts. In general the new gradient map has one magnitude order smaller values than the previous map.

b) Surface gradient map based on SRTM100

The data processing (resampling the 100 m DEM to 1km and 5 km) for the new surface gradient maps were similar to the channel gradient maps assuming that the drainage network are located at the bottom of the valleys and the drainage direction follows the highest gradient. The minimum value of the blocks (1km, 5 km) were taken into consideration and the slope was calculated as the angle of the best plane of curvature defined by the 3x3 neighbourhood. The cell-values of the channel pixels were changes to the stream gradient values *(Figure 4.2.4)*.

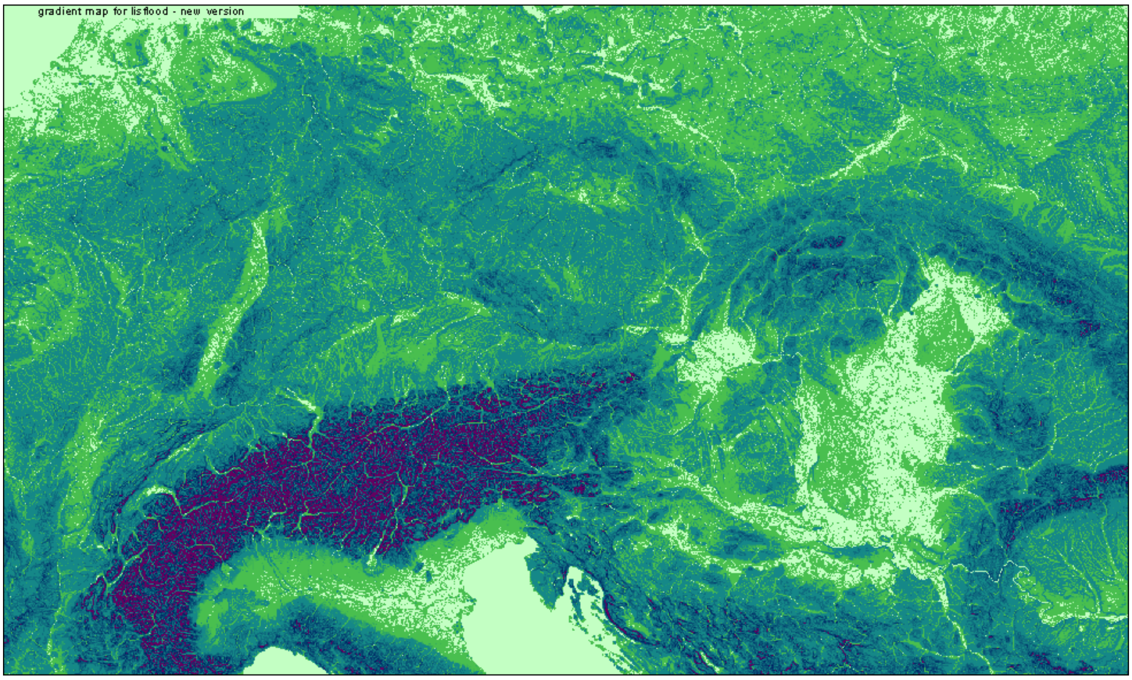
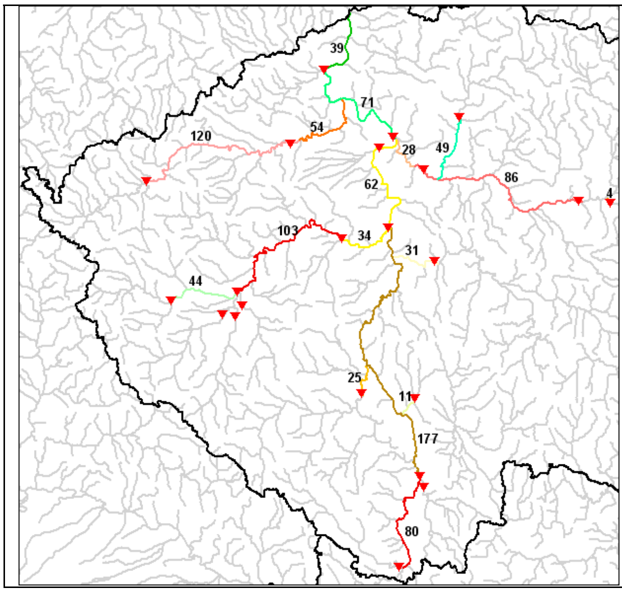


Figure 4.2.4 *The surface gradient map derived from the SRTM100 DEM integrated with national data sources.*

4.2.3 Channel length maps

In the 1 km resolution the Elbe setup, the user can define the actual river channel length, which in reality will be typically larger than 1000m. From national data sources, vector-based river data and coordinates of gauging stations enabled to make a reasonable estimate of actual channel length. The calculations were based on known river kilometres (Danube and Elbe Basin) and vector data from the Catchment-based Information System (CIS) dataset (Hiederer and de Roo, 2003).



The 1 km dataset was upgraded first. In the case of the Danube Basin and the Czech part of the Elbe Catchment the location of sufficient gauging stations were defined by two reference systems; they were given in geographic coordinates and in river kilometres (figure 5.2.5). Length of river sections between the gauging stations were calculated based on the river kilometre distances and the rounded integer values were assigned to each river section as an attribute data. This calculated distance was divided by the number of river pixels belonging to each section.

In the case of the German part of the Elbe the dense cross-section data provided the information to the calculations.

Figure 4.2.5 *Applied gauging stations in the Czech Elbe basin*

Simple statistical comparison showed that the distances based on surveying (river kilometres) were averagely 8 % longer than the geometrical length of the necessarily generalized vector river sections. Using this information all the other river pixels of the 1 km network were changed.

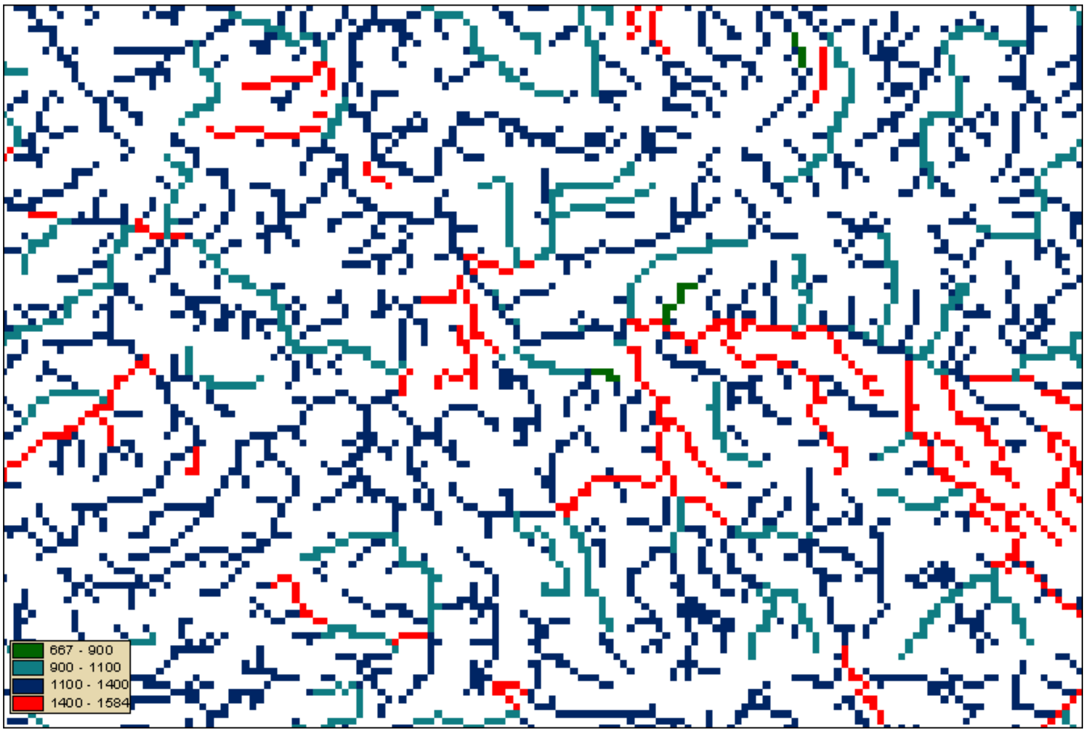


Figure 4.2.6 The new calculation of river length shows spatial diversity (the dimension of the legend is meter)

The range of the new channel length cell-values is between 667 and 1584 metres.

4.2.4 Channel width, depth and Manning maps

Estimates of channel width, depth and Manning values were obtained from available river cross sections, Image2000 satellite images *(Figure 4.2.10)* and tables from scientific literature.

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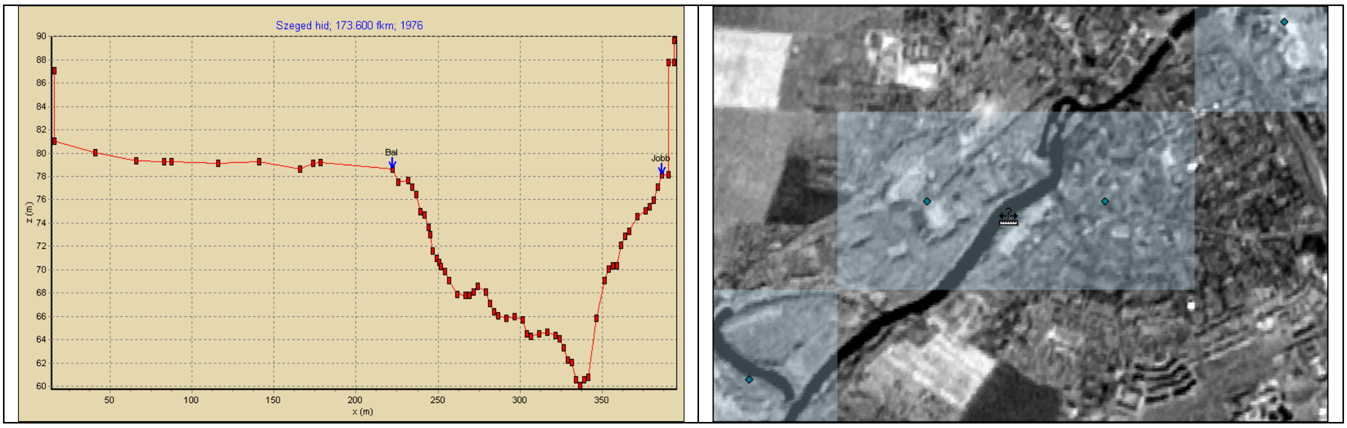


Figure 4.2.10 *Estimating channel width value based on cross-sections (Tisza River) and Image2000 (Saale)*

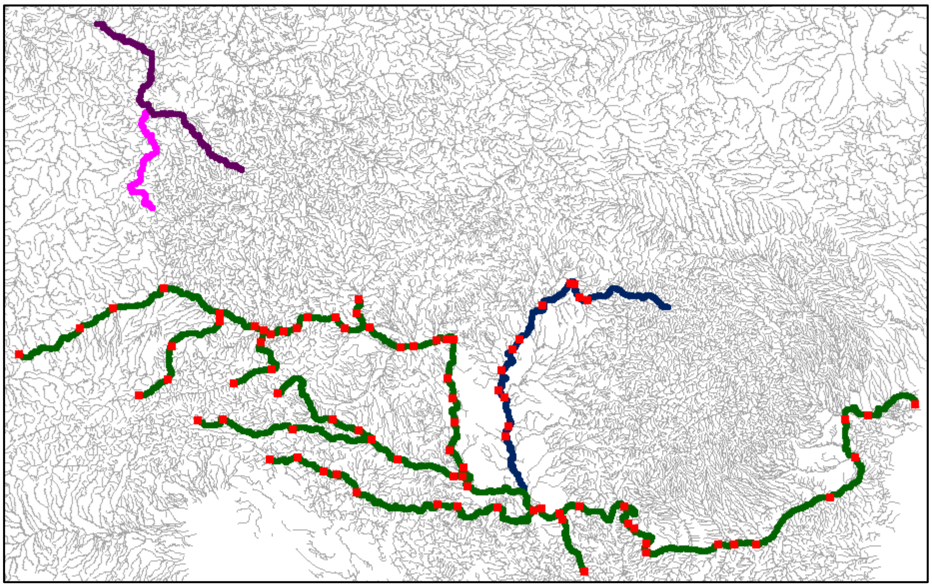
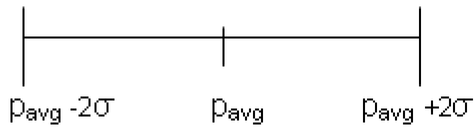


Figure 4.2.11 Channel width values obtained from cross sections and Image2000 analysis along the main rivers in the Danube and German Elbe.

4.3 Precipitation data-checking and filtering

Since precipitation is the most important input to any hydrological model, the precipitation data received have been carefully pre-processed, before being submitted to the modelling system. A filtering of the time series has to be performed prior to the spatial interpolation of the station data, in order to identify anomalies in the received precipitation data. For filtering the anomalous values of precipitation data two parameters have been calculated: the precipitation average of the 5 nearest neighbour stations and the standard deviation (σ) for each of these stations.

The heuristic idea is to calculate the σ and duplicate its value. If the value is out of the range of p_{avg}±2σ then the precipitation value for the station is recommended to be checked.



4.4.0 Pre-processing of meteorological data

The key input for any hydrological model is the meteorological data set since it mainly determines the volume of runoff in a catchment. Accurate rainfall and temperature input data in time and space are crucial factors in runoff modelling. Particularly it is important to know the amount and spatial distribution of precipitation as well as the reliable estimation of temperature-fields, because this information strongly influences all hydrological elements and processes.

Meteorological data are measured at point locations. In order to get all these information spatially everywhere an interpolation method is used to obtain maps. In distributed hydrological models spatial interpolation is typically applied to a grid with estimates made for all cells. That means when surface data have to be overlaid with other spatial data for proper modelling and analysis spatial interpolation is indicated to be used.

4.4.1 Kriging overview

The most promising stochastic tools are the variogram analysis and kriging [*Cressie*, 1985]. Kriging is called the best linear unbiased estimator, because it provides linear regression estimate, which is unbiased and has a minimum error variance. In general, the basic mathematical models are:

A). No trend in the data: Ordinary Kriging (**OK**) is used for spatial prediction:

$$Z(\mathbf{s}) = \delta(\mathbf{s}) \tag{1}$$

B). Trend in the data: Universal Kriging (**UK**) is used supposing that the trend is linear:

$$Z(\mathbf{s}) = \alpha_0 + \alpha_1 x(\mathbf{s}) + \alpha_2 y(\mathbf{s}) + \delta(\mathbf{s}) \tag{2}$$

where: **s** – is the location,
$Z(\mathbf{s})$ – is a random variable at location **s**,
α_i – are coefficients of the linear trend (i= 0,1,2),
$x(\mathbf{s})$, $y(\mathbf{s})$ – are the coordinates of the location **s**,
$\delta(\mathbf{s})$ – is random process with existing semi-variogram $\gamma(\mathbf{h})$, and here **h** is a distance vector.

According to the kriging theory [*Cressie*, 1985] an estimated value $Z^*(\mathbf{s}_0)$ can be expressed as a linear combination of the measured values on “n” locations:

$$Z^*(\mathbf{s}_0) = \sum_{i=1}^{n} \lambda_i Z(\mathbf{s}_i) \tag{3}$$

where the unknown λ_i (i=1,2,….,n) are constrained by: $\sum_{i=1}^{n} \lambda_i = 1$, which means that the expected value of the error of estimation $\left(E\left[Z^*(\mathbf{s}_0) - Z(\mathbf{s}_0)\right]\right)$ is zero. Under second-order stationary, the estimation variance for spatial prediction using weighted average of the neighbouring precipitation data:

$$\sigma_E^2(\mathbf{s}_0) = E\left\{\left[Z^*(\mathbf{s}_0) - Z(\mathbf{s}_0)\right]^2\right\} = \sum_{i=1}^{n}\sum_{j=1}^{n} \lambda_i \lambda_j \gamma(\mathbf{s}_i - \mathbf{s}_j) - 2\sum_{i=1}^{n} \lambda_i \gamma(\mathbf{s}_0 - \mathbf{s}_j) \quad (4)$$

Hence, determine the vector of weights λ in equation (3) leads to the following mathematical programming problem:

$$\min_{g(\boldsymbol{\lambda})=0} \sigma_E^2(\mathbf{x}_0) \ , \quad \text{where} \quad g(\boldsymbol{\lambda}) := \sum_{i=1}^{n} \lambda_i - 1 \quad (5)$$

The solution of problem (5) can be find in Cressie (1985).

4.4.2 Description of interpolation method for mapping of temperature data

Ordinary Kriging is used for spatial prediction when there is no trend in the data. If there is a trend in the data, universal Kriging (UK) is used. Because the air temperature is rather correlated with the elevation than with the location of points, it was necessary to modify the basic equation of **UK** (2) as [*Szabó, J.* 2005]:

$$T(\mathbf{s}) = \beta A(\mathbf{s}) + \delta(\mathbf{s}) \quad (6)$$

where: **s** – is the location,
T(**s**) – is the estimated temperature,
A(**s**) – is the altitude at location **s**,
β – is the coefficient of *A*(**s**)
δ(**s**) – is a random process with existing variogram.

In order to use the experimental semi-variogram information in kriging it is necessary to model the experimental semi-variogram (see equation 4). Three theoretical semi-variogram models were tested: exponential, Gaussian, and spherical. Following many several tests the spherical semi-variogram model was chosen (supposing that no nugget effect, in other words, the measurement error/variability is negligible or equal to zero):

$$\begin{cases} \gamma(h) = c \cdot \left[1.5\dfrac{h}{a} - 0.5\left(\dfrac{h}{a}\right)^3\right] & h \le a \\ \gamma(h) = c & h > a \end{cases} \quad (7)$$

where: *a* - is the spherical model range.
c - is the spatial variance (sill value when *h*=*a*);

This approach of interpolation can give finer detailed texture of interpolated temperature than many other methods. In actual practice uses of this method can be particularly significant in case of estimating *accumulation and snow melting*.

The above mentioned MUK interpolation technique was programmed on FORTRAN language with GINO graphics development tool, using OPENGL API. A user-friendly graphical program-system for temperature interpolation in automatic way was developed on large-scale too.

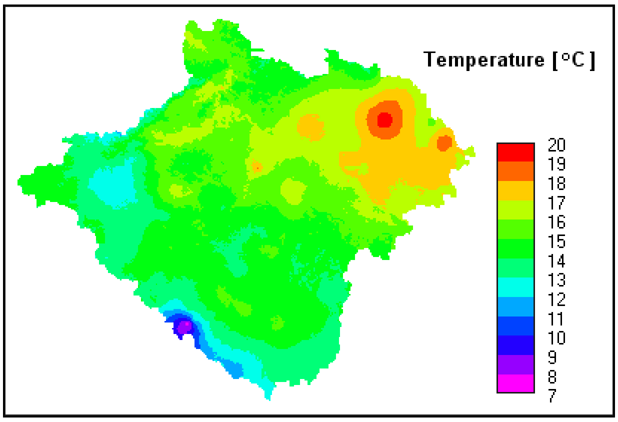


Figure 4.4.1 *Interpolated temperature field over Czech part of Elbe catchment using universal kriging [Szabó, J. 2005]*

4.4.3 Description of interpolation method for mapping of precipitation data

The interpolation of precipitation is more complicated than for example interpolating temperature or other parameters, because the precipitation is a strongly anisotropic process, although sometimes this may not be detectable on a "small" scale. However, real spatial phenomena often show directional, complicated, non-linear spatial structures *(Figure 4.4.2).*

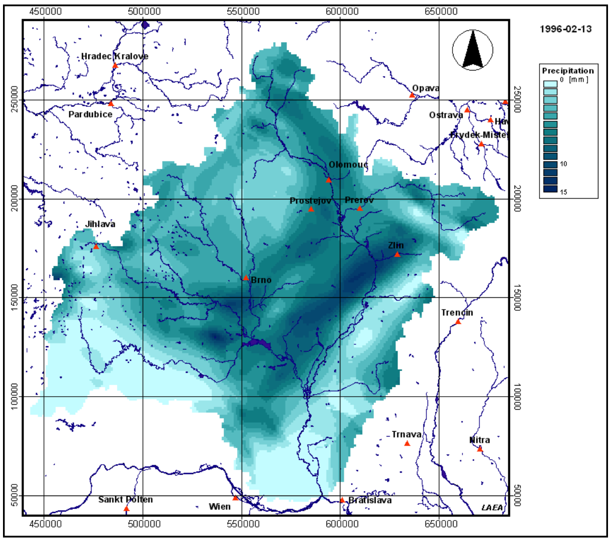


Figure 4.4.2 *Illustrative sample for non-linear spatial structures in precipitation fields (Morava River Basin)*

In meteorological processes it is typical that the measurements along a particular direction may be highly correlated *(Figures 4.4.3-4.4.4),* whereas the orthogonal direction shows little or no correlation (such processes are called *anisotropic*). One possible way to deal with directional effects in the covariance structure is to introduce geometric anisotropy.

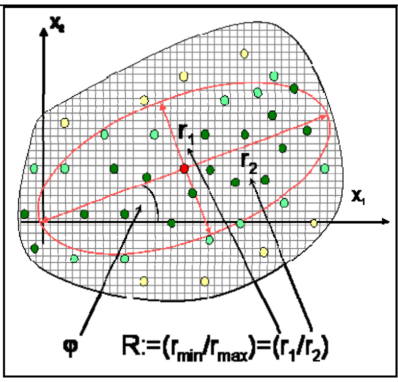


Figure 4.4.3 Example for a simple, linear directional effect

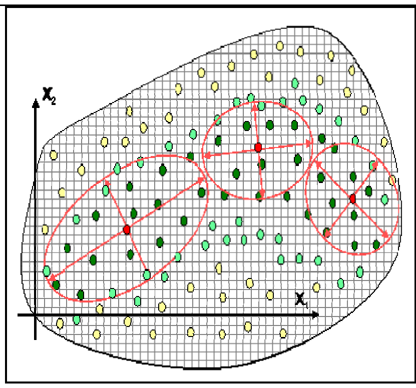


Figure 4.4.4 Example for a non-linear directional effect

This corresponds to rotation and stretching of the original coordinate system by:

$$\mathbf{x}'^T = \mathbf{x}^T \begin{pmatrix} \cos\varphi & -\sin\varphi \\ \sin\varphi & \cos\varphi \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ 0 & R \end{pmatrix} \qquad (8)$$

and modelling the correlation as a function of the distance *between the transformed points*. Here „φ" is the anisotropy angle, and „R" (R≤1) is the rate of anisotropy.

However, the meteorological spatial phenomena often show very complicated, non-linear directional effects. Particularly, in case of precipitation, measurements along a non-linear structured direction are might be highly correlated as it is shown in Figures 4.4.3 and 4.4.4. One option to describe these so complicated directional effects in the covariance structure is to use sequential local linear coordinate transformation with equation (8) on the target area, taking a moving „window" for scanning.

The approach, (used here **KLAM** "Kriging with Local Anisotropy Model"), is based on a combination of "Kriging" and the above mentioned local automatic „structure recognition" algorithm [*Szabó, J.* 2005].

The final purpose of semi-variogram analysis is to find an optimal parameterization of a semi-variogram model which can be used to describe the correlation structure of the selected set of data. Minimising the goal function, which is often called the cost criterion, performs the automatic variogram fitting:

$$J(\mathbf{p}) = \sum_{i=1}^{n} w_i \left[\gamma^*(h_i, \mathbf{p}_1) - \gamma(h_i, \mathbf{p}_2)\right]^2 , \qquad (9)$$

where:

n - is the number of points of experimental semi-variogram;

$\gamma^*(h,\mathbf{p}_1)$ - is the value of the experimental semi-variogram for lag *h* and the vector of anisotropy model parameters $\mathbf{p}_1=(\varphi,R)$;

$\gamma(h,\mathbf{p}_2)$ - is the value of the theoretical semi-variogram (mathematical model), which depends on *h* and the vector of model parameters $\mathbf{p}_2=(c,a)$;

p - is the joint parameter vector of $\mathbf{p}_1$ and $\mathbf{p}_2$ {p=(φ,R,c,a)}, and;

w_i - are the weight coefficients.

The simplest situation exists if the weight coefficients are equal to 1, which is called the ordinary least square method. This method assumes that the *differences are normally distributed, are independent one from each other and the estimated values have the same variances*. These assumptions seem to be unrealistic. The usage of some other weights leads us to the method called weighted least square method. The weight coefficients can be different, but the well-known are those proposed by Cressie [*Cressie*,1985]:

$$w_i = \frac{N(h_i)}{[\gamma(h_i, \mathbf{p}_2)]^2}\,, \tag{10}$$

where:

N(h_i) - is the number of pairs of points separated by the distance h_i.

It is worth to mention that this weight coefficient makes the cost criteria sensible to the number of pairs and to the value of the semi-variogram. Hence, the above mentioned task leads to a mathematical programming problem of the following form:

$$\min_{\mathbf{p}\in[\mathbf{a},\mathbf{b}]} J(\mathbf{p})\,, \tag{11}$$

where:

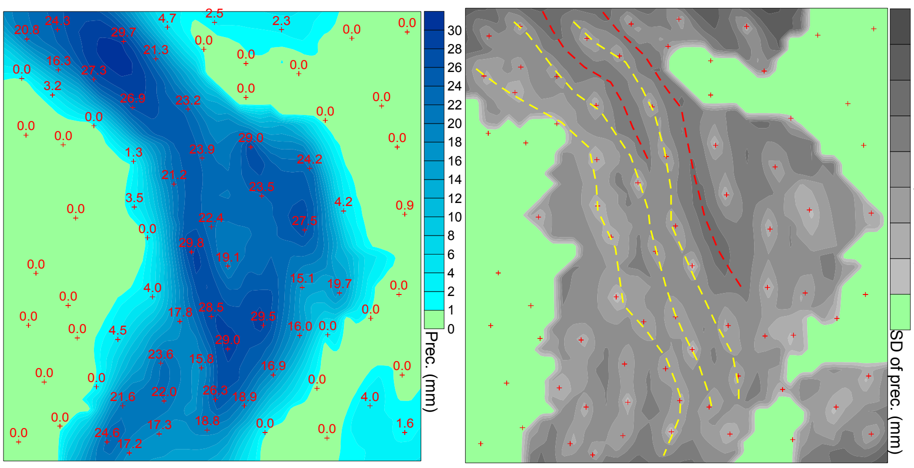
[**a**,**b**] is a closed interval of $\mathbf{R}^4$, which represents the possibility values of the parameters, and here **a** and **b** are the boundary minimum and maximum, as regards practically **a** = (0, 1, min (γ_i^*), 0), and **b** = (π, 15, max (γ_i^*), max (h_i));

J(**p**) is the goal function in (9), and we assume that *J*(.) belongs to the class of Lipschitz-continuous real functions, which have only a finite number of global optima on [**a**,**b**].

At this stage we seek for a global optimal solution of (11) whereas it may have several local optima. However, the most optimisation methods – and, consequently, most techniques currently used for parameter estimation – are capable of finding only the local optimum. In other words, unless the problem (11) is specified *a priori* to have only a single local (thus global) optimum, there may be significant differences between local optima, depending on the starting point of the applied locally convergent algorithm. We emphasize, however, the mentioned multi-extremality is also fairly typical in many cases, as in (11) too.

In order to find an optimal parameterization of a semi-variogram model a general class of globally convergent (derivate-free) univariate Optimisation Algorithm (GOA) was applied for solving problem (11). The details of GOA theoretical investigations are described in Pintér and Szabó, 1985/a, and description of some applications can be found in Pintér, Szabó, 1985/b or Pintér, Szabó, Somlyódy, 1986.

The above outlined **KLAM** interpolation technique was programmed on FORTRAN language with GINO graphics development tool, using OPENGL API, and also was developed a user-friendly graphical program-system for interpolating precipitation data in automatic way on large-scale and long term. To demonstrate the principle of **KLAM** interpolation technique a synthetic rain gauge network and data have been prepared *(Figure 4.4.5).*



4.4.5a **4.4.5b**

Figure 4.4.5 Interpolated rain front (a) and the standard deviation of the estimation (b)

These data were generated randomly taking some assumptions into consideration in order to get a characteristic, spatially coherent non-linear structured precipitation front, which is fairly a typical meteorological situation. The result of the kriging estimation can be seen in Figure 4.4.5a, whereas Figure 4.4.5b shows the standard deviation of the estimation, which is the basis of the statistical uncertainty calculation. As it is shown in Figure 4.4.5a the **KLAM** interpolation technique could describe the non-linear structure represented by the network of the point samples.

The quality of the kriging estimation in Figure 4.4.5a was examined on the basis of a kriging variances analysis. It deserves closer attention on the non-linear spatial structure of the standard deviation in Figure 4.4.5b. On one hand the yellow and the red dashed curves show a very particular structure, but on the other hand a real natural one, which has a low level of uncertainty along the yellow curves and a high level of uncertainty along the red curves. The explanation of this phenomenon is quite simple, and the reasons are pretty natural: As it is derivable from the construction of **KLAM** the “normal” Euclidean space and distances are changed by means of anisotropy transformations (equation 8). Therefore the correlation structures between the measuring points are also changing according to direction (φ) and the distortion (R) parameters. In addition there should be a low (or high) uncertainty along this path where the measuring points are fit (or not fit) within the path of anisotropy. Figure 4.4.2 presents a map of the kriging estimation on Morava catchment using **KLAM**. The estimation is based on historical records of rainfall gauging stations when high precipitation took place.

4.4.4 Cross-validation and sensitivity-analysis of KLAM algorithm

The comparison of spatial interpolation methods is usually based on statistical methods. Cross validation compares the interpolation methods by repeating the following procedure for each interpolation method to be compared:

Let $\left\{\mathbf{x}_i = \left(x_1^i, x_2^i\right)\right\}_{i=1}^N$ be the coordinates of the measuring points (rain-gauges), and let $\left\{P_i = P(\mathbf{x}_i)\right\}_{i=1}^N$ be the value measured at the point *i*. Now do the following algorithm:

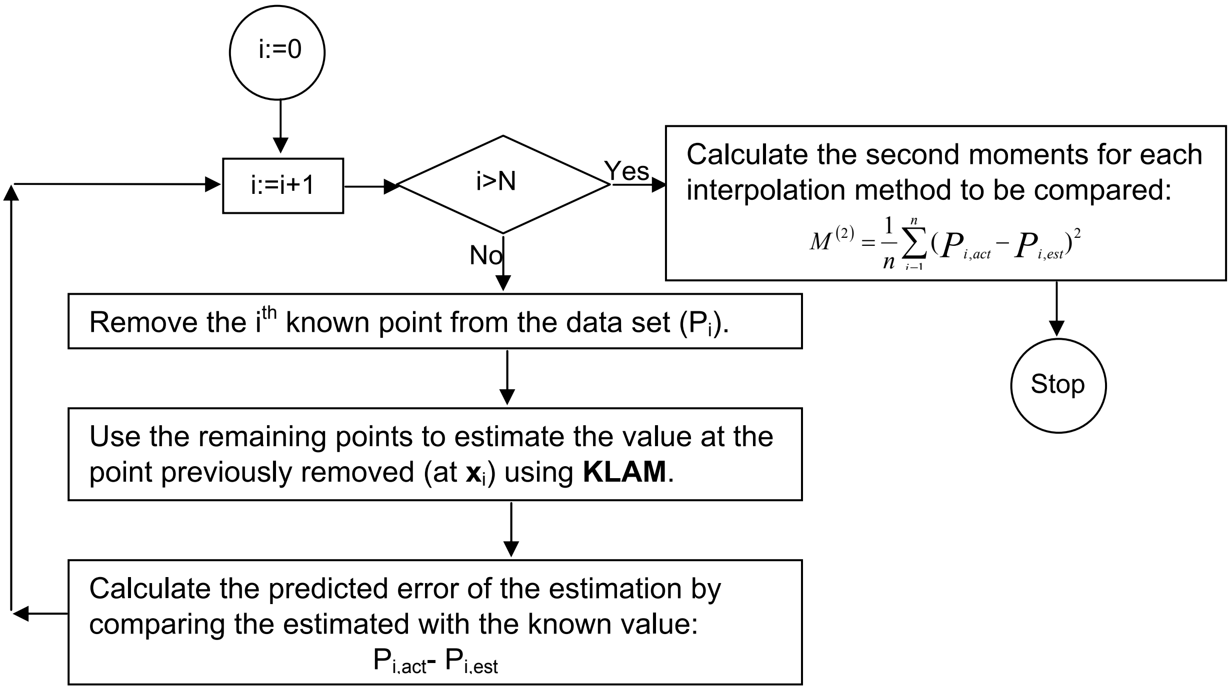


Figure 4.4.6 Flowchart of the cross-validation algorithm

Basically it is important to analyze the sensitivity of statistics parameter for reduction of points (in other words sensitivity for the missing data). A Monte-Carlo type algorithm can be appropriate to compares sensitivity of the interpolation methods to be selected: (Fig 4.4.7)

In the end of this process you can obtain an average variability of statistics for each interpolation method to be compared.

For the examination of the interpolation efficiency the new algorithm and the well-known “Nearest Neighbour” and “Inverse Distance (pow=3)” methods were compared based on cross-validation and Monte-Carlo type sensitivity analysis. In order to compare these methods the analysis was applied on 200 points of real data collection network of precipitation. Figure 4.4.8 shows that the KLAM algorithm is consequently less sensitive for the missing data than the other tested methods.

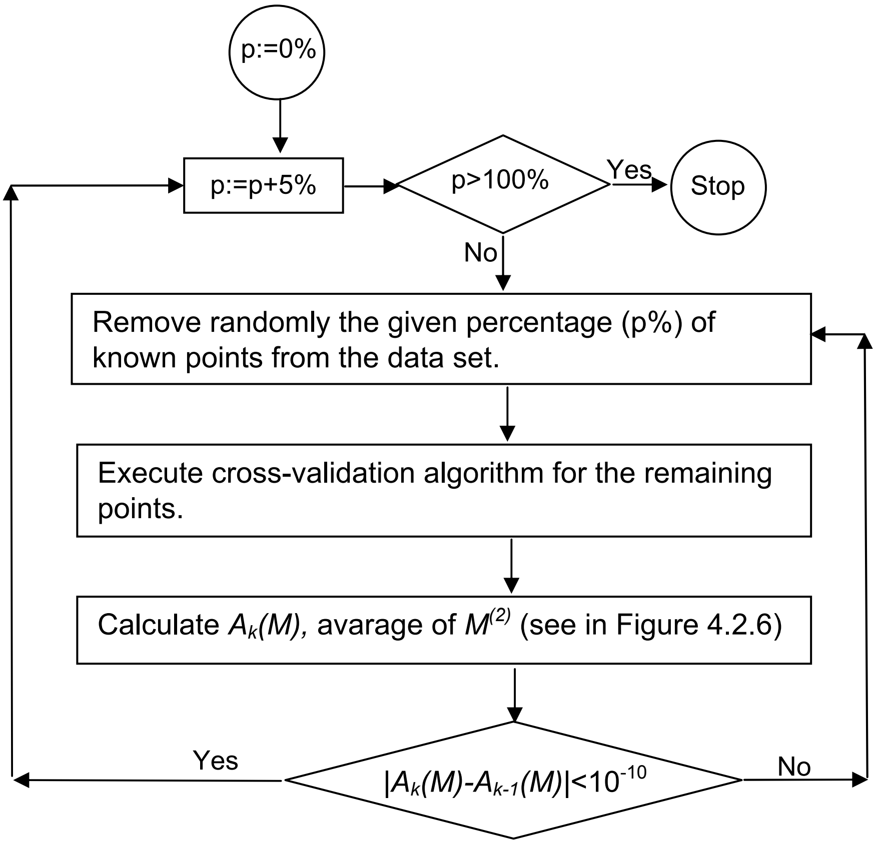


Figure 4.4.7 Flowchart of the Monte-Carlo type sensitivity analysis algorithm

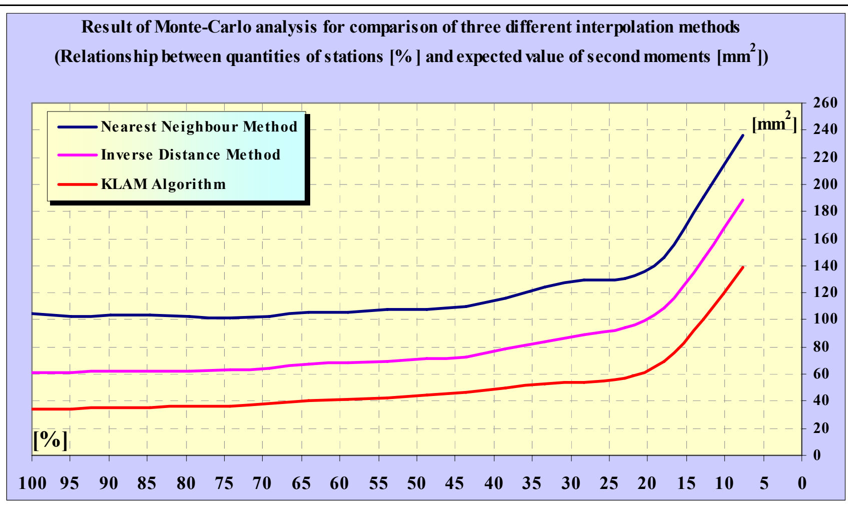


Figure 4.4.8 Results of the sensitivity analysis

The main advantage of using these described methods is that they allow the estimation of uncertainty of interpolated fields as well as consequently the uncertainty within flood forecasting. By applying these methods the uncertainty is consequently smaller compared to other popular methods. Subsequently the calculation of initial conditions from observed rainfall point data of gauging networks could be improved significantly. In addition this method allows analyzing the influence of calculated uncertainty on river runoff.

4.5 Discharge/Water Level data-checking and filtering

National discharge and water level data have been delivered by water authorities for the time period 1993/1994 until 2002/2003. Not for all stream gauges the data are complete for these time periods. For a couple of gauges the measurement has started later than 1994 or even only in 1998. The chosen gauges for the calibration have been selected in order to include the most important gauges, in particular with regard to flood forecasting, as well as these gauges that had a consistent and reliable data set.

In a few cases the delivered data files also contained “gaps” of observation or measurement respectively. In these cases those gaps has been treated as “missing values” or this gauge itself, depending on the importance in the river system, was not considered or only used for tests in the available time period. In case where no hourly or momentary values respectively have been provided the daily mean discharge has been used what certainly reduced the quality of calibration results. For data sets with irregular time series the data has been interpolated.

4.6 Analysis of influence of calculated uncertainty on river runoff

In order to assess the reliability of model output and evaluation, the influence of uncertainty of precipitation interpolation to model output was examined through the following steps [S*zabó J. A., M. Kalaš, A. De Roo*, 2004]:

1. Run the hydrological simulation model for a certain period taking expected values of interpolated precipitation (EVP) fields into consideration. This result represents the expected values of discharge for the selected period *(purple line in Figure 4.6.1).*

2. Run the model again two times for the same period using EVP-2σ and EPV+2σ, where σ is symbolized the standard deviation field of interpolation *(black lines in Figure 4.6.1)*. This result represents the uncertainty with 95 % probability.

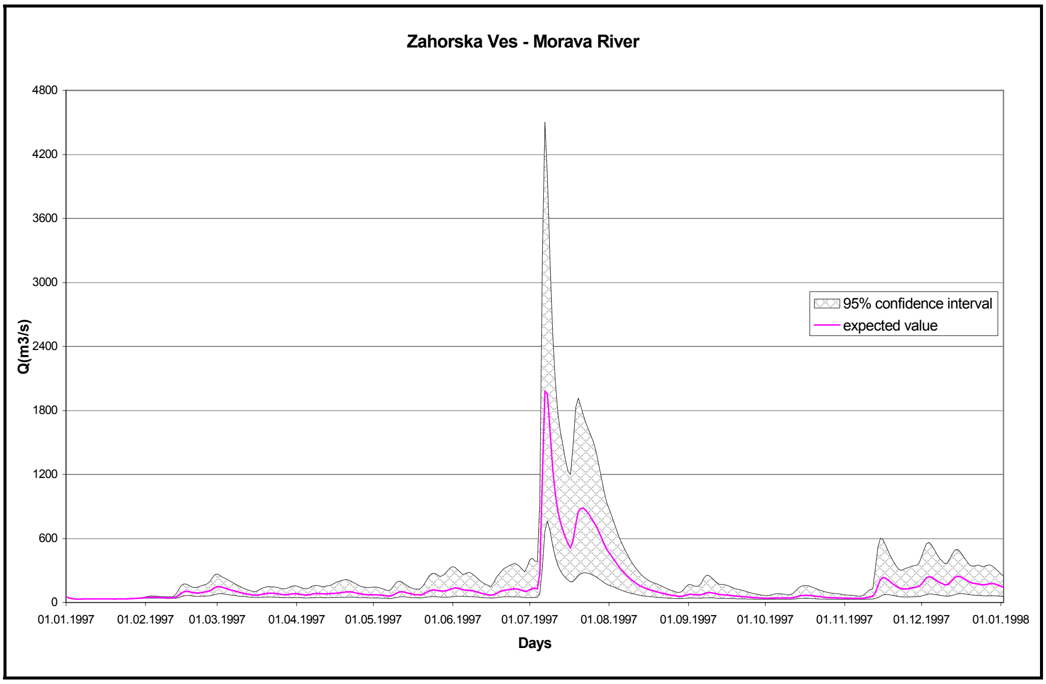


Figure 4.6.1 *Example of influence of uncertainty of interpolated precipitation fields on simulations*

5. Model calibration and validation

5.1 Introduction

The calibration of the Elbe LISFLOOD setup is achieved by adjusting the parameter maps in order to match volume and peak discharge at the outlet of each sub-basin. Because of the diversity and complexity of the physical system, including the heterogeneity of basin characteristics influencing the runoff processes, the Elbe catchment has been divided into smaller sub-catchments *(Figure 5.1.1).*

Figure 5.1.1 *Elbe river basin split into sub-catchments*

The sub-catchments are defined to represent as much as possible homogeneous regions (land use, topography, soil types). These parameters usually control the response of the catchment, timing and the shape of the simulated hydrograph. This process is very often limited by the availability of hydrological stream gauges observations.

The model calibration with historical data is an essential part of the model development itself. It is a procedure of adjusting parameters until the model satisfactorily simulates the observed physical processes in the hydrologic system and produces reliable results. The aim and the purpose of calibration are to obtain a set of parameters so that the model will respond like the physical system it represents, event to event, over seasons and inter annually for each defined sub-catchment separately. It is essential to have the computed hydrograph the same as an observed one, not only for the calibration event period but for others as well. The trial-and-error procedure is normally accomplished in which a hydrograph is computed with default parameter and compared with the observed hydrograph. On the basis of comparison the model was re-run after adjusting the parameters until a suitable fit is obtained.

5.2 Parameter set used for model calibration

Although LISFLOOD is based on physics to a certain extent, some processes are only represented in a lumped conceptual way. As a result, some parameters lack physical basis and cannot be directly obtained from field data. In the current version of LISFLOOD, there remain seven parameters that need to be estimated by calibration against measured stream flow records.

The calibration parameters basically used are tabulated in the table below *(Table 5.2.1)*, with upper and lower bounds of the prior distributions used in the inverse procedure. The Upper Zone Time Constant (UZTC) and Lower Zone Time Constant (LZTC) reflect the residence time of water in the upper and lower groundwater zone, respectively. As such, they control the amount and timing of outflow from the respective groundwater reservoirs. The Groundwater Percolation Value (GWPV) controls the flow from the upper to the lower groundwater zone. The Xinanjiang parameter b (Xb) is an empirical shape parameter in the Xinanjiang model [*Zhao and Lui*, 1995] that is used to simulate infiltration. In controls the fraction of saturated area within a grid cell that is contributing to runoff, hence it is inversely related to infiltration. The Power Preferential Bypass Flow parameter (PPBF) is an empirical shape parameter in the power function relating preferential flow with the relative saturation of the soil. The Channel Manning parameter is a multiplier that is applied to the Manning's roughness maps of the channel system. The Ground Water Loss Fraction (GwLossFraction) is the rate of flow out of the lower groundwater zone, expressed as a fraction [-] of the inflow, GwPercValue. Upper and lower bounds can be found in Table 5.2.1.

Parameter	Lower bound	Upper bound
Upper Zone Time Constant (UZTC)	1	10
Lower Zone Time Constant (LZTC)	10	5000
Ground Water Percolation Value (GWPV)	0	0.5
Xinanjiang parameter b (Xb)	0.05	0.5
Power Preferential Bypass Flow (PPF)	5	15
Channel Manning (CalChanMan)	1	5
Ground Water Loss	0	1

Table 5.2.1 *Calibration parameters of the LISFLOOD model with upper and lower bounds of the prior uniform distributions*

An automatic calibration algorithm developed by Szabó (2005) has been used in this study. This automatic calibration algorithm provides also the possibility to apply various calibration approaches with regard to three different weighting functions.

Three different approaches have been applied:

1. normal calibration, without forcing the model to calibrate in a particular way;
2. forcing the model weighted on "peak" discharge;
3. forcing the model weighted on "base" flow.

5.3 The applied "goodness-of-fit" parameters for analyzing the Model Output

Correlation-based measures are used to evaluate the "goodness-of-fit" of hydrologic models. A primary goal of modelling physical processes in hydrologic sciences is the prediction of a variable (discharge, water level, etc.) in time and/or space from a given set of inputs. How well a model fits the observed data usually is determined by pair-wise comparisons of model-simulated values with observations. Evaluations of model performance utilize a number of statistics and techniques. Usually included in these tools are "goodness-of-fit" or relative error measures to assess the capability of a model to simulate the reality. Often these statistics are based on the familiar Pearson's product-moment correlation coefficient (R) or its square, the coefficient of determination (R^2).

In the Elbe study, several alternative measures are used for the evaluation of the LISFLOOD model. In general, this chapter addresses comparisons of model-simulated data (S) with the observed data (O) for the same set of conditions (i.e., a pair-wise comparison) over a given time period divided into time increments that can be of arbitrary duration (e.g., daily or hourly time steps). Table 5.3.1 shows the statistical parameters used.

Statistics	Expression in an analytic form	Remarks
Mean of simulation error [Exp.]	$\bar{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)$	This statistic is suited to estimate the additive component of the error.
Standard deviation of simulation error (root mean square error) [STD]	$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(\varepsilon_i - \bar{\varepsilon})^2}{n-1}}$	This statistic is used to measure the discrepancy between modelled and observed values on an individual basis, and indicates the overall predictive accuracy of a model.
Pearson Product-Moment Correlation Coefficient [R]	$R = \frac{\sum_{i=1}^{n}\{(S_i - \bar{S})\cdot(O_i - \bar{O})\}}{\sqrt{\sum_{i=1}^{n}(S_i - \bar{S})^2 \cdot \sum_{i=1}^{n}(O_i - \bar{O})^2}}$	where: $\bar{S} = \frac{1}{n}\sum_{i=1}^{n}S_i$ and $\bar{O} = \frac{1}{n}\sum_{i=1}^{n}O_i$ The R value is a measure of the degree of linear association between two variables, and represents the amount of variability that is explained by another variable (in this case, the simulated values).
Nash-Sutcliffe Coefficient [NSC]	$N = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$	Like the R measure described above, it is another indicator of "goodness-of-fit", and is one that has been recommended by ASCE for use in hydrological studies. With this coefficient, values equal to 1 indicate a perfect fit model, and values equal to 0 indicate that the model is predicting no better than using the average of the observed data.
First value of the autocorrelation function [ε_{xx}]	$r_{\varepsilon\varepsilon}(1) = corr(\varepsilon_{t+1};\varepsilon_t)\ \ \forall t \in (1,2,.....,n-1)$	This value is related to the time-shift between modelled and observed values.

Table 5.3.1 *Statistical parameters used for model evaluation.*

These statistical parameters are automatically analyzed and visualized on measured-simulated hydrographs using automatic software developed by Szabó (2005).

5.4 Calibration results

5.4.1 Introduction

To facilitate the calibration, validation and testing of the LISFLOOD model for the Elbe river basin, the Czech part of the Elbe was evaluated separately from the German part. For the German part of the Elbe basin, the Czech inflow at the stream gauging station "*Ústí nad Labem"* near the border has been used.

As mentioned above, the Elbe basin has been split into sub-catchments to obtain parameter sets for each of those sub-basins *(Figure 3.1).* An overview of used stream gauging stations can be found in Figure 5.4.1-1. All available hydrological data were checked using statistical analysis's [*Szabo*, 2005] to find potential outliers or other discrepancies in the delivered data sets. The runoff coefficient was calculated to figure out, whether the chosen sub-catchments are split in a proper way.

During the calibration of the model, both split-samples and goodness-of-fit statistics were adopted as measures of performance. A simulation 'warming-up' period of 1 year is used to tune the model to the initial conditions. For the German part of the Elbe the time period between 1994 and 1998 was used for model calibration. However, not for all stream gauges all hourly or daily discharge data were available.

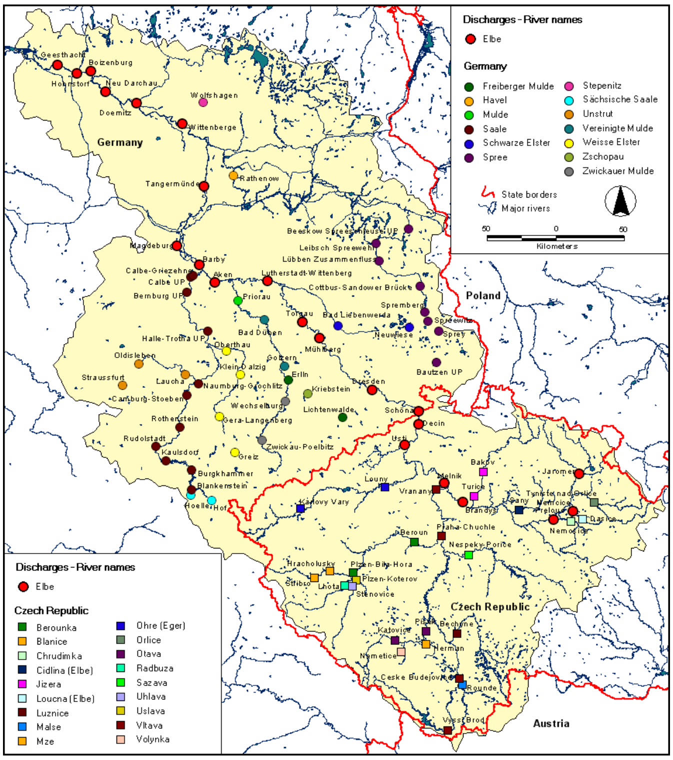


Figure 5.4.1.1 *Overview of used stream gauging station within the Elbe River Basin*

5.4.2 Results

The model has been calibrated on a daily discharge for the time period 1994-1998, in which the year 1994 is considered as the "initial run" or so called "warm-up phase". For all sub-catchments, A two-step calibration procedure was used, first without reservoirs, later with reservoirs.

River routing in the tributaries to the Elbe river are simulated using the kinematic wave approximation, and those parts are calibrated accordingly. Since river geometry information was available for the main Elbe, here the dynamic wave approximation has been applied.

Below, first the calibration of all tributary rivers will be shown. In the last section, the calibration of the main Elbe river will be discussed.

Note: even though many scenario calculations in the end use observed inflow data from the tributary rivers, it was still attempted to calibrate all of them, also to cover ungauged parts and smaller inflow tributaries for which measurements do no exist. The obtained parameter set can also be used for simulations without observed discharge data being available, or for simulations using changed landuse etc.

River STEPENITZ

The River *Stepenitz* (size of river basin 862 km²) is a tributary of the River Elbe in the *State Brandenburg.* It has its source on a long mountain range approximately 140 maSL southern-east of *Meyenburg*. The most important tributaries are *Doemnitz, Schlatbach* and *Jeetzebach*.

In particular the upper course is still widely semi-natural. Due to the altitude difference of 84 m along the river length of approximately 86 km water levels and discharges increase very fast in flood cases. Furthermore, because of the large amount of bed sediments, there is also a minor influence of seepage capacity. The wave propagation is quite fast. These characteristics could be the reasons for some of the difficulties encountered n the calibration procedure with the LISFLOOD model for this river. In the middle section, a reservoir (rainfall retention basin - similar a natural polder) is situated with a flood storage of approximately 1.5 million m^3. It is not regularly steered and will be only used in case of floods or heavy rain. The calibration has been done without considering this reservoir (Rainfall Retention Basin).

The calibration for the *Stepenitz* with the given parameters has shown that there are no further possibilities to improve the simulated discharge hydrograph for this river segment. Furthermore the amount of delivered observed discharge data (apart from 5min-values for flood events only observed daily mean discharge data have been available) has not been sufficient. The shape of the simulated discharge hydrograph is already reasonable, but partly the simulated discharge is still too high. The best calibration what could be achieved is shown in Figures 5.4.2-1a and b**.**

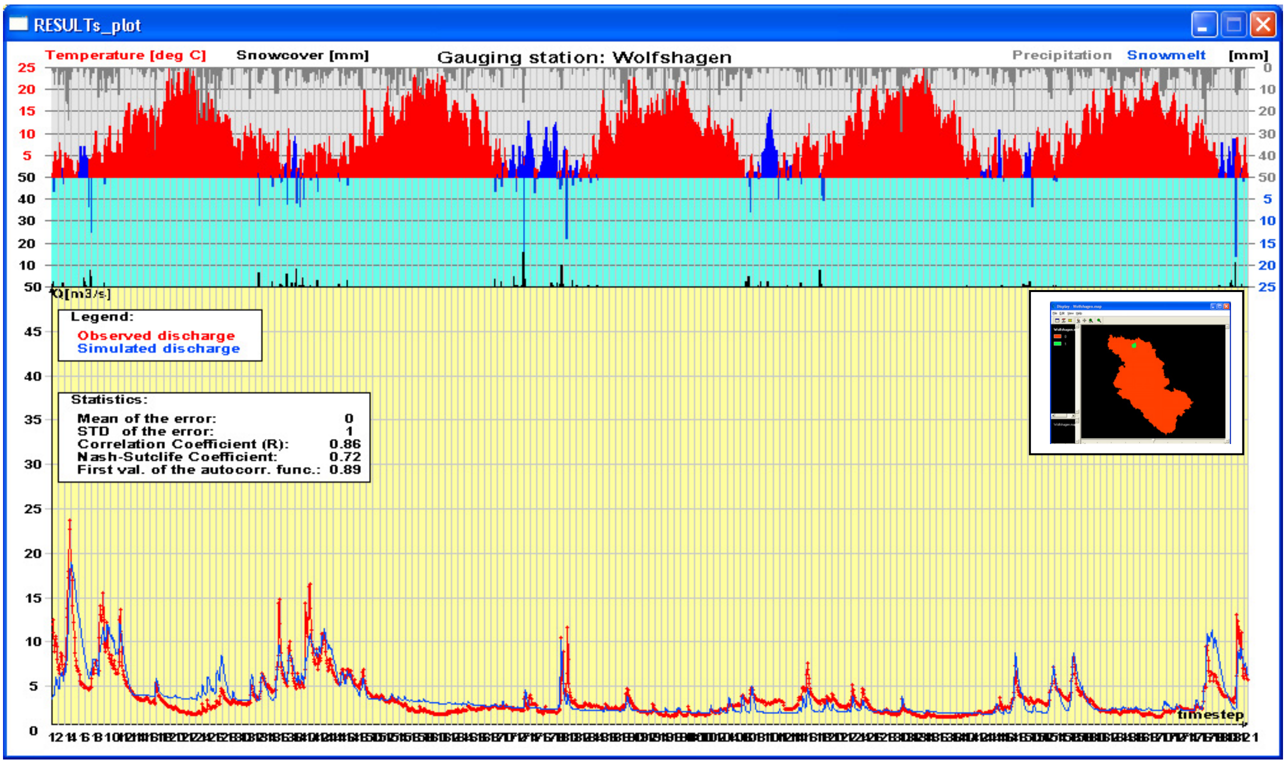


Figure 5.4.2-1a *Simulation results of Stepenitz up to the stream gauge Wolfshagen (1994 – 1998)*

Fig 5.4.2.1b shows a zoom in of a section of the Stepenitz river.

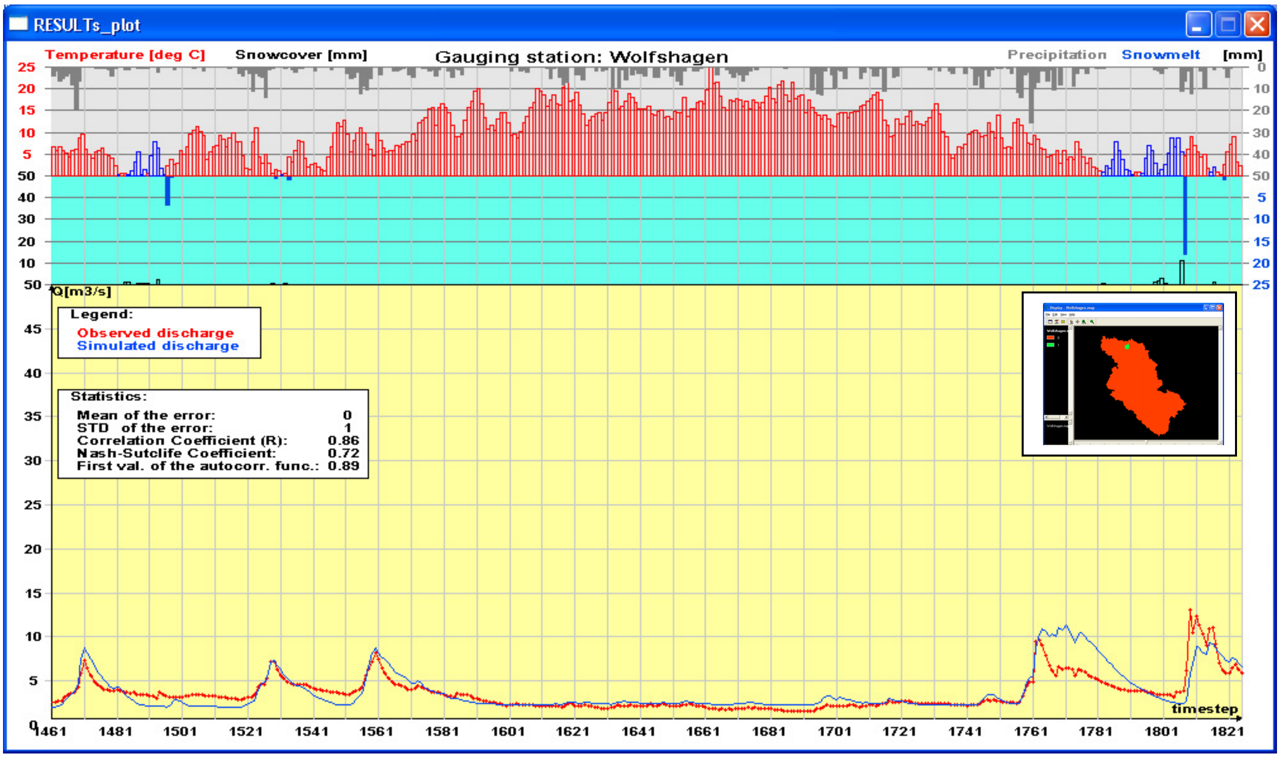


Figure 5.4.2-1b *Simulation results of Stepenitz up to the stream gauge Wolfshagen for the time period 01/01/1998 - 31/12/1998*

River HAVEL

The River *Havel* (size of river basin 23,858 km^2) is one of the most important tributaries of the Elbe. It has its source 2 km southern-west of *Ankershagen (State Mecklenburg-Western Pomerania)* at an altitude of 62.6 maSL. Together with its main tributary *Spree* both form the main part of the river network of the *Mark-Region*. Other large tributaries are *Rhin, Nuthe and Dosse.* The *Havel* meets the Elbe north-east of *Havelberg (State Saxony-Anhalt).*

The river itself is a typical lowland river with a balanced low water channel flow. Likewise it consists of many lake chains as well as canalised sections. With a river length of 333.7 km it overcomes an altitude of 39 m. The slope mounts up to about 12cm/km. The mean annual discharge at the river mouth corresponds to approximately 108 m^3/s so that the *Havel* ranks on place three among the three biggest tributaries of the River *Elbe* (*Vlatava* 150 m³/s and *Saale* 115 m³/s).

Because of the *Spree* tributary (size of river basin 9,858 km^2) the *Havel* is strongly influenced not only geographically but also hydrologically and is practically split up into two different river sections at the Spree mouth. At the river junction of *Havel* and *Spree* the latter one brings the double amount of runoff (38 m³/s compared to 15 m³/s) into the *Havel* than the *Havel* has itself and is even much longer than it. In addition, the *Havel* is regulated by a lot of weirs. Due to many natural retention areas in the upper and lower course the *Havel* has a balanced low-water flow conditions.

In case of floods the wave is characterized as long-lasting and not heavily shaped. A few lowland polders are available for inundation in case of floods in the *Havel* itself and in the *Elbe*. Particular models to calculate this issue in space and time already exist in the national Water Authorities. Because of the mentioned river character the *Havel* could not be calibrated sufficiently. Specific model approaches are needed to fulfil this crucial issue.

The best calibration what could be achieved is shown in Figures 5.4.2-2a and b**.**

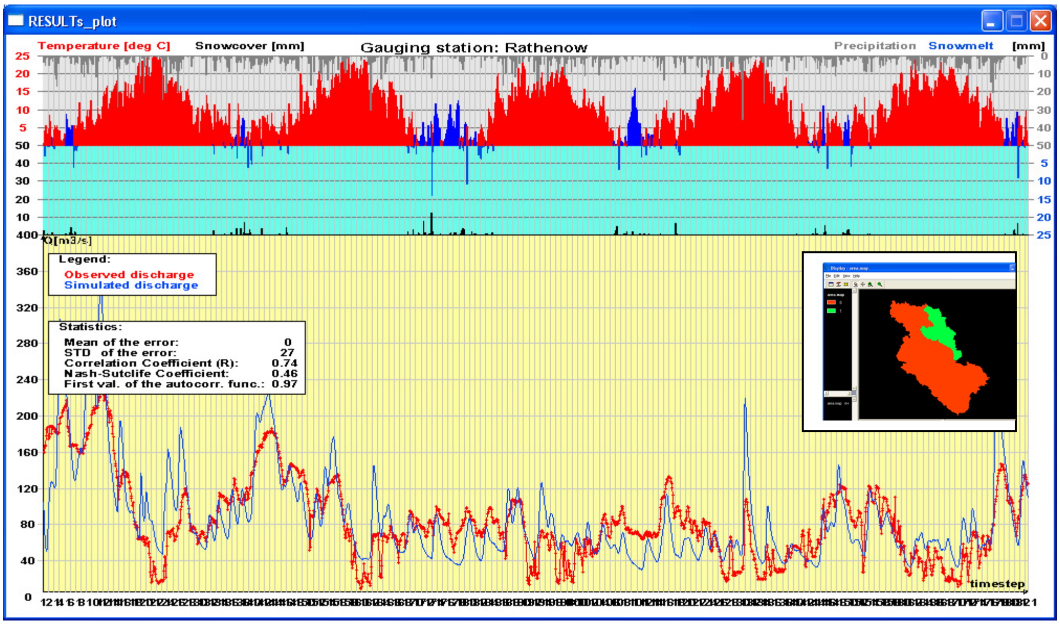


Figure 5.4.2-2a *Simulation of Havel up to stream gauge Rathenow (1994-1998)*

…zoom in sample:

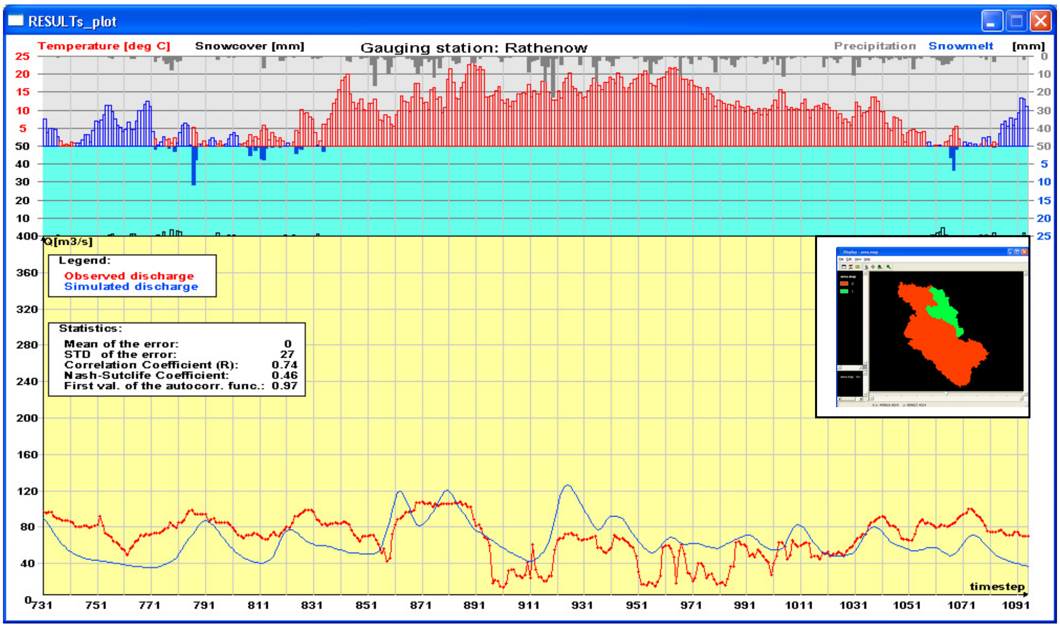


Figure 5.4.2-2b *Simulation of Havel up to stream gauge Rathenow for the time period 01/01/1996 - 31/12/1996*

River SPREE

Another example where calibration was not easy is the River *Spree* which is a tributary of the *Havel* (see also explanations under “River HAVEL”). The Spree (size of river basin 9,858 km^2) has a length of 380 km. The river originates from three different sources, at *Spreedorf (Lausitzer Bergland)* close to the Czech border in Ebersbach/Neugersdorf and at the *Kottmar (Oberlausitz).*The Spree flows through the *German States Saxony, Brandenburg and Berlin.* At the river junction of Havel and Spree the River *Spree* brings the double amount of runoff (38 m^3/s compared to 15 m^3/s) into the *Havel* than the *Havel* carries itself and is even much longer than the River *Havel*.

Its runoff in the upper and middle course is sustainable disturbed through significant ground water inflow due to intensive coal mining activity over years as well as the infiltration from the river bed and the water withdrawal for industrial and communal supply respectively. Because of coal mining activities in this region parts of the Spree river basin in the upper and middle course are situated in the ground water recession funnel. During the last years former coal-mines were filled successively, but irregularly, with water in particular even during small flood events. Unfortunately, the water authority in charge of could not provide sufficient data for these particular filling procedures. Only daily mean discharge data for the time period between 1993 and 2003 (apart from 15 min-values for flood events) are available.

In addition, the hydrological processes in the River *Spree* basin are strongly influenced by one of the oldest and most important cultural landscapes in Europe – the *“Spreewald-Region” (Spree-Forest),* which is split into *Upper and Lower Spree-Forest*. There the *Spree* behaves hydrologically like *“continental delta”*. The discharge behaviour is comparatively balanced. The flow velocity amounts to approximately 50 cm/s since there is a very low slope within in the river course. Further downstream the velocity becomes even less (17 cm/s – 9 cm/s) The whole area consists of many small streams and depends strongly on the discharge in the River *Spree*. For instance during hot summer periods the small streams have to be filled up with water from the *Spree*. This filling procedure is depending on many situations (weather, precipitation, temperature, ecological minimum discharge, etc.) as well. Data on these processes have not been delivered to us to make a better calibration.

The best calibration achieved in the upstream part of the River *Spree* is shown in Figures 5.4.2-3a and b.

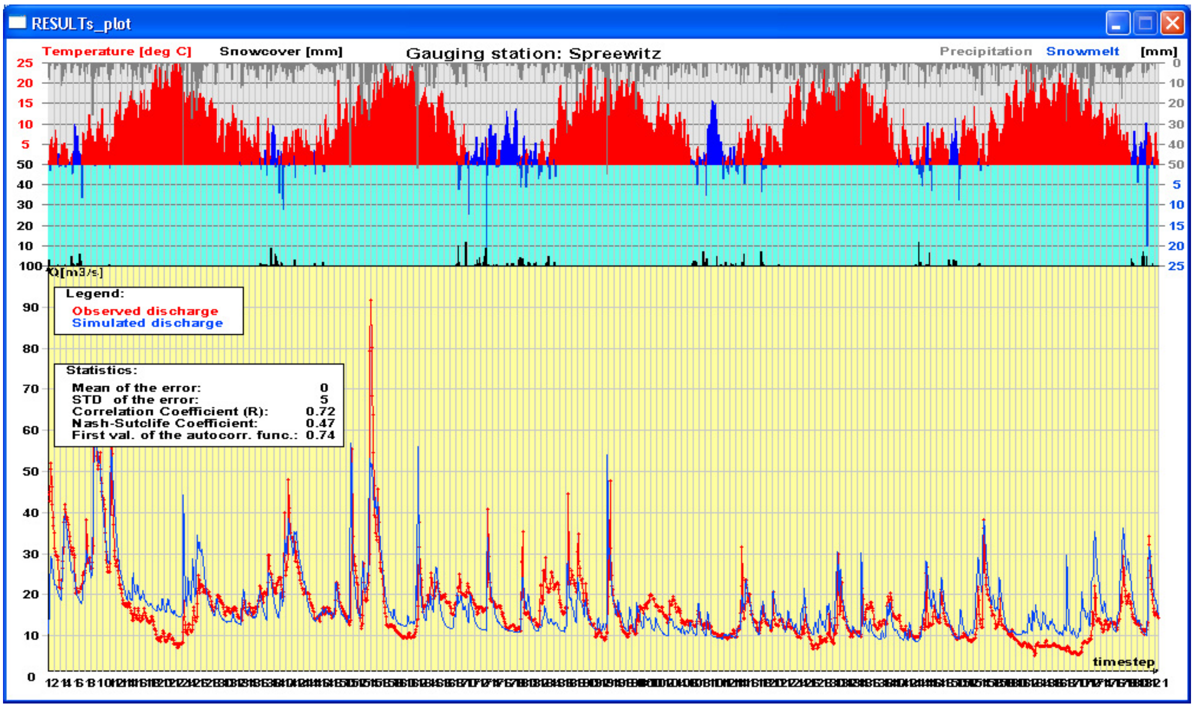


Figure 5.4.2-3a *Simulation of Spree up to stream gauge Spreewitz (1994-1998)*

…zoom in sample:

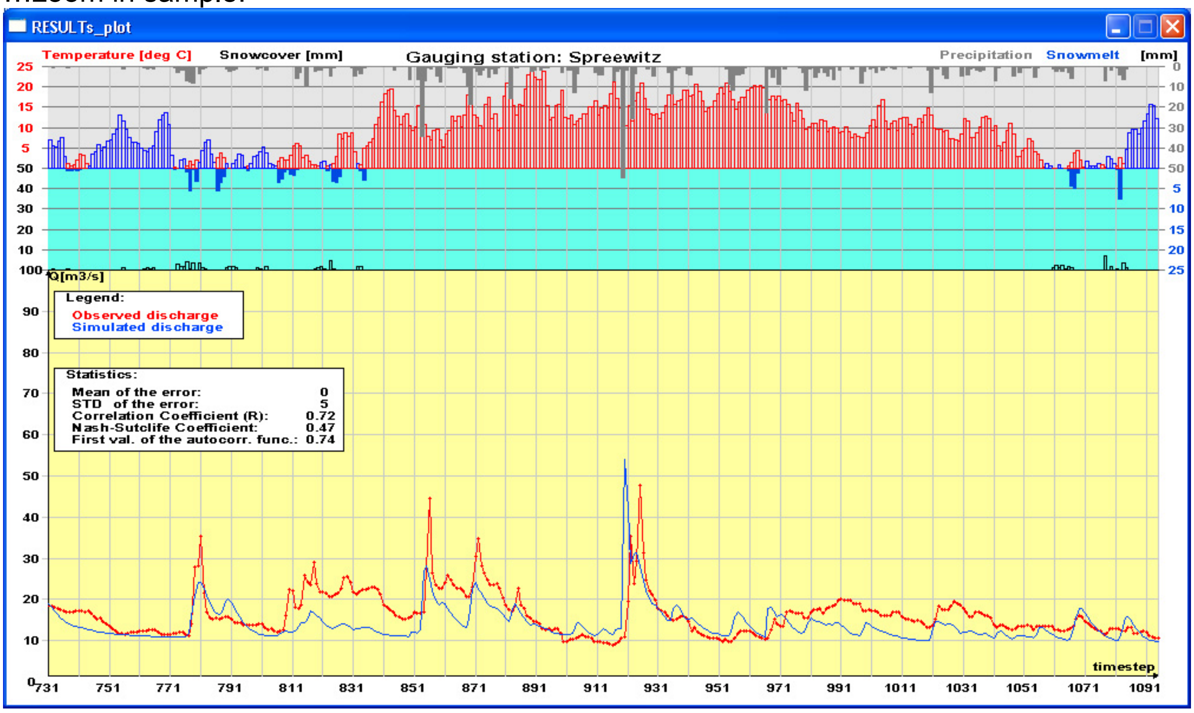


Figure 5.4.2-3b *Simulation of Spree up to stream gauge Spreewitz for the time period 01/01/1996 - 31/12/1996*

River SCHWARZE ELSTER

The River *Schwarze Elster* (size of river basin 5,704.9 km^2) is a tributary of the River *Elbe* and has a length of 179 km. It has its source in the *Nordwestlausitzer Hügelland (Oberlausitz).* East of *Lutherstadt Wittenberg* the river flows at *Elster (Elbe)* into the Elbe.

The calibration has been done for the upstream sub-catchment up to the stream gauge *Spreewitz.* The calibration for the same time could not be done for the stream gauge further downstream *(Bad Liebenwerda)*, because of data gaps in the time series. The shape of the simulated discharge hydrograph seems to be reasonable, but the simulated discharge itself is still too high (Figures 5.4.2-4a and b).

The best calibration achieved is shown in Figures 5.4.2-4a and b.

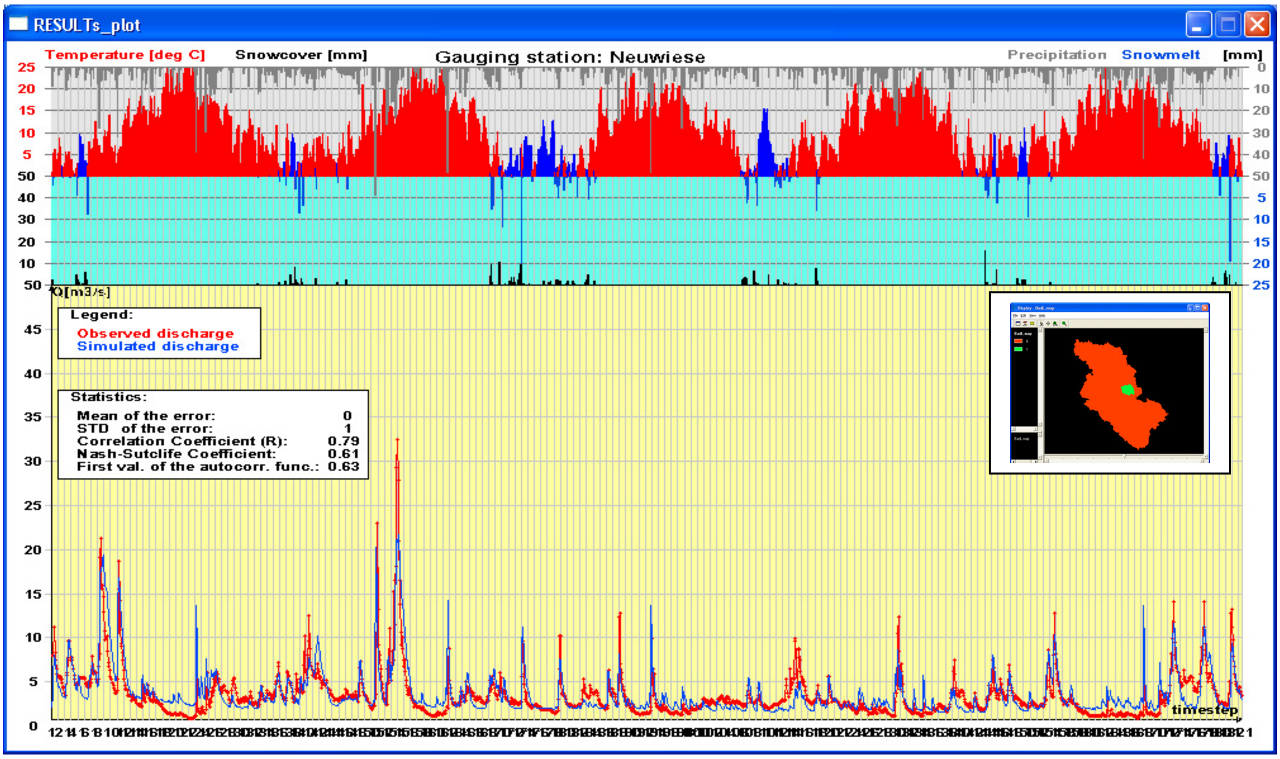


Figure 5.4.2-4a *Simulation results of Schwarze Elster up to stream gauge Neuwiese (upper course) (1994 – 1998)*

…zoom in sample:

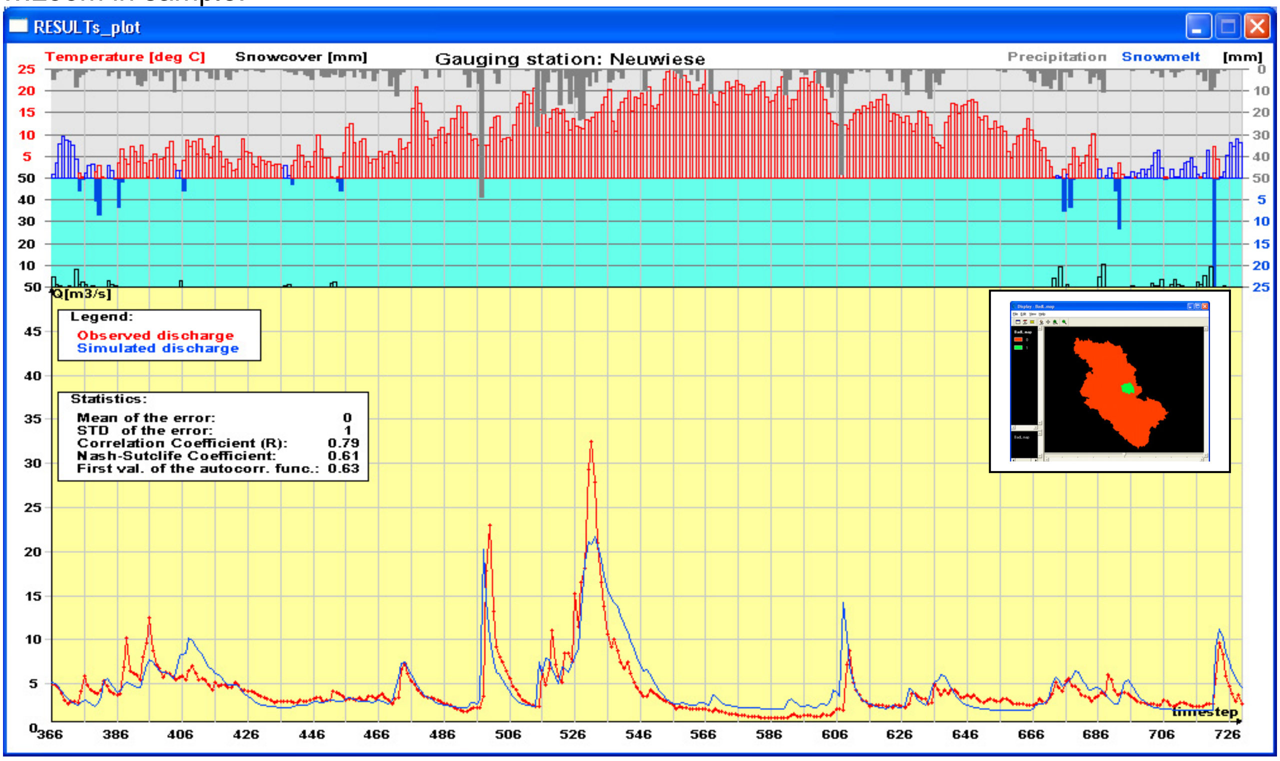


Figure 5.4.2-4b *Simulation results of Schwarze Elster up to stream gauge Neuwiese (upper course) for the time period 01/01/1995 – 31/12/1995*

River VEREINIGTE MULDE

The *Vereinigte Mulde* is a tributary of the *Elbe* and has a length of 313.7 km. The whole river basin of the *Mulden* amounts to 7,400 km^2, where 2,984.6 km^2 (15%) account for the *Freiberger Mulde*, 2,360.5 km^2 (32%) for the *Zwickauer Mulde*, 1,847 km^2 (25%) for the *Zschopau* and 2,054 km^2 (28 %) for the *Vereinigte Mulde*. All three Mulden have about the same length of 100 km. The Freiberger Mulde originates above the *Moldava* in the *Czech Republic,* the *Zwickauer Mulde* in the *Vogtland (Thuringia)* and the Zschopau at the north part of the *Fichtelgebirge* at an altitude of 1,070 maSL. The River *Mulde* is the fastest flowing river within Europe. The *Vereinigte Mulde* meets the *Elbe* between *Dessau and Rosslau*.

Particularly, the discharge events are determined by the weather of the *Erzgebirge* and the *Erzgebirgsvorland* (mountain foreland). The highest mountains within the river basin are the *Klinovec* Mountain with 1,244 maSL, the *Fichtelberg* with 1,114 m and the *Auersberg* with 1,019 m. The flow conditions underlie remarkable fluctuations since the precipitation fall very irregularly. Normally in springtime high water stages occur because of snow melting. Afterwards the discharge decreases usually up to autumn until it reaches its lowest discharge in October/November. This discharge regime often will be interrupted through heavy rain during summer time which falls basically in the *Erzgebirgsvorland* (mountain foreland).

Sub-catchment up to stream gauge Golzern - upper course

The best calibration achieved is shown in Figures 5.4.2-5a and b**.**

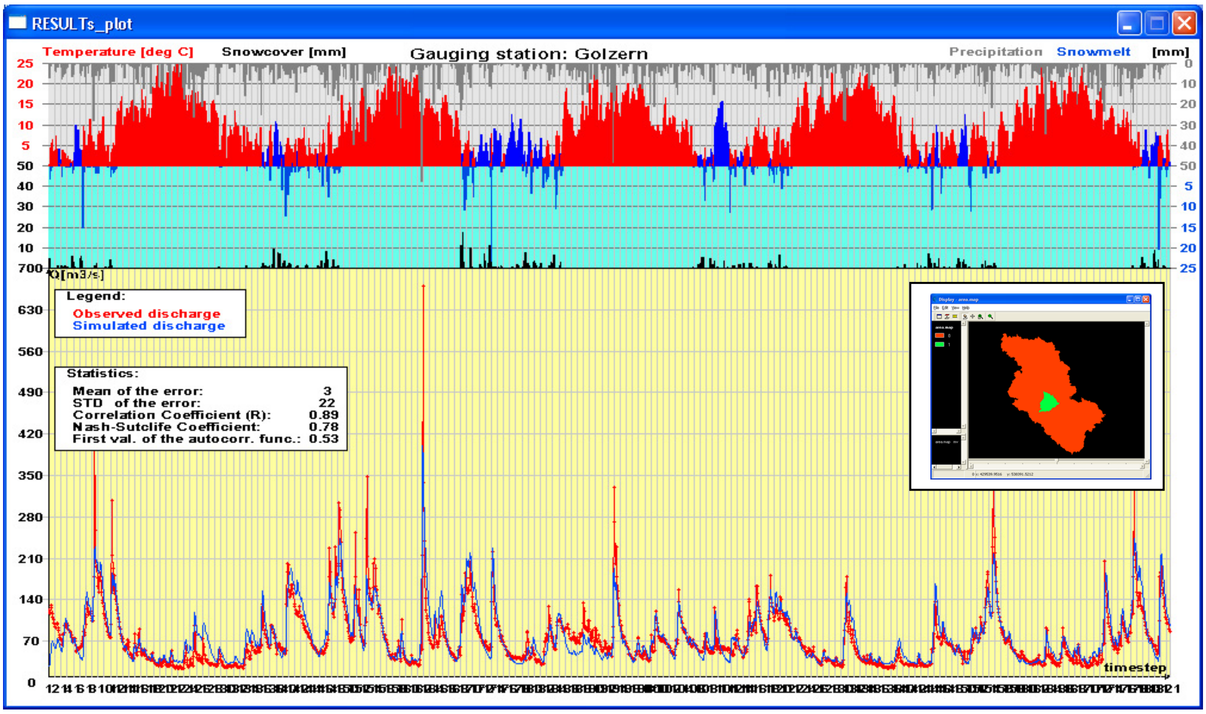


Figure 5.4.2-5a *Simulation results of Mulde up to stream gauge Golzern (upper course) (1994 – 1998)*

…zoom in sample:

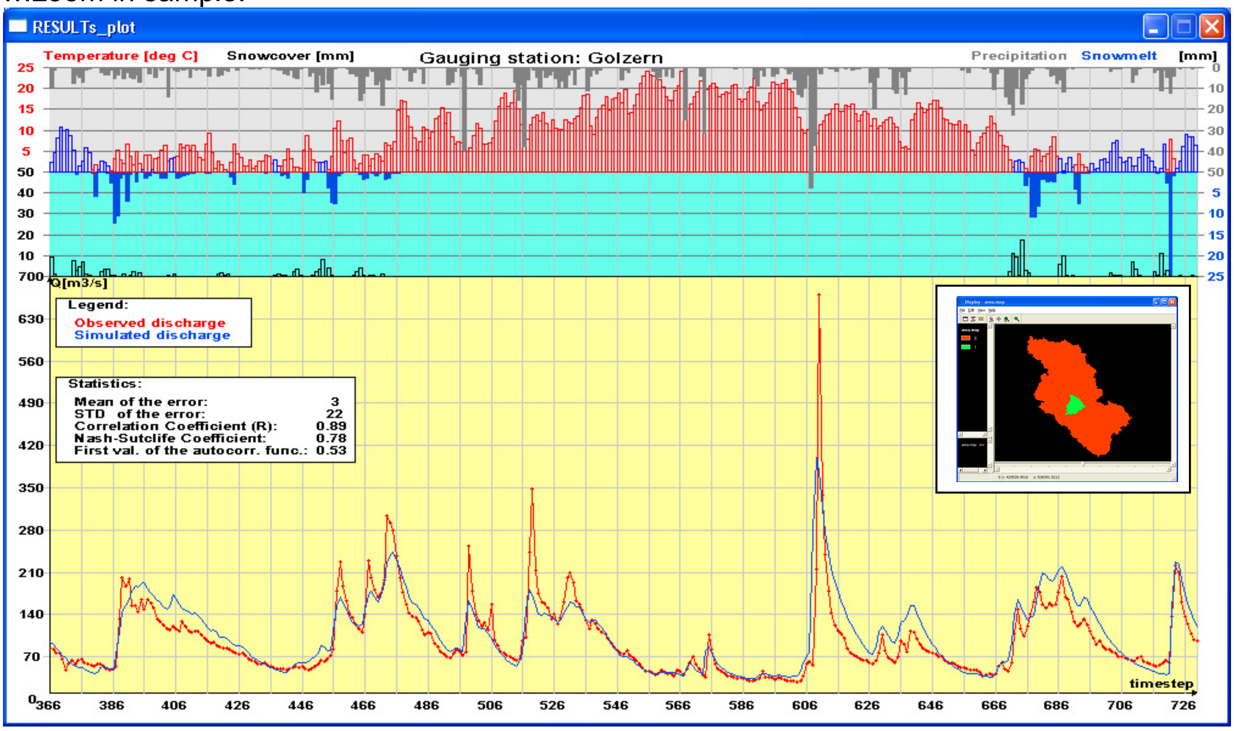


Figure 6.4.2-5b *Simulation results of Mulde up to stream gauge Golzern (upper course) for the time period 01/01/1995 – 31/12/1995*

Sub-catchment between stream gauges Golzern and Bad Dueben

The best calibration achieved is shown in Figures 5.4.2-6a and b.

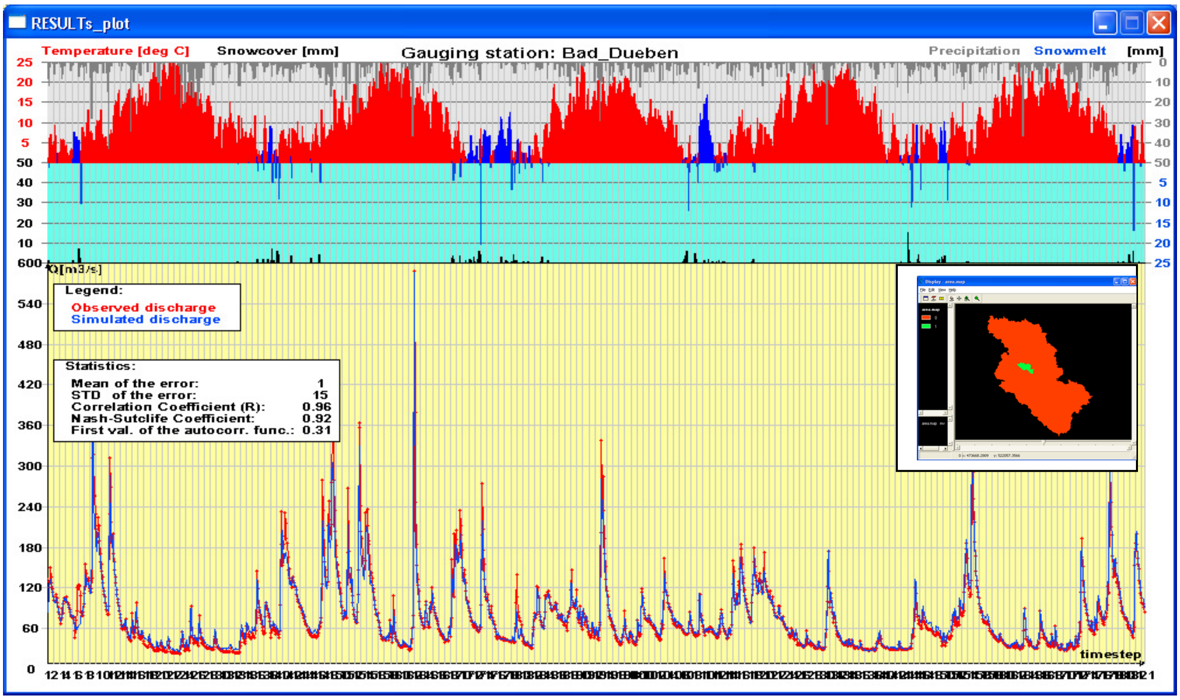


***Figure 5.4.2-6a** Simulation results of Mulde between stream gauges Golzern and Bad Dueben (1994 – 1998)*

…zoom in sample:

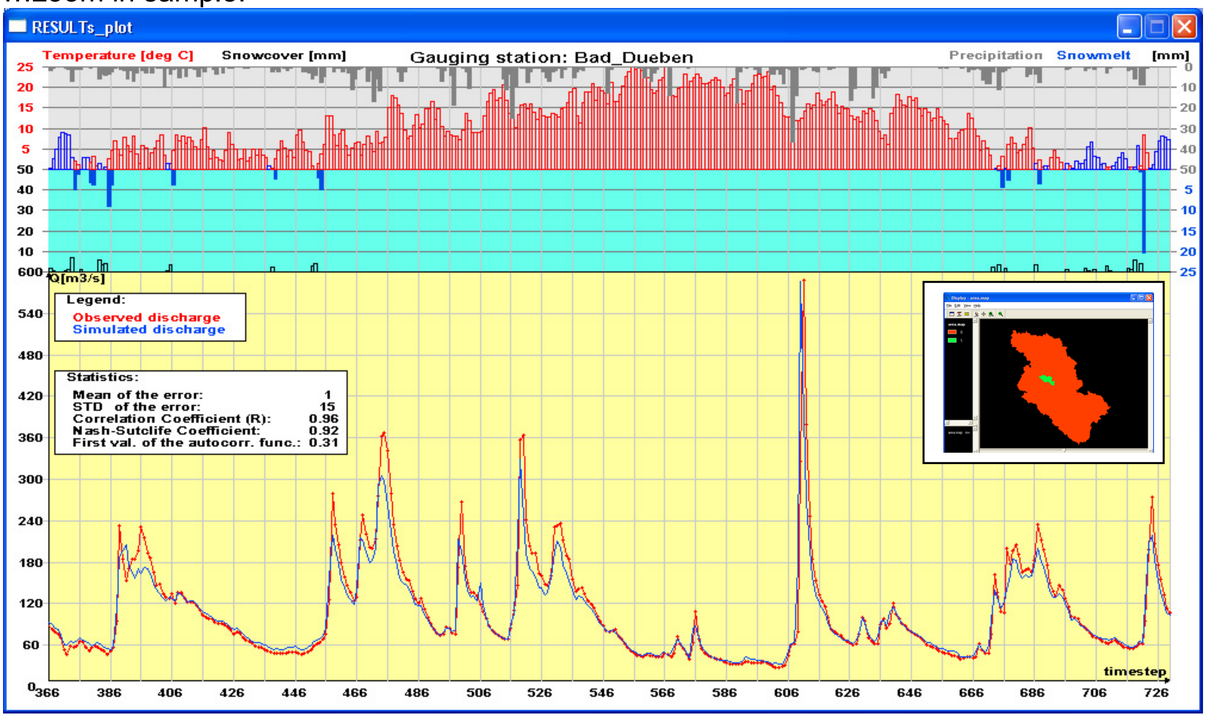


***Figure 5.4.2-6b** Simulation results of Mulde between stream gauges Golzern and Bad Dueben for the time period 01/01/1995 – 31/12/1995*

River WEISSE ELSTER

The River *Weisse Elster* (size of the river basin 5,154 km^2) has a length of 247.1 km and is a tributary of the *Saale*. It originates in the *Czech Republic in the Elster-Mountains* at an altitude of 724 maSL and flows into the *Elbe* near *Halle/Saale*. Important tributaries are *Weida* and *Pleisse*.

First, the calibration has been done for the first gauge downstream “Greiz”. Available were only daily mean discharge data for the whole time period between 1993 and 2002. The calibration results are quite reasonable.

Sub-catchment up to stream gauge Greiz – upper part

The best calibration achieved is shown in Figures 5.4.2-7a and b.

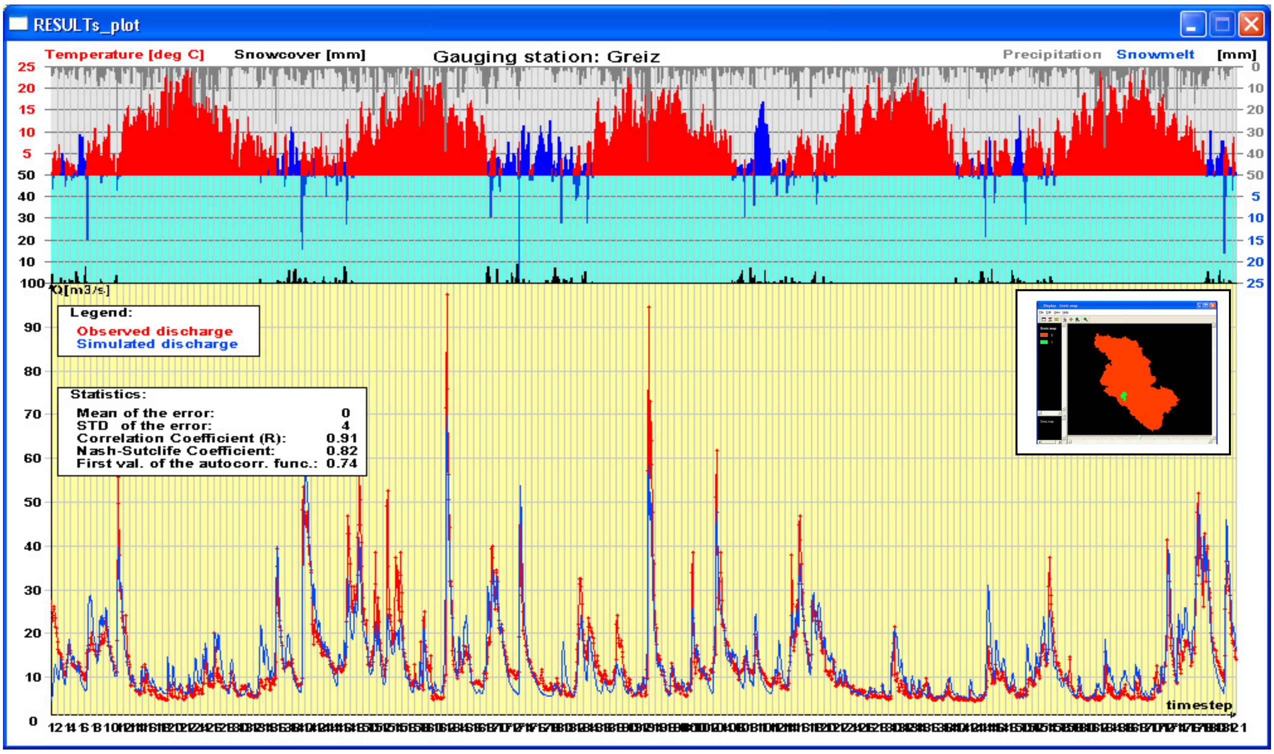


Figure 5.4.2-7a *Simulation results of Weisse Elster up to stream gauge Greiz (upper course) (1994 – 1998)*

…zoom in sample:

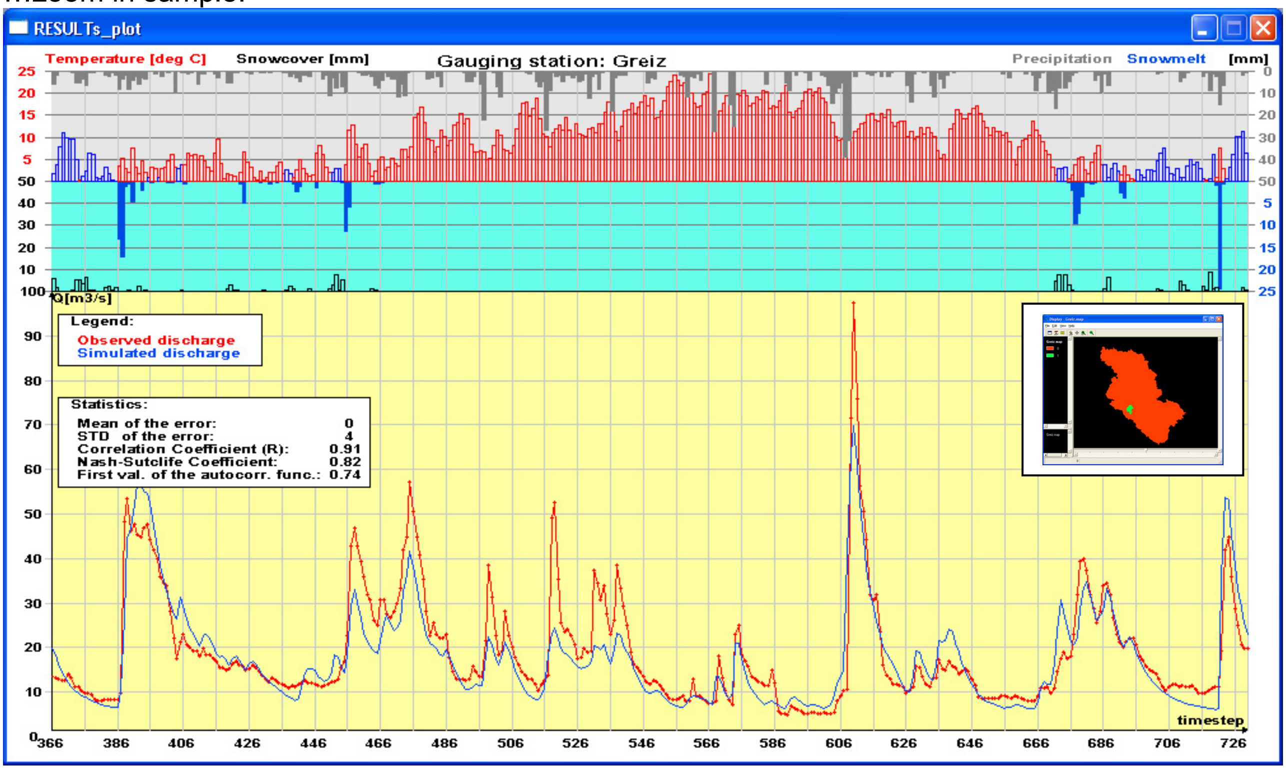


Figure 5.4.2-7b *Simulation results of Weisse Elster up to stream gauge Greiz (upper course) for the time period 01/01/1995-31/12/1995*

Sub-catchment between stream gauges Greiz and Klein Dalzig – lower course

The next stream gauge along the *Weisse Elster* which has been taken in consideration as a proper outlet point is “Klein Dalzig”, the last gauge before the river mouth to the *Saale*. But also for this gauge only daily mean data have been available, and also here frequently there are gaps over longer time periods in the data set between 1993 and 2003. However, the calibration results seem to be quite reasonable.

The best calibration achieved is shown in Figures 5.4.2-8a and b.

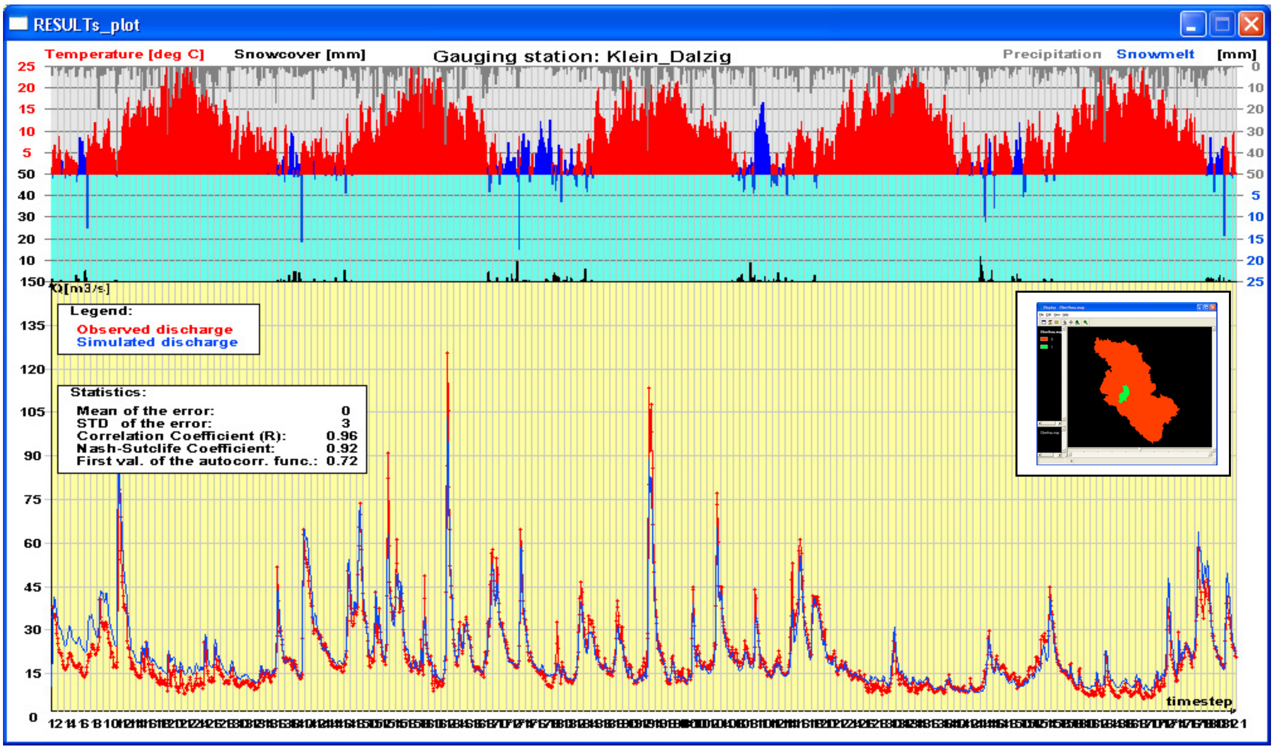


Figure 5.4.2-8a *Simulation results of Weisse Elster between stream gauges Greiz and Klein Dalzig (1994 – 1998)*

…zoom in sample:

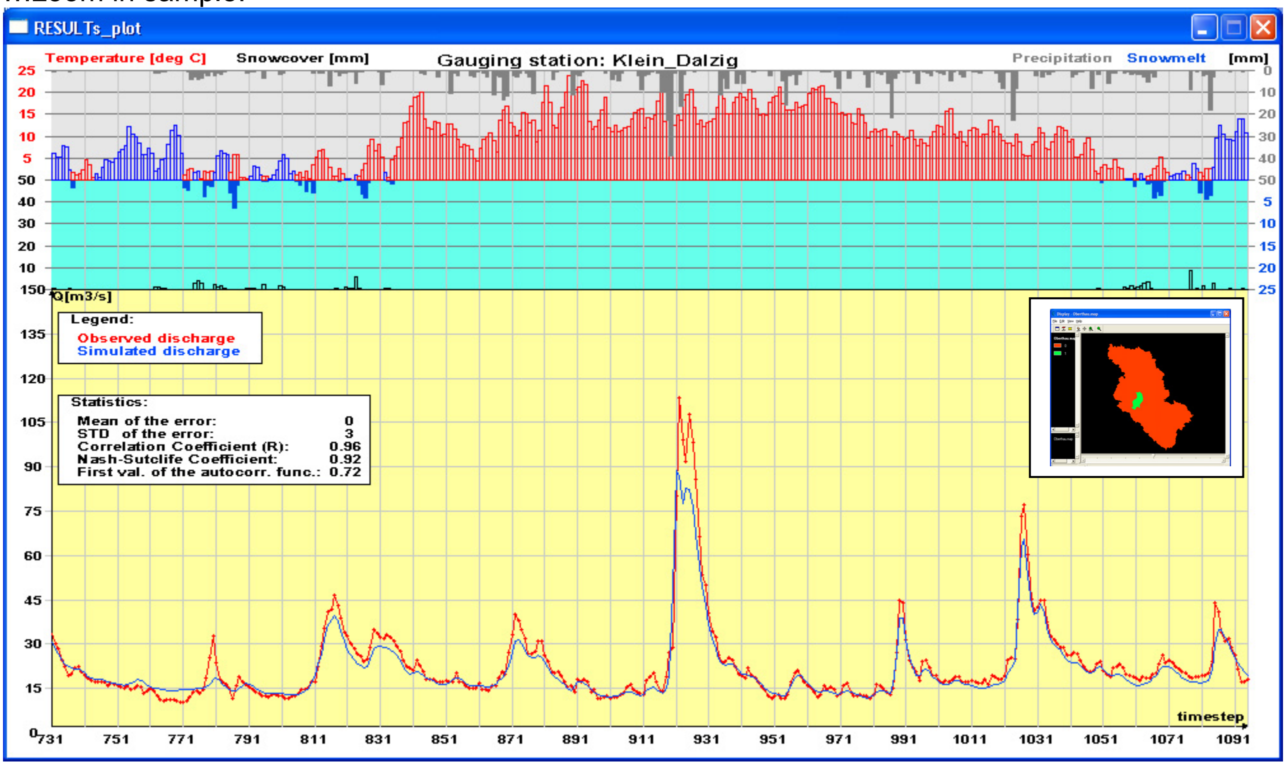


Figure 5.4.2-8b *Simulation results of Weisse Elster between stream gauges Greiz and Klein Dalzig for the time period 01/11/1995-31/12/1995*

River UNSTRUT

The River *Unstrut* (size of river basin 6,342.7 km^2) is 190 km long tributary of the River *Saale* and has its source west of *Kefferhausen at Dingelstaedt (in the North of the State Thuringia)* within the landscape *Eichsfeld*. It flows a short section through the *Thueringer Becken* and reaches then a wide valley area. In the lower course the *Unstrut* passes the state *Saxony-Anhalt* and meets the *Saale* near *Naumburg*. Important tributaries are *Gera, Wipper, Helme, Helbe and Lossa.* Regarding data, only daily mean data have been available.

Sub-catchment up to stream gauge Straussfurt - upper course; *one Rainfall Retention Basin exists close to the stream gauge Straussfurt.* The best calibration achieved is shown in Figures 5.4.2-9a and b**.**

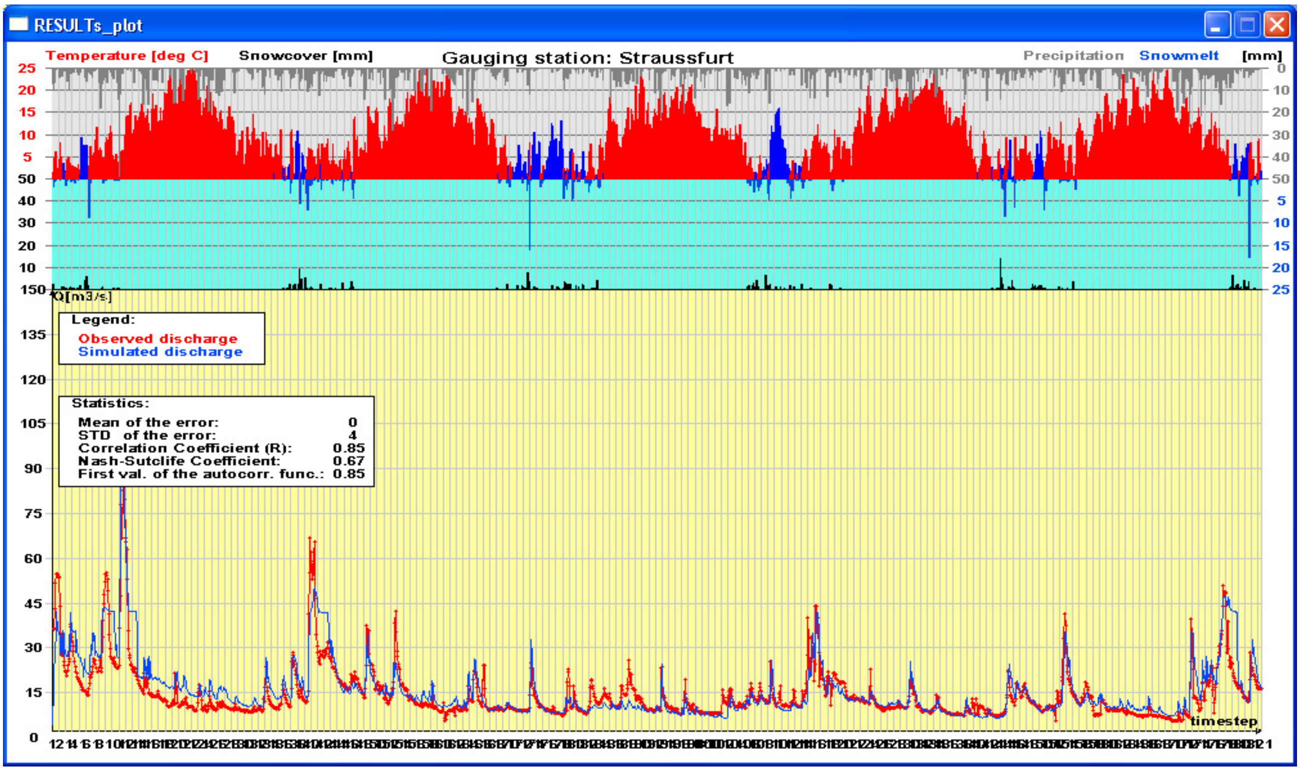


Figure 5.4.2-9a *Simulation results of Unstrut up to stream gauge Straussfurt (upper course) (1994 – 1998)*

…zoom in sample:

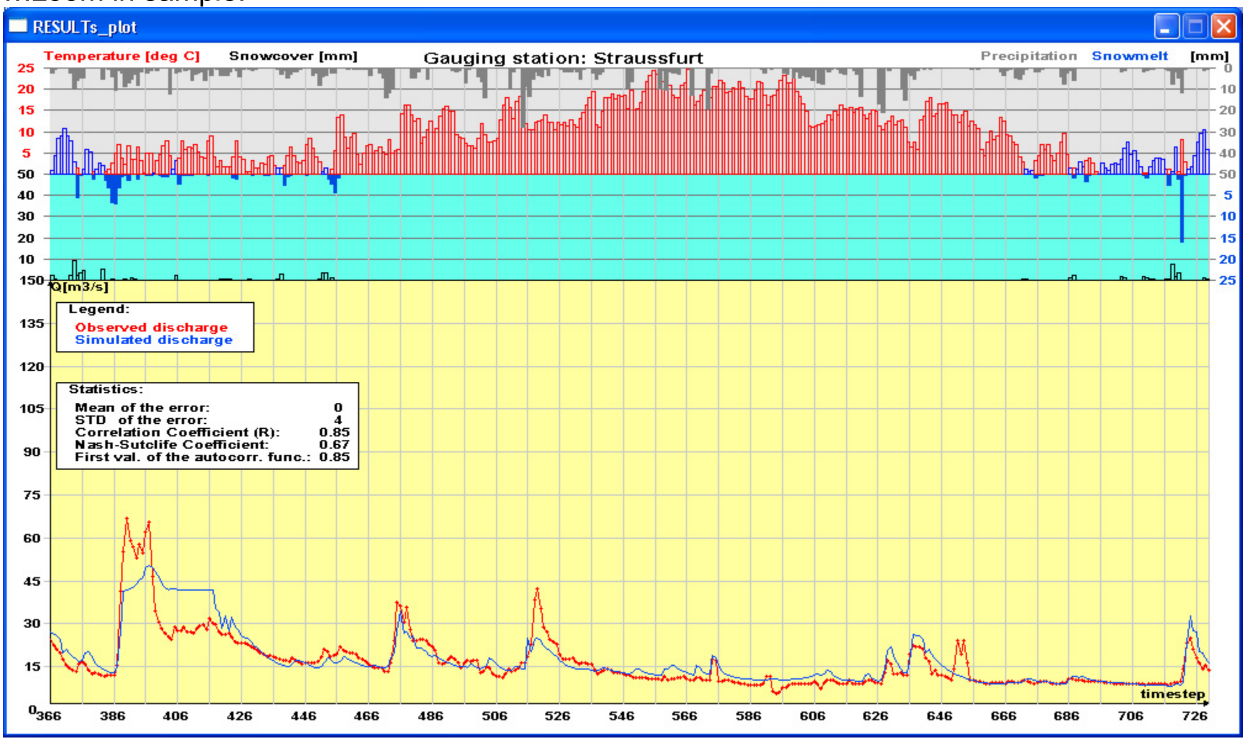


Figure 5.4.2-9b *Simulation results of Unstrut up to stream gauge Straussfurt (upper course) for the time period 01/11/1995-31/12/1995*

Sub-catchment between stream gauges Straussfurt and Oldisleben

The best calibration achieved is shown in Figures 5.4.2-10a and b.

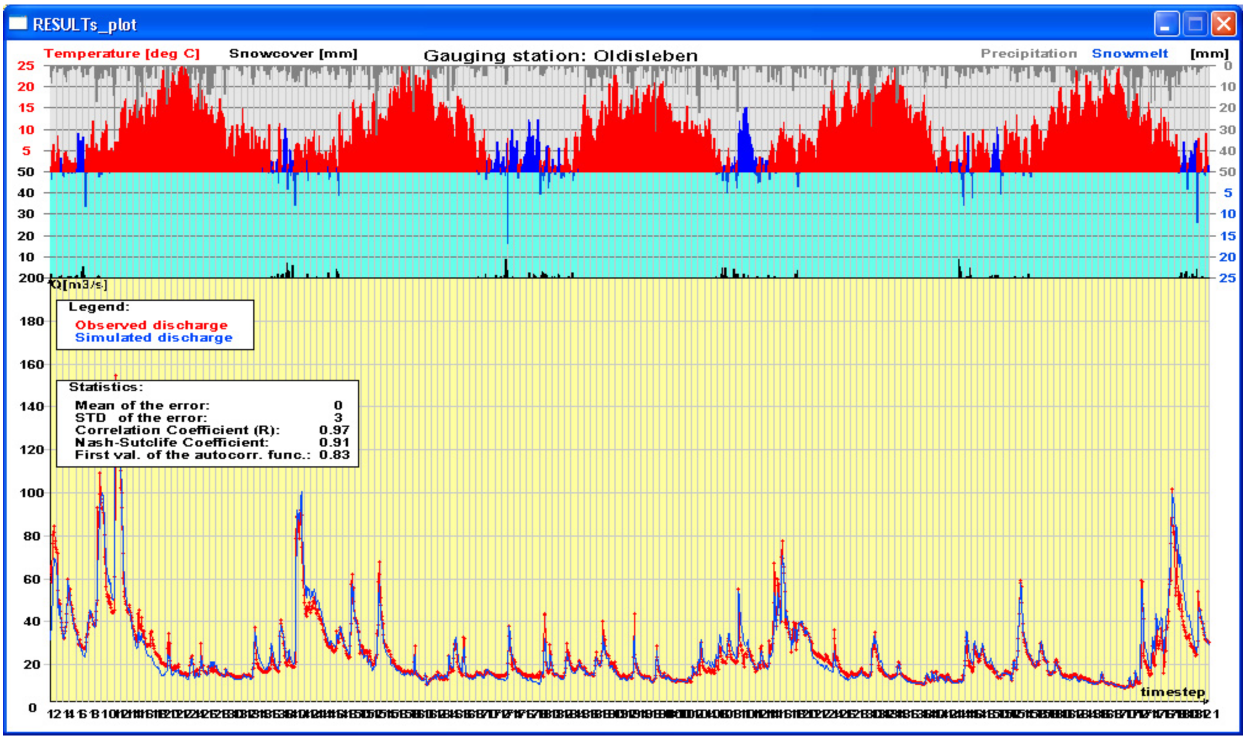


***Figure 5.4.2-10a** Simulation results of Unstrut between stream gauges Straussfurt and Oldisleben (1994 – 1998)*

…zoom in sample:

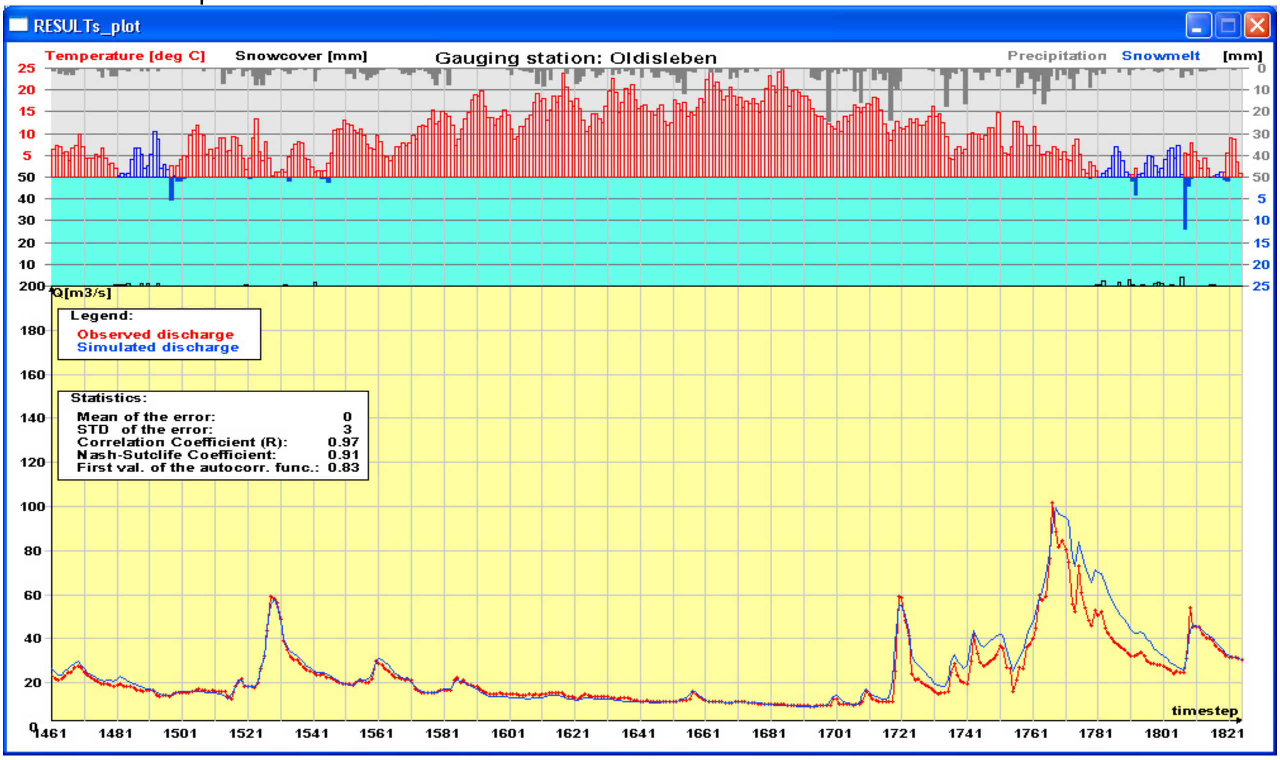


***Figure 5.4.2-10b** Simulation results of Unstrut between stream gauges Straussfurt and Oldisleben for the time period 01/11/1998-31/12/1998*

River SAALE

The River *Saale* (size of the river basin 24,079 km^2) represents with its length of 433.9 km the second longest tributary of the River *Elbe* after the *Vlatava (Czech Republic).* It flows through the German states *Bavaria, Thuringia and Saxony-Anhalt.* The *Saale* has its source on the north-west part of the *Waldstein* in the *Fichtelgebirge* near *Zell* in *Oberfranken (State Bavaria*) at an altitude of 728 maSL. Important tributaries are the *Schwarza, Ilm, Unstrut, Wipper, Bode, Orla and Weisse Elster*. The *Saale* meets the *Elbe* at *Barby*.

In the upper river course the *Saale* runs more or less leisurely. Further on, it passes the *Thueringer Schiefergebirge*. The upstream part of the river basin contains a six-step reservoir cascade *(Bleiloch, Wisenta, Burgkhammer, Walsburg, Hohenwarte, Eichicht).* The largest and most important reservoirs are the *Bleiloch* reservoir and the *Hohenwarte* reservoir.

Sub-catchment up to stream gauge Blankenstein - upper part

The best calibration achieved is shown in Figures 5.4.2-11a and b**.**

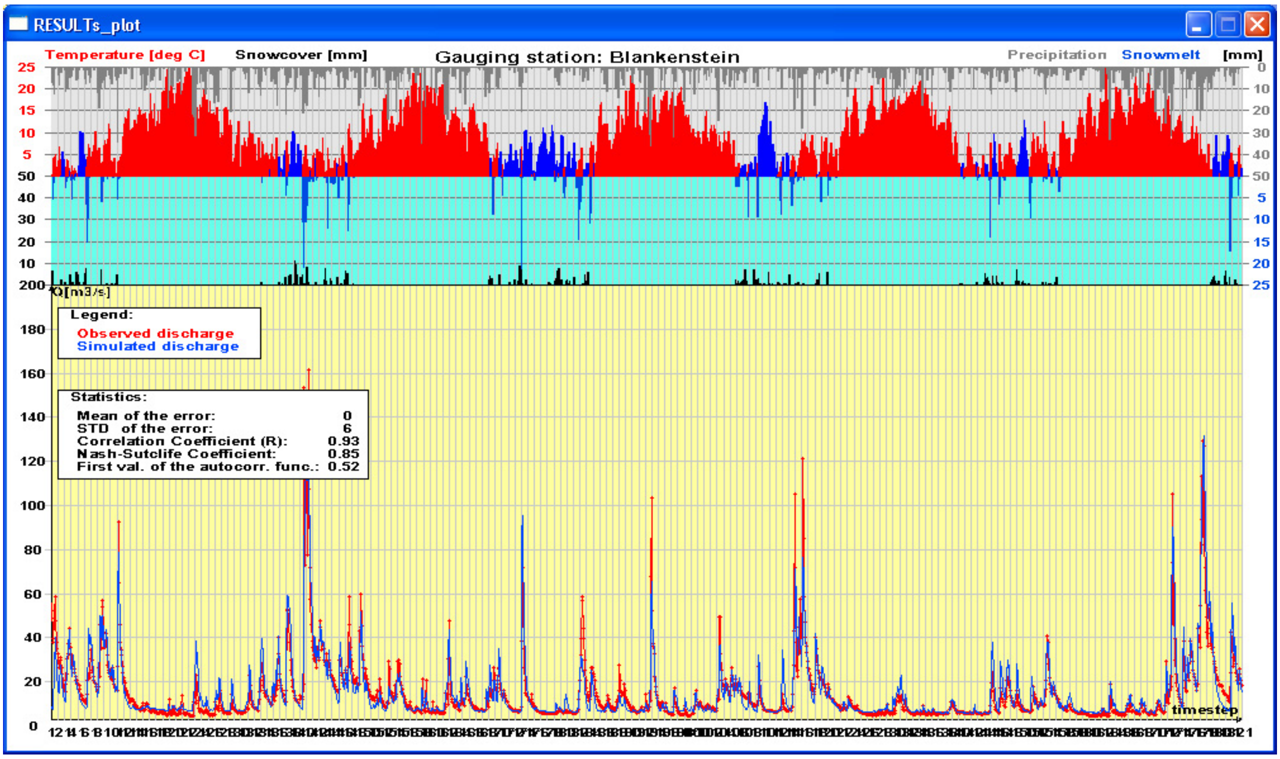


***Figure 5.4.2-11a** Simulation results of Saale up to stream gauge Blankenstein (1994–1998)*

…zoom in sample:

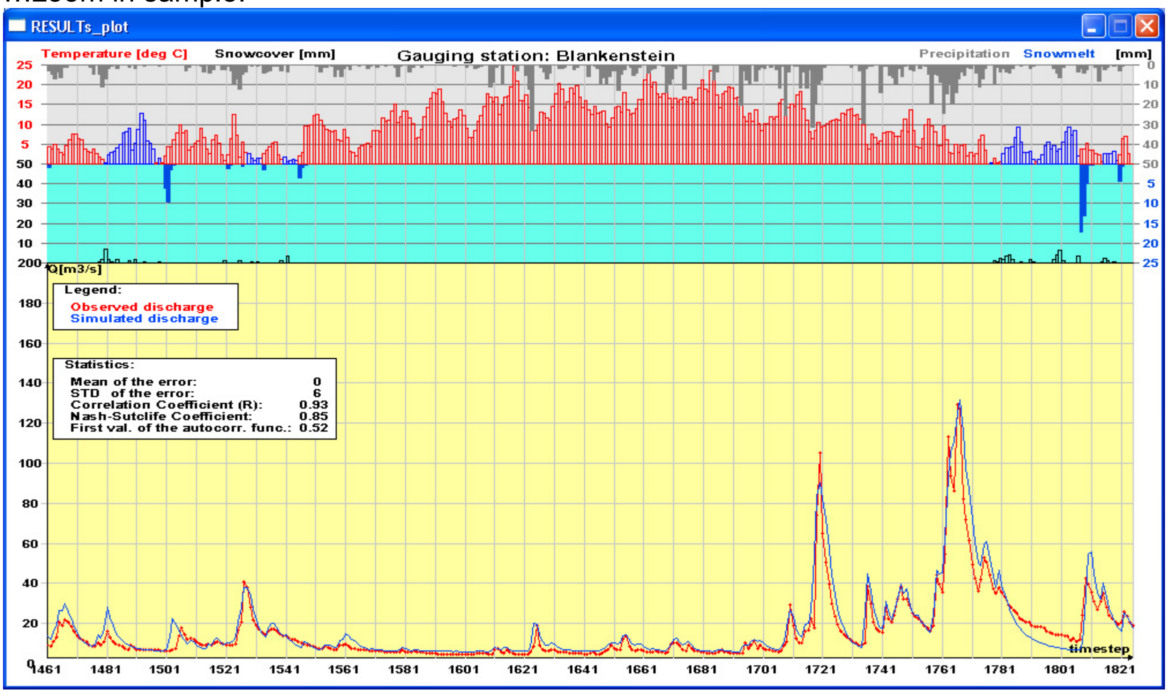


***Figure 5.4.2-11b** Simulation results of Saale up to stream gauge Blankenstein for the time period 01/01/1998 – 31/12/1998*

Sub-catchment between stream gauges Blankenstein and Kaulsdorf (reservoir cascade) - upper course

The best calibration achieved is shown in Figures 5.4.2-12a-c.

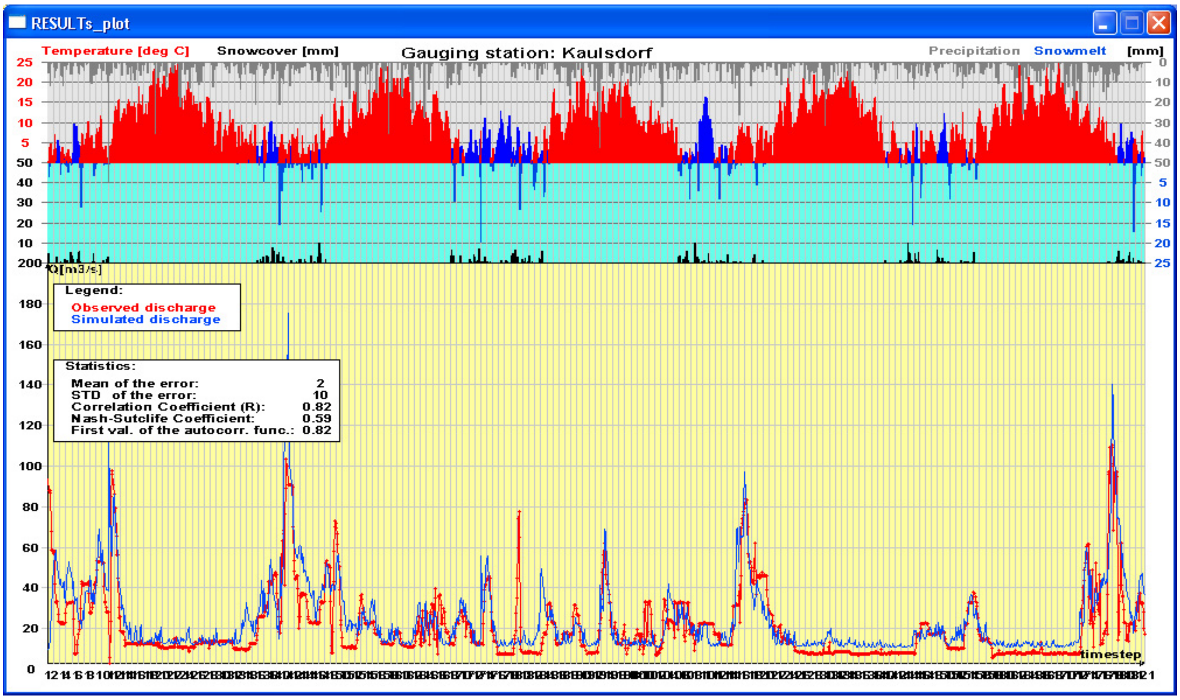


***Figure 5.4.2-12a** Simulation results of Saale between stream gauges Blankenstein and Kaulsdorf – Saale cascade (1994 – 1998)*

…zoom in sample:

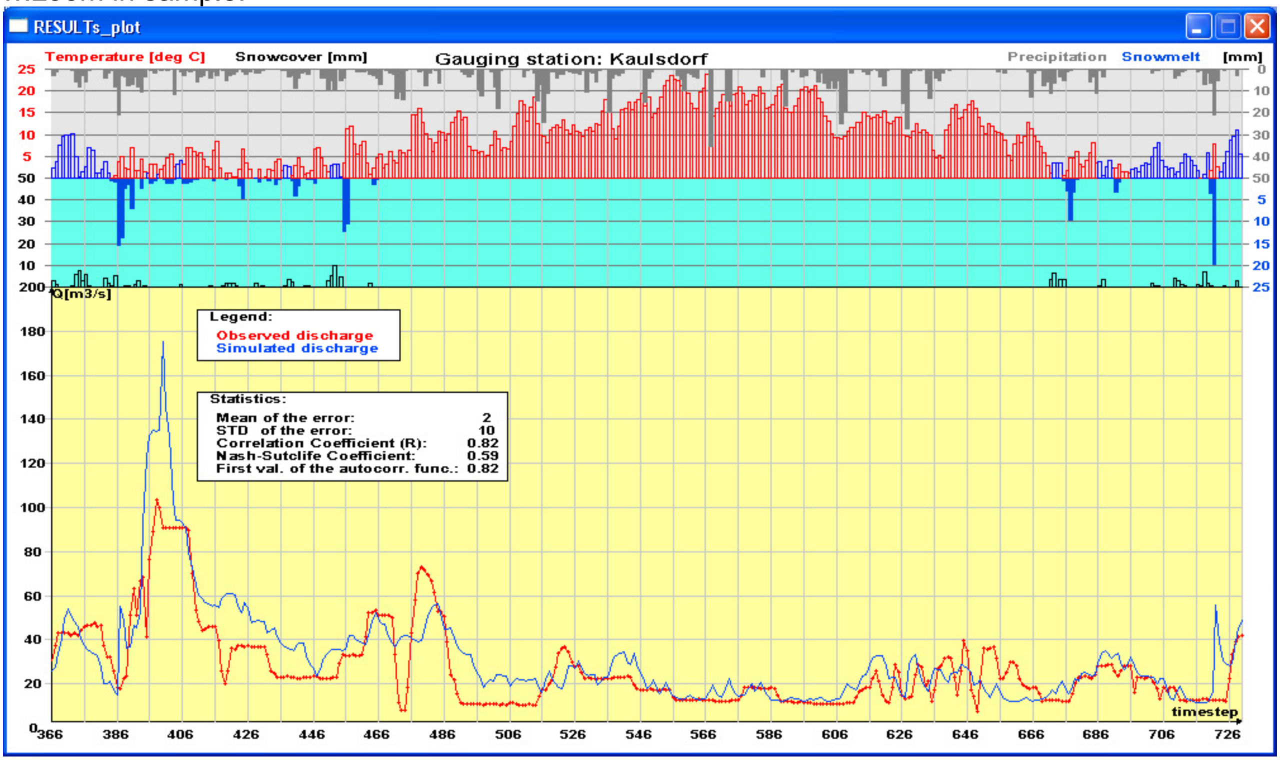


***Figure 5.4.2-12b** Simulation results of Saale between stream gauges Blankenstein and Kaulsdorf – Saale cascade for the time period 01/01/1995 – 31/12/1995*

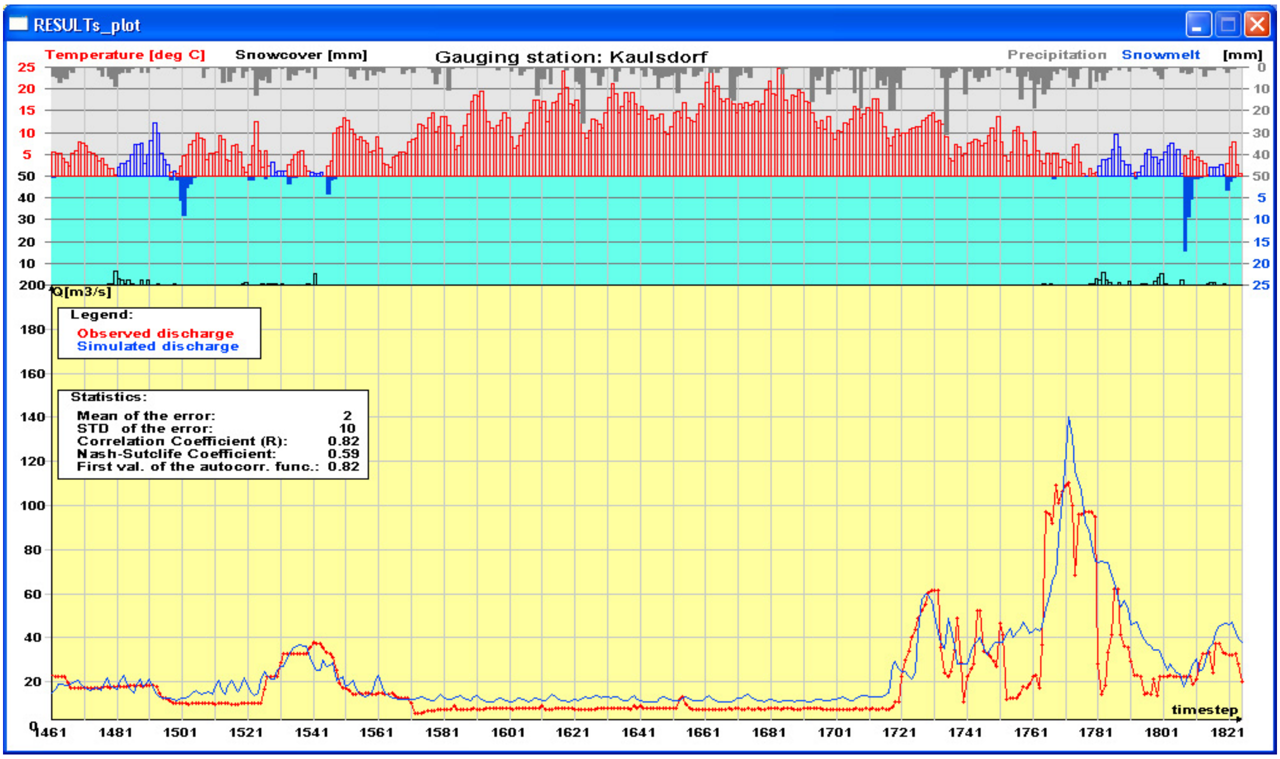


Figure 5.4.2-12c *Simulation results of Saale between stream gauges Blankenstein and Kaulsdorf – Saale cascade for the time period 01/01/1998 – 31/12/1998*

Sub-catchment between stream gauges Kaulsdorf and Naumburg – middle course

The best calibration achieved is shown in Figures 5.4.2-13a and b.

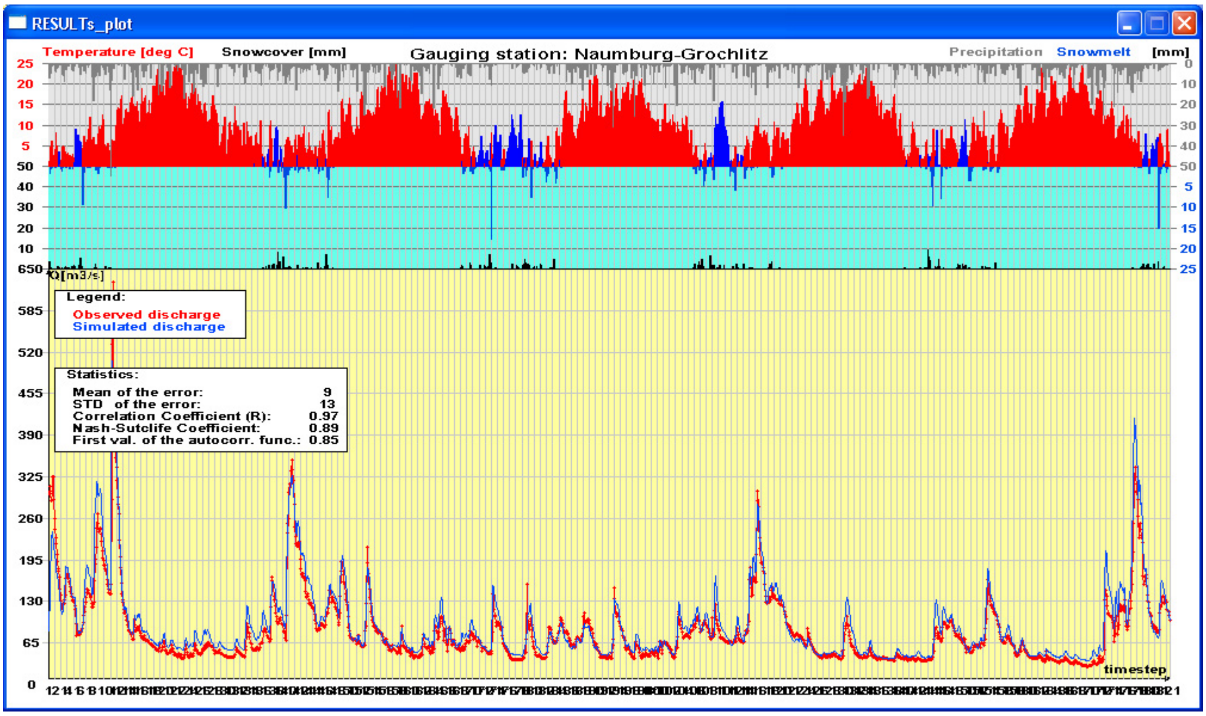


Figure 5.4.2-13a *Simulation results of Saale between stream gauges Kaulsdorf and Naumburg-Grochlitz (1994 – 1998)*

…zoom in sample:

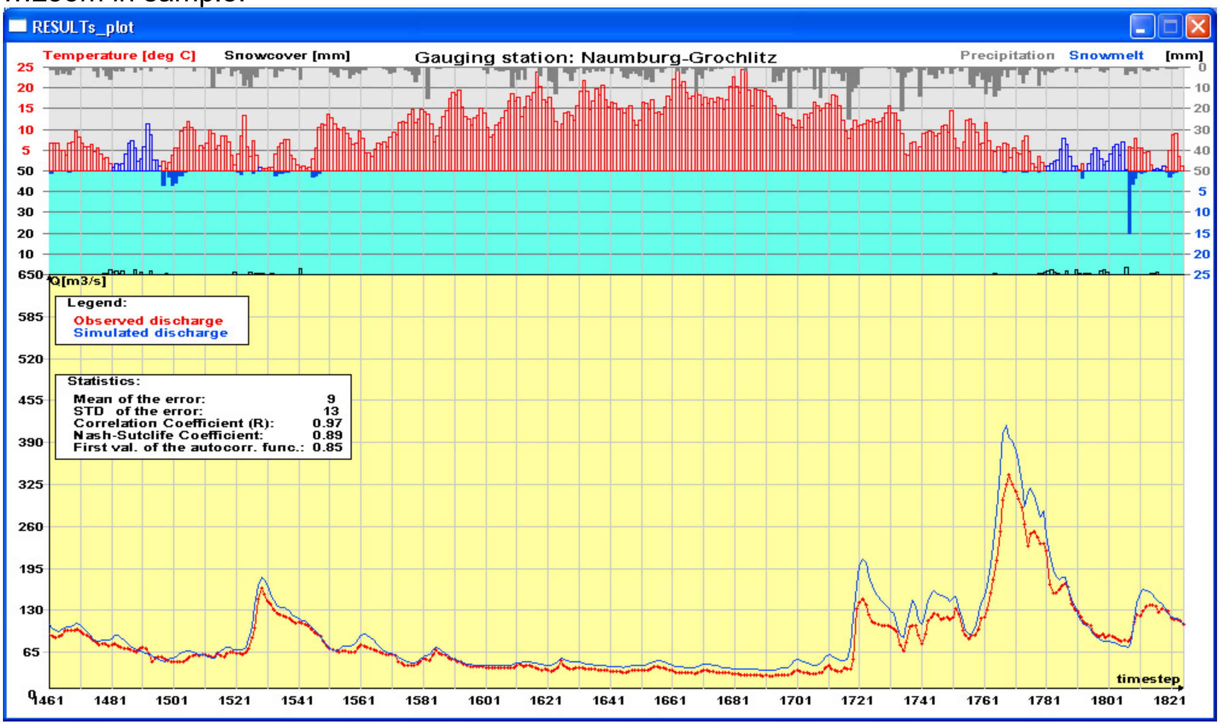


Figure 5.4.2-13b *Simulation results of Saale between stream gauges Kaulsdorf and Naumburg-Grochlitz for the time period 01/01/1998 – 31/12/1998*

Sub-catchment between stream gauges Naumburg and Calbe-Griezehne – lower course

This river section represents a typical lowland river. Before going to the calibration results, the following analysis of the observed discharge data is important. The names of the gauging stations are referred to in Figure 5.4.2-14.

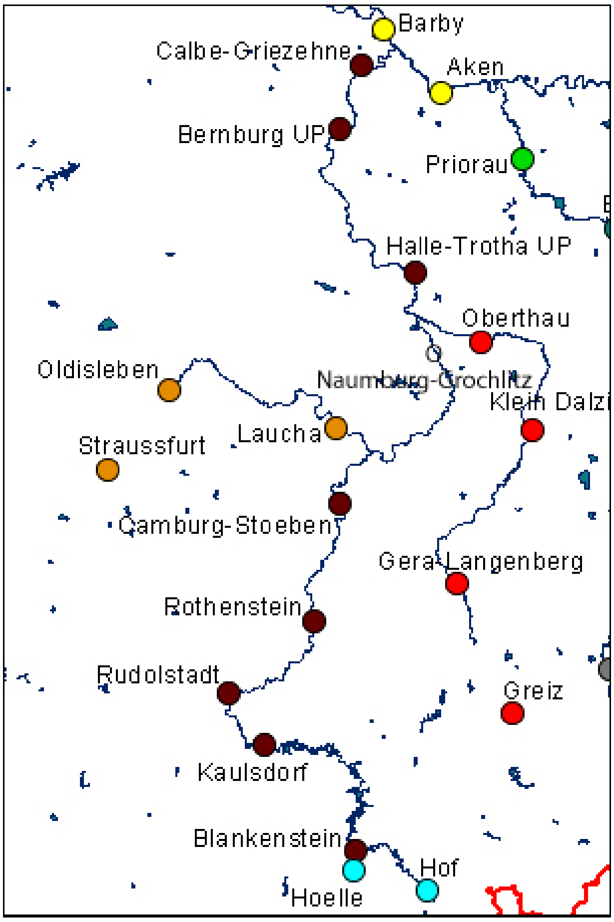


Figure 5.4.2-14 *Discharge gauging stations in the Saale tributary*

Comparing hourly discharge of the stream gauges Calbe-Griezehne, Bernburg, Halle-Trotha, Naumburg-Grochlitz as well as the summed discharge sum of Oberthau (Weisse Elster tributary) and Naumburg-Grochlitz (downstream Laucha and Camburg-Stoeben) for the 2002 event, resulted in the graph presented below as *Figure 5.4.2-15.*

If all observed data would be right, discharge at

- Laucha + Camburg/Stoeben <= Naumburg-Grochlitz
- Oberthau + Naumburg-Grochlitz <= Halle-Trotha
- Halle-Throtha <= Bernburg
- Bernburg <= Calbe-Griezehne
- Aken + Calbe-Griezehne <= Barby

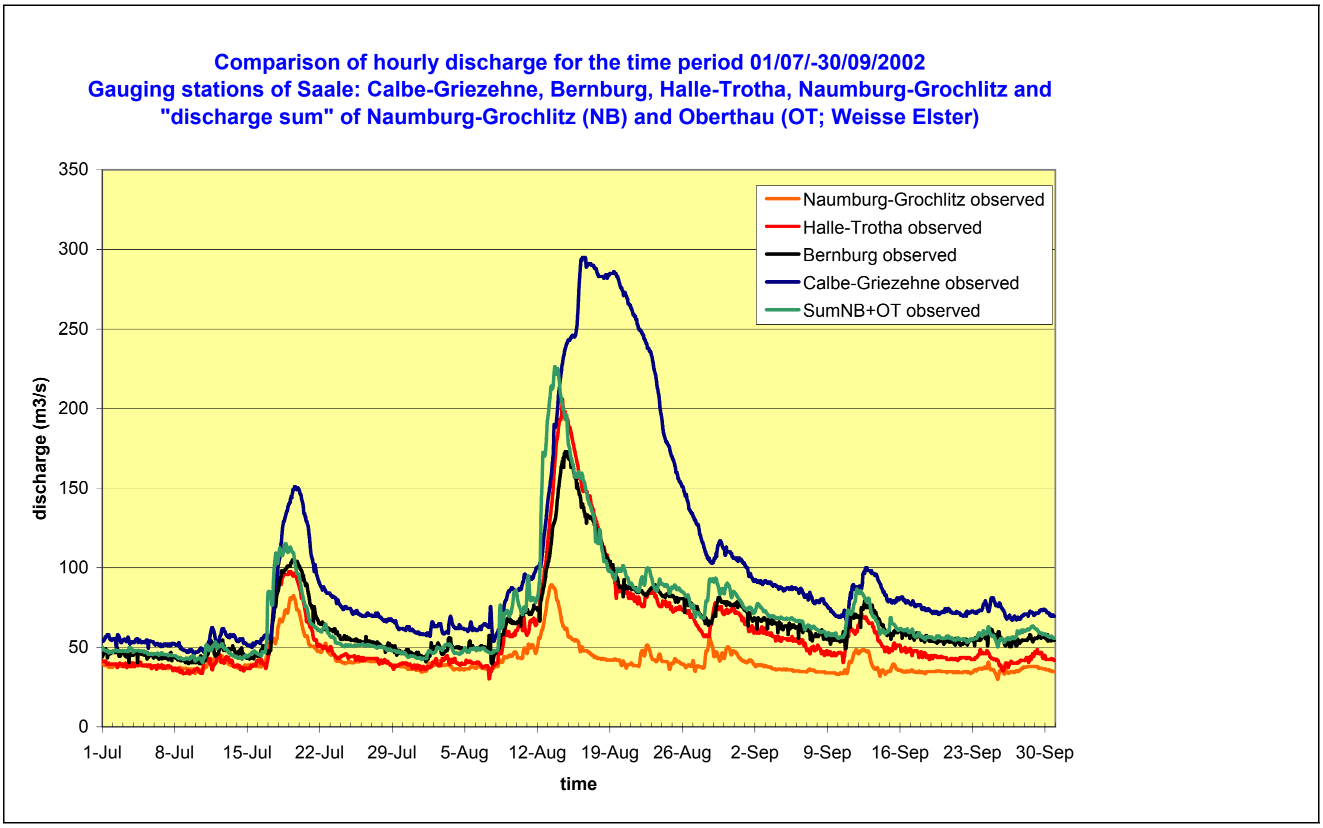


Figure 5.4.2-15 *Comparison of hourly discharge time series of stream gauging stations along the River Saale (downstream)*

From figure 5.4.2-15 it can be concluded that the discharge observed at Calbe-Griezehne is much higher than the summed discharge of Oberthau and Naumburg-Grochlitz. One would expect that it would only be a little higher.

There could be several explanations for this:

- The observed data at Calbe-Griezehne are wrong (are too high)
- The data at Naumburg-Grochlitz are wrong (too low)
- There is a large additional inflow of water downstream of Oberthau and Naumburg-Grochlitz

Although the data at the stream gauge Calbe-Griezehne look a bit strange, they are probably reliable because the summation of the closest neighbor stream station within the Elbe – Aken and Calbe-Griezehne itself – equals almost the “data” given at stream gauge Barby in the Elbe, after the River Saale as a tributary flows into the Elbe *(Figure 5.4.2-16).*

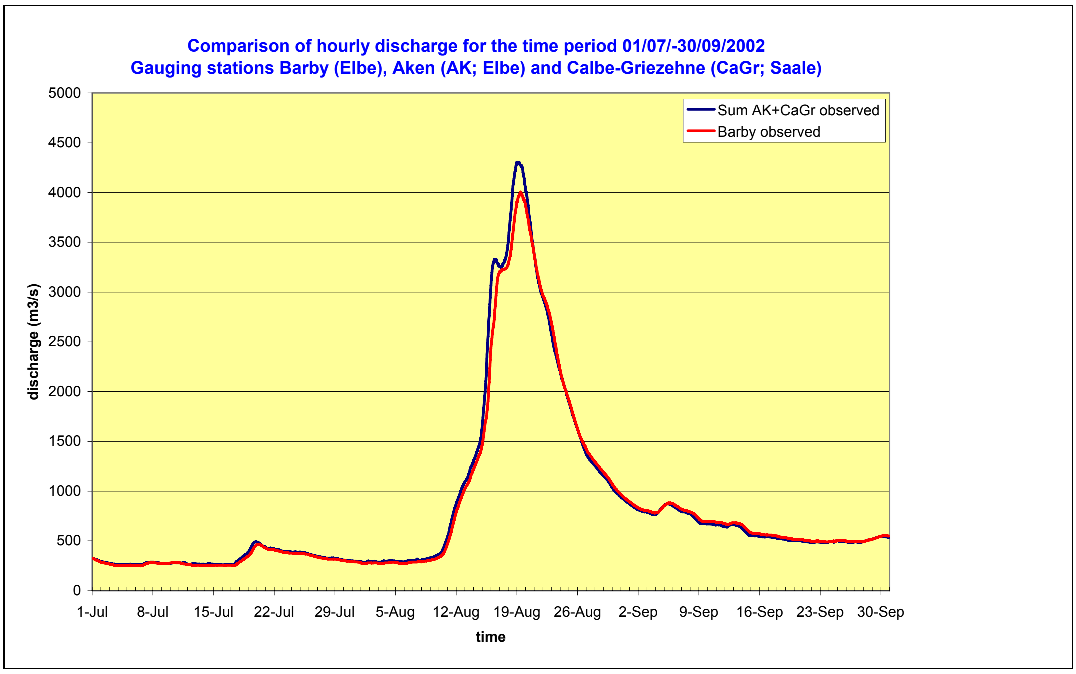


Figure 5.4.2-16 *Comparison of hourly discharge time series of stream gauging station Barby (Elbe) with the pure discharge summation of the gauges Aken (Elbe) and Calbe-Griezehne (Saale; last gauge before confluence with Elbe)*

Furthermore, since the summation of the data at gauge Laucha (Unstrut tributary) and Camburg-Stoeben (Saale) has a similar magnitude and pattern, you could assume the data at Naumburg-Grochlitz (Saale) are correct too *(Figure 6.4.2-17).*

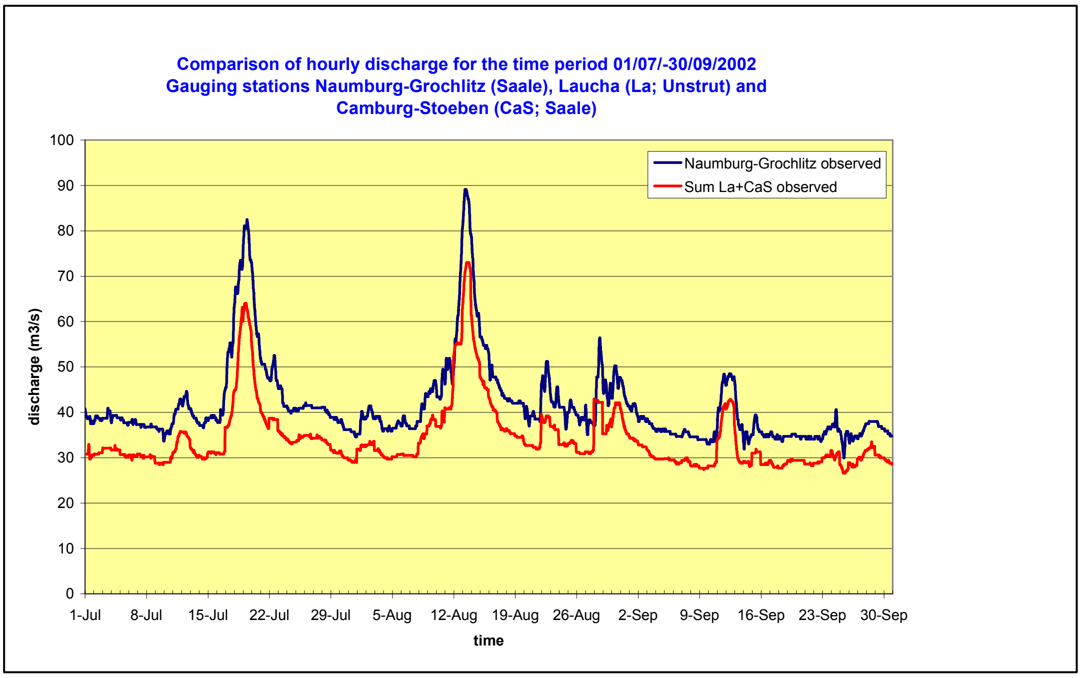


Figure 5.4.2-17 *Comparison of hourly discharge time series of stream gauging station Naumburg-Grochlitz (Saale) with the pure discharge summation of the gauges Laucha (Unstrut tributary) and Camburg-Stoeben (Saale).*

Next, it can be seen that the summed discharge of stream gauges Naumburg-Grochlitz and Oberthau (Weisse Elster tributary) is larger than the discharge further downstream at the gauge Halle-Trotha (Figure 5.4.2-18)

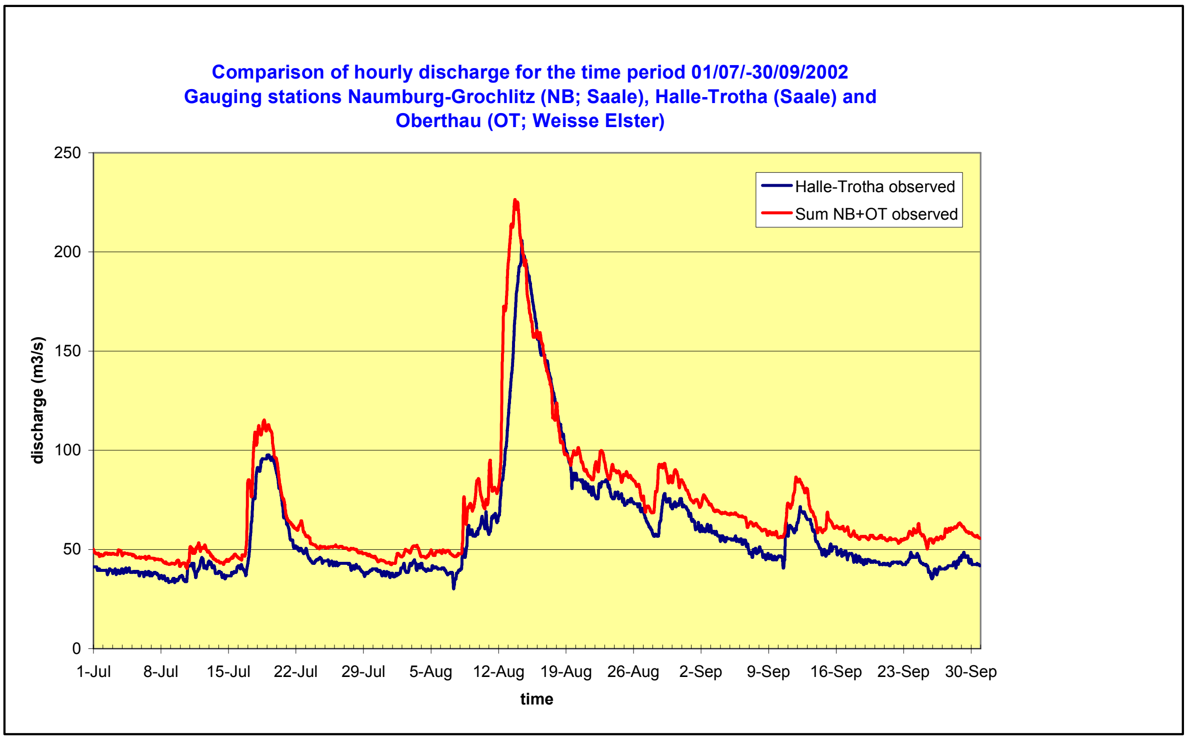


Figure 5.4.2-18 *Comparison of hourly discharge time series between stream gauging station Halle-Trotha and the pure discharge summation of Naumburg-Grochlitz (Saale) and Oberthau (Weisse Elster)*

Summarizing these "observed" data sets show that:

- Upstream discharges seem to be all ok and consistent;
- Discharge at Calbe-Griezehne is also correct;
- There seems to be water disappearing directly upstream of Halle-Trotha; if not the case, than the observed data at Halle-Trotha and Bernburg must be slightly inaccurate;
- There is a sudden extreme increase in discharge between Bernburg and Calbe-Griezehne.

One hypothesis is that a slight amount of water from the River Saale is lost in the neigbourhood of Halle-Trotha. Through several phone calls with staff from German water authorities in charge, this could not be confirmed: no water loss of such an amount of water is known. This leaves only the conclusion that the measured data of Halle and Bernburg are not completely accurate.

As for the sudden increase in discharge at Calbe-Greizehne, we hypothesized that the additional water must come from the River Bode. The River Bode (size of the river basin 3,297.4 km^2) has a length of about 169 km and flows as tributary into the Saale between Bernburg and Calbe. It originates in the *Harz* Mountains. There the highest mountain is the *Brocken* with 1,141 maSL. Through the headwaters and tributaries *Warme Bode*, *Kalte Bode, Rappode* and *Hassel* the River Bode drains a big part of the Harz-Plateau. Within the upper river course a couple of reservoirs influence the streamflow further downstream.

The provided data for the Bode were not sufficient enough to prove that the additional water was coming from the Bode, but there is no other explanation. Therefore, an artificially calculated inflow point of the Bode - close to the river junction with the Saale – has been introduced. The Bode-Inflow has been calculated by subtracting the observed discharge at Bernburg from the observed discharge values at *Calbe-Griezehne.* This approach has been done using observed daily as well as hourly discharge data.

Using this artificially calculated Bode inflow, as well as all other data, the calibration has been carried out for the Saale catchment. It has to be noted – given the findings above - that very likely the data for the stream gauge Bernburg are not fully correct, which would influence the artificially calculated inflow of the river Bode as well.

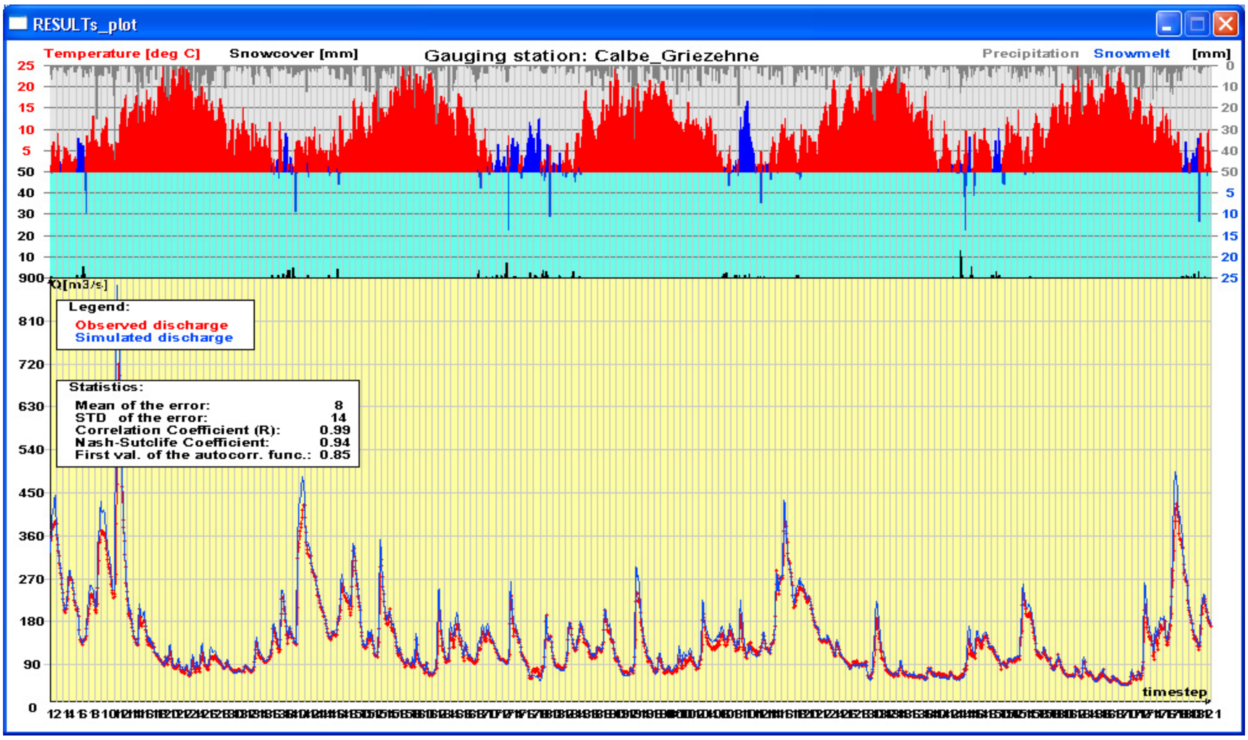


Figure 5.4.2-19 *Simulation results of Saale between stream gauges Naumburg-Grochlitz and Calbe-Griezehne using "artificially calculated" inflow of River Bode (1994 – 1998)*

…zoom in sample:

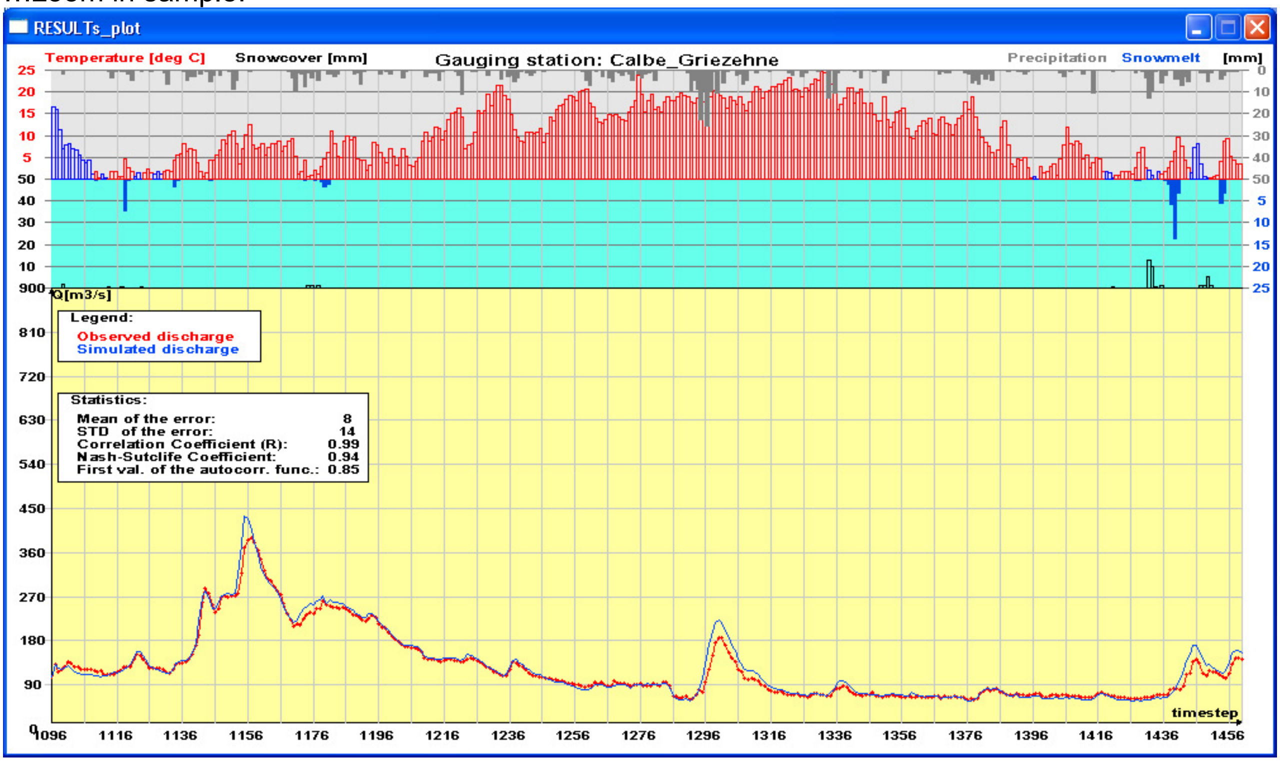


Figure 5.4.2-20 *Calibration results of Saale between stream gauges Naumburg-Grochlitz and Calbe-Griezehne using "artificially calculated" inflow of River Bode for the time period 01/01/1997 – 31/12/1997*

The calibration results using River Bode as an “artificially calculated” inflow show good statistics. The simulated hydrograph fits much better now the observed one. The best calibration achieved is shown in Figures 5.4.2-19 and 20.

In conclusion for the Saale, the LISFLOOD model simulates the water balance of the Saale catchment with reasonable quality and simulates the response of the Saale and its tributaries satisfactory for the winter flood events in April 1994 and in January 2003. For the summer event in August 2002 the results have been reasonable while applying a derived inflow of the tributary Bode.

River ELBE (main Elbe)

The German part of the main Elbe river – in this report referring to the Elbe between the stream gauges Schoena at the German-Czech border and gauge Geesthacht – has been simulated using the dynamic wave algorithm in LISFLOOD, with an hourly simulation time-step. The calibration and validation has been done for the flood events in April 1994, August 2002 and January 2003.

As the inflow for the main stream the observed discharge of the Czech stream gauge Usti has been used. In addition, measured inflow discharges from the following German tributaries:

- Bad Liebenwerda (Schwarze Elster);
- Priorau (Mulde);
- Calbe-Griezehne (Saale);
- Rathenow (Havel);
- Wolfshagen (Stepenitz).

All other inflow has been simulated, using the parameter sets as calibrated and discussed in this report in earlier chapters.

River cross sections have been made available by several German authorities, and have been processed for the use in LISFLOOD model (see Chapter 4.2.4). All provided cross sections downstream of Wittenberge have not been used, since unrealistic results were obtained using them, and the cross sections themselves seem only to refer to the river, and not the adjacent floodplain.

The channel river roughness (Manning value) has been used as a calibration parameter. A first estimate was made of the Manning value based on scientific literature and simulations in other river basins. A separate roughness multiplier was used for each individual river section between the available gauging stations. The following sections were calibrated separately:

- Schöna - Dresden;
- Dresden – Torgau;
- Torgau - Lutherstadt/Wittenberg;
- Lutherstadt/Wittenberg – Aken;
- Aken - Barby;
- Barby – Magdeburg;
- Magdeburg – Tangermünde;
- Tangermünde - Wittenberge;
- Wittenberge - Neu-Darchau;
- Neu Darchau - Geesthacht.

The discharge calibrations for the 2002 summer flood event are shown in the following figures (Figures 5.4.2-21 - 5.4.2-27).

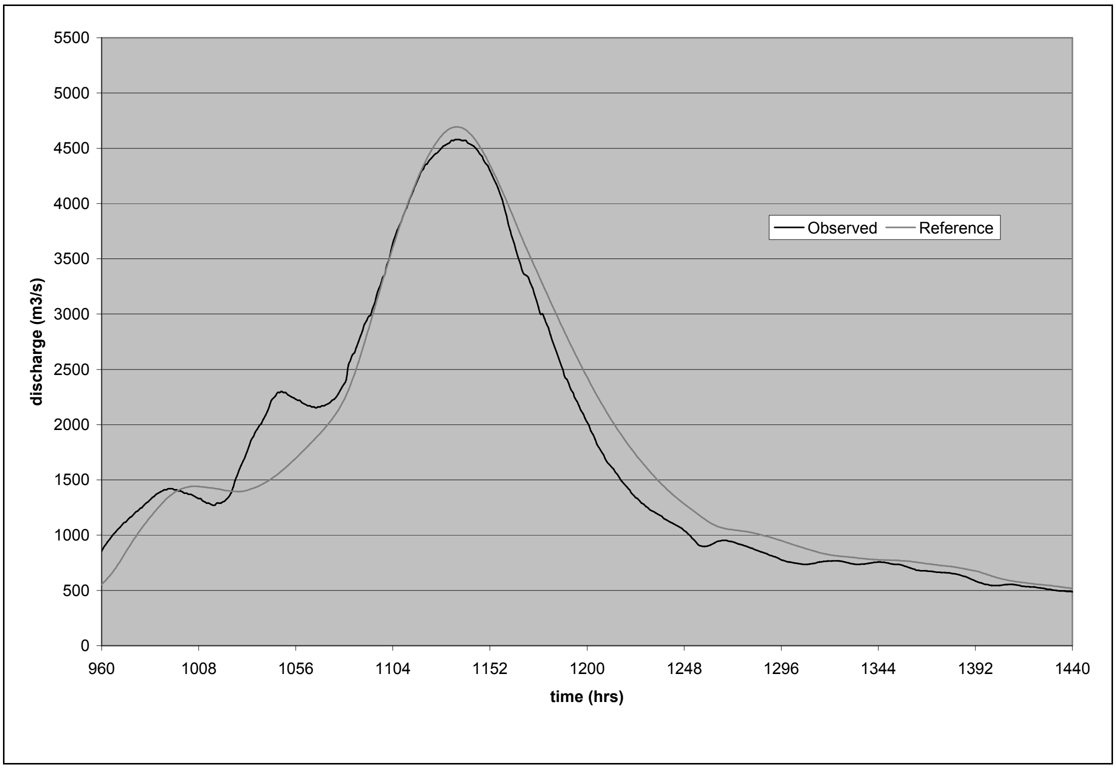


Figure 5.4.2-21 *Calibration results of the main Elbe at Dresden, August 2002 event: observed and simulated discharge (timesteps in hours)*

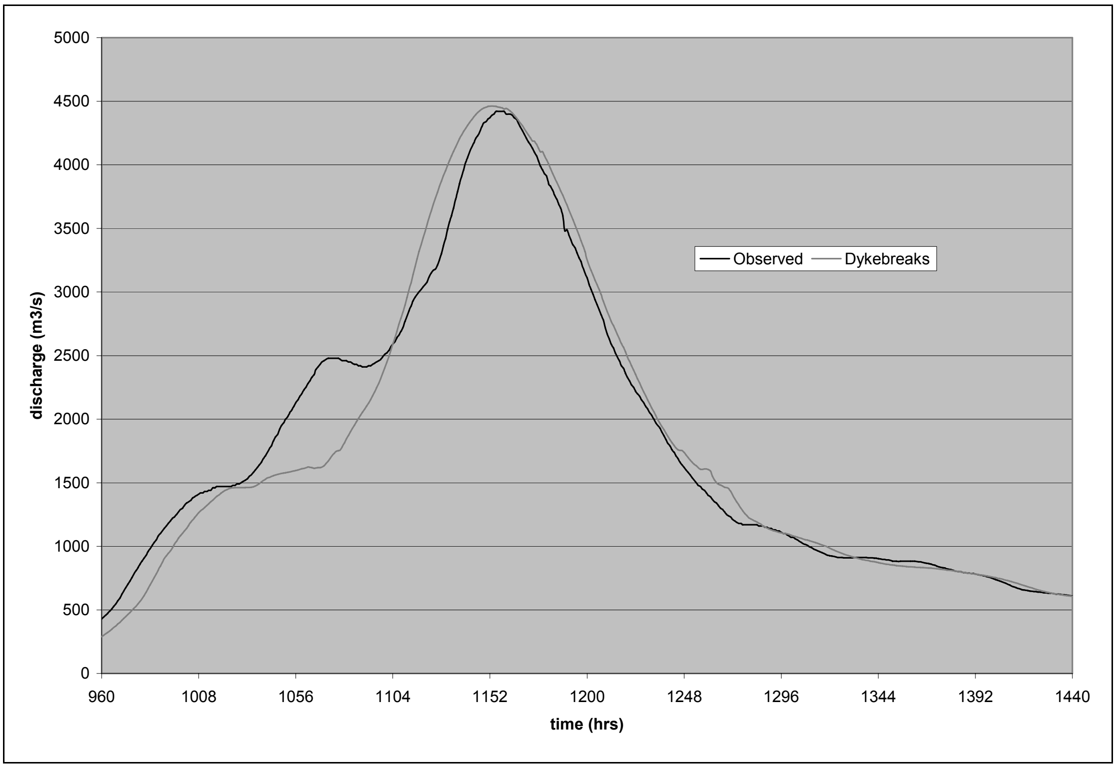


Figure 5.4.2-22 *Calibration results of the main Elbe at Torgau, August 2002 event: observed and simulated discharge incl dyke-breaks (timesteps in hours)*

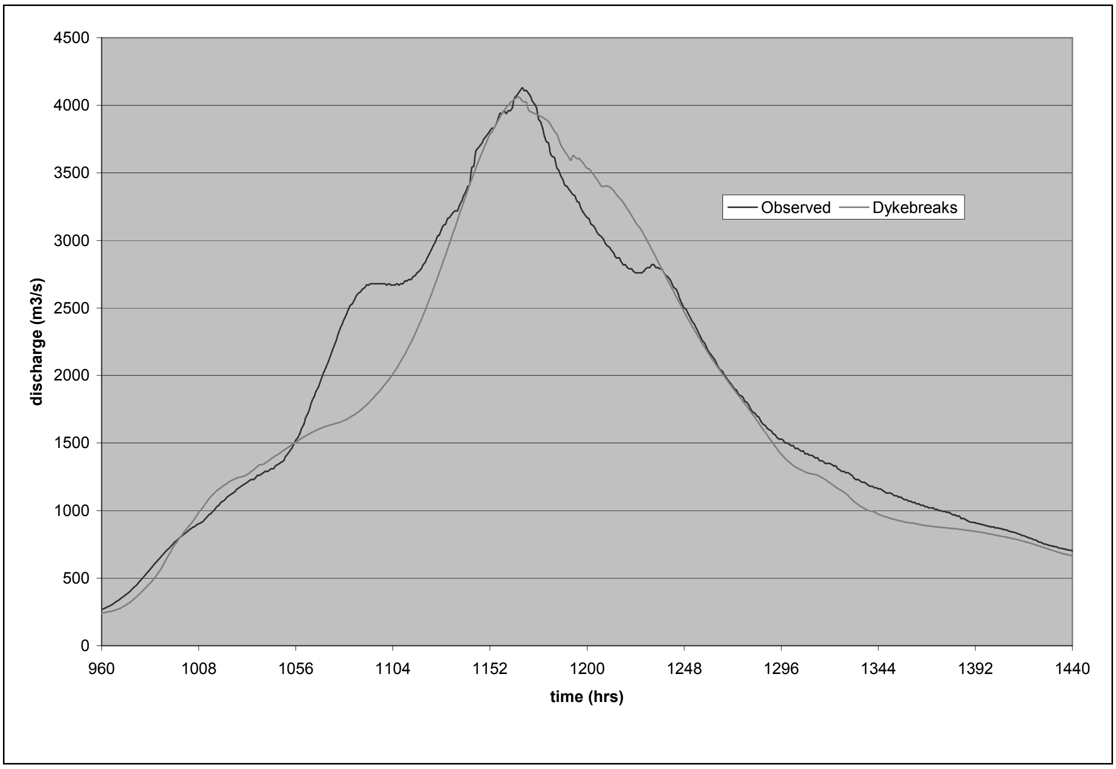


Figure 5.4.2-23 *Calibration results of the main Elbe at Lutherstadt-Wittenberg, August 2002 event: observed and simulated discharge incl dyke-breaks (timesteps in hours)*

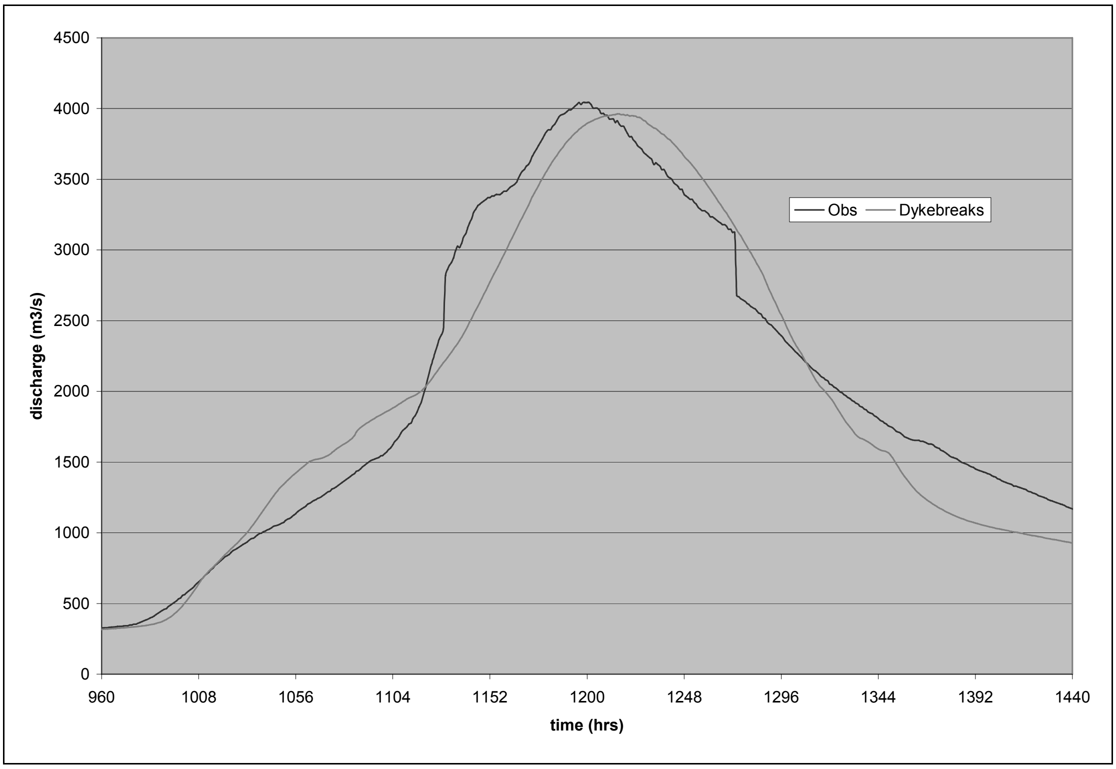


Figure 5.4.2-24 *Calibration results of the main Elbe at Magdeburg, August 2002 event: observed and simulated discharge incl dyke-breaks (timesteps in hours)*

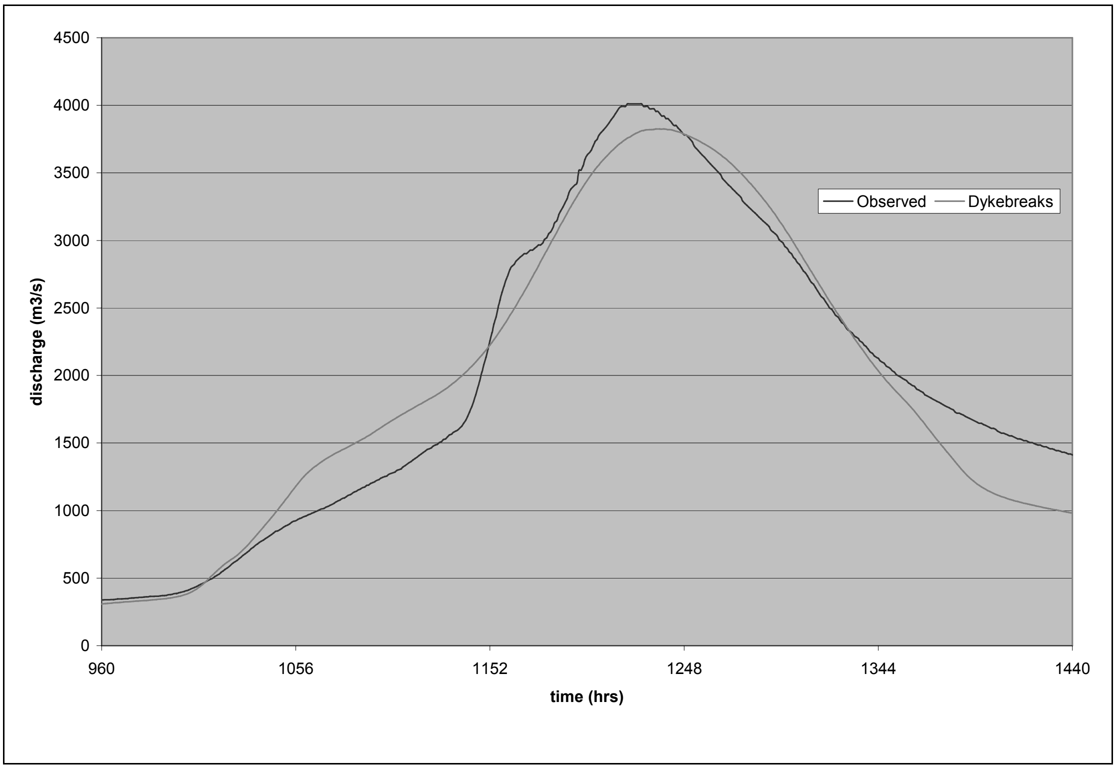


Figure 5.4.2-25 *Calibration results of the main Elbe at Tangermunde, August 2002 event: observed and simulated discharge incl dyke-breaks (timesteps in hours)*

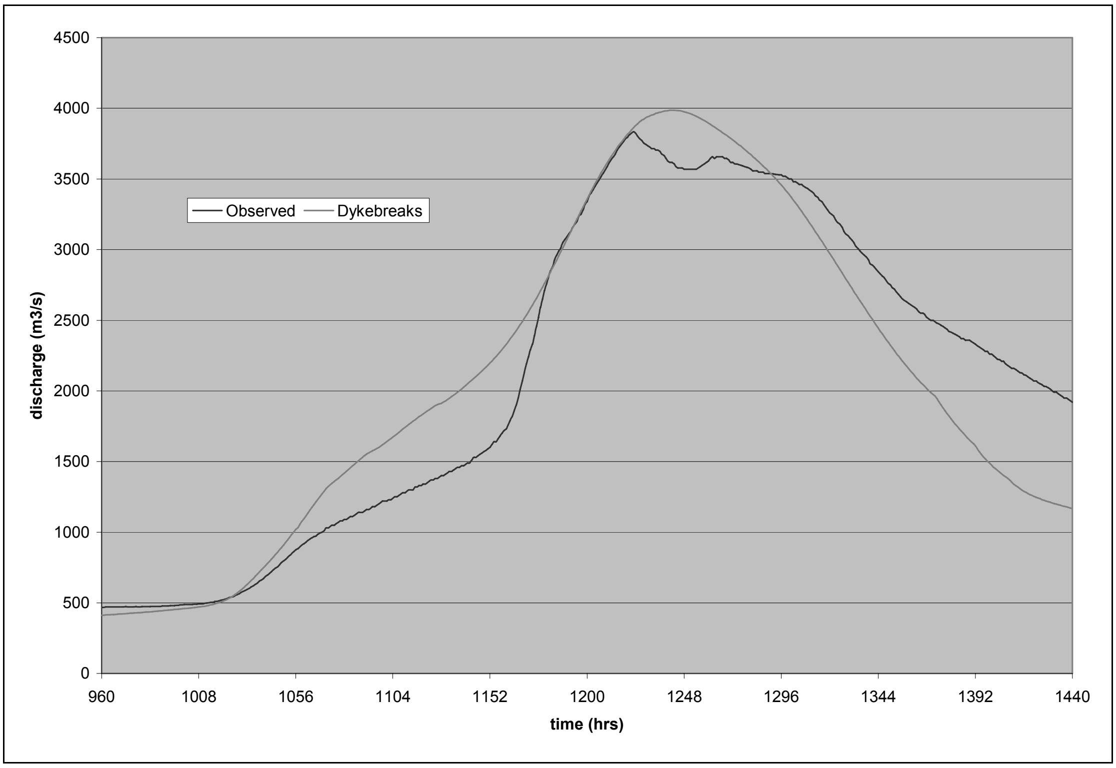


Figure 5.4.2-26 *Calibration results of the main Elbe at Wittenberge, August 2002 event: observed and simulated discharge incl dyke-breaks (timesteps in hours)*

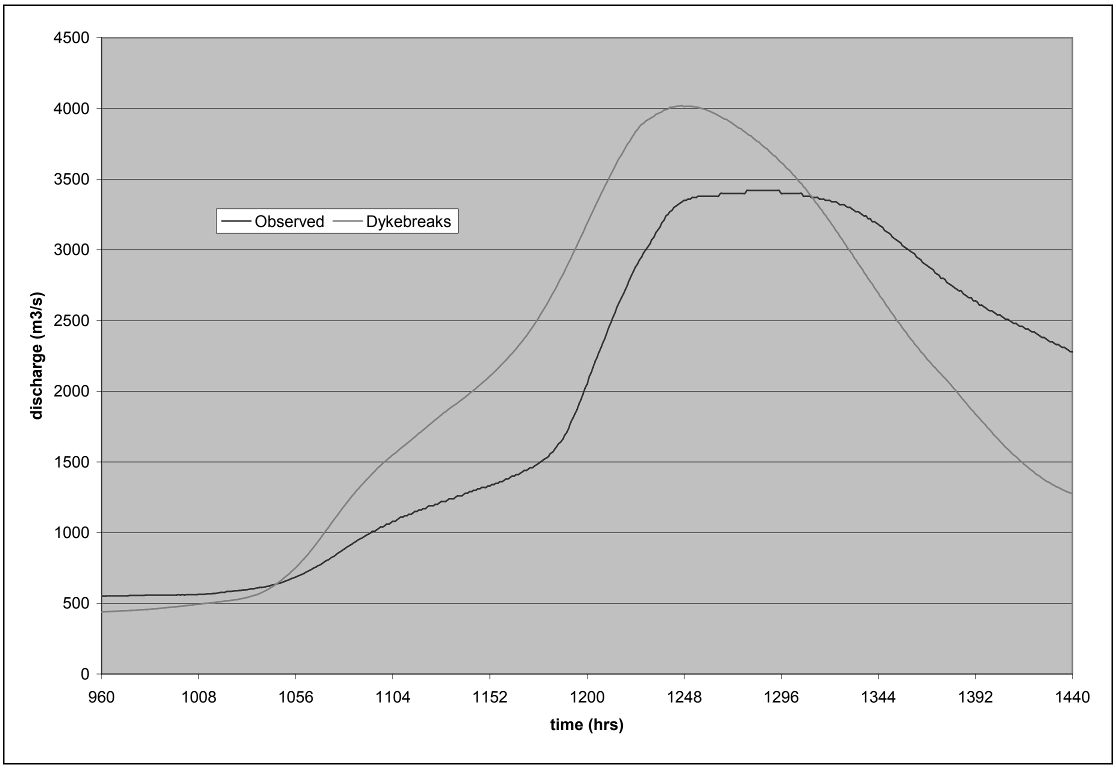


***Figure 5.4.2-27** Calibration results of the main Elbe at Neu Darchau, August 2002 event: observed and simulated discharge incl dyke-breaks (timesteps in hours)*

For the main Elbe river the calibration results are reasonable, although estimating the effects of the dyke-breaks, that need to be included in order to get realistic results, is not straightforward. The calibration sets obtained on the much smaller floods of 1994 and 2003 needed were good starts, but needed to be adjusted for the 2002 flood.

The finally obtained waterlevels have been compared to the observed waterlevels as far as they were available to the JRC. Although they were reasonably close, the waterlevel estimations made here are slightly corrected to match observed waterlevels.

6. The impact of the reservoir cascade in the Saale river on the discharge in the Saale and Elbe river

6.1 Introduction

Based on discussions and meetings with members of the Working Group "Flood Protection" of the ICPER, two scenarios have been defined for the Saale reservoirs:

Reference (Status - current operation):
The flood storage for the reservoirs Bleiloch and Hohenwarte together amounts to 25 million m^3 in summer and 40 million m^3 in winter. The minimum discharge (Q min) amounts to 5 m^3/s downstream the confluence of the Loquitz and Saale rivers.

Scenario (Plan – optimised operation):
The flood storage for the reservoirs Bleiloch and Hohenwarte together amounts to 35 million m^3 in summer and 55 million m^3 in winter. The minimum discharge (Q min) amounts to 6 m^3/s as reservoir outflow of the reservoir Eichicht.

The following three flood events are taken into consideration:

- flood in April 1994
- flood in August 2002
- flood in January 2003.

As for reporting, the following stations have been selected:

- Rudolstadt
- Camburg-Stöben
- Naumburg-Grochlitz
- Halle-Trotha
- Calbe-Griezehne

In the last section of this chapter, the combined effects of the Vltava cascade reservoirs and the Saale reservoir cascade on the discharge in the Elbe is estimated.

6.2 Scenario results 1994

The simulation results at the last Saale stream gauge Calbe-Griezehne – the last gauge before the confluence with the main Elbe (Fig 6.1) - show no differences between current and planned steering rules of the Saale reservoir cascade. Thus, it is concluded that there is no significant influence of the planned reservoir steering to the discharge behaviour of the Elbe, for this flood event.

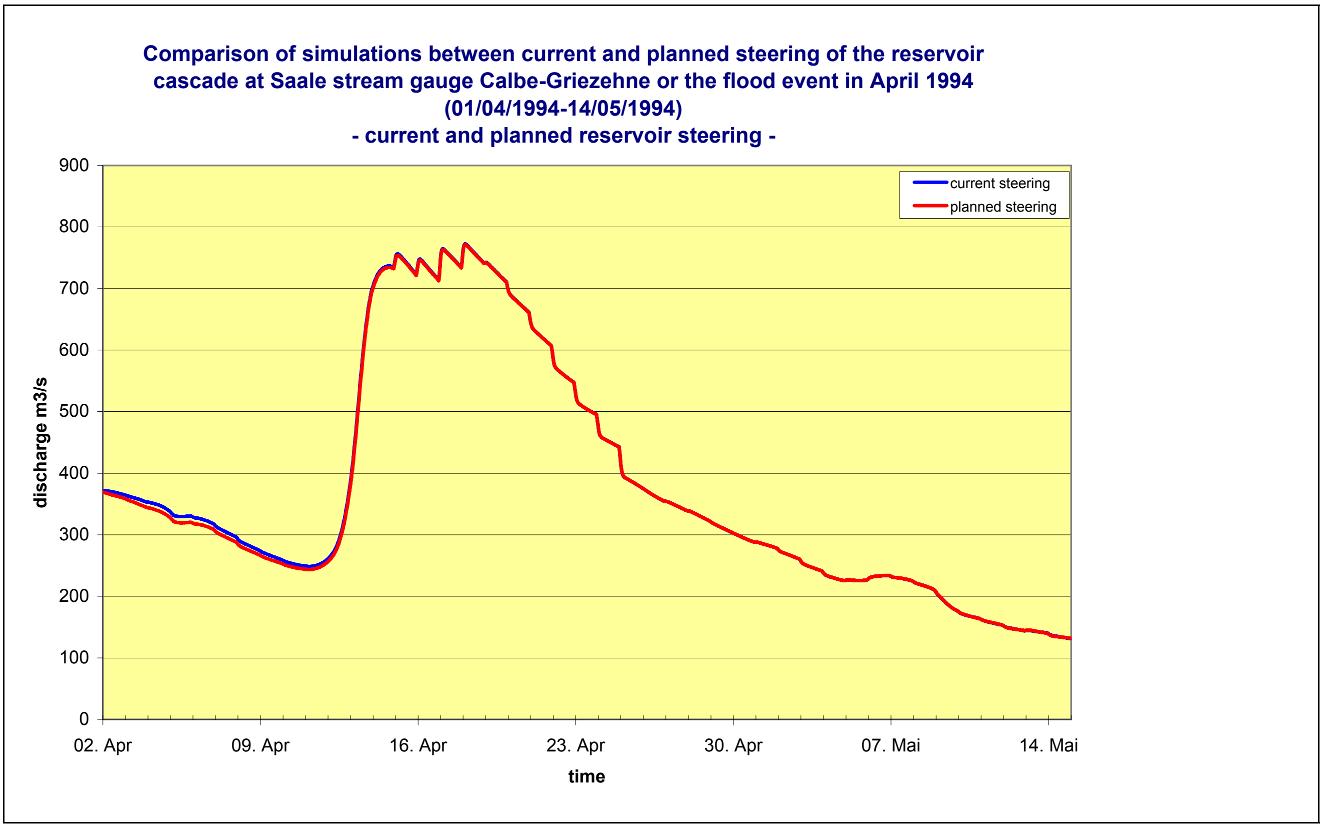


Figure 6.1 *Comparison of current and planned reservoir steering at Saale stream gauge Calbe-Griezehne, for the 1994 event*

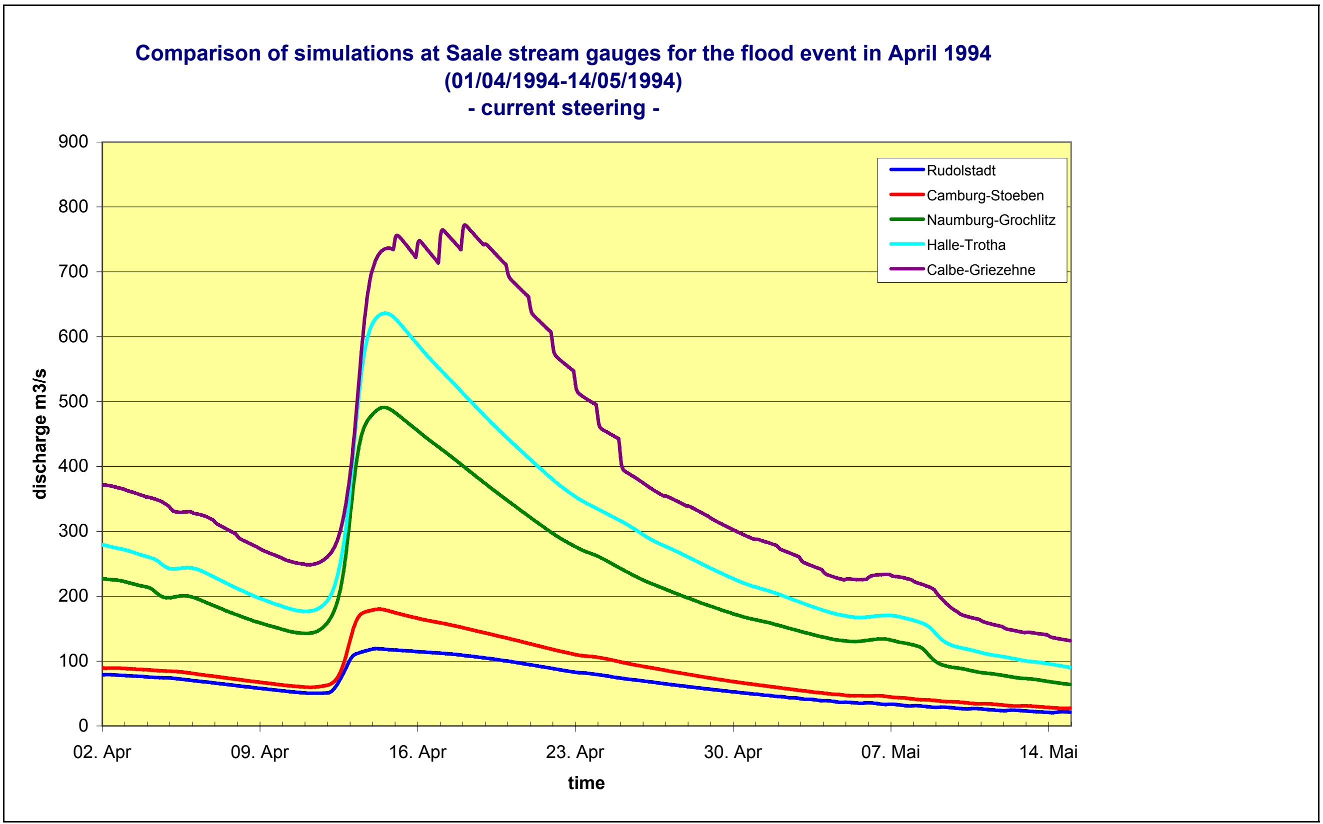


Figure 6.2 *Comparison of simulation results at Saale stream gauges for the flood event in April 1994 – current reservoir steering*

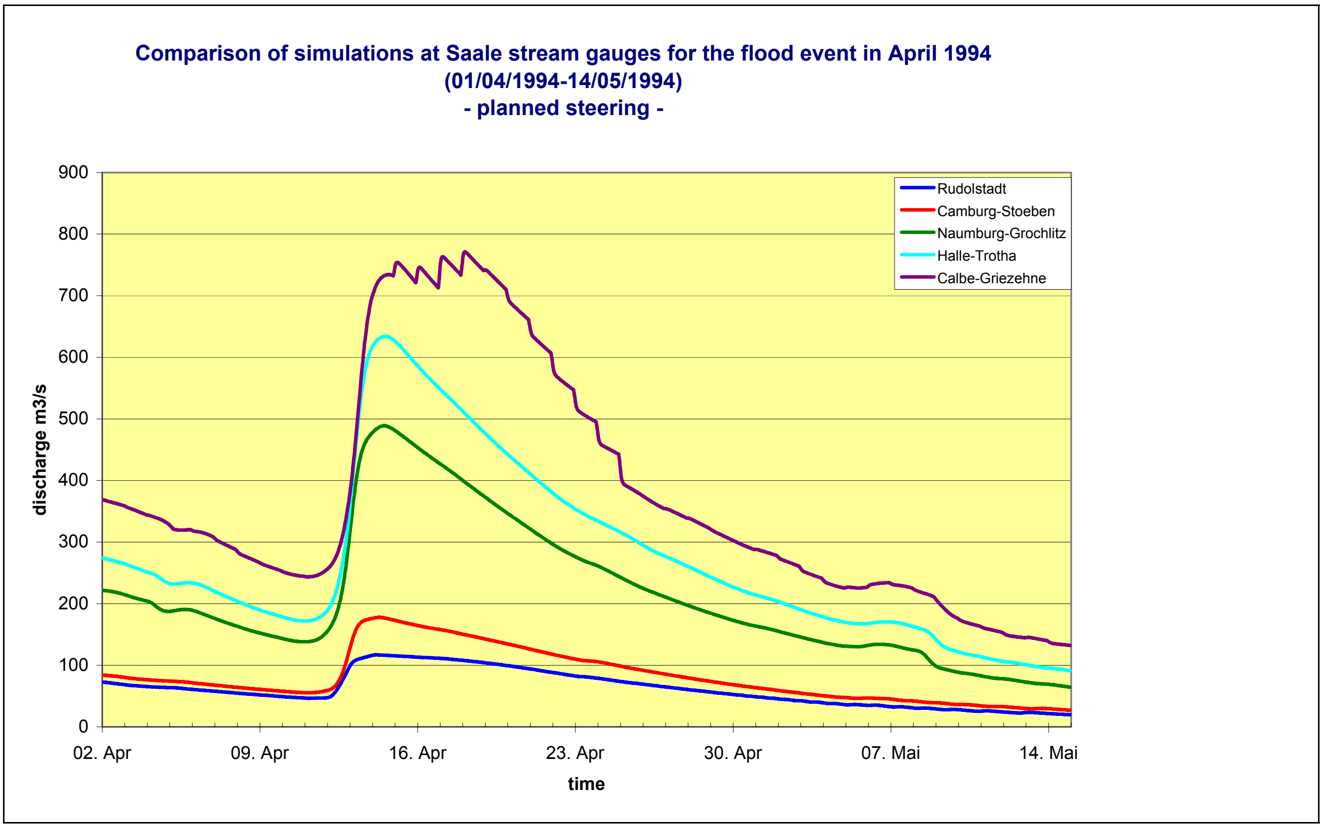


Figure 6.3 *Comparison of simulation results at Saale stream gauges for the flood event in April 1994 – planned reservoir steering*

6.3 Scenario results 2002

The simulation results at the last Saale stream gauge Calbe-Griezehne – the last gauge before the confluence with the main Elbe - show a minor difference between current and planned steering rules of the Saale reservoir cascade. Thus, it is concluded that there is no significant influence of the planned reservoir steering to the discharge behaviour of the Elbe, for this flood event.

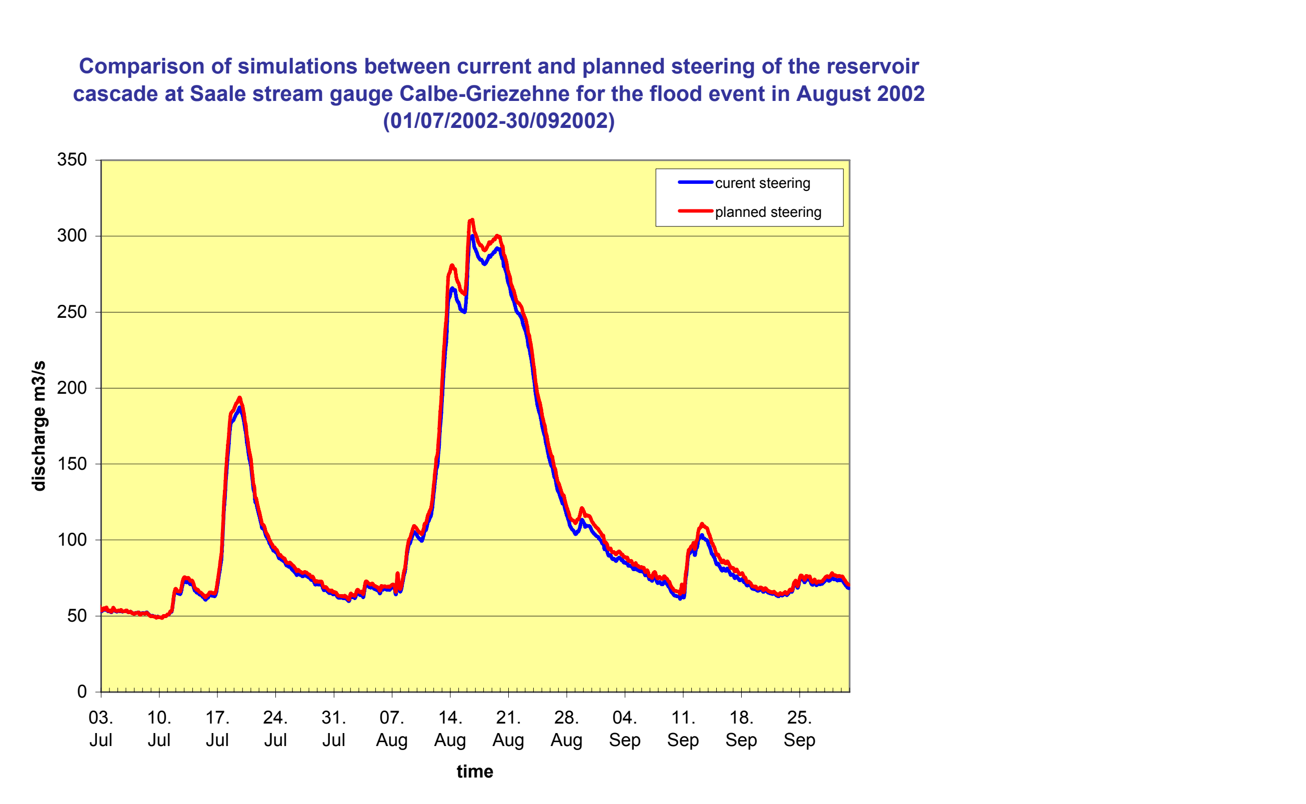


***Figure 6.4** Comparison of current and planned reservoir steering at Saale stream gauge Calbe-Griezehne, for the 2002 flood event*

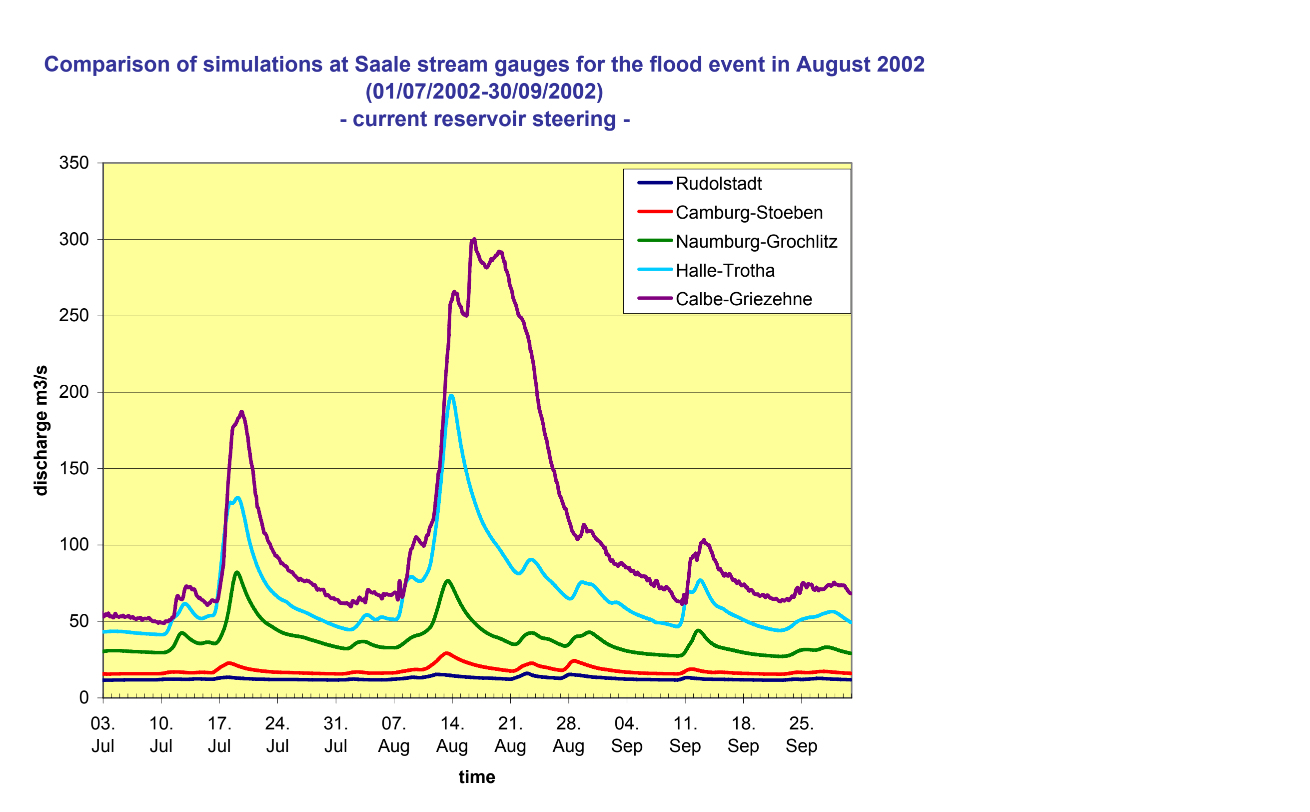


Figure 6.5 *Comparison of simulation results at Saale stream gauges for the flood event in August 2002 – current reservoir steering*

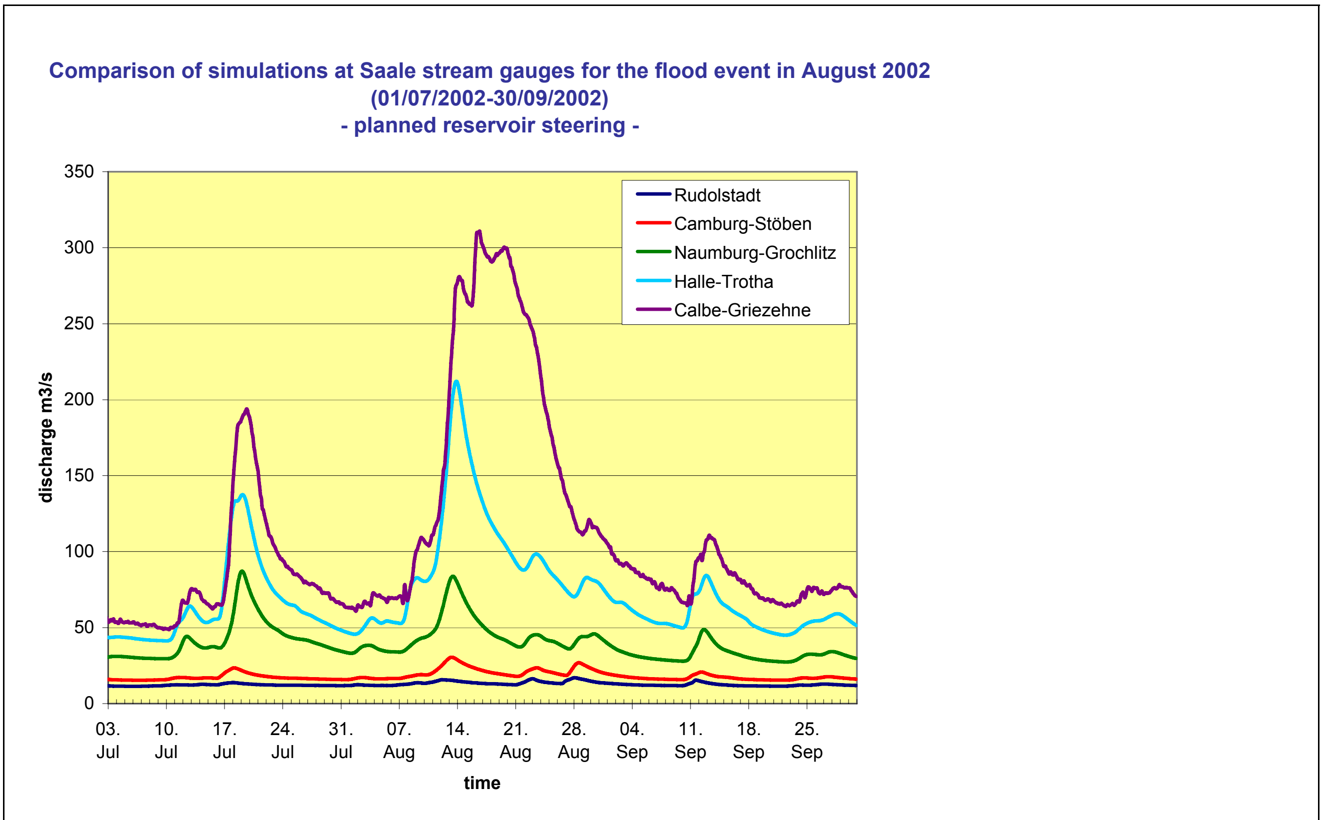


Figure 6.6 *Comparison of simulation results at Saale stream gauges for the flood event in August 2002 – planned reservoir steering*

6.4 Scenario results 2003

The simulation results at the last Saale stream gauge Calbe-Griezehne – the last gauge before the confluence with the main Elbe - show very little differences between current and planned steering rules of the Saale reservoir cascade. Thus, it is concluded that there is no significant influence of the planned reservoir steering to the discharge behaviour of the Elbe, for this flood event.

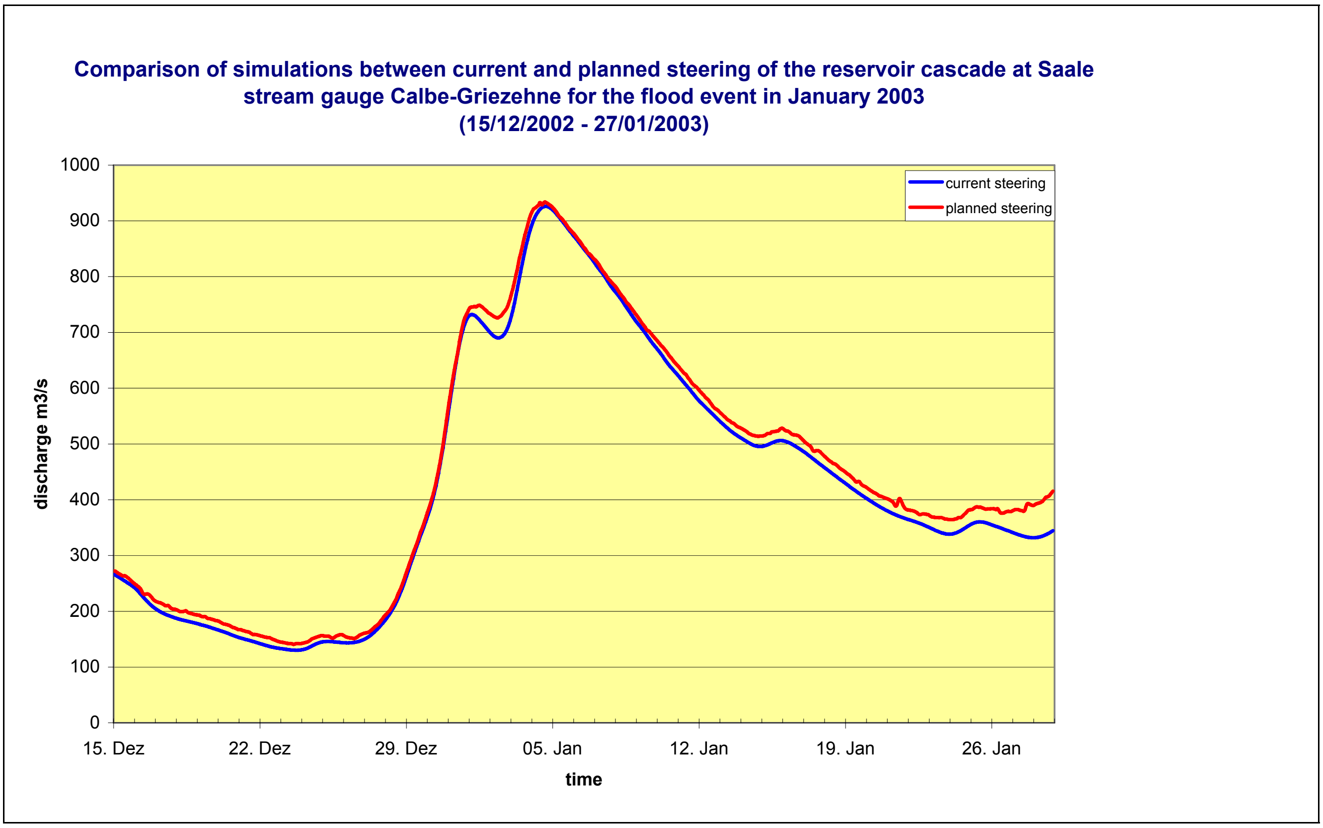


Figure 6.7 *Comparison of current and planned reservoir steering at Saale stream gauge Calbe-Griezehne, for the 2003 flood event*

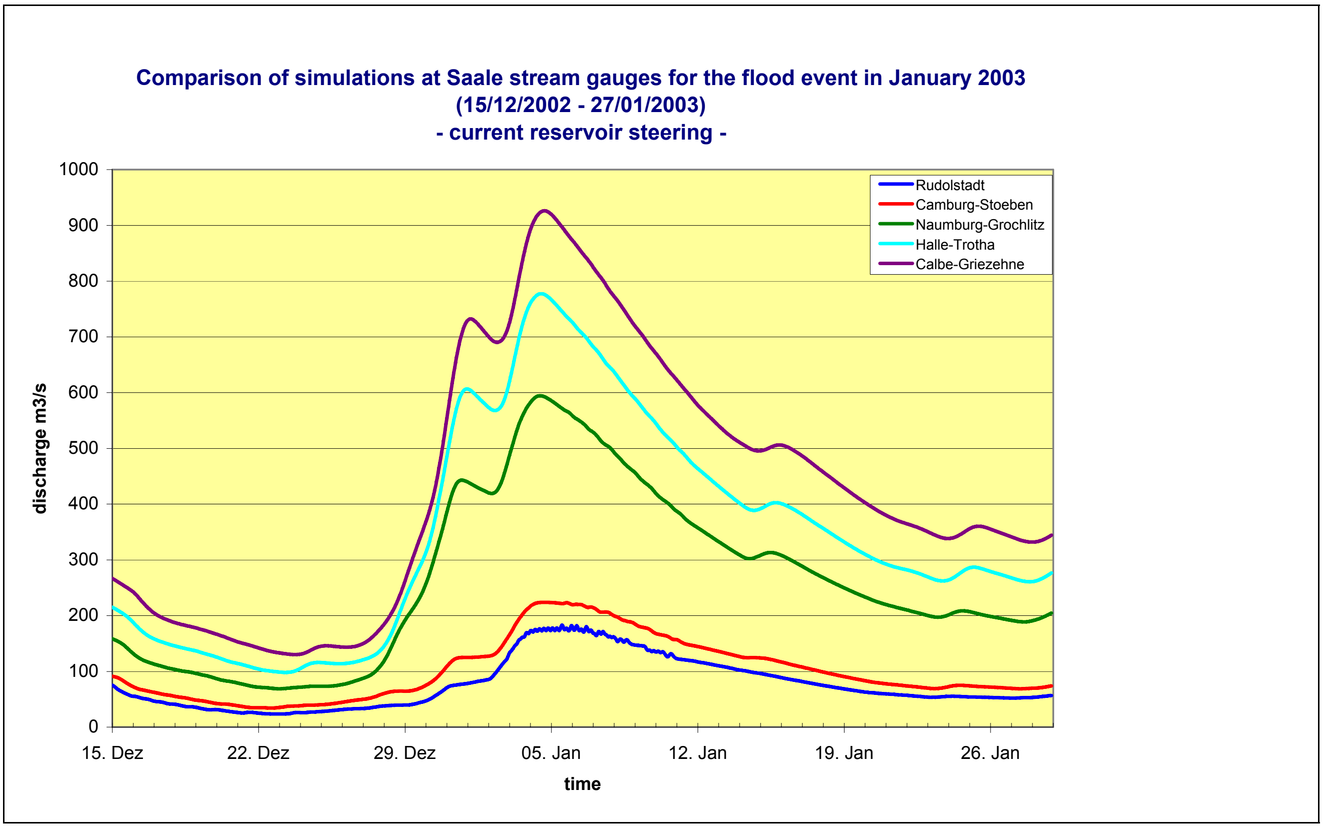


Figure 6.8 *Comparison of simulation results at Saale stream gauges for the flood event in January 2003 – current reservoir steering*

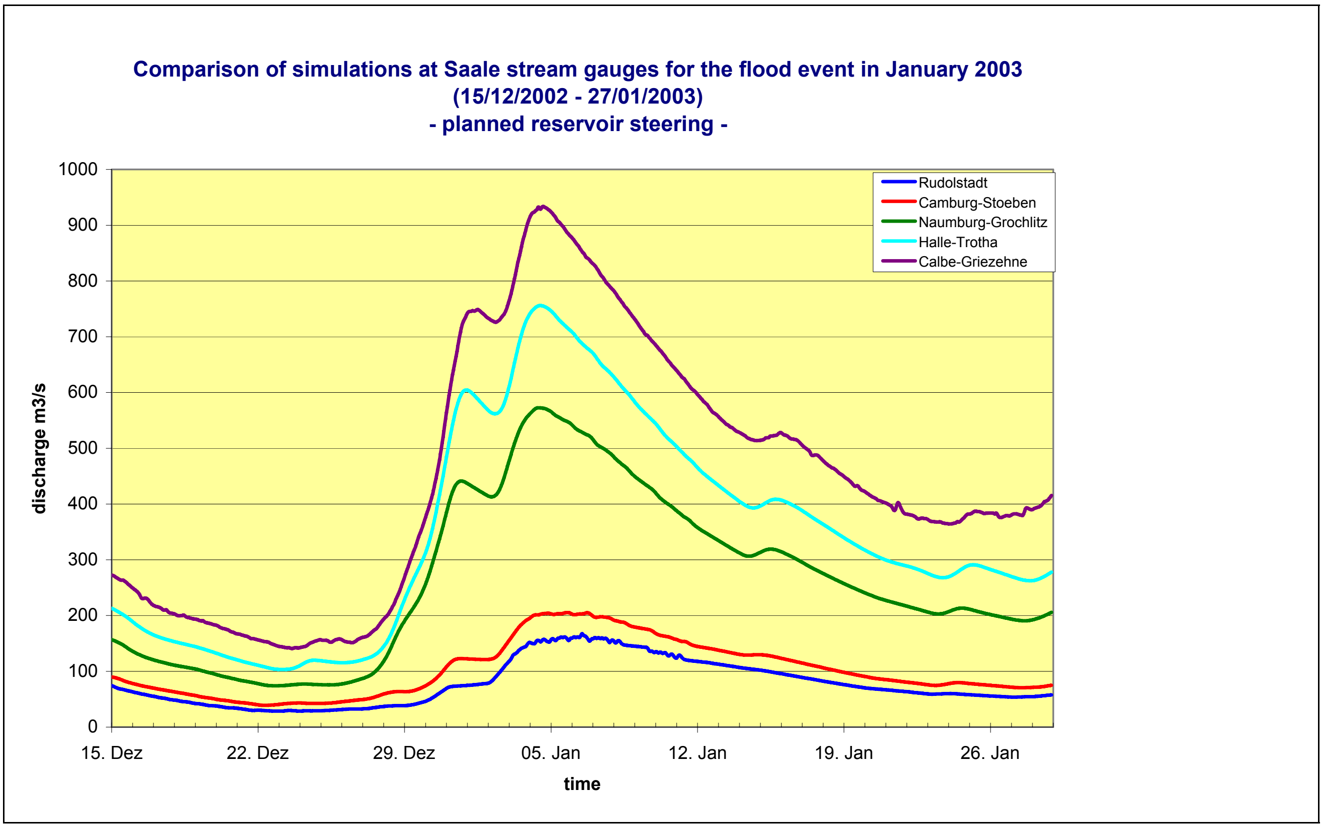


Figure 6.9 *Comparison of simulation results at Saale stream gauges for the flood event in January 2003 – planned reservoir steering*

6.5 Impact of the Saale reservoir scenarios on the river Elbe discharge

The simulated discharge at the last Saale stream gauge Calbe-Griezehne was used as inflow in a simulation of the entire Elbe river basin. For this simulation, observed discharge at Usti nad Labem has been used – as provided by CHMI -, as well as observed inflow discharges of other tributary rivers – as provided by several German authorities. The aim of this scenario is to assess the influence of changing the scenario steering of the Saale reservoirs to the discharge in the main river Elbe. In both scenarios, dyke-breaks – as they occurred in August 2002 - are not simulated. The results are shown in Table 6.1

The Reference scenario in all Elbe simulations described in this report, is defined as

- Observed discharge at Usti Nad Labem
- Observed discharges of all tributary rivers, except Saale
- Simulated Saale inflow under reference conditions = current steering of reservoirs
- No dyke-breaks simulated
- No polders or retention areas simulated

Station	Reference (m3/s)	Scenario Steering (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	4750	4750	0	0.0	0.00
Dresden	4694	4694	0	0.0	0.00
Torgau	4579	4579	0	0.0	0.00
Lutherstadt-Wittenberg	4348	4347	0	0.0	0.00
Aken	4064	4064	0	0.0	-0.01
Barby	4275	4267	-8	-0.2	-0.01
Magdeburg	4302	4295	-8	-0.2	-0.01
Tangermuende	4209	4202	-8	-0.2	-0.01
Wittenberge	4360	4351	-8	-0.2	0.00
Doemitz	4370	4361	-8	-0.2	0.00
N.Darchau	4380	4372	-8	-0.2	0.00
Boitzenburg	4402	4395	-7	-0.2	0.00
Hohnstorf	4403	4398	-6	-0.1	-0.01
Geesthacht	4397	4394	-4	-0.1	0.00

Table 6.1 *Peak discharge in the Elbe river for simulations of the 2002 flood event with the current reservoir steering (reference), and with the planned reservoir steering (scenario steering), and the difference between the two scenarios.*

It can be concluded that the influence of the planned Saale reservoir steering - as used in the scenario here - has no significant influence on the discharge in the river Elbe. Changes in peak discharge downstream the Saale-confluence are in the order of 0.1-0.2%

6.6 Effects of Vltava reservoirs on Elbe discharge

In a further model simulation, it was investigated what the influence is of the Vltava reservoir cascade on Elbe river discharge. CHMI provided the JRC with two data series for Usti Nad Labem, based on a study carried out by the T.G. Masaryk Water Research Institute in Prague, in close collaboration with the Czech Ministry of the Environment and CHMI (Kasparek et al, 2006)[1] (Figure 6.10)
:

- Simulated 6-hourly discharge including the Vltava reservoirs with their current operational steering rules
- Simulated 6-hourly discharge not including the Vltava reservoirs

It should be noted that the provided timeseries of discharge with the Vltava cascade differs from the observed discharge in August 2002. This is due to the fact that it has been assumed that the flow remains in the main river bed. Observed peak discharge (Qmax) in August 2002 is reported to be 4700 m3/s. In the provided timeseries, the peak discharge of the dataset with the Vltava cascade ("Affected") is 5111 m3/s, whereas in the series without the Vltava cascade ("Non-Affected"), the peak discharge is: 5198 m3/s. Furthermore, also a timeshift can be observed.

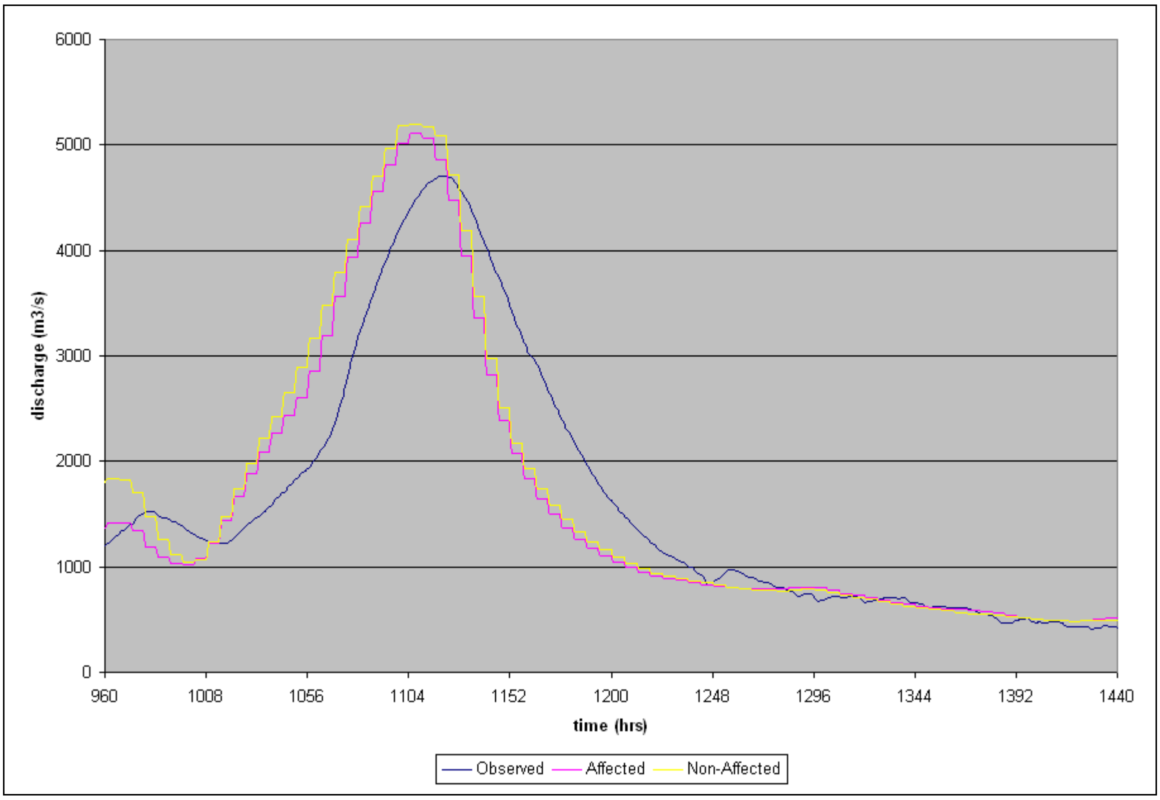


Figure 6.10 *River discharge timeseries for Usti Nad Labem, received from CHMI and used for this scenario study, as compared to the observed discharge in August 2002. Note: the CHMI discharge data are provided as daily data, whereas LISFLOOD uses them and simulates with an hourly timestep. This explains the stepped-look of the CHMI data and the smooth simulated curve.*

Using these two datasets for the simulation of discharge in the entire Elbe basin yields the results as shown in Table 6.2

[1] *Kasparek, Ladislav, Oldrich Novicky, Michal Jenicek, Stepan Buchtela, Pavel Rehak (2006), Influence of large reservoirs in the Elbe river basin on reduction of flood flows; T.G. Masaryk Water Research Institute, Prague; ISBN 80-85900-60-2.*

Station	With Vltava reservoirs (m3/s)	Without Vltava reservoirs (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	5163	5247	84	1.6	0.18
Dresden	5080	5219	139	2.7	0.17
Torgau	4920	5062	143	2.9	0.28
Lutherstadt-Wittenberg	4672	4844	171	3.7	0.20
Aken	4302	4455	153	3.6	0.28
Barby	4448	4609	161	3.6	0.20
Magdeburg	4466	4626	160	3.6	0.19
Tangermuende	4338	4500	162	3.7	0.18
Wittenberge	4502	4664	162	3.6	0.10
Doemitz	4511	4673	162	3.6	0.10
N.Darchau	4524	4686	162	3.6	0.10
Boitzenburg	4544	4705	161	3.5	0.09
Hohnstorf	4547	4707	160	3.5	0.12
Geesthacht	4545	4705	160	3.5	0.08

Table 6.2 *Peak discharge in the Elbe river for simulations of the 2002 flood event with the Vltava reservoir cascade, and without the cascade.*

From Table 6.2 it can be concluded that for the 2002 flood, the effect of the Vltava reservoirs on discharge in the German section of the Elbe river varies between 1.6% and 3.7%. In absolute discharge, the difference in the peak is between 84 and 171 m3/s. Waterlevel changes are between 8 and 28 cm.

6.7 Combined effects of Vltava and Saale reservoirs on Elbe discharge

In this paragraph it is investigated what the combined effect is of the Vltava reservoirs and the Saale reservoirs on the discharge in the river Elbe, combining the results of section 6.5 and 6.6.

Station	Vltava + Saale reservoirs (m3/s)	Saale Scenario Steering (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	5163	5163	0	0.0	0.00
Dresden	5080	5080	0	0.0	0.00
Torgau	4920	4920	0	0.0	0.00
Lutherstadt-Wittenberg	4672	4672	0	0.0	0.00
Aken	4302	4302	0	0.0	-0.01
Barby	4448	4442	-7	-0.2	-0.01
Magdeburg	4466	4457	-9	-0.2	-0.01
Tangermuende	4338	4331	-7	-0.2	-0.01
Wittenberge	4502	4495	-7	-0.2	-0.01
Doemitz	4511	4504	-7	-0.2	0.00
N.Darchau	4524	4517	-7	-0.2	0.00
Boitzenburg	4544	4536	-8	-0.2	0.00
Hohnstorf	4547	4538	-9	-0.2	-0.01
Geesthacht	4545	4536	-9	-0.2	0.00

Table 6.3 *Peak discharge in the Elbe river for simulations of the 2002 flood event* ***with*** *the Vltava reservoir cascade, with current (column 1) and scenario steering (column 2) of the Saale reservoirs.*

Conclusions from table 6.3 are consistent with paragraph 6.5, namely that the influence of the planned Saale reservoir steering - as used in the scenario here - has no significant influence on the discharge in the river Elbe. Changes in peak discharge downstream the Saale-confluence are in the order of 0.2%

Station	Without Vltava reservoirs (m3/s)	Saale Scenario Steering (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	5247	5247	0	0.0	0.00
Dresden	5219	5219	0	0.0	0.00
Torgau	5062	5062	0	0.0	0.00
Lutherstadt-Wittenberg	4844	4844	0	0.0	0.00
Aken	4455	4455	0	0.0	-0.01
Barby	4609	4601	-8	-0.2	-0.01
Magdeburg	4626	4617	-8	-0.2	-0.01
Tangermuende	4500	4492	-8	-0.2	-0.01
Wittenberge	4664	4656	-8	-0.2	0.00
Doemitz	4673	4665	-9	-0.2	0.00
N.Darchau	4686	4678	-7	-0.2	0.00
Boitzenburg	4705	4699	-6	-0.1	0.00
Hohnstorf	4707	4699	-8	-0.2	-0.01
Geesthacht	4705	4696	-9	-0.2	0.00

Table 6.4 *Peak discharge in the Elbe river for simulations of the 2002 flood event* ***without*** *the Vltava reservoir cascade, with current (column 1) and scenario steering (column 2) of the Saale reservoirs.*

Conclusions from table 6.4 are again consistent with paragraph 6.5 and table 6.3, namely that the influence of the planned Saale reservoir steering - as used in the scenario here - has no significant influence on the discharge in the river Elbe. Changes in peak discharge downstream the Saale-confluence are in the order of 0.2%.

6.8 Conclusions

In this chapter, the influence of changing the flood storage in the Bleiloch and Hohenwarte reservoirs in winter from 40 to 55 Mm3 and in summer from 25 to 35 Mm3 on river discharge has been assessed. The scenario results have shown that this planned scenario for reservoir steering in the Saale cascade does not have a significant influence on the discharge of the river Elbe, for the investigated flood events in 1994, 2002 und 2003 at gauging station Calbe-Griezehne (lower Saale). Also the influence on the discharge in the river Elbe is marginal: changes in peak discharge downstream the Saale-confluence are in the order of 0.2% (difference in discharge 4-8 m3/s).

Furthermore, the influence of the Vltava reservoir cascade was investigated using two datasets provided by CHMI: one dataset with the actual situation and steering of the Vltava cascade, and a scenario without the Vltava cascade. For floods with a magnitude such as in August 2002, the difference between the scenario with and without the Vltava cascade is between 1.6 and 3.7% (84-171 m3/s) in the German part of the Elbe river.

7. Effects of dyke-shifts and retention polders on discharge in the German section of the Elbe river

7.1 Selected scenarios of dyke-shifts and retention polders

Based on the Action Plan for Flood Protection in the Elbe River Basin (ICPER, 2003) and several consequent discussions and meetings, a list of measures was defined for evaluation with the LISFLOOD model (Table 7.1)

No	Name	Type	Land	Elbe-km	Area (ha)	Volume (Mm3)
1	**Nuenchritz**	Polder	Sachsen	(100.5-108.5)	600	15.0
2	Trebnitz/Lößnig	Polder	Sachsen	(117,5-123,8)	900	18.0
3	**Aussig/Seidewitz**	Polder	Sachsen	(123,0-126,0)	500	17.0
4	Ammelgoßwitz / Dröschkau	Deichrückverlegung	Sachsen	(131,0-138,0)	420	8.6
5	Köllitzsch	Deichrückverlegung	Sachsen	(142,0-145,0)	60	1.4
6	Döbeltitz / Kranichau	Deichrückverlegung	Sachsen	(142,0-146,5)	380	2.2
7	Kamitz / Pülswerda	Deichrückverlegung	Sachsen	(145,5-148,5)	60	1.2
8	Wessnig / Schiffmühlenhaus	Deichrückverlegung	Sachsen	(147,5-148,5)	30	
9	nordlich Pülswerda	Deichrückverlegung	Sachsen	(149,5-149,5))	10	
10	Zwethau	Deichrückverlegung	Sachsen	(156,0-158,0)	120	2.2
11	**Dautzschen/Neublessern**	Polder	Sachsen	(160,0-165,0)	900	32.0
12	Polbitz	Deichrückverlegung	Sachsen	(167,7-171,0)	100	
13	Dommitzsch Nord / Grenzbach / Proschwitz	Deichrückverlegung	Sachsen	(173,0-176,5)	90	1.8
14	Sachau - Priesitz	Deichrückverlegung	Sachsen-Anhalt	(180,0-184,0)	210	
15	**Axien/Mauken**	Polder	Sachsen-Anhalt	(180,5-188,8)	1700	44.3
16	Hemsendorf	Deichrückverlegung	Sachsen-Anhalt	(199,0-199,0)	390	
17	Gatzer Bergdeich (Vockerode)	Deichrückverlegung	Sachsen-Anhalt	(246,5-249,0)	212	
18	Oberluch bei Rosslau fertiggestellt	Deichrückverlegung	Sachsen-Anhalt	(253,5-256,6)	140	
19	Lödderitzer Forst unterhalb Aken	Deichrückverlegung	Sachsen-Anhalt	(278,0-283,7)	600	
20	Hohenwarthe	Deichrückverlegung	Sachsen-Anhalt	(340,0-343,0)	140	
21	Klietznick	Deichrückverlegung	Sachsen-Anhalt	(378,0-384,0)	102	
22	Sandau-Süd	Deichrückverlegung	Sachsen-Anhalt	(412,5-416,0)	124	
23	Sandau-Nord	Deichrückverlegung	Sachsen-Anhalt	(416,5-422,0)	60	
24	Lenzen	Deichrückverlegung	Brandenburg	(476.7-483.8)	420	20.0
25	Neu Bleckdede	Deichrückverlegung	Brandenburg	(546.0-554.0)	100	

Table 7.1 *Dyke-shifts and Polders as included in the scenario calculations reported in this chapter. Sources: ICPER Action Plan for Flood Protection in the Elbe river basin (2003), ICPER First report on the implementation of the Action Plan for the Flood Protection in the Elbe River Basin (2006), BfG ELLA Studie – BfG 1542 (2006), email 4 April 2007 Mr. Pieper.*

Included in the scenario study are five flood retention polders and 20 dyke-shifts. Information on location, area, and volume has been derived from the mentioned sources, including a final cross check in spring 2007.

In the following paragraphs the effects of these measures on river discharge is investigated, both for the August 2002 flood, as well as for the spring 2006 flood.

Water level simulations: As already mentioned in Chapter 2 on LISFLOOD, it should be noted, that since a one-dimensional dynamic wave approach is used in the channel calculations, waterlevel simulations may be less accurate than the discharge simulations. If detailed and accurate waterlevel simulations are aimed for, other river routing models such as Sobek, Mike21 or Wavos should be selected.
The waterlevel estimations made here are slightly corrected to match observed waterlevels.

7.2 Simulations with and without dyke-breaks

All simulations are compared to a reference scenario, as defined below:

The Reference scenario in all Elbe simulations described in this report, is defined as
- Observed discharge at Usti Nad Labem
- Observed discharges of all tributary rivers, except Saale
- Simulated Saale inflow under reference conditions = current steering of reservoirs
- No dyke-breaks simulated
- No polders or retention areas simulated

In order to investigate the most accurate effects of the planned scenarios, the baseline scenario needed to exclude dyke-breaks: it is of interest to know, what would have happened if the 2002 amount of water is passing the Elbe without dyke-breaks, and how the newly planned measures would in that case reduce waterlevels and discharge.

The throughflow through the dyke-breaks in August 2002 has not been recorded. The locations are known however. Therefore, estimations of the throughflow discharge have been made by comparing observations of discharge including the dykebreak effects with simulation runs using observed discharge upstream Dresden and tributary rivers and routing this through the main Elbe. The differences between observed and simulated discharge has been attributed to the dyke-breaks. In this way, dyke-break discharge time series (Figure 7.1) have been created after which observed and simulated discharge matched closely.

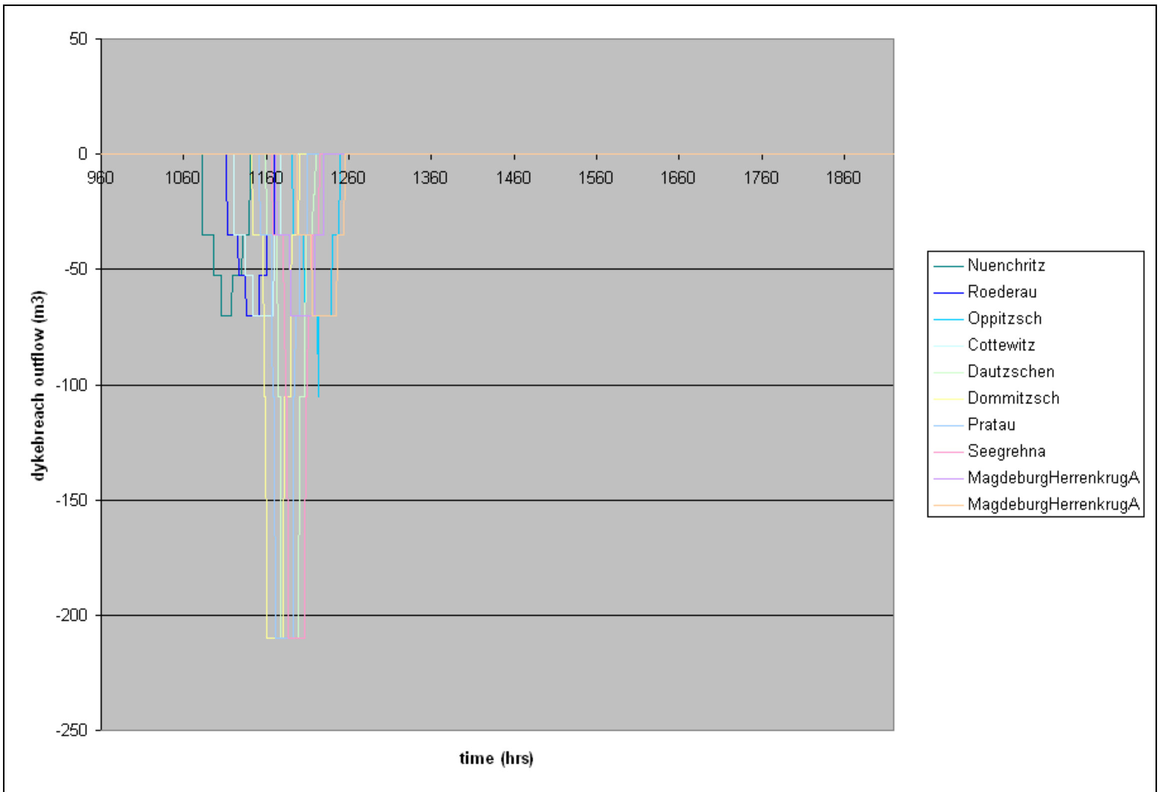


Figure 7.1 *Estimated dyke-break discharge fluxes for the Elbe river during August 2002.*

Next, it was possible to compare a simulation of Elbe discharge with and without the inclusion of these dyke-breaks, as shown in Table 7.2.

Station	Dykebreaks (m3/s)	No Dykebreaks / Reference (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	4750	4750	0	0.0	0.00
Dresden	4694	4694	0	0.0	0.00
Torgau	4462	4579	117	2.6	-0.24
Lutherstadt-Wittenberg	4063	4348	285	6.5	-0.32
Aken	3705	4064	359	8.8	-0.54
Barby	3933	4275	343	8.0	-0.36
Magdeburg	3962	4302	341	7.9	-0.43
Tangermuende	3825	4209	384	9.1	-0.42
Wittenberge	3986	4360	373	8.6	-0.24
Doemitz	4004	4370	366	8.4	-0.23
N.Darchau	4019	4380	361	8.2	-0.23
Boitzenburg	4042	4402	361	8.2	-0.20
Hohnstorf	4043	4403	360	8.2	-0.27
Geesthacht	4042	4397	355	8.1	-0.18

***Table 7.2** Simulations of Elbe discharge with and without the influence of dyke-breaks.*

From Table 7.2 it can be observed that without dyke-breaks, the discharge in the lower part of the Elbe river would have been 2.6 – 9.1 % higher (117-384 m3/s). Waterlevel changes are between 18 and 54 cm.

The scenario without dyke-breaks is used as the reference scenario to evaluate the effect of all measures.

7.3 Methods used to simulate polders and dyke-shifts

Within the LISFLOOD model, polders can be simulated on river channel pixels where the dynamic wave routing is used (Van Der Knijff & De Roo, 2006). Polders are simulated as points in the channel network. The polder routine is adapted from Förster et. al (2004), and based on the weir equation of Poleni (Bollrich & Preißler, 1992). The flow rates from the channel to the polder area and vice versa are calculated by balancing out the water levels in the channel and in the polder, as shown in Figure 7.2.

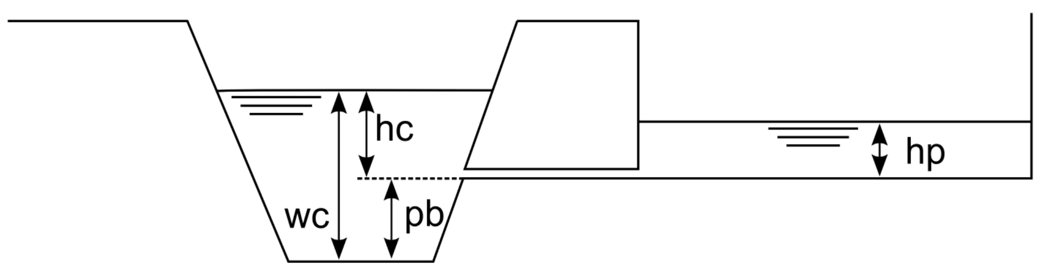


***Figure 7.2** Schematic overview of the simulation of polders. pb is the polder bottom level (above the channel bottom); w_c is the water level in the channel; h_c and h_p are the water levels above the polder in- / outflow, respectively*

From the Figure, it is easy to see that there can be three situations:

1. $h_c > h_p$: water flows out of the channel, into the polder. The flow rate, $q_{c,p}$, is calculated using:

$$q_{c,p} = \mu c b \sqrt{2g} h_c^{3/2};$$
$$c = \sqrt{1 - \left[\frac{h_p}{h_c}\right]^{16}}$$

where *b* is the outflow width [m], *g* is the acceleration due to gravity (9.81 m s^{-2}) and *μ* is a weir constant which has a value of 0.49. Furthermore $q_{c,p}$ is in [m^3 s^{-1}].

2. $h_c < h_p$: water flows out of the polder back into the channel. The flow rate, $q_{p,c}$, is now calculated using:

$$q_{p,c} = \mu c b \sqrt{2g} h_p^{3/2};$$
$$c = \sqrt{1 - \left[\frac{h_c}{h_p}\right]^{16}}$$

3. $h_c = h_p$: no water flowing into either direction (note here that the minimum value of h_c is zero). In this case both $q_{c,p}$ and $q_{p,c}$ are zero.

The above equations are valid for *unregulated* polders. It is also possible to simulated *regulated* polders, which is illustrated in Figure 7.3. Regulated polders are opened at a user-defined time (typically during the rising limb of a flood peak). The polder closes automatically once it is full. Subsequently, the polder is opened again to release the stored water back into the channel, which also occurs at a user-defined time. The opening- and release times for each polder are defined in two lookup tables.

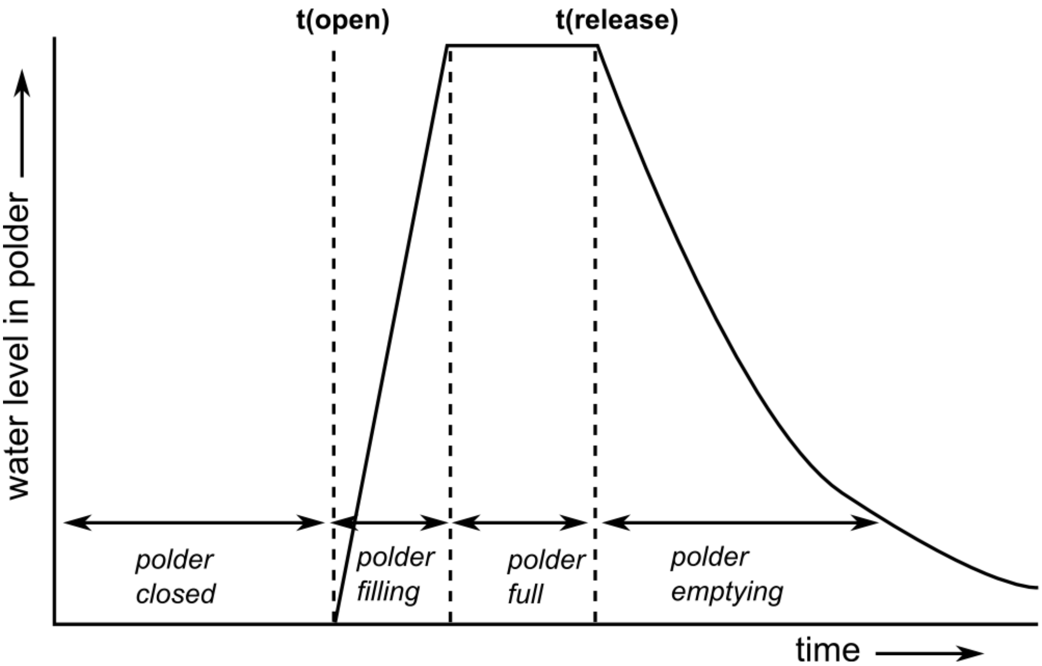


Figure 7.3 *Simulation of a regulated polder. Polder is closed (inactive) until user-defined opening time, after which it fills up to its capacity (flow rate according to Eq 1). Water stays in polder until user-defined release time, after which water is released back to the channel (flow rate according to Eq 2).*

For the Elbe simulations, all polders are simulated as regulated polders, with opening times optimised to the 2002 flood event.

All dyke-shifts – due to a lack of precise cross section changes at the proposed sites – are simulated as unregulated polders with a fixed bottom level, which should closely match the behaviour of dyke-shifts.

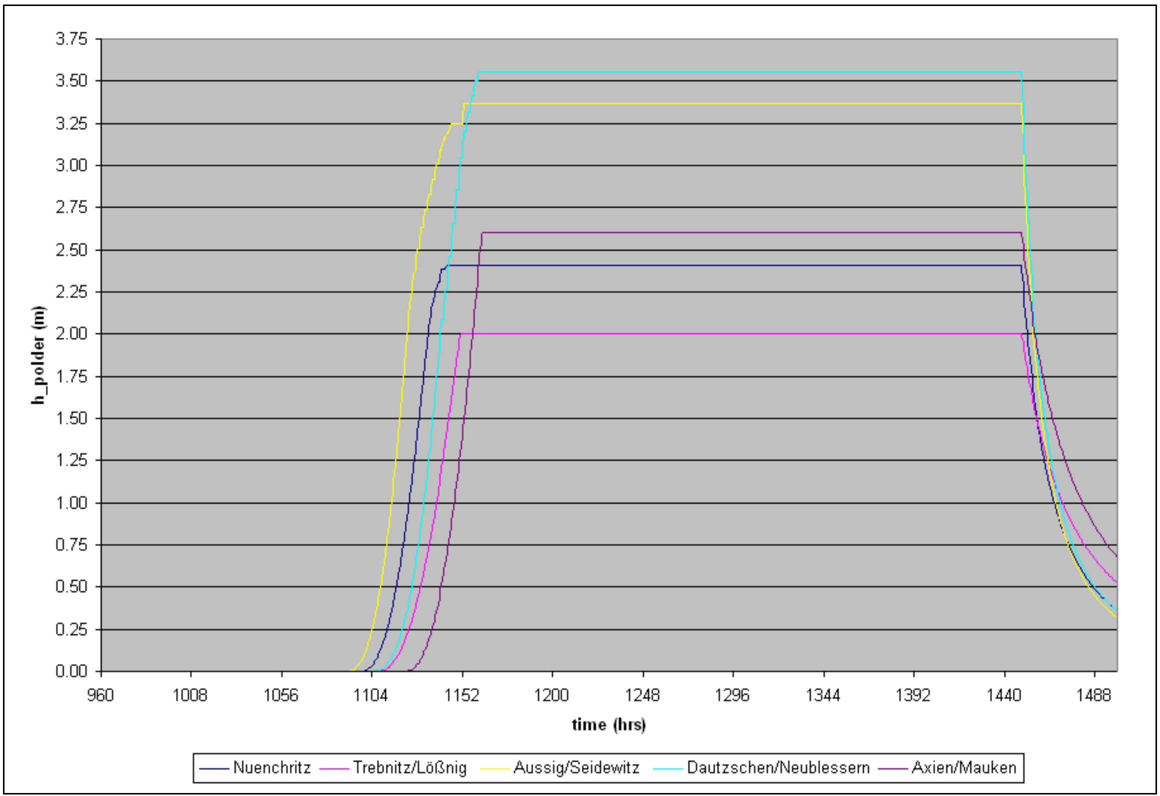


Figure 7.4 *Simulation of polder filling for the Elbe polders. Filling and timing are optimised specifically for the 2002 flood event. Polder is closed (inactive) until user-defined opening time, after which it fills up to its capacity (flow rate according to Eq 1). Water stays in polder until user-defined release time, after which water is released back to the channel (flow rate according to Eq 2).*

Figure 7.4 shows for the 2002 flood case, the model simulation of the filling of all polders. The opening times are optimised with an iterative process in such a way, that the polder is not opened too soon before the actual flood discharge peak arrives: for each individual polder it has been checked which maximum peak discharge reduction could be achieved. Following the finding of the maximum peak discharge reduction, and thus the optimum parameterisation of this polder, an iterative process of finding the optimum values for the next polder was started. It was also checked that a polder was not activated too late, such that it would not get filled to its maximum capacity. Finally, the polders are emptied long after the passing of the flood wave: in this model simulation at time-step 1450 hrs (see Fig 7.4).

7.4 Scenario with and without dyke-shifts

A series of calculations has been done to simulate the effects of the proposed dyke-shifts only, so not including the planned polders. Included in the calculations are the planned dyke-shifts at:

No	Name	Land	Elbe-km	Area (ha)	Volume (Mm3)	Einlaufbreite (m)	Hmax (m)
4	Ammelgoßwitz / Dröschkau	Sachsen	(131,0-138,0)	420	8.6	5600	2.05
5	Köllitzsch	Sachsen	(142,0-145,0)	60	1.4	2600	2.33
6	Döbeltitz / Kranichau	Sachsen	(142,0-146,5)	380	2.2	2600	0.58
7	Kamitz / Pülswerda	Sachsen	(145,5-148,5)	60	1.2	2000	2.00
8	Wessnig / Schiffmühlenhaus	Sachsen	(147,5-148,5)	30	*0.9*	1600	3.00
9	nordlich Pülswerda	Sachsen	(149,5-149,5))	10	*0.3*	400	3.00
10	Zwethau	Sachsen	(156,0-158,0)	120	2.2	2000	1.83
12	Polbitz	Sachsen	(167,7-171,0)	100	*3.0*	3000	3.00
13	Dommitzsch Nord / Grenzbach / Proschwitz	Sachsen	(173,0-176,5)	90	1.8	2900	2.00
14	Sachau - Priesitz	Sachsen-Anhalt	(180,0-184,0)	210	*6.3*	4600	3.00
16	Hemsendorf	Sachsen-Anhalt	(199,0-199,0)	390	*11.7*	2400	3.00
17	Gatzer Bergdeich (Vockerode)	Sachsen-Anhalt	(246,5-249,0)	212	*6.4*	2300	3.00
18	Oberluch bei Rosslau fertiggestellt	Sachsen-Anhalt	(253,5-256,6)	140	*4.2*	3000	3.00
19	Lödderitzer Forst unterhalb Aken	Sachsen-Anhalt	(278,0-283,7)	600	*18.0*	5700	3.00
20	Hohenwarthe	Sachsen-Anhalt	(340,0-343,0)	140	*4.2*	3000	3.00
21	Klietznick	Sachsen-Anhalt	(378,0-384,0)	102	*3.1*	3300	3.00
22	Sandau-Süd	Sachsen-Anhalt	(412,5-416,0)	124	*3.7*	4300	3.00
23	Sandau-Nord	Sachsen-Anhalt	(416,5-422,0)	60	*1.8*	3300	3.00
24	Lenzen	Brandenburg	(476.7-483.8)	420	20.0	1800	4.76
25	Neu Bleckdede	Brandenburg	(546.0-554.0)	100	*3.0*	8000	3.00

Table 7.3 *Dyke-shifts as included in the scenario calculations reported in this chapter. Sources: ICPER Action Plan for the Flood Protection in the Elbe river basin (2003), ICPER First report on the implementation of the Action Plan for the Flood Protection in the Elbe River Basin (2006), BfG ELLA Studie – BfG 1542 (2006), email 4 April 2007 Mr. Pieper.*

As mentioned earlier, all dyke-shifts – due to a lack of precise cross section changes at the proposed sites – are simulated as unregulated polders with a fixed bottom level, which should closely match the behaviour of dyke-shifts.

Below, a few examples are given of hydrographs with and without these dyke-shifts included in the simulations (Figs 7.5-7.7)

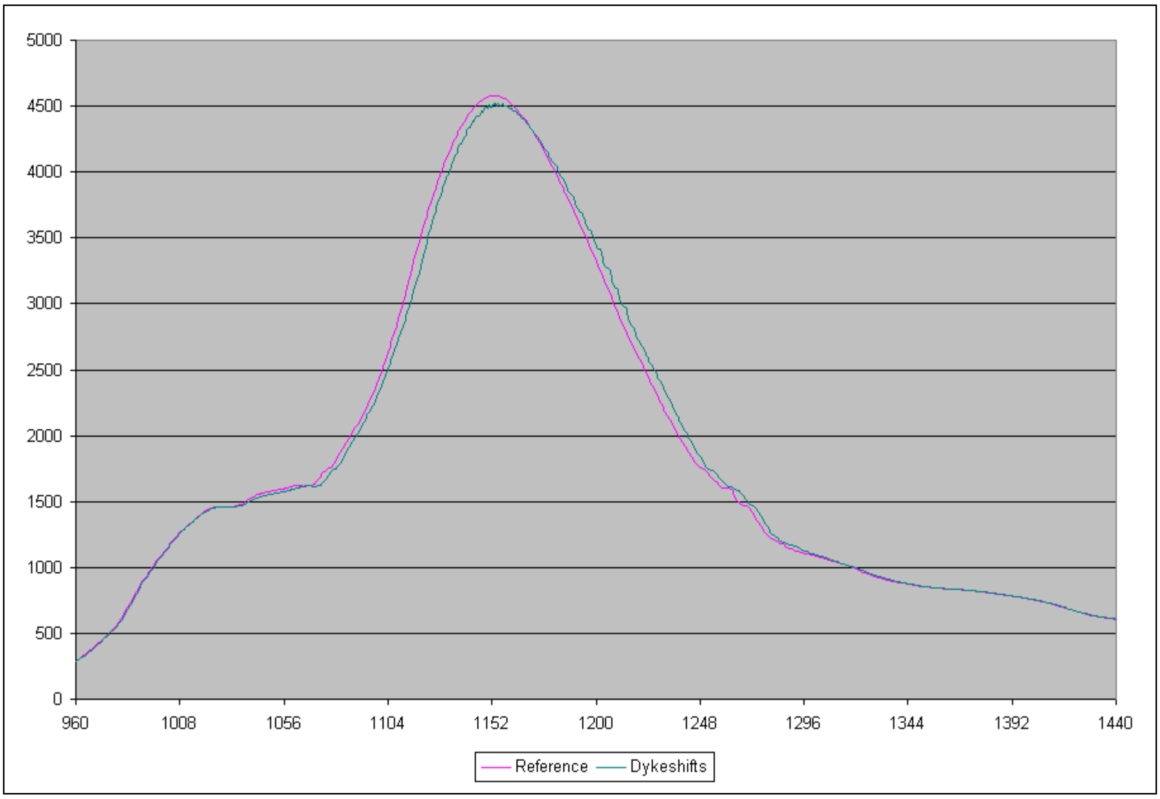


Figure 7.5 *The effects of the scenario with the planned dyke-shifts as compared to the baseline simulation, for gauge Torgau, during the 2002 flood.*

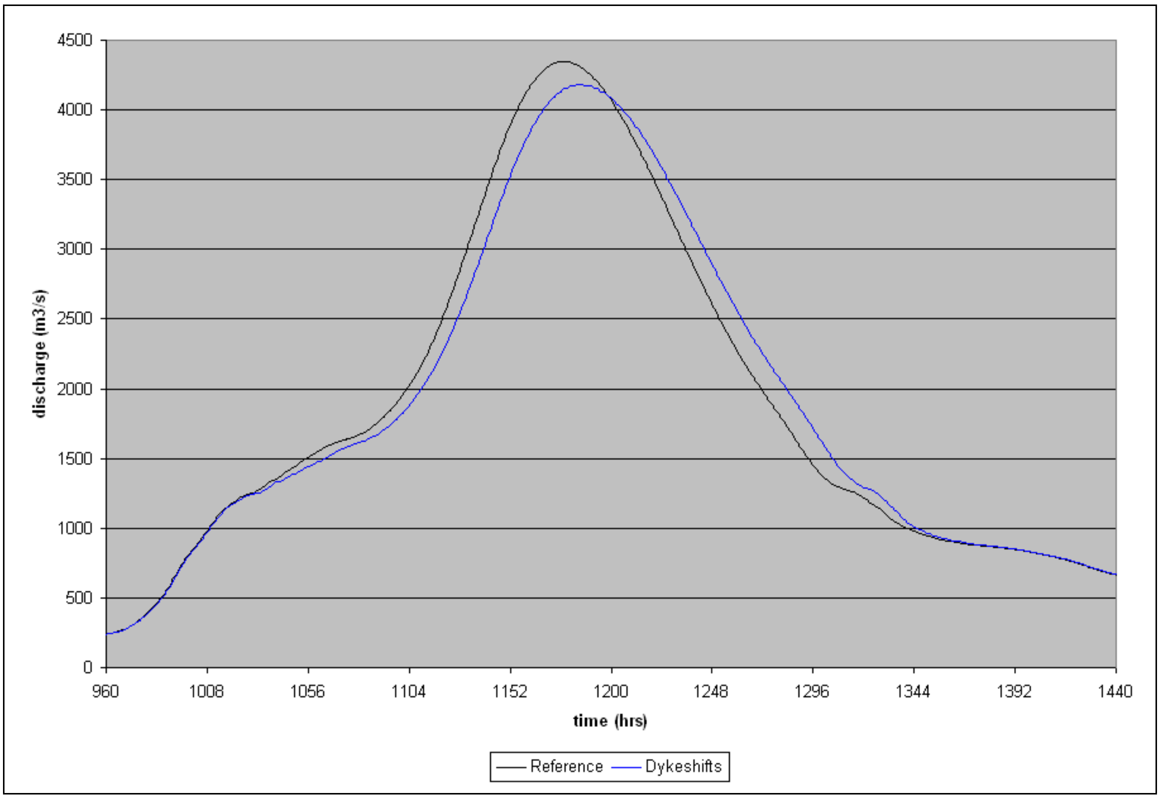


Figure 7.6 *The effects of the scenario with the planned dyke-shifts as compared to the baseline simulation, for gauge Lutherstadt-Wittenberg, during the 2002 flood.*

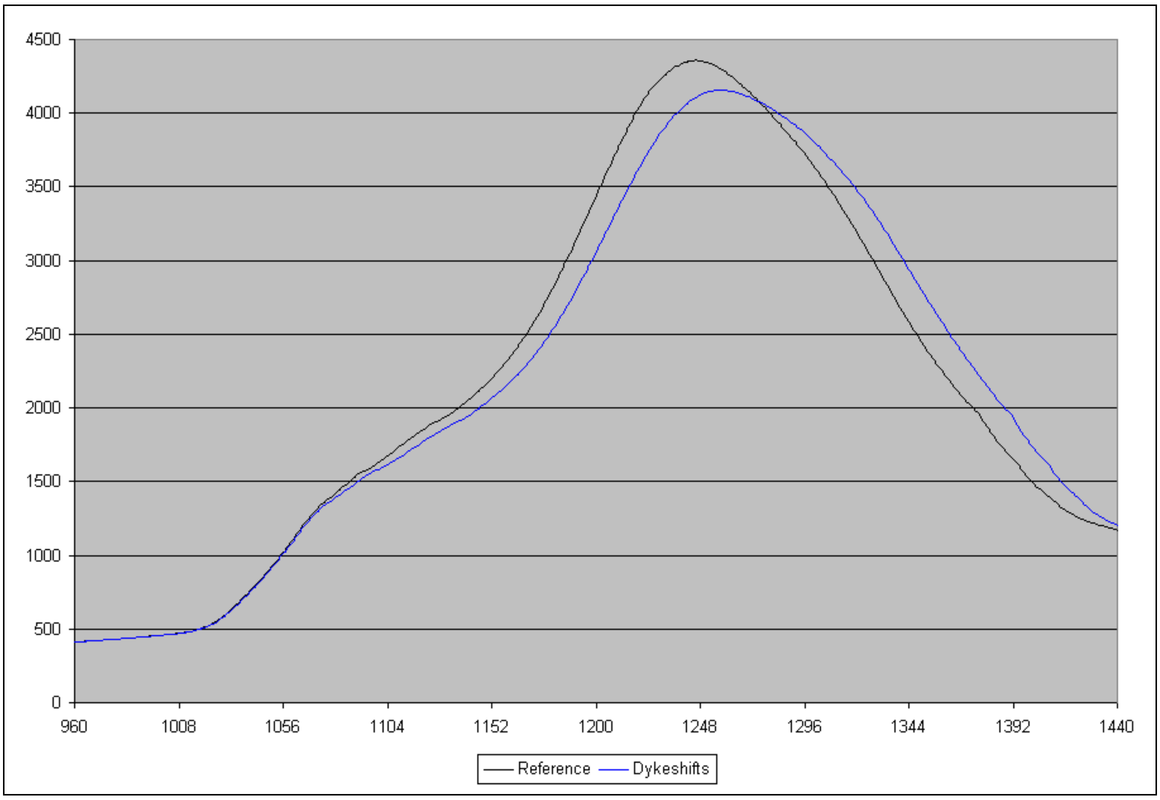


Figure 7.7 *The effects of the scenario with the planned dyke-shifts as compared to the baseline simulation, for gauge Wittenberge, during the 2002 flood.*

Figures 7.5-7.7 clearly show the effects of these dyke-shifts: a delay as well as a reduction of the flood peak. Table 7.3 gives a full overview of the effects of dyke-shifts on peak discharge as compared to the baseline scenario 2002

Station	Reference (m3/s)	Dykeshifts (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	4750	4750	0	0.0	0.00
Dresden	4694	4694	0	0.0	0.00
Torgau	4579	4521	-58	-1.3	-0.22
Lutherstadt-Wittenberg	4348	4182	-165	-3.8	-0.21
Aken	4064	3896	-168	-4.1	-0.31
Barby	4275	4121	-154	-3.6	-0.24
Magdeburg	4302	4130	-172	-4.0	-0.20
Tangermuende	4209	4042	-167	-4.0	-0.17
Wittenberge	4360	4158	-202	-4.6	-0.13
Doemitz	4370	4169	-201	-4.6	-0.12
N.Darchau	4380	4180	-200	-4.6	-0.12
Boitzenburg	4402	4200	-202	-4.6	-0.11
Hohnstorf	4403	4201	-202	-4.6	-0.15
Geesthacht	4397	4199	-198	-4.5	-0.10

***Table 7.4** Peak discharge in the Elbe river for simulations of the 2002 flood event with and without the planned dyke-shifts.*

From Table 7.4 it can be concluded that for the 2002 flood, the effect of the planned dyke-shifts (given in Table 7.3) on discharge in the German section of the Elbe river varies between 1.3% and 4.6%. In absolute discharge, the difference in the peak is between 58 and 202 m3/s. Waterlevel changes are between 10 and 31 cm.

7.5 Scenario with dyke-shifts and polders

Next to evaluating the dyke-shifts, both polders and dyke-shifts are evaluated. In addition to the 20 dyke-shifts listed in Table 7.3, also 5 polders are simulated (Table 7.5).

No	Name	Land	Elbe-km	Area (ha)	Volume (Mm3)	Einlaufbreite (m)	Hmax (m)
1	**Nuenchritz**	Sachsen	(100.5-108.5)	600	15.0	30	2.50
2	Trebnitz/Lößnig	Sachsen	(117,5-123,8)	900	18.0	6300	2.00
3	**Aussig/Seidewitz**	Sachsen	(123,0-126,0)	500	17.0	30	3.40
11	**Dautzschen/Neublessern**	Sachsen	(160,0-165,0)	900	32.0	50	3.56
15	**Axien/Mauken**	Sachsen-Anhalt	(180,5-188,8)	1700	44.3	50	2.61

***Table 7.5** Polders as included in the scenario calculations reported in this chapter. Sources: ICPER Action Plan for the Flood Protection in the Elbe river basin (2003), ICPER First report on the implementation of the Action Plan for the Flood Protection in the Elbe River Basin (2006), BfG ELLA Studie – BfG 1542 (2006), email 4 April 2007 Mr. Pieper.*

The opening times of the polders are optimised with an iterative process in such a way, that the polder is not opened too soon before the actual flood discharge peak arrives: for each individual polder it has been checked which maximum peak discharge reduction could be achieved. Following the finding of the maximum peak discharge reduction, and thus the optimum parameterisation of this polder, an iterative process of finding the optimum values for the next polder was started. It was also checked that a polder was not activated too late, such that it would not get filled to its maximum capacity. Finally, the polders are emptied long after the passing of the flood wave, in this model simulation at time-step 1450 hrs.

Below, a few examples are given of hydrographs with and without these polders included in the simulations (Figs 7.8-7.10). Note that the dyke-shifts are also simulated in these runs, so the effects of both polders and dyke-shifts are shown together. The figures show both the dyke-shift only simulation, and the combined polder-dyke-shift simulation, as compared to the baseline simulation.

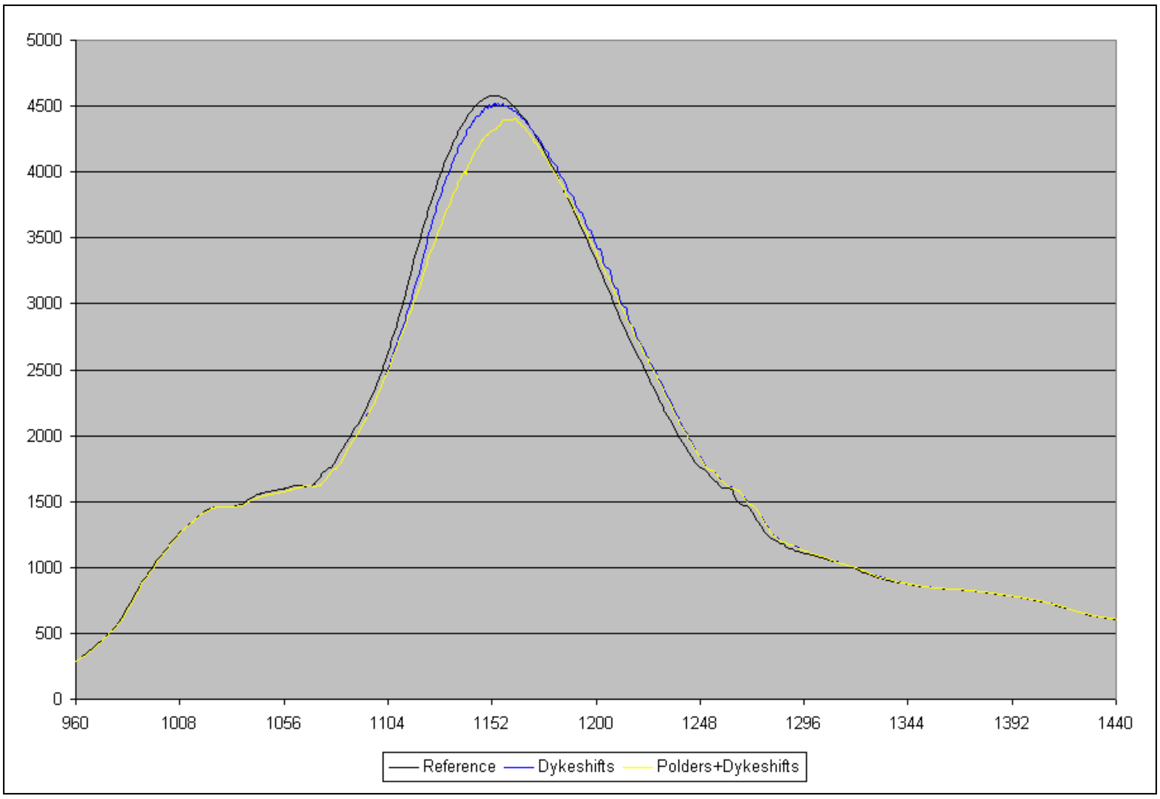


Figure 7.8 *The effects of the scenario with the planned polders and dyke-shifts as compared to the baseline simulation, for gauge Torgau, during the 2002 flood. The figures show both the dyke-shift only simulation, and the combined polder-dyke-shift simulation, as compared to the baseline simulation.*

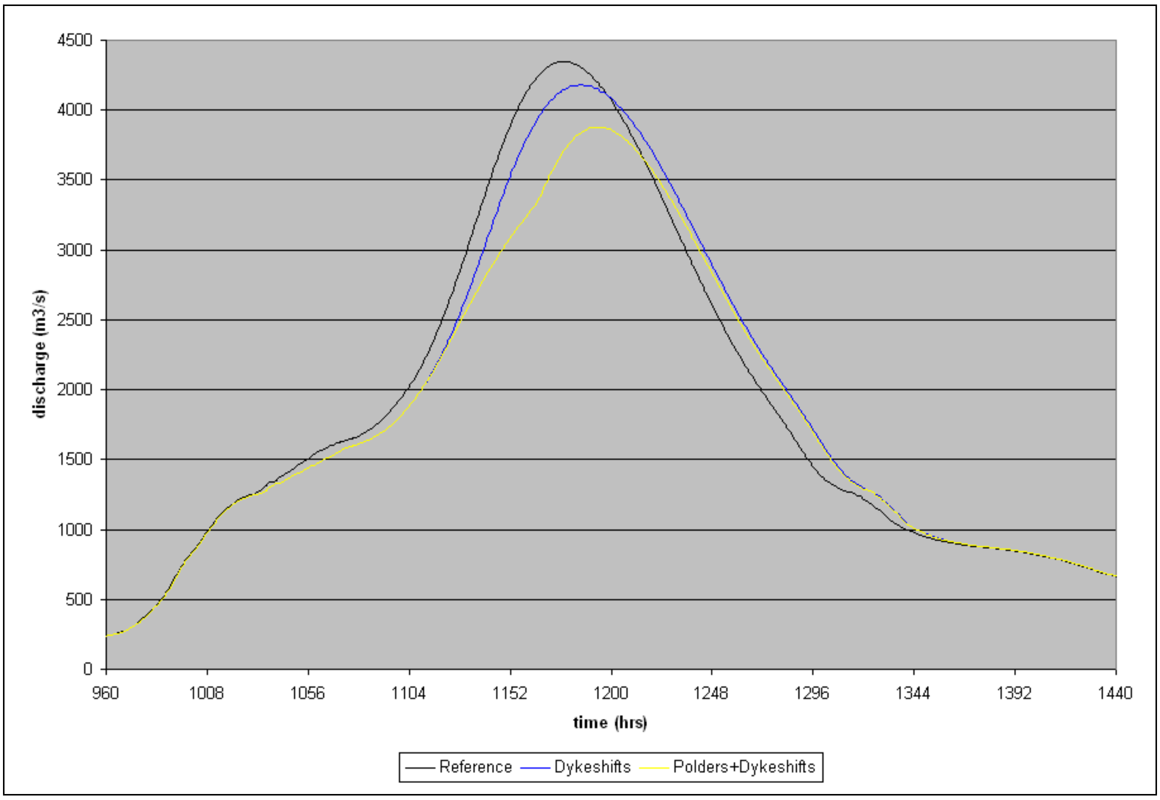


Figure 7.9 *The effects of the scenario with the planned polders and dyke-shifts as compared to the baseline simulation, for gauge Lutherstadt-Wittenberg, during the 2002 flood. The figures show both the dyke-shift only simulation, and the combined polder-dyke-shift simulation, as compared to the baseline simulation.*

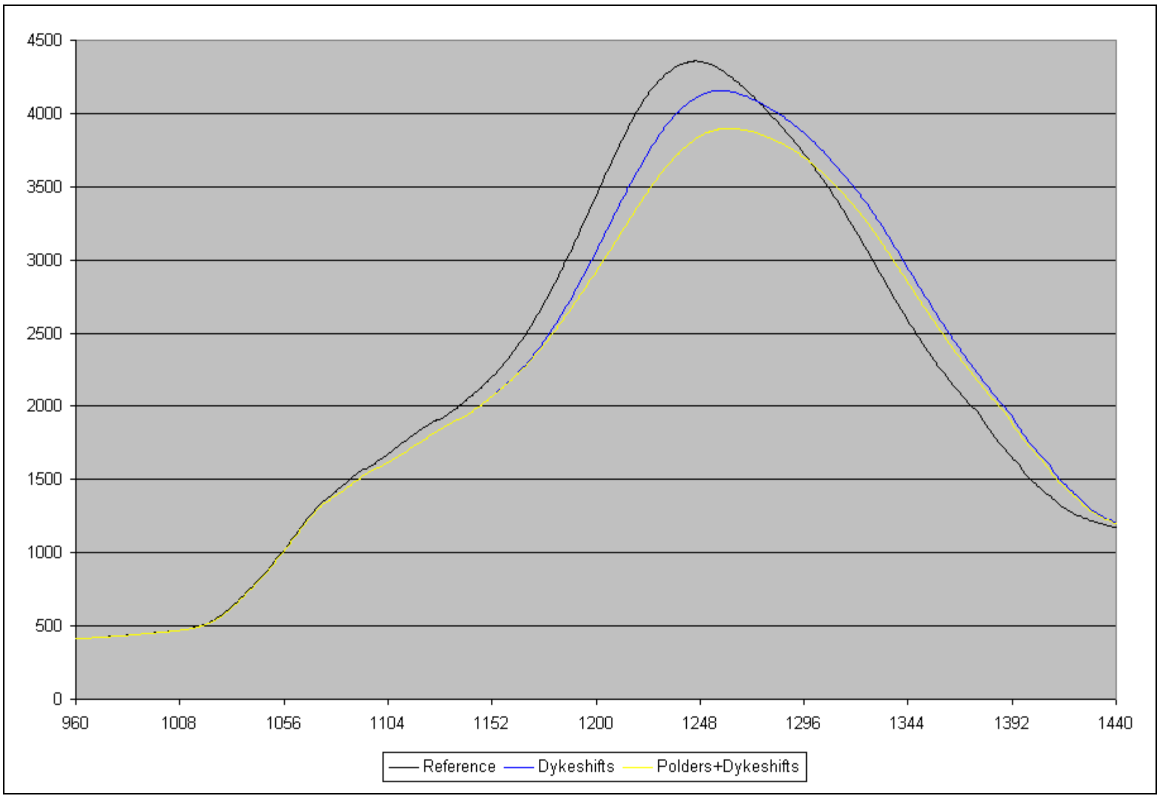


Figure 7.10 *The effects of the scenario with the planned polders and dyke-shifts as compared to the baseline simulation, for gauge Wittenberge, during the 2002 summer flood. The figures show both the dyke-shift only simulation, and the combined polder-dyke-shift simulation, as compared to the baseline simulation.*

Figures 7.8-7.10 clearly show the effects of these polders as compared to the baseline and dyke-shifts only simulation: a further delay as well as a further reduction of the flood peak. Table 7.6 gives a full overview of the effects of polders and dyke-shifts on peak discharge as compared to the baseline scenario 2002.

Station	Reference (m3/s)	All measures (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	4750	4750	0	0.0	0.00
Dresden	4694	4694	0	0.0	0.00
Torgau	4579	4401	-178	-3.9	-0.71
Lutherstadt-Wittenberg	4348	3879	-469	-10.8	-0.57
Aken	4064	3641	-424	-10.4	-0.74
Barby	4275	3868	-407	-9.5	-0.55
Magdeburg	4302	3874	-428	-10.0	-0.50
Tangermuende	4209	3797	-412	-9.8	-0.45
Wittenberge	4360	3900	-460	-10.6	-0.30
Doemitz	4370	3913	-457	-10.5	-0.29
N.Darchau	4380	3924	-456	-10.4	-0.29
Boitzenburg	4402	3947	-455	-10.3	-0.26
Hohnstorf	4403	3950	-453	-10.3	-0.35
Geesthacht	4397	3949	-448	-10.2	-0.23

Table 7.6 *Peak discharge in the Elbe river for simulations of the 2002 flood event with and without the planned combined polders and dyke-shifts.*

From Table 7.6 it can be concluded that for the 2002 flood, the combined effect of the planned polders and dyke-shifts (given in Table 7.1) on discharge in the German section of the Elbe river varies between 3.9% and 10.8%. In absolute discharge, the difference in the peak is between 178 and 469 m3/s. Waterlevel changes vary from 71cm at Torgau, 74cm at Aken, down to 23cm at Geesthacht.

7.6 Difference of effects between 2002 and 2006 flood

As compared to the August 2002 flood, the 2006 spring flood wave was longer but less extreme in maximum peak. Thus, it has been investigated if the planned measures would have had a different effect during a flood of the type of spring 2006 as compared to a flood such as the one of August 2002.

Station	Reference (m3/s)	Dykeshifts (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	2637	2638	0	0.0	0.00
Dresden	2642	2642	0	0.0	0.00
Torgau	2639	2629	-10	-0.4	-0.03
Lutherstadt-Wittenberg	2839	2814	-25	-0.9	-0.03
Aken	2770	2778	8	0.3	-0.10
Barby	3470	3428	-42	-1.2	-0.04
Magdeburg	3471	3429	-42	-1.2	-0.07
Tangermuende	3460	3416	-44	-1.3	-0.05
Wittenberge	3616	3570	-46	-1.3	-0.05
Doemitz	3617	3569	-48	-1.3	-0.05
N.Darchau	3621	3574	-47	-1.3	-0.05
Boitzenburg	3653	3607	-46	-1.3	-0.04
Hohnstorf	3654	3609	-45	-1.2	-0.05
Geesthacht	3652	3606	-47	-1.3	-0.03

Table 7.7 *Peak discharge in the Elbe river for simulations of the 2006 spring flood event with and without the planned dyke-shifts.*

Station	Reference (m3/s)	All measures (m3/s)	Difference (m3/s)	%	Waterlevel Difference (m)
Schoena	2637	2638	0	0.0	0.00
Dresden	2642	2642	0	0.0	0.00
Torgau	2639	2609	-31	-1.2	-0.08
Lutherstadt-Wittenberg	2839	2778	-61	-2.2	-0.06
Aken	2770	2718	-52	-1.9	-0.21
Barby	3470	3368	-102	-2.9	-0.10
Magdeburg	3471	3369	-102	-2.9	-0.17
Tangermuende	3460	3353	-107	-3.1	-0.15
Wittenberge	3616	3502	-113	-3.1	-0.13
Doemitz	3617	3498	-118	-3.3	-0.13
N.Darchau	3621	3502	-120	-3.3	-0.12
Boitzenburg	3653	3533	-120	-3.3	-0.11
Hohnstorf	3654	3535	-119	-3.3	-0.14
Geesthacht	3652	3531	-121	-3.3	-0.09

Table 7.8 *Peak discharge in the Elbe river for simulations of the 2006 spring flood event with and without the planned combined polders and dyke-shifts.*

From Table 7.7 and 7.8 it can be concluded that for the 2006 spring flood, the results shower a smaller effect of the planned measures as compared to effect the measures would have had during the 2002 summer flood.

7.7 Conclusions

From the calculations done in this chapter, the following conclusions are made for the simulations using the 2002 event as a reference:

- Without dyke-breaks, peak discharge in 2002 would have been 2.6-9.1% higher, with the largest increase in the lower Elbe. Waterlevels would have been 18-54 cm higher.
- The 20 planned dyke-shifts reduce the peak discharge of the 2002 flood with 1.3-4.6% (58-202 m3/s). Waterlevels would have been 10-31cm lower.
- The 5 planned polders and 20 planned dyke-shifts simulated here, reduce the peak discharge of the 2002 flood with 3.9-10.8% (178-469 m3/s). Waterlevels would have been 23-74 cm lower.

Since the flood of spring 2006 had different characteristics, the effects of the scenarios have been also estimated with this event as a reference:

- The 20 planned dyke-shifts reduce the peak discharge of the 2006 flood with 0.4-1.3% (10-48 m3/s). Waterlevels would have been 3-10cm lower.
- The 5 planned polders and 20 planned dyke-shifts simulated here, reduce the peak discharge of the 2006 flood with 1.2-3.3% (31-121 m3/s). Waterlevels would have been 8-21cm lower.

8. Deviations from the aims of the Action Plan

The Action Plan for the Flood Protection of the Elbe River Basin (ICPER, 2003) defines detailed aims of the two studies on flood retention polders and reservoirs.

The study described in this report solely describes the quantitative hydrological modelling results, and does not include a cost-benefit analysis, nor descriptions on advantages and disadvantages of the planned measures. Statements on these issues are outside the competence of the authors.

The list of planned retention polders and dyke-shifts has been revised several times since the start of the study and the end of the study, on the request of the ICPER. The list used here for the calculations is a result of the last agreed list in April 2007.

The requested estimation of the maximum storage potential of the polders was not carried out, since that maximum was a given fact (see table of polders).

Due to delays in basic data delivery to the authors, or the lack of relevant data, several other components of the studies could not be carried out, such as:

- Decrease of damage potential after the implementation of the measures;
- Polder and Dyke-shift scenario calculations for the 1994 and 2003 flood

Furthermore, basic data that have arrived after the deadline set by the authors, have not been taken into account. The complete simulation chain, including calibration, would need to be repeated whenever new data arrive. The deadline for the end of the study would have been jeopardised.

Towards the end of the study, following the 2006 spring flood, new requests of the ICPER to evaluate the scenarios for the 2006 flood were carried out and are included in this report. This further limited the time to carry out some of the above issues.

As for the reservoir study, a dataset was available to the authors on the estimated influence of the Vltava reservoirs for 2002 only, so no calculations could be made for other, longer periods, to establish HQ_T values with and without reservoirs. Also for the Saale, the data provided did not enable the authors to investigate the period 1890-2002.

With the 2002 and 2006 flood calculations of the scenarios, the most important aims of the studies are reached. The effects of the planned scenarios for minor floods such as 1994 and 2003 are expected to be larger as a percentage, since the flood waves are smaller., but lower in magnitude.

9. Conclusions

A hydrological model simulation study has been carried out in the Elbe basin using detailed data obtained from the relevant Czech and German institutes. The LISFLOOD model has been calibrated for the Elbe river basin using these data. Using this calibrated model setup, two studies have been carried out in the framework of the Action Plan for the Flood Protection of the International Commission for the Protection of the Elbe River (ICPER).

The 2002 flood without dyke-breaks

The first part of the simulation study was a simulation of the 2002 flood without dyke-breaks. It has been estimated here that without dyke-breaks, the discharge in the lower part of the Elbe river would have been 2.6 – 9.1 % higher (117-384 m3/s). Waterlevels would have between 18 and 54 cm higher.

Reservoir Study

The planned scenario for Saale reservoir steering investigated here does not have any significant influence on the discharge of the Elbe. The influence of changing the flood storage in the Bleiloch and Hohenwarte reservoirs in winter from 40 to 55 Mm3 and in summer from 25 to 35 Mm3 on river discharge has been assessed. The scenario results have shown that this planned scenario for reservoir steering in the Saale cascade does not have a significant influence on the discharge of the river Elbe, for the investigated flood events in 1994, 2002 und 2003 at gauging station Calbe-Griezehne (lower Saale). Also the influence on the discharge in the river Elbe is marginal: changes in peak discharge downstream the Saale-confluence are in the order of 0.2% (difference in discharge 4-8 m3/s).

Furthermore, the influence of the Vltava reservoir cascade was investigated using two datasets provided by CHMI: one dataset with the actual situation and steering of the Vltava cascade, and a scenario without the Vltava cascade. For floods with a magnitude such as in August 2002, the difference between the scenario with and without the Vltava cascade is between 1.6 and 3.7% (84-171 m3/s) in the German part of the Elbe river.

Polder and Dyke-shift Study

The potential effects of 5 polders and 20 dyke-shifts on discharge in the river Elbe have been estimated. The main outcomes are the following:

The 20 planned dyke-shifts reduce the peak discharge of the 2002 flood with 1.3-4.6% (58-202 m3/s). Waterlevels would have been 10-31cm lower. For the 2006 flood the results are similar in character, but lower in magnitude. The measures reduce the peak discharge of the 2006 flood with 0.4-1.3% (10-48 m3/s). Waterlevels would have been 3-10cm lower.

The 5 planned polders and 20 planned dyke-shifts simulated here, reduce the peak discharge of the 2002 flood with 3.9-10.8% (178-469 m3/s). Waterlevels would have been 23-74cm lower. For the 2006 flood, the results are again lower: the measures reduce the peak discharge of the 2006 flood with 1.2-3.3% (31-121 m3/s). Waterlevels would have been 8-21cm lower.

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Abstract

Following the disastrous floods in the Elbe and Danube river basin in August 2002, the Directorate General (DG) Joint Research Centre (JRC) of the European Commission (EC) offered to carry out a flood scenario study in the Elbe river in support of the "Flood Action Program Elbe" of the ICPER (International Commission for Protection of the Elbe River). This report describes the two studies that have been carried out, the methods used, and the results obtained.

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