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Development of rainfall-runoff models for the Sieg and Lippe

Final Report, Volume I: Main Text

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ABSTRACT :

The FLORIJN Project concerns the development of rainfall-runoff models for the rivers Sieg and Lippe in Germany. In this Volume of the Final Report (i.e. Volume I: Main Text) the rainfall-runoff models for the Sieg and Lippe are described. In addition their calibration and validation results as well as their results of a sensitivity analysis are discussed.

REFERENCES:

REV.	ORIGINATOR		DATE	REMARKS	REVIEWED BY		APPROVED BY	
	M. van Mierlo	[signature]	19-12-1997		K. van Heynert	[signature]	E. van Beek	[signature]

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Contents

1 Introduction

The FLORIJN project concerns the development of a flood forecasting model for level gauge Lobith. The aim of the FLORIJN project is to be able to forecast high water levels at Lobith three days in advance with sufficient reliability. A part of the FLORIJN model comprises of rainfall-runoff models for the rivers Sieg and Lippe in Germany. RIZA commissioned the development of these two rainfall-runoff models to WL | Delft Hydraulics.

Three earlier reports, concerning the development of the two rainfall-runoff models, were produced, respectively: the First Progress Report in November 1996, the Second Progress Report in July 1997 and the Third Progress Report in November 1997. In accordance with the contract (RIZA-overeenkomst nr. RI-2040), the following subjects are to be reported upon in this Final Report, viz:

1. Data collection,
2. Validation of available hydro-meteorlogical data,
3. Preparation of data-sets with different spatial refinement,
4. Determination of spatial relationships between on-line and off-line stations,
5. System analysis (i.e. characteristics of the Sieg and Lippe catchments),
6. Advice on type of snow-melt module required,
7. Calibration & validation of the rainfall-runoff models, and
8. Sensitivity analysis of the rainfall-runoff models.

The Final Report consists of two Volumes, i.e. Volume I: Main Report and Volume II: Annexes, Tables and Figures. The current report concerns Volume I of the Final Report.
In Chapter 2 the characteristics of the Sieg and Lippe basins with emphasis on floods are described. In Chapter 3 an overview of collected data is given, while Chapter 4 concerns the validation and completion of the collected hydro-meteorological data.
In Chapter 5 the selected division of the Sieg and Lippe basins into subbasins is explained. In Chapter 6 off-line available areal rainfall, computed using rainfall data observed by the Landesumweltamt Nordrhein-Westfalen (LUA-NRW), are discussed. Chapter 7 concerns the derivation of spatial relationships between off-line areal rainfall and on-line available point-observations at KL-climatic stations operated by the Deutscher Wetterdienst (DWD).
In Chapter 8 the applied FLORIJN rainfall-runoff model is described including method of handling snow as well as its most important modelling aspects. Chapter 9 comprises the validation and calibration of the Sieg and Lippe rainfall runoff models. In Chapter 10 sensitivity analysis results are discussed. The sensitivity analysis comprised of: senstivity to variations in model parameters; sensitivity to overestimation and underestimation of forecasted rainfall; and sensitivity to the use of off-line available areal rainfall (i.e. LUA-NRW) or on-line available areal rainfall, computed by using on-line available point-observations at DWD KL-climatic stations and the established spatial relationships. In Chapter 11 aspects of importance in the real-time use of the Sieg and Lippe rainfall runoff models are discused.

In Chapter 12 concluding remarks and recommendations are made.

For Annexes, Tables and Figures, reference is made to Volume II: Annexes, Tables and Figures of this Final Report.

2 System analysis

2.1 Sieg

2.1.1 General description of the Basin

The Sieg is a tributary of the Rhine river, entering the Rhine at km. 660. This is at about 200 km from the station Lobith, which is the first gauging station in the Netherlands. At the gauging station of Menden, located at 8.4 km from the confluence with the Rhine at an altitude of 49.3 m+NN, the area of the basin is 2,832 km^2. The total area is 2,861 km^2.

The river flows through Rheinland-Pfalz and Nordrhein-Westfalen. The total length of the river is about 150 km. An overview of the Sieg basin is shown on Fig. 3.1 and 3.3. The Sieg is a typical mountain river with steep slopes and a dendritic network of tributaries. Four main tributaries can be distinguished: Agger, Bröl, Heller and Nister. The other tributaries are all relatively small and have their confluence directly with these three tributaries or with the main river. This configuration implies that a sub-division of the river into smaller subbasins will normally follow the same tributaries. On Fig. 2.1 a longitudinal profile is shown of the river, which indicates that the gradient of the river is rather uniform. On Fig. 2.2 the cumulative contributing area is shown, which shows that this is also uniformly distributed along the river stretch, with the exception of the last 20 km when the Agger river enters the main river.

The Sieg is a rather steep river, with a slope of about 0.0025 in the upper basin, slowly decreasing to about 0.001 near the confluence (see Fig. 2.3).

Geology, soils and vegetation

The description of the geology and soil types is taken from the publication 'Grosskonzept zur Renaturierung der Siegaue - Sieg und Aggerauenkonzept' (C+S Consult GmbH, 1993) and the Rhine Monography ("Le Bassin du Rhin/Das Rheingebiet", CHR/KHR, 1970). The basin of the Sieg river forms part of the Rheinische Schiefergebirge. As the name indicates, the geology is dominated by metamorphic rocks, mainly slates, grauwackes and quartzites. The permeability is normally low, except for secondary permeability through joints and fissures, and the contribution from groundwater to flood generation is likely to be neglectable. The few outcrops of extrusive (volcanic) rocks, mainly in the Agger basin, will show similar characteristics. The soils in the Sieg basin are dominated by cambisoils, containing both sand and silt. They are typical for metamorphic areas and may impede locally the infiltration. This contributes to the general character of the Sieg basin having a rather low permeability and in consequence probably large contribution of overland flow and subsurface stormflow (or macropore flow) to flood generation.

The vegetation of the Sieg basin is a combination of cultivated land and forest, the latter occurring more on the upper part and the steeper slopes which are less attractive for cultivation.

2.1.2 Climatology

As in most of the tributaries to the Rhine river in the northern and middle part of Germany, floods are formed by different weather types depending on the season. In summer, convective thunderstorms can lead to high-intensity local rainfall. The resulting floods are severe on smaller tributaries that are affected by the storm, but only major thunderstorms over a large area will lead to floods at the point of outflow. In winter most rainfall is due to frontal systems and this type of weather system is characterised by relatively low intensity rainfall of long duration (often several days) over a very large area (e.g. the total area of the Rhine basin in Germany). Floods resulting from this type of rainfall can be locally unimportant, but may lead to a major flood on the major tributaries and as such also on the Rhine. For the Sieg basin there is a clear gradual increase in annual rainfall from West to East, from the relatively mild and dry climate in the Rhine valley to the cooler and wetter region of the hilly area in the eastern part of the basin. Most of the Sieg basin has an average yearly rainfall of 800 - 1,000 mm, but the Agger basin has a much more unequally distributed pattern with values increasing up to 1,500 mm on the northern edge. In the lower area close to the confluence with the Rhine, the value is about 700 mm. The discharge pattern reflects closely the meteorology in that most of the floods occur in the winter period between December and March. Some floods occur in April-May, but they are often different in character, with high intensity rainfall over a smaller area. The rare summer floods are very localised as they are normally due to thunderstorms.

There is only one station (i.e. Bad Marienberg, altitude: 547 m, DWD KL-climatic station) in the Sieg basin for which snow measurements (snow height and new snow) are available. On Fig 2.4 snow measurements at Bad Marienberg are given, which indicates that snow occurs regularly each year, with the exception of the beginning of the 90es. In theory, snow may be important in flood generation during periods of temperature increase (snow being present) and/or rainfall on snow. In the available hydro-meteorological data, there are no clear examples of a significant contribution from snow melt on the generation of flood peaks. On Fig. 2.5 the rainfall, actual snow height, amount of fresh snowfall and minimum temperatures observed at the station Bad-Marienberg are depicted together with observed discharges at the station Weidenau. From Fig. 2.5 it can be observed that an increase in temperatures will result in snow-melt, but the flood wave appears to be much stronger related to rainfall than to snow-melt. In the analysis of the calibration and validation results of the Sieg rainfall-runoff model (see section 9.7), more evidence is gained for the conclusion that snow-melt is not important in flood generation in the Sieg basin.

2.1.3 Hydrologic and hydraulic aspects

Only a small part of the Sieg valley is still in natural state. From about 1900 several dykes were build along the Sieg for flood protection. Along the main river, inundation areas are present, which have been redefined recently (1995) by the Länder Authorities in Koln. The inundation areas are defined as those areas which are flooded with a flood of a return period of 100 years. A consequence of the assignment of inundation areas is that it has become very difficult, or even impossible, to get permission to build in the flood-prone areas along the main course of the river. A comparison between maps from the end of the 19th century with the present situation shows that up till 60% of the retention areas have been lost to constructions, etc. (C+S Consult GmbH, 1993).

Of a total length of 75 km of the downstream part of the Sieg, for which plans are made for flood protection, 10 km has dykes on both sides, 15 km on one side, and about 51 km has no protection.

A comparison between the relative importance of the discharges of the tributaries is based on the hourly values available for the fourteen floods selected for this project. The discharge from the Agger, which is the main tributary of the Sieg, during flood situations is about 25% of the total discharge at Menden. However, the peak on the Agger normally occurs a few hours earlier than that on the Sieg due to the general eastern movement of storms and the difference in travel time. The relative contribution of the other tributaries, like the Heller, is not known as there are no hourly discharge data available, but from information in the Yearbooks, the Heller is also an important tributary with peak discharges that can supersede those of the Agger (e.g. in March 1988).

The reaction time of the tributaries of the Sieg river can be seen from Fig. 2.6 and Fig. 2.7. On Fig. 2.6 the reaction time of the Agger is shown for a flood in 1980. However, the comparison is made between the meteorological station Suelze and the gauging station Lohmar. Suelze is located in the north-western corner of the Agger basin and as such the reaction time of the total basin depends on the direction and speed of movement of the storm. The travel time between the stations Eitorf and Menden (distance 30 km) is about 4 hours.

2.1.4 Reservoirs

The information for this chapter is drawn from Wildenhahn & Klaholz (CHR, 1996). This report gives data on all reservoirs in the Rhine basin with a capacity of more than 0.3 hm^3. River weirs, even when having a larger capacity than indicated before, are not included. An overview of the reservoirs in the Sieg basin is given in Table 2-1.

Table 2-1 Reservoirs in the Sieg basin

Nr.	Name	Basin	Volume (hm3)	Average inflow (hm3)	Contributing area (km2)	Degree of development (%)	Year of inauguration	Purpose
5.11-1	Breitenbachtalsperre	Breitenbach	7.8	9.3	11.64	83.9	1956	T / H / A
5.11-2	Obernautalsperre	Obernau	14.9	17.3	21.52	86.1	1972	T / H
5.11-3	Wahnbachtalsperre	Wahnbach	41.4	38.6	69.97	107.3	1958	T / H / A
5.11-4	Genkeltalsperre	Genkel	8.2	9.8	11.5	83.7	1954	T
5.11-5	Aggertalsperre	Agger	19.3	34.7	40.57	55.6	1930	T / H / A /K/
5.11-6	Wiehltalsperre	Wiehl	31.5	30	45.87	105	1974	T / H

Degree of development = quotient of the storage lake volume and the mean annual inflow, indicated as percentage.

Purpose:
T = drinking water supply
H = protection against flooding
K= energy production
E = recreation
A= compensation reservoir

The location of the reservoirs, together with those on the Lippe basin. is shown in Fig. 2.15.

The total volume of the reservoirs in the Sieg basin is 123 hm^3 and a total contributing area of 201 km^2. This is only 7% of the total area of the Sieg basin. It is clear that in general the influence of reservoirs in the flood situation in the Sieg basin is small compared to e.g. the Ruhr, which has a total of 24 basins with a total volume of nearly 500 hm^3.

It is interesting to see that, with the exception of the Genkeltalsperre, officially all reservoirs have the double purpose of drinking water supply and protection against flooding. However, the function of a reservoir for flood mitigation is much dependent on:

- location (area of upstream basin)
- size
- annual inflow
- steepness and volume of peak inflow
- conflicting purposes

The actual role of these reservoirs in flood situations can be determined by obtaining detailed information on the reservoir operation during historical floods, including the inflow and outflow discharges.
However, it is clear that the reservoirs are in such a position in the Sieg basin, that their flood mitigation potential is very limited and only of local interest. For this reason their function is neglected in the project.

2.1.5 Hydrometeorological stations

A distinction is made between meteorological stations and river gauging stations. Meteorological stations in the Sieg basin are either operated by the Landesumweltamt Nordrhein-Westfalen (LUA) or by the Deutscher Wetterdienst (DWD). The location of these meterorological stations are depicted on Fig. 3.1. For the type of available data, reference is made to Chapter 3, Annex 2 and Annex 3.
Rated river gauging stations in the Sieg basin are operated by the Staatliches Landesumweltamt (StuA). The location of these river gauging stations are depicted in Fig. 3.3. For the availability of discharges, reference is made to Chapter 3, Annex 2 and Annex 3.

2.2 Lippe

2.2.1 General description of the Basin

The Lippe river enters the Rhine at km. 810, which is about 50 km from the station Lobith on the Dutch border. At the gauging station Schermbeck, the total area of the basin is 4,783 km^2. The station is at 22.4 km from the confluence at an altitude of 22.7 m+NN. The total area of the Lippe basin is 4,886 km^2. The total length of the river is about 230 km, with about 215 km as lowland river with a slope of about 0.00032. An overview of the Lippe basin is shown on Fig. 3.2 and 3.4.

The basin of the Lippe river is totally different from the Sieg. Only in the upper part of the basin there is a hilly region, but much gentler in slope than the Sieg. The lower part of the Lippe, starting from the city of Paderborn, is a typical low-land river with a small slope. This has direct implication for the reaction time of the Lippe compared to the Sieg.

The Lippe doesn't have such well defined tributaries as in the case of the Sieg river. The main tributaries that can be distinguished are: Alme, Ahse, Seseke, Halterner/Muhlenbach and Stever; the latter two entering as one tributary into the Lippe. There are a number of canals parallel to the main river in the lower part of the Lippe basin, but they are not important for flood modelling. A longitudinal profile is shown in Fig. 2.8, which shows clearly the strong change in topography in the upper part of the basin. In Fig. 2.9 the cumulative contributing area is shown, which indicates that this is rather equally distributed along the length of the river. The slope of the Lippe river is very gentle in the lower reach (about 0.0003), but in the upper basin a strong change in slope occurs (see Fig. 2.10). This is due to the threshold in the topography directly downstream from the city of Paderborn. The steepest slope is found between the gauging stations Neuhaus-2 and Bentfeld (about 0.003).

Geology, soils and vegetation

The valley bottom of the Lippe river in the flood plain is formed by sediment, mainly of fluvial origin, but partly also fluvio-glacial, the latter having a much higher clay and silt content and in consequence a rather low permeability. The fluvial deposits, mainly consisting in sand and gravel in which podzols soils are formed, are highly permeable and can store considerable quantities of infiltrated rainfall. Parallel to the valley bottom, on the southern part of the basin, (glacial) moraines are found, which will only locally have high permeabilities. Most of these formations are impermeable due to high clay content.

The upper hilly basin is dominated by karstified limestone and dolomite, which implies that they are highly permeable and infiltration will lead to fast subsurface contribution to floods. Overland flow is normally absent on these type of rocks, unless covered by soil, which are mainly redzinas. These type of soils contain a high percentage of clay and silt and as such may locally hamper the infiltration of rainfall. However, in karstic limestone areas, overland flow on this type of soils normally occurs only over a short distance, after which it infiltrates completely when encountering an outcrop of the limestone formation. This is confirmed by the observation that the Alme and its tributaries are dry over part of their profile. Both limestone and dolomite form excellent aquifers for long-lasting base-flow.

The landuse, and as such the vegetation, is dominated by farmland. There are only small patches of forest, mainly confined to the eastern part of the basin close to the watershed.

2.2.2 Climatology

The open character of the Lippe basin implies that rainfall is much more evenly distributed than in the case of the Sieg basin. The average yearly precipitation is about 600 - 700 mm, but a strong gradient exists in the upper (hilly) region where the average value increase towards about 1,200 mm due to orographic influence. Snow is likely to play only a minor part in the hydrology of the Lippe, and if so only for the upper part upstream from Paderborn. There is (yet) no station available with snow data to confirm whether this is correct.

2.2.3 Hydrologic and hydraulic aspects

The time of concentration for rainfall in the upper part of the basin towards the station of Schermbeck is in the order of about 1-2 days. The actual timing of the peak (and the shape of the hydrograph) depends on the direction of the storm. It is theoretically possible to have a flood peak occurring earlier at Schermbeck than at one of the upstream stations if the rain field travels from West to East. This is actually observed for several storms among those that have been chosen for analysis. In several cases, e.g. for the floods of February 1983, May 1984 and January 1987 the maximum discharge at Lippstadt 2 (at 168 km from the confluence) occurs several hours later than at Schermbeck. Apart from pertinent measurement errors it is most likely due to the travel direction of the rainfall front.

In Fig. 2.11 and 2.12, the discharge is given for the stations Lippstadt2, Leven and Schermbeck, resp. at 168 km, 65 km and 22 km from the confluence with the Rhine. In Fig. 2.11 (flood February 1984) the peaks form a logic combination, but in Fig. 2.10 (flood of May-June 1984), the peak at Lippstadt 2 is several hours later than at Schermbeck, although the travel time should be up to a day. In Fig. 2.13 the flood generation process is shown for the flood of December 1993 - January 1994. It is evident that rainfall in the lower Lippe basin can result in a sudden increase in the total discharge at Schermbeck, as can be seen in the second flood wave when comparing the form of the flood wave between Leven and Schermbeck.

The relative contributions of both the Ahse and the Seseke tributaries during floods is about 10% of the total discharge at Schermbeck. For the Stever, the percentage is up to 30%. However, the occurrence of the peak is normally not simultaneous with the main river.

The large difference in flood peak between the Lippe and Sieg rivers is shown in Fig. 2.14 for a number of periods. The Lippe has a much wider flatter peak than the Sieg and subsequently the flood peak value of the Sieg is more than double that of the Lippe. This is especially remarkable were the area of the Lippe (4,886 $km^{2)}$ is much larger than that of the Sieg river (2,861 km^2). In general the flood peaks arrive nearly simultaneously at their respective confluences with the Rhine. Although the flood peak in the Sieg is nearly always much higher, major differences occur such as in Period no. 9 when the first peak is in the same order of magnitude, while the second peak on the Lippe is hardly existent.

2.2.4 Reservoirs

An overview of the reservoirs in the Lippe basin is given in Table 2-2

Table 2-2 Reservoirs in the Lippe basin

Nr.	Name	Basin	Volume (hm3)	Average inflow (hm3)	Contributing area (km2)	Degree of development (%)	Year of inauguration	Purpose
5.15-1	Aabachtalsperre	Aabach	19.51	17.3	34.8	112.8	1982	T/H
5.15-2	Talsperre Hullern	Stevern	10	133.5	603.15	7.2	1985	T
5.15-3	Stevertalsperre Haltern	Stevern	20.5	240	908.31	8.5	1930	T

Degree of development = quotient of the storage lake volume and the mean annual inflow, indicated as percentage.

Purpose:
T = drinking water supply
H = protection against flooding
K= energy production
E = recreation
A= compensation reservoir

The location of the reservoirs (together with those on the Ruhr basin) is shown on Fig. 2.15.
The total volume is only 50 hm3. The total contributing area is 943 km2, which is about 20% of the total area of the Lippe basin. Although this percentage is much higher than in the case of the Sieg, the small volume of the each of the reservoirs rules out their importance as flood mitigating structures.

For the Lippe, only the Aabachsperre is important for the upper tributary Alme. For the modelling for the flood forecasting the area upstream from the reservoir can be disregarded. The two reservoirs on the Stevern have a much too small a volume to have any noticeable influence on flood mitigation. This is also indicated in the official purpose of the reservoirs as being designed for drinking water purpose.

There are still a number of retention basins build (or planned) in the upper basin of the Lippe, most of them with a contributing area of less than 100 km^2 (25 Jahre Wasserverband Obere Lippe, 1971-1996). Although studies exist which indicate that the influence of the retention basins on the flood regime of the Lippe is considerable, there are no data on the operation of these reservoirs. *For the present study the existing of these reservoirs have to be neglected,* which may lead to an overestimation of the flood peak at Schermbeck when more basins become available in the future.

2.2.5 Hydro-meteorological stations.

A distinction is made between meteorological stations and river gauging stations. Meteorological stations in the Lippe basin are either operated by the Landesumweltamt Nordrhein-Westfalen (LUA) or by the Deutscher Wetterdienst (DWD). The location of these meterorological stations are depicted on Fig. 3.2. For the type of available data, reference is made to Chapter 3, Annex 2 and Annex 3.
Rated river gauging stations in the Lippe basin are operated by the Staatliches Landesumweltamt (StuA). The location of these river gauging stations are depicted in Fig. 3.4. For the availability of discharges, reference is made to Chapter 3, Annex 2 and Annex 3.

3 Overview of collected data

In this Chapter an overview of the collected data is given. In consultation with Rijkswaterstaat RIZA, fourteen time-periods of interest for modelling purposes were selected on basis of the following criteria, viz:

- There should also be a considerable flood wave on the river Rhine, and
- Only time-periods after 1980 were considered in order to minimize effects of recent changes in the catchment area on its runoff-characteristics.

Based on the above criteria the following fourteen time-periods were selected:

1. January - February 1980,
2. December 1981 - February 1982,
3. January - February 1983,
4. April - June 1983,
5. February 1984,
6. May - June 1984,
7. January - February 1986,
8. December 1986 - January 1987,
9. February- March 1987,
10. March - April 1988,
11. December 1988,
12. February - March 1990,
13. December 1993 - January 1994, and
14. January - February 1995.

The data comprise:
- precipitation (rainfall and snow)
- temperature
- discharges
- evapotranspiration

The evapotranspiration is not important during floods (especially during winter) and for this reason this data was disregarded.

3.1 Rainfall

3.1.1 Off-line observed rainfall by the LUA Nordrhein-Westfalen.

In this subsection rainfall data collected from the Landesumweltamt Nordrhein-Westfalen (LUA-NRW) is described. The LUA-NRW rainfall data is not on-line available and is, therefore, in this report refered to as *off-line* rainfall data. The rainfall is measured by pluviographs and has been aggregated to hourly rainfall. Hereafter, particulars of the LUA-NRW meteorological stations (including their data availability) are discussed catchment-wise.

Sieg

The LUA-NRW meteorological stations available for the Sieg basin are given in Table 3-1. *All the stations are pluviographs*. The location of the meteorological stations are depicted in Fig. 3.1.

Table 3-1 LUA-NRW meteorological stations available for the Sieg basin.

Name of station	Latitude	Longitude	Altitude (m)	Agency
Aue	51:03:04N	008:19:05E	429.00	Stawa Hagen
Bonn Bockeroth	50:43:43N	007:14:35E	155.00	Stawa Bonn
Bonn-Heizkraftwerk	50:42:41N	007:07:14E	59.00	Stadt Bonn
Brenzingen	50:52:08N	007:36:00E	241.00	Stawa Bonn
Eitorf	50:46:43N	007:25:21E	81.00	Stawa Bonn
Eschmar Muellekoven	50:46:47N	007:07:13E	51.00	Stawa Bonn
Frielingsdorf	51:02:51N	007:25:14E	210.00	Stawa Bonn
Haenscheid	50:50:13N	007:25:37E	177.00	Stawa Bonn
Helgersdorf	50:51:33N	008:11:02E	380.00	Stawa Hagen
Homburg-Broel	50:54:53N	007:31:28E		
Kuchenbach	50:44:53N	007:18:53E	98.00	Stawa Bonn
Lahnhof-Geiersgrund	50:53:03N	008:15:18E	520.00	Stawa Hagen
Lehruch (Lehmbach)	50:56:07N	007:11:53E	88.00	Stawa B44
Marienfeld	50:53:10N	007:26:11E	193.00	Stawa Bonn
Neunkirchen Seelsch.	50:50:14N	007:20:22E	165.00	Stawa Bonn
Olpe	51:01:60N	007:50:32E	305.00	RV Essen
Rehringhausen	51:02:47N	007:54:20E	390.00	Stawa Hagen
Siegen Ghs (Ges. Hochsch)	50:54:13N	008:01:50E	300.00	Ges. Hoch-schule Siegen
Suelze	51:01:28N	007:16:23E	145.00	Stawa Bonn

The rainfall data availability is rather simple as there are only periods to distinguish, i.e. there are no missing data within the periods. An overview of the availability of the data is given in Annex 2.

All stations have rainfall data for the Periods no. 1-12, except for:

Aue:	data not available for Period no. 1- 6
Lahnhof-1:	data not available for Period no. 1 - 10
Olpe:	data not available for Period no. 1- 4
Rehringhausen:	data not available for Period no. 12.

The implication is that the station of Lahnhof-1 is not used, because there is another station (Lahnhof-Geiersgrund) close by with sufficient data.

For the last two Periods (no. 13 & no. 14), i.e. the major floods of 1993/94 and 1995, hourly rainfall is only sparsely available.

Period no. 13 (1/12/1994 - 31/1/1994)

Data available for the following stations:
Bonn-HKW
Bonn-Bockeroth
Brenzingen
Eitorf
Eschmar
Frielingsdorf
Haenscheid
Homburg
Kuchenbach
Lehruch (Lehmbach)
Marienfeld
Neunkirchen

Period no. 14 (1/1/1995 - 28/2/1995)

In Period no. 14, there are only data for the station of Bonn-HKW.

Lippe

The LUA-NRW meteorological stations available for the Lippe basin are given in Table 3-2. The stations in **bold** are pluviographs. The location of the meteorological stations are depicted in Fig. 3.2.

Table 3-2 LUA-NRW meteorological stations available for the Lippe basin.

Name of station	Latitude	Longitude	Altitude (m)	Agency
Baumberg	51:57:59N	007:21:39E	180.00	Stawa Muenster
Boenen	51:35:14N	007:45:30E	66.0	Lippeverband
Boke	51:34:36N	008:32:06E	87.00	Stawa Lippstadt
Bottrop Eigen	51:33:04N	006:56:45E	38.00	Emschergenossenschaft
Brilon 1	51:23:53N	008:34:59E	420.00	Stawa Lippstadt
Buke	51:44:41N	008:57:26E	322.00	Stawa-Lippstadt
Castrop-Rauxel	51:34:54N	007:18:58E	56.00	Emschergenossenschaft
Detmold-Zentral KLG.	51:56:51N	008:51:45E	123.00	Stadt Detmold
Dorsten	51:39:30N	006:59:03E	35.00	Lippeverband Essen
Dortmund Kurl	51:33:21N	007:27:59E	66.00	Lippeverband
Dortmund-Aplerbeck	51:30:27N	007:33:28E	108.00	Emschergenossenschaft
Dortmund-Marten	51:30:53N	007:22:57E	81.00	Emschergenossenschaft
Dortmund-Nettebach	51:32:39N	007:23:33E	70.00	Emschergenossenschaft
Effeln	51:31:41N	008:21:30E	262.00	Stawa Lippstadt
Herringen	51:40:21N	007:44:07E	62.00	Lippeverband Essen
Kleinenberg	51:35:14N	008:59:04E	344.00	Stawa Lippstadt
Lippstad Lipperbr.	51:42:48N	008:21:30E	76.00	Stawa Lippstadt

Name of station	Latitude	Longitude	Altitude (m)	Agency
Luedinghausen KLG	51:45:20N	007:27:37E	55.00	Lippeverband
Madfeld	51:25:50N	008:43:50E	485.00	Stawa Lippstadt
Niedermarsberg	51:29:01N	008:52:54E	239.00	Stawa Lippstadt
Oberhausen-osterfeld	51:29:41N	006:54:39E	37.00	Emschergenossenschaft.
Olfen-Fuchtelner Muhle	51:40:50N	007:22:38E	15.93	STAWA Muenster
Ostbueren	51:30:49N	007:46:56E	220.00	Stawa Hagen
Paderborn PS1	51:42:37N	008:45:60E	157.00	Stawa Lippstadt
Rhynern	51:37:59N	007:52:08E	96.00	Wetteramt Essen+Lippev.
Unna	51:32:33N	007:42:01E	88.00	Lippeverband
Waltrop1	51:38:33N	007:24:43E	53.00	Lippeverband Essen
Westerholt	51:36:37N	007:05:12E	63.00	Lippeverband Essen
Wippringsen	51:31:02N	008:05:32E	226.00	Lippeverband

The actual data availability of each station and period is shown in Annex 3. From this information it is evident that the data availability is rather complete for the Period no. 1-12. But only seven stations have data for the last two periods, viz:

Station	Period 13	Period 14:
Boenen	X	X
Herringen	X	X
Ostbueren	X	-
Rhynern	X	X
Unna	X	X
Waltrop 1	X	X
Westerholt	X	X

3.1.2 On-line observed rainfall by the Deutscher Wetterdienst.

In this subsection rainfall data, collected from the Deutscher Wetterdienst (DWD) and which is *on-line* available is described. The DWD operates about 200 "synoptisch-klimatologischen Meldestellen (SY-Kollektiv)" for which point-rainfall observations are on-line availabe. In this report these 200 stations are refered to as **synoptic stations**. At about 120 of the in total 200 synoptic stations not only rainfall but also climatic data is collected. These 120 stations are also included in the so-called "KL-Kollektiv" of the DWD. In this report the 120 synoptic stations at which also climatic data is collected are refered to as **KL-climatic stations**. According to the official list of stations, most of the KL-climatic stations are pluviographs. In general measurements are made at hourly intervals by trained observers, partly with the help of pluviographs. The data of the synoptic stations are recorded in 4 to 8 measurements per day, but for the more recent years (starting around 1992) hourly values are available.

Although the KL-climatic stations are only a selection of the synoptic stations, they are very useful for the purpose of spatial correlation with the rainfall data collected from the Landesumweltamt Nordrhein-Westfalen, because the KL-climatic data are validated and as such should be less prone to error than the data of the other synoptic stations (see Chapter 7). Hereafter, particulars of the synoptic/KL-climatic stations operated by the DWD, which are located in or near the Sieg and Lippe catchment are discussed catchment-wise.

Sieg

The data that have been obtained for the synoptic/KL-climatic stations, operated by the DWD, are given in Table 3-3 (KL-climatic stations are indicated in **bold**). *All the stations are pluviographs*. The location of the DWD synoptic/KL-climatic stations are depicted in Fig. 3.1. Their data availability for the fourteen flood periods is given in Annex 2.

Table 3-3 DWD synoptic/KL-climatic stations in the Sieg basin

Name of station	Latitude	Longitude	Altitude (m)
Bad Marienberg	**50:40:00N**	**007:58:00E**	**547**
Bendorf (WST)	50:25:00N	007:35:00E	127
Bonn-Friesdorf (AWST)	**50:42:00N**	**007:09:00E**	**64**
Bonn-Hardthoehe	*50:42:00N*	*007:03:00E*	*159*
Koln-Wahn (Flugwewa)	**50:52:00N**	**007:10:00E**	**92**
Mendig	50:22:00N	007:19:00E	182
Noervenich	50:50:00N	006:40:00E	135

The station Bonn-Hardthoehe is set in italics, because it is foreseen that this station will be removed from the list of synoptic stations for which real-time data will be available.

Lippe

The data that have been obtained for the synoptic/KL-climatic stations, operated by the DWD, are given in Table 3-4 (KL-climatic stations are indicated in **bold**). The location of the DWD synoptic/KL-climatic stations are depicted in Fig. 3.2. Their data availability for the fourteen flood periods is given in Annex 3.

In Table 3-4, three stations (Bocholt-Liedern, Guetersloh and Laarbruch) are set in italics as they will probably not be available anymore in the future.

It is evident that there are many more synoptic stations available in the area around the Lippe basin than for the Sieg basin.

None of the synoptic stations is useful for both basins.

Table 3-4 DWD synoptic/KL-climatic stations in the Lippe basin

Name of station	Latitude	Longitude	Altitude (m)
Bad-Lippspringe (WST)	**51:47:00N**	**008:50:00E**	**157**
Bad-Salzuflen (WST)	**52:06:00N**	**008:45:00E**	**135**
Bocholt-Liedern (WST)	***51:50:00N***	***006:32:00E***	***21***
Duesseldorf (Flugwewa)	**51:18:00N**	**006:46:00E**	**37**
Essen (WST)	**51:24:00N**	**006:58:00E**	**152**
Guetersloh (RAF)	***51:55:00N***	***008:18:00E***	***72***
Hopsten	52:20:00N	007:33:00E	39
Kahler-Asten (WST)	**51:11:00N**	**008:29:00E**	**839**
Kalkar	51:44:00N	006:16:00E	25
Koeterberg (AWST)	51:51:00N	009:19:00E	492
Laarbruch (RAF)	*51:36:00N*	*006:09:00E*	*32*
Luedenscheid (WST)	**51:15:00N**	**007:39:00E**	**387**
Munster/Osnabr. (FWW)	**52:08:00N**	**007:42:00E**	**48**
Rheine-Bentlage	52:18:00N	007:23:00E	38
Warburg	51:30:00N	009:11:00E	225

3.2 Snow

Snow data is only available at the synoptic/KL-climatic stations, operated by the Deutscher Wetterdienst (DWD). These stations are nearly all (far) outside the basins of the Sieg and Lippe and as such hardly useful for the assessment of the snow conditions in the basins. However, a few stations (for their location see Fig. 3.1 and 3.2) might be used:

1. Bad Lippspringe (nr. 120) for the upstream area of the Lippe
2. Bad Marienberg (nr. 143) for the southern part (Nister basin) of the Sieg

Other stations can be used with caution:

- Essen (nr. 117), although in the Ruhr basin, it is very close to the watershed with the Lippe basin:
- Koeln-Wahn (nr. 138), in the downstream part of the Sieg..

At the synoptic/KL-climatic stations, daily measurements are made of the snow height and the new snow at 06:00 hours. The water-equivalent of the snow is determined irregularly.

3.3 Temperature

Only daily-averaged temperatures are available at the LUA-NRW meteorological stations (see subsection 3.1.1). Daily-averaged, daily-minimum and daily-maximum temperatures are available at the DWD synoptic/KL-climatic stations (see subsection 3.1.2). However, the location of these stations are often far from the Sieg and Lippe basins, which limites the applicability of this temperature data. Only data of DWD synoptic/KL-climatic stations that are mentioned in section 3.2 (i.e. on available snow data) might be used for temperature in the basins.
The time periods for which temperature data is available at LUA-NRW meteorological stations and DWD synoptic/KL-climatic stations coincides with the time-periods for which rainfall data is available. Hence the availability of temperature data for the Sieg and Lippe basins can respectively be obtained from Annex 2 and Annex 3.

Sieg

For the Sieg, no temperature data is available for the following stations and periods:

Station Aue:	Period no. 1-6
Station Lahnhof-1:	Period no. 1-10 / 14
Station Olpe:	Period no. 1-4
Station Lahnhof-G:	Period no. 14

Lippe

For the Lippe, there are no gaps in available temperatures for the fourteen periods.

3.4 Discharges

All discharge data are obtained from the Staatliche Umweltämter (StUA's). Hereafter, particulars of discharge stations (including their data availability) are discussed catchment-wise.

Sieg

In Table 3-5 particulars of the rated river gauging stations in the Sieg basin for which discharge data have been obtained, are given. The location of these stations are depicted in Fig. 3.3. Please note that the Landesumweltamt Nordrhein-Westfalen also operates meteorological stations near Lahnhof and Helgersdorf (see subsection 3.1.1).

Table 3-5 Rated river gauging stations in the Sieg basin for which discharge data are available

Name of station	River	Basin area (km^2)	Distance from confluence (km)[1]	Latitude	Longitude	Altitude (m)
Overath	Agger	449.4	21.4	50:56:06N	007:17:35E	88.50
Lohmar	Agger	785	5.6	50:50:34N	007:12:08E	57.94
Broel	Broelbach	216	1.15	50:47:15N	007:19:12E	69.19
Heimborn	Nister			50:42:38N	007:45:08E	
Lahnhof-1	Geiersgrundbach / Werthenbach	0.14	6	50:53:43N	008:14:37E	610.00
Helgersdorf	Ochsenbach / Werthenbach	0.35	1.3	50:51:33N	008:11:02E	380.00
Weidenau	Sieg	132	131	50:53:44N	008:01:39E	240.45
Niederschelden	Sieg	425.3	119	50:50:45N	007:58:05E	213.33
Betzdorf	Sieg	754.5	98.5	50:47:42N	007:51:52E	176.46
Eitorf	Sieg	1472	39	50:46:40N	007:26:38E	81.44
Siegburg-Kaldauen	Sieg	1889	17.6	50:47:56N	007:15:29E	58.84
Menden	Sieg	2832	8.4	50:47:57N	007:09:37E	49.34

In Annex 2 the availability of hourly discharge data is shown for the stations in Table 3-5. The most important missing data are:

- Betzdorf: no data before 1988
- Niederschelden: no data in the period 1980-1988
- Heimborn (Nister): missing data in the period 1984-1988
- Overath (Agger): Q-h curve lacking.

Especially the absence of a full series for Betzdorf is a problem, because the station is at a rather crucial location for the possible division of the Sieg basin into subbasins (see section 5.1). Another crucial station in the basin is Rosbach, in the middle of the Sieg (see Fig. 3.3), but the measurements at this station are considered as unreliable by the responsible authority.

Lippe

In Table 3-6 particulars of the rated river gauging stations in the Lippe basin for which discharge data is available, are given. The locations of these stations are depicted in Fig. 3.4. In Annex 3 the availability of hourly discharges at these stations are given.

[1] *The distance to the confluence refers to the immediate confluence,e.g. for the stations Overath and Lohmar on the Agger to the distance up till the Sieg main river.*

Table 3-6 Rated river gauging stations in the Lippe basin for which discharge data are available

Name of station	River	Basin area (km2)	Distance from confluence (km)	Latitude	Longitude	Altitude (m)
Westtunnen	Ahse	415.2	4.1	51:40:03N	007:52:04E	58.03
Niedertudorf	Alme	400.7	15.8	51:38:33N	008:40:57E	141.22
Nordborchen	Altenau/Alme	330.5	1.0	51:39:53N	008:43:10E	129.33
Bentfeld	Lippe	1049.8	195.9	51:45:02N	008:37:53E	88.97
Lippstadt 2	Lippe	1395.6	168.0	51:40:25N	008:20:01E	70.00
Kesseler 3	Lippe	2003	147.3	51:39:52N	008:05:25E	63.65
Luenen	Lippe	3162.0	91.7	51:36:32N	007:25:13E	43.14
Leven	Lippe	3324.6	65.3	51:42:58N	007:17:54E	34.11
Haltern	Lippe	4273.2	53.3	51:43:57N	007:11:15E	30.95
Schermbeck	Lippe	4783	22.4	51:40:31N	006:51:07E	20.68
Niederaden	Seseke	265.0	5.6	51:35:46N	007:35:21E	50.59
Olfen	Stever	531.0	15.9	51:43:23N	007:21:02E	15.93

4 Data validation and completion

4.1 Methodology

4.1.1 Validation

The data validation is done for the rainfall and discharge data.

The validation of the discharge stations is based on:
1. checking of individual time-series on outliers.
2. comparing the hydrographs of neighbouring stations;

The checking is done first in order to identify and remove data that are evidently wrong. The reason for the errors is often difficult to find. In general these data are simply removed and (if possible) replaced with new values by applying simple linear interpolation or relationships with neighbouring stations.

The validation of the meteorological stations can be based on the following methods:
- visual inspection of pluviographs of representative stations in each of the subbasins
- screening on simultaneous timing of the peaks by tabulation of the data
- control of the data on outliers by statistical analysis
- spatial correlation analysis.

Visual inspection is always a very strong method to find obvious errors in the data, although it is rather cumbersome for hourly values.
The screening of the data on simultaneous timing of the peaks is useful for daily values, but in this case it is hampered by the travel time of the rain front that is important in hourly values.
Spatial correlation analysis has the same drawback, but it is a rather simple method to find out quickly which stations are strongly linearly correlated. This method has been used for this purpose.

4.1.2 Completion

Completion of the data is done by two methods:

1. linear interpolation
2. relation curves between stations

Completion of the data refers only to discharges. Rainfall is a much too localised variable to allow for completion by linear interpolation. Relations with other stations can be used if the correlation is very strong, but for hourly values this is nearly impossible. Instead it is better to derive first areal rainfall, with the same gaps (missing data) as in the original data, and then ignore these data by replacing them with zeros.

In general, linear interpolation should be used sparsely, especially over longer time periods when dealing with hourly values, because it is easy to omit a flood peak. However, in the hourly discharge data of the Sieg and Lippe, there are many gaps of only one or two hours. After checking the position of the gap within the hydrographs, they have been completed by linear interpolation. Only those cases when relatively long periods have been filled in are reported.

Relation curves are used for the completion of data when other methods, like linear regression, are not possible. It is especially useful for discharge data of stations that are close to each other and without any significant tributaries in between. It is used sparingly as the relationship should be very strong to allow for completion. For the Sieg, e.g., the correlation between Betzdorf and Eitorf can be seriously hampered by the large number of tributaries in the intermediate region (e.g. Nister). This effect is particularly strong for hourly values. It is evident that the filling in several hours of data during a recession is much more trustworthy than during the rising limb of a flood wave.

4.2 Sieg

4.2.1 Validation of discharge data

The available discharge stations on the Sieg are given in Chapter 3.4. In this list, the stations of Lahnhoff and Helgersdorf are less important as they represent only a very small part of the upstream basin of the Sieg. For the main river, the validation of the discharge series should be done in the following order (from upstream to downstream):

Main station	Other upstream station
Weidenau	-
Niederschelden	-
Betzdorf	Heimborn
Eitorf	Broel
Siegburg	Lohmar
Menden	

However, given the fact that the data of the stations Niederschelden and Betzdorf are not available, the checking of the stations Weidenau and Eitorf by comparing with neighbouring stations is difficult as the distance between Weidenau and Eitorf is such that the correlation between these stations is small (see subsection 4.2.2 on relation curves).
On the Agger the station of Lohmar should be validated with the upstream station of Overath, but at present no data are available for the latter.

The validation of the stations by comparing hydrographs is shown in Fig. 4.1. In this figure the following stations are plotted:

- Broel (Broel tributary)
- Eitorf (Sieg)
- Siegburg (Sieg)
- Lohmar (Agger)
- Menden (Sieg)

The visual inspection of the hydrographs not only shows some small time-blocks (normally one to four hours) of missing values, but also some obvious errors which occur all in the same series (Siegburg):

- Period no. 1: sharp drop, on 7/1/1980, 10:00 and 11:00 hours
- Period no. 2: sharp drop, on 4/1/1982, 08:00 and 09:00 hours
- Period no. 12: sharp rise and fall, on 16/2/1990, 05:00 - 08:00 hours
- Period no. 12: sharp fall with negative value, on 29/3/1990, 21 hours
- Period no. 13: sharp fall with negative value, on 2/1/1994, 19:00 - 23:00 hours
- Period no. 13: sharp rise and fall, on 13/2/1994, 11:00 - 16:00 hours

All these values have been replaced by missing values, after which they can be completed by e.g. linear interpolation (see next paragraph).

Other errors:

- Period no. 12: sharp fall with negative value in series Niederschelden, on 5/3/1990, 18:00 - 21:00 hours, subsequent 22:00 - 23:00 hours already missing;
- Period no. 13: sharp rise, before missing value in series Lohmar, on 11/1/1994, 22:00 hours;
- Period no. 14: irregularity in peak in series Lohmar, on 11/1/1995, 11:00 - 18:00 hours

Only in Period no. 10 (1/3/1988 - 30/4/1988) longer omissions occur:

- Siegburg: 9/3/1988, 00:00 - 23:00 hours (i.e. one day);
- Lohmar: 18/3/1988, 14:00 - 23:00 hours

A major error occurs in the series Lohmar (Agger) for the Period no. 11 (December 1988), when in the beginning of December the values start to diminish steadily, without any correlation anymore with occurring floods. These data have been deleted completely (period starting 5/12/1988 - 31/12/1988). It is not possible to replace them as there are no hourly data for the upstream stations on the Agger.

4.2.2 Completion of discharge data

Completion by linear interpolation

Careful studying of the hydrographs in Fig. 4.1 shows that for all of the omissions, which are normally only one to four hours, this method is valid. It is even permissible to fill in the larger gaps in Period no. 10 (see above) with linear interpolation as they occur in the falling limb of the flood with rather uniform decrease in discharge in time.

Completion with relation curves

For the Sieg there are major gaps in the data for the stations Niederschelden (1980-1988) and Betzdorf (1980-1988), as well as for the station of Heimborn on the Nister (1984-1988). This poses a major problem as there are no other gauging stations in the entire river stretch up to Eitorf. The only exception is the station of Rosbach, which is considered to be unreliable. There are many tributaries between the stations of Eitorf and Betzdorf, the major being the Nister for which data are also missing.

The only possibility is the relation between the stations of Weidenau and Niederschelden. However, there are only two periods (Dec.1993-Jan.1994 and Jan.-Feb. 1995) for which data are available. Derivation of the relation curves between these stations for the periods mentioned results in both a weak correlation and, more important, different relations for the two periods. Given the fact that the relations should be used to fill in the flood data for many other periods, the relation is considered too weakly established to be useful. It is therefore considered unfeasible to fill in the data of these stations by using relation curves.

4.2.3 Validation of meteorological data

Visual inspection

For the visual inspection of the pluviographs, plots are made for each of the four subbasins, with a maximum of five rainfall stations in each basin. Those stations have been chosen which will have the highest relative weight in the determination of the areal rainfall. The following stations have been checked:

1. Subbasin Lower Sieg:
    - Bonn-Bockeroth
    - Kuchenbach
    - Bonn-Heiz Kw.
    - Eschmar M.
    - Neunkirchen S.
2. Subbasin Middle Sieg
    - Brenzingen
    - Eitorf
    - Marienfeld
    - Homburg
3. Subbasin Upper Sieg
    - Siegen Ges. Hoch.
    - Helgerdorf
    - Lahnhof-Geiers.
    - Rehringhausen
4. Subbasin Agger
    - Frielingsdorf
    - Suelze
    - Lehruch/Lehmbach
    - Homburg

In general the visual similarity between the rainfall data can be expected to be higher in winter than in summer, due to the convective nature of the rainfall in winter. In summer, isolated thunderstorms can occur, although normally some precipitation is found in nearby stations.

In the lower basin the precipitation series should be rather similar as there is not that much of relief in the area close to the confluence. This is evident from the pluviographs, which are rather uniform for the stations. Some doubtful values have been found, which have been replaced by data from neighbouring stations.

Corrected errors:

- Bonn-Bockeroth, 16/1/1983, 00:00 hours: unlikely high value (7.8 mm), not found in neighbouring stations: value removed
- Bonn-Heiz. Kw., Period no. 1 (January 1980): first small rainfall event not recorded. However, this has most likely no influence on the areal rainfall in the second major event in February: *not corrected.*
- Bonn-Bockeroth, 13/1/1982, 12:00 hours and 14/1/1982, 12:00 hours: rainfall events not found in neighbouring stations: values removed

In the middle basin, the difference in depth of the rainfall is higher than in the lower basin. Especially the station of Neunkirchen has normally slightly higher values.

Corrected errors:

- Homburg, 6/12/1988, 04:00 hours: unlikely high value (5.6 mm), not found in neighbouring stations: value removed
- Eitorf, 15/1/1986, 10:00 hours: unlikely high value (7.0 mm), not found in neighbouring stations: value removed
- Brenzingen, 24/6/1983, 18:00 hours: unlikely high value (9.0 mm), not found in neighbouring stations: value removed

In the upper basin, the values of the station Lahnhof-Geiers are often different from the other stations, due to the position of this station at the edge of the watershed.

Corrected errors:

- Lahnhof-Geiers., 26/3/1990, 10:00 hours: unlikely high value (6.5 mm), not found in neighbouring stations: value removed
- Lahnhof-Geiers, no registration of the main rainfall event in Period no. 10 (1/3/1988 - 30/4/1988): station disregarded for areal rainfall during this period
- Helgerdorf, 27/2/1987, 12:00 hours: unlikely high value (6.6 mm), not found in neighbouring stations: value removed
- Rehringhausen, 13/1/1983, 07:00 hours: unlikely high value (16.6 mm), not found in neighbouring stations. This aberration is possible, due to the position of the station outside the basin, but should not be used for areal rainfall: value removed

In the Agger subbasin, the station of Frielingsdorf is not reliable, because in many instances the hourly data are accumulated and averaged over several hours, obliterating the rainfall pattern. However, this station is located at a crucial place in the basin, with no other stations in the neighbourhood. As the final simulations are made on 6-hourly values (see Chapter 9 and 10), the accumulation of hours will have little impact on the results. A surprising high value occurs at both Frielingsdorf (37.8 mm) and Suelze (20.7 mm) on 24/6/1983, 18:00 hours, but as this occurs at both stations, the values are retained.

As mentioned in the beginning of this Chapter, no effort has been made to complete the hourly rainfall data.

4.3 Lippe

4.3.1 Validation of discharge data

The discharge stations in the Lippe basin are given in Chapter 3.4.

The validation of the discharge series on the main river should be done in the following order (from upstream to downstream):

Main station	Other upstream station(s)	
Nierdertudorf	-	
Nordborchen	-	
Neuhaus 2	-	
Bentfeld	-	
Lippstadt 2	-	
Kesseler 3	-	
Luenen	West-tuenen	Nieder-raden
Leven	-	
Haltern	Olfen	
Schermbeck	-	

However, due to data availability, the validation of the data is mainly based on the stations Schermbeck, Haltern and Leven (in **bold** in table above). There are no hourly data for the station Niedertudorf. For the station of Luenen, only water levels are available. The data of the station Bentfeld are unreliable. The stations in the upstream part of the basin (e.g. Nordborchen) drain only a small part of the basin and are not useful for the modelling effort in the project.

In Fig. 4.2 the hydrographs of the following stations are given:
Olfen (Stever tributary)
Lippstadt 2
Leven
Schermbeck

The following data have been corrected:

Period no. 1:
Station Leven:
19/1/1980, 00:00 and 01:00 hours, unlikely high values (25.9 and 35.8 m^3/s), not found in neighbouring stations: values removed
5/2/1980, 10:00 and 11:00 hours, unlikely high values (108.6 and 82.7 m^3/s), not found in neighbouring stations: values removed

Period no. 2:
Station Haltern:
22/2/1982, 02:00 - 18:00 hours, period with high values, not found in neighbouring stations: values removed
2/2/1982, 05:00 - 11:00 hours, idem, values up to 200 m^3/s

Period no. 4:
Station Haltern:
19/5/1983, 14:00 - 21:00 hours, period with high values, not found in neighbouring stations: values removed
2/6/1983, 11:00 - 18:00 hours, period with obvious errors (e.g. negative values), values removed

4.3.2 Completion of discharge data

Completion by linear interpolation

Haltern:
14/12/1981 19:00 hours - 15/12/1981 00:00 hours
2/ 1/1981 04:00 hours - 2/ 1/1981 12:00 hours
19/ 1/1986 04:00 hours - 20/ 1/1986 12:00 hours
6/ 1/1987 12:00 hours - 6/ 1/1987 19:00 hours
7/ 3/1987 23:00 hours - 8/ 3/1987 12:00 hours
14/ 2/1990 19:00 hours - 14/ 2/1990 22:00 hours
28/ 3/1990 12:00 hours - 28/ 3/1990 14:00 hours

Leven
21/3/1987 23:00 hours - 22/3/1987 06:00 hours
14/2/1990 20:00 hours - 14/2/1990 22:00 hours

Lippstadt
8/3/1987 02:00 hours - 8/3/1987 08:00 hours

Completion with relation curves

The Lippe basin has a more stable discharge pattern, typical for a lowland river, and in general is more apt for the application of relation curves. The relative location of the gauging stations is also favourable for this method. They have been used in several cases to fill in missing data over periods that are too long to warrant the use of linear interpolation. However, the relationship must always be established within the same period (or close to it) and application in other periods is not always possible. An example is the relationship Haltern - Schermbeck, derived for 1982, which was not reliable for January 1986.

Relation curves have been used in the following cases:

Haltern - Schermbeck (see Fig. 4.3)
Period no.: 20/2/1982 - 28/2/1982, missing values in station Haltern

Lippstadt - Bentfeld (see Fig. 4.4)
Period no.: 1/12/1981 - 31/12/1981 (i.e. full month), missing values in station Lippstadt

4.3.3 Validation of meteorological data

The stations in the Lippe basin are first grouped according to their relative position and the subbasins that have been distinguished in Chapter 0. All the stations have been checked.

The data of the station Bottrop are found to be unreliable and have been disregarded for further use in the project.

Period no. 2:
The following missing data have been replaced by zero:

Station Rhynern:	1/1/1982 07:00 - 2/1/1982 07:00 hours
Station Wippringsen:	1/11980 00:00 - 07:00 hours
	29/12/1982 07:00 - 1/1/1983 07:00 hours

Period no. 4:
Error in station Dortmund-NB:
24/6/1983, 17:00 and 18:00 hours: probably error in decimal, values 62.7 and 32.0 mm changed into resp. 6.3 and 3.2 mm

Period no. 7:
Major error in station Madfeld in the period Jan. 1986. The data are shifted several hours and the data of this station is not used for this period.

As mentioned in the beginning of this Chapter, no effort has been made to complete the hourly rainfall data.

4.4 Conclusion

After the validation and completion of the data, a set of hydro-meteorological data results for which an overview is provided in Annex 3 (Sieg) and Annex 4 (Lippe). Based on the available data, choices were made on the level of detail in basin subdivision (see Chapter 5) and the selection of flood periods used in calibration and validation (see Chapter 9).

5 Divisions into subbassins

At the start of the project, it was anticipated that lumping the entire Sieg and Lippe basins might result in too-coarse modelling results. It was, therefore, decided to divide the Sieg and Lippe basins into subbasins. The difference in modelling results between rainfall-runoff models corresponding to lumping the entire basins and rainfall-runoff models corresponding to the division into subbasins is discussed in Chapter 9.

The first criterion for the division into subbasins is the location of the gauging stations as hourly discharge data are needed for the calibration of the model. A second major criterion is the availability of the data. However, other factors have also been taken into account:

- topography,
- soils and vegetation cover, and
- areal rainfall distribution.

The latter three criteria are used in order to have subbasins that can be considered hydrologically homogeneous, i.e. it is reasonable to consider the area as uniform in its reaction towards rainfall under assumed "winter" circumstances.

Although many divisions are possible, a number of *levels* have been defined in the subdivision of the Sieg basin and the Lippe basin, which are respectively described in sections 5.1 and 5.2 and shown in Fig. 5.1. and 5.2. The areas given in the sections 5.1 and 5.2 are based on official information on the contributing areas of the various river gauging stations.

Finally reflections on the selected division into subbasins are made in section 5.3.

5.1 Subdivision of the Sieg basin

For the Sieg basin, the following four levels were discerned:

Level 1 Total Sieg basin

Name of subbasin	Gauging station	Area (km^2)
Total Sieg	Menden	2,832

Level 2 Subdivision

Name of subbasin	Gauging station	Area (km^2)
Lower Sieg	Menden	158
Agger	Lohmar	785
Middle/Upper Sieg	Siegburg	1,889

Level 3 Subdivision

Name of subbasin	Gauging station	Area (km^2)
Lower Sieg	Menden	158
Middle Sieg	Siegburg	1,134
Agger	Lohmar	785
Upper Sieg	Betzdorf	755

Level 4 Subdivision

Name of subbasin	Gauging station	Area (km^2)
Lower Sieg	Menden	158
Agger	Lohmar	785
Middle Sieg 1	Siegburg	417
Middle Sieg 2	Eitorf	717
Upper Sieg	Betzdorf	755

5.2 Subdivision of the Lippe basin

The following three levels were discerned:

Level 1 Total basin

Name of subbasin	Gauging station	Area (km^2)
Total Lippe	Schermbeck	4,783

Level 2 Subdivision

Name of subbasin	Gauging station	Area (km^2)
Lower Lippe	Schermbeck	510
Stever	Haltern - Leven	948
Upper / Middle Lippe	Leven	3,325

Level 3 Subdivision

Name of subbasin	Gauging station	Area (km^2)
Lower Lippe	Schermbeck	510
Stever	Haltern - Leven	948
Middle Lippe	Leven	1,929
Upper Lippe	Lippstadt 2	1,396

5.3 Discussion and conclusion

In order to reach a conclusion on the choice of the subdivision, the information in this Chapter is combined with the information in Chapter 3 on data availability.

5.3.1 Sieg basin

In the Sieg, the major basin of the Agger has been distinguished as a separate basin, because of its special location in the total basin. This basin has a rather different areal rainfall pattern, the total yearly average being relatively high (about 1,200 mm) and the occurrence of several small reservoirs may also lead to a different reaction towards rainfall than in other similar basins.

The rest of the Sieg basin has been divided into subbasins taking into account the data availability and location of measuring stations. The subdivision of the Middle/Upper Sieg (i.e. Sieg Level 3 subdivision and Sieg Level 4 subdivision) were prepared in anticipation that discharge data for the station Betzdorf might become available, unfortunately discharge data for this station appeared not to be available.

5.3.2 Lippe basin

The Lippe basin does not have such a clear division into subbasins as the Sieg river (see subsection 2.2.1). Here the availability of the data and the average basin size was the more important criteria. The only station in the tables with lack of data is Lippstadt 2, for which no data are available in the Periods no. 1, 2, and 14.

6 Areal rainfall and temperature

6.1 Off-line areal rainfall

The areal rainfall discussed in this section is refered to as *off-line* or LUA-NRW areal rainfall, since it is based on rainfall observed by the Landesumweltamt Nordrhein-Westfalen (LUA-NRW) which is not on-line available. The off-line areal rainfall was established using the Thiessen polygons method.

6.1.1 Sieg.

For the Sieg basin, the so-called *off-line* areal rainfall is determined for the total basin and for the subbasins that are defined in section 5.1. and shown in Fig. 5.1. The available LUA-NRW meteorological stations are given in subsection 3.1.1 and shown in Fig. 5.3. In Table 6-1 it is indicated which LUA-NRW meteorological stations are used in computing areal rainfall for the total basin and for the various subbasins.

Table 6-1 LUA-NRW meteorological stations used for determination of areal rainfall (Sieg basin)

Level 1	**Sieg**					
Level 2	**Lower Seig**	**Middle/Upper Sieg**			**Agger**	
Level 3	**Lower Sieg**	**Middle Sieg**		**Upper Sieg**	**Agger**	
Level 4	***Lower Sieg***	***Middle Sieg 1***	***Middle Sieg 2***	***Upper Sieg***	***Agger***	
Name of station						Data absent in period:
Aue				X		1 - 6 / 13 - 14
Bonn Bockeroth	X	X				14
Bonn-Heizkraftwerk	X					-
Brenzingen		X	X		X	14
Eitorf		X	X			14
Eschmar Muellekoven	X				X	14
Frielingsdorf					X	14
Haenscheid		X	X			14
Helgerdorf				X		13 -14
Homburg-Broel		X	X		X	14
Kuchenbach	X	X				14
Lahnhof-Geiersgrund				X		13 - 14
Lehruch (Lehmbach)					X	14
Marienfeld		X	X		X	14
Neunkirchen Seelsch.	X	X			X	14
Olpe		X		X	X	1 - 4 / 13 - 14
Rehringhausen				X		12 - 14
Siegen Ghs		X		X		13 - 14
Suelze					X	13 - 14

In Table 6-1, the maximum subdivision of the Sieg basin is given. Level 4 is set in *italics* as no effort was made to prepare data for this level, i.e. no areal rainfall was derived for the subbasins Middle Sieg 1 and Middle Sieg 2. For the configuration of subbasins using only one Middle/Upper Sieg basin (level 2), the combination of stations were used as indicated for the Middle Sieg 1, Middle Sieg 2 and Upper Sieg subbasins. In Tables 6-2 to 6-7 the LUA-NRW meteorological stations for which the weighting factor are equal to zero are omitted.

Total Sieg basin (level 1)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Total Sieg basin (2,832 km^2) are given in Table 6-2.

Table 6-2 Weighting factors of the LUA-NRW meteorological stations for the Total Sieg basin

Stations	Period 1 -4	Period 5 - 6	Period 7 - 11	Period 12	Period 13
Aue	-	-	0.0050	0.0050	-
Bonn-Bockeroth	0.0241	0.0241	0.0241	0.0241	0.0241
Brenzingen	0.1733	0.1657	0.1657	0.1821	0.5342
Eitorf	0.0591	0.0591	0.0591	0.0591	0.0591
Eschmar	0.0169	0.0169	0.0169	0.0169	0.0169
Frielingsdorf	0.0812	0.0761	0.0761	0.0884	0.1094
Haenscheid	0.0192	0.0192	0.0192	0.0192	0.0192
Helgerdorf	0.1161	0.1161	0.1161	0.1161	-
Homburg-Broel	0.0655	0.0594	0.0594	0.0757	0.0757
Kuchenbach	0.0400	0.0400	0.0400	0.0400	0.0400
Lahnhof-G.	0.0223	0.0223	0.0206	0.0206	-
Lehmbach	0.0297	0.0297	0.0297	0.0297	0.0438
Marienfeld	0.0355	0.0355	0.0355	0.0355	0.0362
Neunkirchen	0.0416	0.0416	0.0416	0.0416	0.0416
Olpe	-	0.0494	0.0494	-	-
Rehringhausen	0.0382	0.0099	0.0099	-	-
Siegen	0.2017	0.1993	0.1960	0.2103	-
Suelze	0.0357	0.0357	0.0357	0.0357	-
Sum	1.000	1.000	1.000	1.000	1.000

There are no data for Period no. 14. The areal rainfall in Period no. 13 is strongly dominated by the values in station Brenzingen. This applies also to the Total Sieg, Middle Sieg and Upper Sieg basins as all data of the LUA-NRW meteorological stations for these basins are unavailable.

Lower Sieg basin (Levels 2 -3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Lower Sieg basin (158 km^2) are given in Table 6-3.

Table 6-3 Weighting factors of the LUA-NRW meteorological stations for the Lower Sieg basin

Station	Period 1-13
Bonn-Bck	0.3719
Eschmar	0.2595
Kuchenbach	0.2660
Neunkirchen	0.1026
Sum	1.0000

There is no data available for Period no. 14.

Middle/Upper Sieg basin (level 2)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Middle/Upper Sieg basin (1,889 km^2), are given in Table 6-4.

Table 6-4 Weighting factors of the LUA-NRW meteorological stations for the Middle/Upper Sieg.

Station	Period 1 - 4	Period 5 - 6	Period 7 - 11	Period 12	Period 13
Aue	-	-	0.0097	0.0097	-
Brenzingen	0.2423	0.2393	0.2393	0.2393	0.9222
Eitorf	0.0751	0.0751	0.0751	0.0751	0.0751
Haenscheid	0.0009	0.0009	0.0009	0.0009	0.0009
Helgerdorf	0.2245	0.2245	0.2245	0.2245	-
Lahnhof-Geiers.	0.0431	0.0431	0.0397	0.0397	-
Olpe	-	0.0109	0.0109	0.0205	-
Rehringhausen	0.0225	0.0191	0.0191	-	-
Siegen	0.3898	0.3853	0.3789	0.3885	-
Sum	1.000	1.000	1.000	1.000	-

It is evident that the areal rainfall for the last period (1/12/1994 - 31/1/1994) is dominated by the values of the station Brenzingen and as such may differ significantly from the data for the other periods.

Middle Sieg (Level 3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Middle Sieg basin (1,134 km^2) are given in Table 6-5. The stations of Homburg, Marienfeld and Neunkirchen have a very low weight. The areal rainfall is mainly determined by the station Brenzingen.

Table 6-5 Weighting factors of the LUA-NRW meteorological stations for the Middle Sieg basin.

Station	Period 1-12
Brenzingen	0.4166
Haenscheid	0.1180
Homburg	0.0462
Kuchenbach	0.0953
Marienfeld	0.0550
Neunkirchen	0.0461
Siegen	0.2228
Sum	1.0000

Upper Sieg basin (level 3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Upper Sieg basin (755 km^2) are given in Table 6-6.

Table 6-6 Weighting factors of the LUA-NRW meteorological stations for the Upper Sieg basin

Station	Period 1 - 6	Period 7 - 11	Period 12
Aue	-	0.0191	0.0202
Helgerdorf	0.2957	0.2957	0.3697
Lahnhof-Geirers.	0.0848	0.0782	-
Rehringhausen	0.0375	0.0375	-
Siegen	0.5820	0.5695	0.6101
Sum	1.0000	1.000	1.0000

There are no data for the stations for the Periods no. 13 and 14.

Agger basin (level 2 -3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Agger basin (785 km^2) are given in Table 6-7.

Table 6-7 Weighting factors of the LUA-NRW meteorological stations for the Agger basin

Station	Period 1 - 4	Period 5 - 11	Period 12	Period 13
Brenzingen	0.1212	0.0659	0.1212	0.1212
Eschmar	0.0003	0.0000	0.0003	0.0003
Frielingdorf	0.3212	0.2766	0.3212	0.4535
Homburg	0.2083	0.1493	0.2083	0.2083
Lehmbach	0.1080	0.1080	0.1080	-
Marienfeld	0.0497	0.0497	0.0497	0.0714
Olpe	-	0.1590	-	-
Neunkirchen	0.0617	0.0619	0.0617	0.1452
Suelze	0.1296	0.1296	0.1296	-
Sum	1.000	1.000	1.000	1.000

For Period no. 14 (1995), there are no data available.

Concluding remarks regarding Sieg areal rainfall:

It is possible to compute areal rainfalll for the Total Sieg basin and the Sieg Level 2 subbasins for Period no. 13. The areal rainfall is, however, highly dominated by the data of the station Brenzingen (this especially yields for the Middle/Upper Sieg basin), since none of the stations in the Middle and Upper Sieg basins have data for Period no. 13. The fact that the station Brenzingen is not used for the derivation of the areal rainfall in the Upper Sieg basin (see Table 6-6) indicates that it is probably hardly representative for the Middle/Upper Sieg basin. This is reflected in Fig. 6.1 in which the Thiessen polygons are shown for the areal rainfall of the Total Sieg basin, for the Periods no. 7-11 and for Period no. 13. From the two Figs. 6.1 it can be concluded that although it is theorectically possible to calculate areal rainfall for the Sieg basin and its subbasins for Period no. 13, this areal rainfall will not be representative for the real areal rainfall in the Sieg basin and its subbasins.

Further on it is to be mentioned that no data is available for Period no. 14 and hence no areal rainfall for this period can be established.

Resuming it is to be stated that no areal rainfall is available for the Sieg basin and its subbasins for the Periods no. 13 and no. 14.

6.1.2 Lippe

For the Lippe basin, the so-called *off-line* areal rainfall is also determined for the total basin and for the subbasins that are defined in section 5.3. and shown in Fig. 5.2. The available LUA-NRW meteorological stations are given in subsection 3.1.1 and shown in Fig. 3.2. In Table 6-8 it is indicated which LUA-NRW meteorological stations are used in computing areal rainfall for the total basin and for the various subbasins.

Table 6-8 LUA-NRW meteorological stations used for determination areal rainfall (Lippe basin)

Level 1	**Lippe**				
Level 2	**Lower Lippe**	**Middle/Upper Lippe**		**Stever**	
Level 3	**Lower Lippe**	**Middle Lippe**	**Upper Lippe**	**Stever**	
Name of station					Data absent in period:
Baumberg				X	13 - 14
Boenen		X			-
Boke		X	X		13 - 14
Bottrop Eigen	-	-	-	-	(unreliable)
Brilon 1			X		13 - 14
Buke			X		11 - 14
Castrop-Rauxel	X	X		X	13 - 14
Detmold-Zentral KLG.		X	X		13 - 14
Dorsten	X			X	13 - 14
Dortmund Kurl		X			13 -14
Dortmund-Aplerbeck		X			13 - 14
Dortmund-Marten					13 - 14
Dortmund-Nettebach		X			13 - 14
Effeln		X	X		13 - 14
Herringen		X		X	-
Kleinenberg	X				8 - 14
Lippstad Lipperbr.		X	X		13 - 14
Luedinghausen KLG	-	-	-	-	1 - 14
Madfeld			X		7 / 13 - 14
Niedermarsberg			X		12 - 14
Oberhausen-osterfeld	X				13 - 14
Olfen-Fuchtelner Muhle			X		13 - 14
Ostbueren		X			14
Paderborn PS1		X	X		13 - 14
Rhynern		X			-
Unna		X			-
Waltrop 1	X	X		X	-
Westerholt	X	X		X	-
Wippringsen		X			13 - 14

In Tables 6-9 to 6-14 the LUA-NRW meteorological stations for which the weighting factor are equal to zero are omitted.

Lippe (level 1)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Total Lippe basin (4,783 km^2) are given in Table 6-9.

Table 6-9 Weighting factors of the LUA-NRW meteorological stations for the Total Lippe basin

Station	Period 1-6	Period 7	Period 8-10	Period 11	Period 12
Baumberg	0.0877	0.0877	0.0877	0.0877	0.0877
Boenen	0.0255	0.0255	0.0255	0.0255	0.0255
Boke	0.0686	0.0711	0.0686	0.0686	0.0691
Brilon 1	0.0006	0.0143	0.0006	0.0006	0.0006
Buke	0.0596	0.0596	0.0764	-	-
Castrop-Rauxel	0.0094	0.0094	0.0094	0.0094	0.0094
Detmold-Zentral	0.0068	0.0068	0.0068	0.0165	0.0165
Dorsten	0.0775	0.0775	0.0775	0.0775	0.0775
Dortmund-Aplerbeck	0.0094	0.0094	0.0094	0.0094	0.0094
Dortmund-Kurl	0.0075	0.0075	0.0075	0.0075	0.0075
Effeln	0.0418	0.0418	0.0418	0.0418	0.0418
Herringen	0.0605	0.0605	0.0605	0.0605	0.0605
Kleinenberg	0.0468	0.0468	-	-	-
Lippstadt	0.0822	0.0822	0.0822	0.0822	0.0822
Madfeld	0.0307	-	0.0307	0.0307	0.0675
Niedermarsberg	0.0324	0.0469	0.0577	0.0645	-
Paderborn PS1	0.0746	0.0746	0.0793	0.1392	0.1663
Rhynern	0.0608	0.0608	0.0608	0.0608	0.0608
Unna	0.0288	0.0288	0.0288	0.0288	0.0288
Waltrop 1	0.0933	0.0933	0.0933	0.0933	0.0933
Westerholt	0.0378	0.0378	0.0378	0.0378	0.0378
Wippringsen	0.0578	0.0578	0.0578	0.0578	0.0578
Sum	1.000	1.000	1.000	1.000	1.000

Lower Lippe (level 3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Lower Lippe basin (510 km^2) are given in Table 6-10.

Table 6-10 Weighting factors of the LUA-NRW meteorological stations for the Lower Lippe basin

Station	Period 1 - 12
Castrop-Rauxel	0.0688
Dorsten	0.5405
Waltrop1	0.1109
Westerholt	0.2798
Sum	1.000

Middle Lippe (level 3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Middle Lippe basin (1,929 km^2) are given in Table 6-11.

Table 6-11 Weighting factors of the LUA-NRW meteorological stations for the Middle Lippe basin

Station	Period 1 - 12
Boenen	0.0443
Boke	0.0398
Castrop-Rauxel	0.0007
Detmold-zk	0.0213
Dortmund-Kurl	0.0192
Dortmund-A. beck	0.0239
Effeln	0.1067
Herringen	0.0573
Lippstadt	0.1994
Ostbueren	0.0540
Paderborn	0.0335
Rhynern	0.1507
Unna	0.0491
Waltrop1	0.0570
Wippringsen	0.1431
Sum	1.000

Upper Lippe (level 3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Upper Lippe (1,396 km^2) are given in Table 6-12.

Table 6-12 Weighting factors of the LUA-NRW meteorological stations for the Upper Lippe basin

Station	Period 1 - 6	Period 7	Period 8 - 10	Period 11	Period 12
Boke	0.1846	0.1935	0.1846	0.1846	0.1865
Brilon 1	0.0022	0.0497	0.0022	0.0022	0.0022
Buke	0.1994	0.1994	0.2577	-	-
Detmold-zk	0.0004	0.0004	0.0004	0.0283	0.0283
Kleinenberg	0.1630	0.1630	-	-	-
Lippstadt	0.0140	0.0140	0.0140	0.0140	0.0140
Madfeld	0.1069	-	0.1069	0.1069	0.2354
Niedermarsberg	0.1128	0.1632	0.2010	0.2248	-
Paderborn	0.2168	0.2168	0.2333	0.4393	0.5337
Sum	1.000	1.000	1.000	1.000	1.000

Middle/Upper Lippe (level 2)

The same stations as has been used for the separate Middle and Upper Lippe basins (3,325 km^2) are used for the determination of areal rainfall in the Middle/Upper Lippe basin. The weighting factors of the concerning LUA-NRW meteorological stations are given in Table 6-13.

Table 6-13 Weighting factors of the LUA-NRW meteorological stations for the Middle/Upper Lippe basin

Station	Period 1 - 6	Period 7	Period 8 - 10	Period 11	Period 12
Boenen	0.0256	0.0256	0.0256	0.0256	0.0256
Boke	0.1010	0.1048	0.1010	0.1010	0.1018
Brilon 1	0.0009	0.0210	0.0009	0.0009	0.0009
Buke	0.1125	0.1125	0.1125	-	-
Castrop-Rauxel	0.0004	0.0004	0.0004	0.0004	0.0004
Detmold-zk	0.0100	0.0100	0.0100	0.0243	0.0243
Dortmund-Kurl	0.0138	0.0138	0.0138	0.0138	0.0138
Dortmund-A. beck	0.0111	0.0111	0.0111	0.0111	0.0111
Effeln	0.0616	0.0616	0.0616	0.0616	0.0616
Herringen	0.0331	0.0331	0.0331	0.0331	0.0331
Lippstadt	0.1210	0.1210	0.1210	0.1210	0.1210
Madfeld	0.0452	-	0.0452	0.0452	0.0995
Niedermarsberg	0.0850	0.1062	0.0850	0.0950	-
Ostbueren	0.0311	0.0311	0.0311	0.0311	0.0311
Paderborn	0.1169	0.1169	0.1169	0.2050	0.2449
Rhynern	0.0870	0.0870	0.0870	0.0870	0.0870
Unna	0.0283	0.0283	0.0283	0.0283	0.0283
Waltrop1	0.0329	0.0329	0.0329	0.0329	0.0329
Wippringsen	0.0826	0.0826	0.0826	0.0826	0.0826
Sum	1.000	1.000	1.000	1.000	1.000

Stever (level 3)

The weighting factors of the relevant LUA-NRW meteorological stations used in determining areal rainfall for the Stever basin (948 km^2) are given in Table 6-14.

Table 6-14 Weighting factors of the LUA-NRW meteorological stations for the Stever basin

Station	Period 1 - 12
Dorsten	0.0313
Baumberg	0.4647
Herringen	0.2015
Waltrop1	0.2983
Westerholt	0.0042
Sum	1.000

Concluding remarks regarding Lippe areal rainfall:

No sufficient rainfall data is available for the determination of areal rainfall for the Total Lippe basin and its subbasins for the Periods no. 13 and 14.

6.2 Temperature

Daily-averaged temperatures are available at meteorological stations, operated by the Landesumweltamt Nordrhein-Westfalen (LUA-NRW). Daily-averaged, daily-minimum and daily-maximum temperatures are available at synoptic/KL-climatic stations, operated by the Deutscher Wetterdienst (DWD). The temperature data at DWD synoptic/KL-climatic stations were ignored, since these stations are located too-far from the Sieg and the Lippe basins in order to be represenative for areal temperatures within these basins.

Taking the above into account only daily-averaged areal temperatures were established using the LUA-NRW temperature data. The weighting factors are nearly identical to those used for the determination of the so-called *off-line* areal rainfall (see section 6.1).

In order to examine the daily-averaged temperatures and its daily variation, residual series are drawn for the Sieg (Fig. 6.2) and Lippe (Fig. 6.3). In these graphs the average daily temperature over the period 1980 - 1995 is shown as a straight horizontal line. In each plot, both the Lower and Higher subbasins are depicted, showing the differences in average daily temperature between the two subbasins. For both the Sieg and the Lippe, the values lie between 10 °C and 8 °C for resp. the Lower and Upper subbasins, i.e. there is only a small difference in average temperature. The daily variation around the average values are slightly larger for the upper basins than for the lower basins.

7 Spatial relationships

Spatial relationships between rainfall observed at DWD KL-climatic stations and the so-called *off-line* areal rainfall computed, using observed LUA-NRW rainfall (see section 6.1) are determined in order to assess whether, and if so, to what extent, the 6-hourly values of precipitation that are published for the DWD KL-climatic stations are representative for the areal rainfall in (a part of) the Sieg and Lippe basins. These spatial relationships were derived using the data of KL-climatic stations only, since this data refer to validated data, while the data of the none KL-climatic stations (i.e. the other DWD synoptic stations) refer to raw (none-validated) data. In addition spatial relationships were established for the total basins and the subbasins, discussed in sections 5.1 and 5.2.

The so-called *off-line* areal rainfall based on LUA-NRW observed rainfall is derived on an hourly basis. In order to establish spatial relationships between this areal rainfall and the observations at KL-climatic stations (4 to 8 observations per day), the hourly areal rainfall data was aggregated to the same time basis.

First correlation matrixes have been derived for the KL-climatic rainfall series and each of the LUA-NRW (or off-line) areal rainfall series for either the total basin or the subbasins. Subsequently a linear multiple step-wise regression is performed by which those KL-climatic rainfall series enter the multiple linear equation which have the highest correlation with the LUA-NRW areal rainfall series. Using this method, for each of the (sub)basins, a number of KL-climatic rainfall series are rejected and not used in the equation. Except for the muliple-step-wise regression, also checks on the relevance of particular KL-climatic rainfall series were made by visual inspection of the available data.

In the regression analysis, the linear correlation coefficient (r) is determined. It is important to remark that only moderate linear correlation coefficients were obtained, i.e. in the order of r=0.6-0.8. In addition it is to be mentioned that the linear correlation coefficients would have been much smaller in case many data-points in the lower rainfall ranges would have been omitted. The inclusion of relatively many points in the lower rainfall ranges might have introduced a so-called *"spurious correlation"*, which has resulted in relatively too-large linear correlation coefficients.

7.1 Sieg

The relationships have been derived for the following basins (see section 5.1 for details):

- Sieg total basin
- Lower Sieg
- Agger
- Upper Sieg
- Middle/Upper Sieg

The results are shown in detail in Annex 4. Hereunder a summary of the results is given.

Sieg total basin

For the Sieg total basin, linear correlation coefficients (r) between the LUA-NRW (or off-line) areal rainfall and the DWD stations of Bad-Marienberg and Koln-Wahn respectively amount to 0.84 and 0.74 only. The DWD station Bonn-Friesdorf (r=0.64) was rejected in the multiple-step-wise regression.

Agger basin

For the Agger basin, linear correlation coefficients (r) between the LUA-NRW (or off-line) areal rainfall and the DWD stations of Bad-Marienberg and Koln-Wahn were smaller and respectively amounted to 0.76 and 0.73. The DWD station of Bonn-Friesdorf (r=0.58) was also rejected in the multiple-step-wise regression.

Lower Sieg basin

For the Lower Sieg basin, linear correlation coefficients (r) between the LUA-NRW (or off-line) areal rainfall and the DWD stations Bad-Marienberg, Koln-Wahn and Bonn-Friesdorf respectively amounted to 0.72 0.72 and 0.76 only. Since the linear correlation coefficients of these three stations with the LUA-NRW areal rainfall are of the same order of magnitude, none of the three stations were rejected in the multiple-step-wise regression.

Middle Sieg basin

For the Middle Sieg basin, linear correlation coefficients (r) between the LUA-NRW (or off-line) areal rainfall and the DWD stations of Bad-Marienberg and Koln-Wahn amounted respectively to 0.83 and 0.73 only. In the stepwise regression, the DWD station of Bonn-Friesdorf (r=0.64) was rejected.

Upper Sieg basin

For the Upper Sieg basin, linear correlation coefficients (r) between the LUA-NRW (or off-line) areal rainfall and the DWD stations of Bad-Marienberg and Koln-Wahn amounted respectively to 0.81 and 0.65 only. In the stepwise regression, the DWD station of Bonn-Friesdorf (r=0.57) was rejected.

Middle/Upper Sieg basin

For the Middle/Upper Sieg basin, linear correlation coefficients (r) between the LUA-NRW (or off-line) areal rainfall and the DWD stations of Bad-Marienberg and Koln-Wahn amounted respectively to 0.84 and 0.69 only. In the stepwise regression, the DWD station of Bonn-Friesdorf (r=0.61) is rejected.

Conclusions

Although in one case (Lower Sieg basin) the DWD station of Bonn-Friesdorf is not rejected in the stepwise regression (see Annex 4), it seems reasonable to use only the DWD stations of Bad-Marienberg and Koln-Wahn as a basis for the real-time estimation of the areal rainfall in the (sub)basins of the Sieg river. For this configuration, a number of equations have been derived that are given in Table 7-1. The regressions are shown in Figs. 7.1 for each of the (sub)basins. It is to be mentioned that the estimation of areal rainfall in the Sieg basin is only based on two DWD KL-climatic stations (i.e. Bad-Marienberg and Koln-Wahn), which have only moderate linear correlation coefficients with the LUA-NRW (or off-line) areal rainfall. It is, therefore, to be anticipated that using the multiple linear regression equations, given below will result in only moderate estimates for the areal rainfall in the (sub) basin of the river Sieg. In this respect, reference is made to subsection 10.4.1, were the multiple linear regression equations were used for establishing the areal rainfall for the Total Sieg basin for Period no. 5 and no. 12.

Table 7-1 Coefficients of multiple linear regression equations for the (sub)basins of the Sieg

(Sub)basin	Bad-Marienberg	Koln-Wahn	Intercept
Sieg	0.51260	0.35007	0.13379
Agger	0.48287	0.49190	0.17187
Lower Sieg	0.26491	0.34761	0.03487
Middle Sieg	0.52631	0.36434	0.08387
Upper Sieg	0.57413	0.21732	0.20014
Middle/Upper Sieg	0.56900	0.26280	0.14829

It is evident that the summation of the weights of the two KL-climatic stations in the equation need not add up to one, as is the case for the Thiessen polygon method, because the depth of the areal rainfall in each of the basins need not be identical to that in the stations.

7.2 Lippe

There is a gap in the LUA-NRW (or off-line) areal rainfall for the Total Lippe basin and for the Middle Lippe subbasin in Period no. 2 more precisely between 1/1/1982 (06:00 hours) and 2/1/1982 (08:00 hours), which is too large to fill in by linear interpolation. In order to allow for the derivation of the correlation matrices between the LUA-NRW (or off-line) areal rainfall and the synoptic/KL-climatic data, the missing values are replaced by zeros.

The relationships have been derived for the following subbasins (see section 5.2 for details):

- Lippe total basin
- Lower Lippe
- Stever
- Middle Lippe
- Upper Lippe

The results are shown in detail in Annex 5. Hereunder a summary of the results is given.

Lippe total basin

The LUA-NRW (or off-line) areal rainfall of the total Lippe basin is mainly related to the DWD stations Guetersloh and Munster, meaning that these two stations have the highest regression coefficient in the multiple linear equation.The linear correlation coefficients of the stations Guetersloh and Munster respectively amount to 0.84 and 0.82. In the multiple-step-wise regression the DWD station of Luedenscheid is rejected.

Lower Lippe basin

The linear correlation coefficients with the LUA-NRW (or off-line) areal rainfall of the Lower Lippe basin are small only and vary from 0.5 to 0.7. In the multiple-step-wise regression, the DWD stations Essen and Guetersloh are rejected.

Middle Lippe basin

In the Middle Lippe basin, the LUA-NRW (or off-line) areal rainfall is mainly related to the DWD station of Guetersloh, meaning that this station has the highest regression coefficient in the multiple linear equation. The linear correlation coefficient the station of Guetersloh amount to 0.82 only. In the multiple-step-wise regression, the DWD station of Dusseldorf is rejected.

Upper Lippe basin

In the Upper Lippe basin, the LUA-NRW (or off-line) areal rainfall is mainly related to the DWD station of Bad-Lippspringe, meaning that this station has the highest regression coefficient in the multiple linear equation. The linear correlation coefficient of the station Bad-Lippspringe, located in the middle of the Upper Lippe basin, amounts to 0.86 only. In the muliple-step-wise regression, the DWD stations Bad-Salzuflen, Bocholt-L, Essen, Luedenscheid and Munster/Osn. were rejected. Resulting in a multiple linear equation with only the DWD stations of Bad-Lippspringe, Dusseldorf, Guetersloh and Kahler-Asten.

Stever basin

In the Stever basin, the LUA-NRW (or off-line) areal rainfall is mainly related to the DWD station of Munster, meaning that this station has the highest regression coefficient in the multiple linear equation. The station of Munster has a linear correlation coefficient of 0.85 only. The other DWD stations even have all lower linear correlation coefficients in the order of 0.6-0.7. In the multiple-step-wise regression, the DWD stations of Bad-Lippspringe, Dusseldorf and Kahler-Asten are rejected.

Conclusions

In Figs. 7.2 the regressions are shown for each of the (sub)basins. For the Lippe basin, the multiple-step-wise regression results in more DWD KL-climatic stations to be included into the multiple linear regression equations than was the case for the Sieg basin. It is, however, to be mentioned that the number of stations available for the Lippe basin is larger than the number of stations available for the Sieg basin. It is anticipated that the multiple linear regression equations for the Lippe will be more or less of the same quality as the ones for the Sieg basin, since the linear correlation coefficients for the Lippe basin and the Sieg basin are also more or less in the same order of magnitude. In this respect, reference is made to subsection 10.4.2, were the multiple linear regression equations were used for establishing the areal rainfall for the Total Lippe basin for Periods no. 7 and no. 9.

8 FLORIJN rainfall-runoff model and modelling aspects

In section 8.1 a description of the FLORIJN rainfall-runoff model, which was applied in developing the Sieg and Lippe rainfall-runoff models, is given. The FLORIJN rainfall-runoff modelling concept is identical to the FLOFOM (FLOod FOrecasting for the river Meuse) one, which is based on the PhD-thesiswork of Berger (1992).

In section 8.2 some general aspects of the Sieg and Lippe rainfall-runoff models are discussed such as: the selected time step, required forecasting time-horizons, the updating procedure applied in real-time flood forecasting and evaluation criteria for interpreting the modelling results.

8.1 Description of the FLORIJN rainfall-runoff model concept

The FLORIJN rainfall-runoff model makes a distinction between surface runoff and base-flow. The volume of water available for surface runoff is computed using a Horton-type of infiltration model, while the timely-distribution of the surface runoff is taken care of by a Nash Unit Hydrograph (or Nash cascade). Base-flow is computed using an ARIMA (1,1,0) model in which it is assumed that the actual base-flow is a function of previous base-flows only. In the detailed description of the FLORIJN rainfall-runoff model (given hereafter) the following distinction is made:

- Procedure for determining the effective rainfall,
- Timely distribution of the effective rainfall (i.e. the Nash cascade concept),
- Base-flow modelling (i.e. application of a ARIMA (1,1,0) model),
- Computation of total runoff,
- Muskingum routing procedure (applied for Lippe Level 3 only), and
- The method of handling snow.

8.1.1 Procedure for determining the effective rainfall volume.

Some part of the total rainfall (P) is lost due to interception or storage in depression areas. That part of the total rainfall which results in surface runoff is refered to as effective rainfall (P_{eff}). In FLORIJN effective rainfall is determined using the following Horton-type of infiltration method:

$$P_{eff}(t_i) = \psi * \max(0, P(t_i) - f_{pot}(t_i)) \tag{8.1}$$

$$if\ \ f_{\infty}(t_i) \geq f_{pot}(t_i):\ \ f_{pot}(t_{i+1}) = f_{\infty}(t_i) + (f_{pot}(t_i) - f_{\infty}(t_i)) * \exp(-\frac{dt * f_{\min}}{k_B * (f_{\max} + f_{\min})}) \tag{8.2}$$

$$if\ \ f_{\infty}(t_i) < f_{pot}(t_i):\ \ f_{pot}(t_{i+1}) = f_{\infty}(t_i) + (f_{pot}(t_i) - f_{\infty}(t_i)) * \exp(-\frac{dt}{k_B}) \tag{8.3}$$

$$if \quad P(t_i) \le \frac{f_{max} - f_{min}}{\Omega}: \qquad f_\infty(t_i) = f_{max} - \Omega * P(t_i) \tag{8.4}$$

$$if \quad P(t_i) > \frac{f_{max} - f_{min}}{\Omega}: \qquad f_\infty(t_i) = f_{min} \tag{8.5}$$

in which:

dt	= time step
f_{max}	= Maximum infiltration capacity [mm/hour]
f_{min}	= Minimum infiltration capacity [mm/hour]
f_{pot}	= Actual potential infiltration capacity [mm/hour]
$f_\infty(t)$	= Potential infiltration capacity (for equilibrium conditions) at t=t [mm/hour]
k_B	= Decay factor used in determining the actual infiltration capacity [hours]
P(t)	= Total rainfall at t=t [mm]
$P_{eff}(t)$	= Effective rainfall at t=t [mm]
t	= Point in time during computation [hours]
Ω	= Reduction parameter
ψ	= Ratio of area producing surface runoff to the total catchment area.

For a given (at the start an initial) value for f_{pot}, the effective precipitation at t=t is computed. Thereafter the value for f_{pot} for t=t+dt is computed using Eqs. 8.2 to 8.5, whereafter the effective precipitation for t=t+dt is computed. In this way the timely-distribution (i.e. histogram-type) of effective precipitation is established. Conform the recommendation in Berger (1992), a constant value for Ω was applied (i.e. $\Omega=(f_{max}-f_{min})/f_{min}$). Please note that the value for f_{pot} (i.e. actual potential infiltration capacity used in Eq. 8.1 for determining the actual effective rainfall) varies between f_{min} and f_{max}, pending the antecedent rainfall.

8.1.2 Timely distribution of the effective rainfall (Nash cascade)

In FLORIJN the Nash cascade concept is used for transforming the effective precipitation histogram (explained in subsection 8.1.1) into a timely-distributed surface runoff (i.e. hydrograph). The Nash cascade comprises of a number of linear reservoirs, which are placed in serie. It can be shown that an instantaneous volume of effective precipitation ($P_{eff,instant}$) entering a Nash-cascade, comprising of n_n linear reservoirs having a storage coefficient of k_n hours each, results in an instantaneous unit hydrograph denoted by:

$$q_d(t) = P_{eff,instant} \; * \; u(0,t) \tag{8.6}$$

and

$$for \quad t \ge 0: \qquad u(0,t) = (\frac{1}{(n_n - 1)! \, * \, (k_n)^{n_n}}) * t^{(n_n - 1)} * e^{-t/k_n} \tag{8.7}$$

in which:

k_n	= Storage coefficient of the Nash cascade reservoir.
n_n	= Number of Nash cascade reservoirs.
$P_{eff,instant}$	= Effective instanteneous rainfall (i.e. in time-period from t=0 to $t=0^+$).
$q_d(t)$	= Surface runoff at t=t.
t	= Point-in-time.

u(0,t) or IUH(t)= Ordinate of the Instantaneous Unit Hydrograph at t=t.

By introducing the Gamma-function [i.e. $\Gamma(n_n) = (n_n-1)!$], an analytical expression for the Nash instantaneous unit hydrograph ordinates can be obtained for a non-integer number of linear reservoirs (see Eq. 8.8).

$$for \quad t \geq 0: \qquad u(0,t) = \frac{1}{\Gamma(n_n)} * \left(\frac{t}{k_n}\right)^{n_n-1} * \frac{e^{-t/k_n}}{k_n} \tag{8.8}$$

It will be obvious that in reality rainfall will not occur instantaneous. In addition as discussed in subsection 8.2.1 a time step of 6 hours was used for the Sieg and Lippe rainfall-runoff models. Taking this into account in the rainfall-runoff models u(6,t) [i.e. u(6,0), u(6,6), u(6,12) etc.] unit hydrograph ordinates were used instead of the u(0,t) [i.e. u(0,0), u(0,6), u(0,12) etc.] instantaneous unit hydrograph ordinates. It can be shown that for the u(6,t) unit hydrograph ordinates yields:

$$for \quad t = 0: \qquad u(6,0) = u(0,0) \tag{8.9}$$

$$for \quad t = 6: \qquad u(6,6) = \frac{1}{2} * u(0,6) \tag{8.10}$$

$$for \quad t \geq 12: \qquad u(6,t) = \frac{1}{2}\{u(0,t) + u(0,t-T)\} \tag{8.11}$$

in which:
$T = 6\ hours, and\ u(0,0), u(0,6)\ and\ u(0,12)\ etc.\ follow\ from\ Eq.(8.8).$

The surface runoff, induced by a particular storm is calculated by adding the individual u(6,t) unit hydrographs corresponding to the accumulated effective 6-hourly rainfall, hence:

$$Q_d(t = t_j) = A * \sum_{i=0}^{i_{max}} \{P_{eff}(t_{j-1}) * dt * u(6, dt*(i+1))\} \tag{8.12}$$

in which:

A	= Area affected by the rainfall.
dt	= Time step (i.e. 6-hours).
P_{eff}	= Effective 6-hourly rainfall.
i_{max}	= Number of ordinates considered in the u(6,t) unit hydrograph.
$Q_d(t=t_j)$	= Surface runoff at point-in-time $t=t_j$.

8.1.3 Base-flow modelling (ARIMA (1,1,0) model)

In the FLORIJN rainfall-runoff model it is assumed that the base-flow at a particular point-in-time depends on antecedent base-flows only. These antecedent base-flows are computed by substracting computed surface runoffs (see subsection 8.1.2) from observed discharges. In accordance with this assumption it is tried to correlate base-flows with antecedent base-flows using an ARIMA(1,1,0) model as follows:

$$Q_{b,for}(t+i*dt) = \{1+alpha(1,i)\} * Q_{b,\text{determined}}(t) - alpha(1,i) * Q_{b,\text{determined}}(t-dt) \qquad (8.13)$$

in which:

alpha(1,i) = ARIMA (1,1,0) coefficient for determing the base-flow at t=t+i*dt on basis of the base-flow at t=t and the base-flow at t=t-dt.
dt = Time step.
i = Number of time steps.
$Q_{b,determined}(t)$ = Determined base-flow at t=t, obtained by substracting the computed surface runoff at t=t (see subsection 8.1.2) from the observed one.
$Q_{b,for}(t+i*dt)$ = Base-flow forecasted at t=t for $\Delta t = i*dt$ hours in advance.
t = Point-in-time.

It is to be mentioned that in the FLORIJN rainfall-runoff modelling concept, the difference between total rainfall and determined effective rainfall (see subsection 8.1.1) is not entered in some kind of ground-water model, which generates base-flow. In effect the difference between total rainfall and effective rainfall is simply considered to be a lost piece of information.

The assumption that a base-flow at a particular point-in-time depends only on antecedent base-flows might be correct in case of a depletion curve (i.e. no intermediate rainfall), when the volume of the ground-water reservoir is declining. For a linear reservoir yields $S=k*Q_b$ and $Q_b(t)=Q_o*\exp(-t/k)$, in which: k= reservoir coefficient; $Q_b(t)$= base-flow at t=t; Q_o= base-flow at t=0; S=storage volume; and t= point-in-time. Applying an ARIMA(1,1,0) model for base-flows, corresponding to a declining ground-water reservoir will result in a very-good match between observed and computed base-flows. In case of intermediate rainfall, however, some part of the rainfall will flow to the ground-water reservoir and will consequently increase its base-flow. This phenomena can not be accounted for by an ARIMA(1,1,0) model, since it is related to a parameter (i.e. rainfall) which will varies from computational time-step to computational time-step. Resuming it can be concluded that the ARIMA(1,1,0) model has its limitations. For cases of relatively small changes in base-flow or for short period of time over which base-flows are computed (i.e. using Eq. 8.13) might result in acceptable results. However it is anticipated that base-flows computed over long time-periods having substantial rainfall will not be that accurate.

8.1.4 Computation of the total runoff

The total runoff is simply computed by adding for each point-in-time the surface runoffs and base-flows, respectively computed with Eqs. 8.12 and 8.13.

8.1.5 Muskingum routing procedure.

In the Lippe Level 3 model, Musingum routing was applied for the stretches from Lippstadt2 to Leven and from Haltern to Schermbeck (see subsection 9.6.1). The Muskingum routing of discharge through a particular river stretch is described by Eqs. 8.14 to 8.17.

$$Q_{\text{outflow}}(t+dt) = C_0 * Q_{\text{inflow}}(t) + C_1 * Q_{\text{inflow}}(t+dt) + C_2 * Q_{outflow}(t) \qquad (8.14)$$

and

$$C_0 = \{0.5 * dt - K * x\} / [0.5 * dt + K(1-x)] \qquad (8.15)$$

$$C_1 = \{0.5 * dt + K * x)\} / [0.5 * dt + K(1-x)] \qquad (8.16)$$

$$C_2 = \{-0.5 * dt + K(1-x)\} / [0.5 * dt + K(1-x)] \qquad (8.17)$$

in which:

C_0	=	Coefficient.
C_1	=	Coefficient.
C_2	=	Coefficient.
K	=	The storage time constant of the river stretch.
dt	=	Time step (i.e. 6 hours)
Q_{inflow}	=	Discharge flowing into the river stretch.
$Q_{outflow}$	=	Discharge flowing out of the river stretch.
t	=	Point in time.
x	=	Weighting factor of the river stretch ($0.0 < x < 0.5$).

8.1.6 The method of handling snowfall

No snow-melt module is incorporate in the FLOFOM model, since snow-melt plays only a minor role in flood generation in the river Meuse basin. At the start of this project it was considered that snow-melt might be of importance for the upper areas in the Sieg basin. The calibration & validation results of the Sieg rainfall-runoff model (see section 9.7), however, showed that snow-melt is not of importance for the generation of floods in the Sieg basin. Accordingly in FLORIJN, a snow-melt module is not incorporated in the rainfall-runoff models.

In real-time flood forecasting it is important to distinquish between rainfall and snowfall. In case of rainfall a flood might result, while no flood is to be anticipated in case of snowfall. Hence snowfall in real-time flood forecasting is to be considered as no rainfall (i.e. rainfall equal to zero). In updating the rainfall runoff models, corrections are to be made in case forecasted snowfall turned out to be rainfall and vice versa.

8.2 General modelling aspects

8.2.1 Time step used in Sieg and Lippe rainfall-runoff modelling

A suitable time-step for the rainfall-runoff models in real-time flood forecasting depends on:

- The time-interval for which rainfall is forecasted for the Sieg and Lippe catchments,
- The accuracy requirements of the rainfall-runoff models, and
- The required computational time.

At present weather forecasts by the Deutscher Wetterdienst (DWD) are made every twelve hours. In future weather forecasts may become available every six hours (see section 11.1). From an accuracy point of view a time-step of six hours is sufficient, since this results in a sufficient number of computational points describing the flood waves. The total required computational time for the rainfall-runoff models can be considered as relatively small and does not put constraints on the selection of the time-step as such.

Taking the above reasoning into account, a time-step of six hours will be suitable in real-time flood forecasting. The same time-step was applied in calibrating and validating as well as in the sensitivity analysis of the Sieg and Lippe rainfall-runoff models.

8.2.2 Required forecasting time-horizons for Sieg and Lippe

The FLORIJN project aims at forecasting high water levels (and hence discharges) at Lobith three days in advance. The travel time of representative flood waves from the inflow point of the river Sieg to Lobith and from the inflow point of the river Lippe to Lobith, respectively amounts to ± 1.0 and ± 0.5 days. Taking these travel times on the river Rhine into account, the minimum required forecasting time-horizons for the rainfall-runoff models of the Sieg and Lippe are:

- *Sieg:*
  Forecasting discharges at the inflow point with the river Rhine (i.e. at the station Menden) 2 days or 48 hours in advance.
- *Lippe:*
  Forecasting discharges at the inflow point with the river Rhine (i.e. at the station Schermbeck) 2.5 days or 60 hours in advance.

8.2.3 Updating procedure using in real-time flood forecasting

Before making a new flood forecast the rainfall-runoff models are to be updated using on-line collected discharge and rainfall data. Rijkswaterstaat RIZA applies the following updating procedure:

1. Screened on-line collected rainfall and discharge data is entered into the rainfall-runoff models.
2. New computations (i.e. based on the on-line collected -areal- rainfall data) are made for the surface runoff up to $t=t_{update}$, the point-in-time for which observed data is collected. The new values for the surface runoff are refered to as the updated ones, since they refer to observed rainfall and not to forecasted and possible more erroneous rainfall data.
3. New base-flows (i.e. updated ones) are computed by substracting the updated surface runoff from the observed discharges.

After updating a new flood forecast up to $t=t_{forecast}$ is made in the following way:

1. Forecasted rainfall for $t=t_{update}$ up to $t=t_{forecast}$ is entered into the rainfall-runoff models.
2. Forecasted surface runoff (i.e. for $t_{update} < t < t_{forecast}$) is computed using the forecasted rainfall.
3. Base-flows are forecasted (i.e. for $t_{update} < t < t_{forecast}$) using the ARIMA(1,1,0) model and the updated base-flows corresponding to the time period for which yields: $t \leq t_{update}$.
4. Forecasted base-flows and forecasted surface runoff are added, resulting in forecasted total outflow discharges.

For the way in which base-flows, surface runoffs and total runoffs are computed in the FLORIJN rainfall-runoff model, reference is made to subsection 8.1.1 to 8.1.4.

8.2.4 Evaluation criteria for assessing modelling results.

As described in subsection 8.2.3 in real-time flood forecasting, the rainfall-runoff models are first updated before a new forecast is made. In the calibration & validation and in the sensitivity analysis, the rainfall-runoff models were updated for every time-step (i.e. for every six hours), after which a forecast upto 48 hours ahead in case of the Sieg and a forecast up to 60 hours ahead in case of the Lippe was made. This means that for a flood period on the river Sieg lasting for 31 days in total (31-2)*24/6 = 116 forecasts upto 48 hours ahead were made.

The capability of rainfall-runoff models in forecasting discharges for a certain time-horizon ahead (for instance for 48 hours ahead) can be evaluated by the visual comparison of the 48-hours ahead forecasted discharges with actual observed discharges. For a possible more objective interpretation of the validation and calibration results the following indicators were defined and computed accordingly, viz:

1. the mean absolute efficiency of x-hours in advance forecasted discharges:

$$\text{mean.abs.eff}\,(t=x) = \frac{\sum_{i}^{n} \left\| \{(Q_{obs}(t) - Q_{for,t=x}(t))/Q_{obs}(t)\} * 100\% \right\|}{n} \tag{8.18}$$

in which:

$\text{mean.abs.eff}_{(t=x)}$ = mean absolute efficiency of x-hours in advance forecasted discharges

$Q_{obs}(t)$ = observed discharges at t=t

$Q_{for,t=x}(t)$ = discharges forecasted t=x hours ahead for the point-in-time t=t.

n = number of forecasts made for t=x hours ahead.

1. the maximum local efficiency of x-hours in advance forecasted discharges:

$$\text{max.}loc.eff_{\,(t=x)} = Max\left(\frac{Q_{obs}(t) - Q_{for,t=x}(t)}{Q_{obs}(t)} * 100\%\right) \tag{8.19}$$

1. the minimum local efficiency of x-hours in advance forecasted discharges:

$$\text{min.}loc.eff_{\,(t=x)} = Min\left(\frac{Q_{obs}(t) - Q_{for,t=x}(t)}{Q_{obs}(t)} * 100\%\right) \tag{8.20}$$

9 Validation and calibration of Sieg and Lippe rainfall runoff models

In this Chapter the validation and calibration results of the rainfall-runoff models for Sieg Level 1 & 2 and Lippe Level 1 & 3 are discussed. For a description of Levels 1, 2 and 3, reference is made to Chapter 5. A time-step of 6 hours was used in forecasting the outflows of the Sieg and Lippe basins respectively 48 and 60 hours in advance using the same updating procedure as applied in real-time flood forecasting (see subsection 8.2.3). Further on LUA-NRW (or *off-line*) areal rainfall (see Chapter 6) was used in calibrating and validating the rainfall-runoff models.

9.1 Selection of calibration and validation flood events.

The rainfall-runoff model for the Sieg was *calibrated* for **Period no. 5**: February 1984 and *validated* for **Period no. 7**: January - February 1986, **Period no. 8**: December 1986 - January 1987 and **Period no. 12**: February - March 1990. The rainfall-runoff model for the river Lippe was *calibrated* for **Period no. 9**: February- March 1987 and *validated* for **Period no. 7**: January - February 1986, **Period no. 8**: December 1986 - January 1987 and **Period no. 10**: March - April 1988.

For each river the four flood events used in calibration and validation were selected from the fourteen available flood events (see Chapter 3) on basis of the following criteria:

- occurrence of flood events on both Sieg/Lippe and the Rhine,
- data availability,
- magnitude of the flood wave (i.e. preference for the higher flood events),
- period in the year (i.e. preference for the winter flood events).

The above mentioned criteria are summarized for the Sieg in Table 9-1 and for the Lippe in Table 9-2.

Table 9-1 Summary of criteria for selecting the **Sieg** calibration & validation flood events.

Period	Data availability	Time of the year: W=winter/spring S=summer	Peak discharge in m^3/s on river **Sieg** at Menden	Peak discharge in m^3/s on river **Rhine** at Lobith	Period used in calibration or validation
1	-/+	W	475	8,900	-
2	-/+	W	375	8,000	-
3	-/+	W	430	5,500	-
4	-/+	S	250	9,200	-
5	-/+	W	1050	8,700	Calibration
6	-/+	S	675	5,500	-
7	-/+	W	850	6,000	Validation
8	-/+	W	1000	7,500	Validation
9	-/+	W	650	7,000	-
10	-/+	W	475	10,000	-
11	-/+	W	600	5,200	-
12	+	W	550	7,000	Validation
13	-	W	600	11,100	-
14	-	W	725	12,060	-

Table 9-2 Summary of criteria for selecting the **Lippe** calibration & validation flood events.

Period	Data availability	Time of the year: W=winter/spring S=summer	Peak discharge in m^3/s on river **Lippe** at Schermbeck	Peak discharge in m^3/s on river **Rhine** at Lobith	Period used in calibration or validation
1	-	W	270	8,900	-
2	-	W	265	8,000	-
3	+	W	200	5,500	-
4	+	S	150	9,200	-
5	+	W	320	8,700	-
6	+	S	300	5,500	-
7	+	W	300	6,000	Validation
8	+	W	350	7,500	Validation
9	+	W	315	7,000	Calibration
10	+	W	250	10,000	Validation
11	+	W	275	5,200	-
12	-	W	215	7,000	-
13	-	W	310	11,100	-
14	-	W	375	12,060	-

9.2 Determination of model parameters.

The FLORIJN rainfall-runoff model makes a distinction between surface runoff and base-flow. The volume of water available for surface runoff is computed using a Horton-type of infiltration model, while the timely-distribution of the surface runoff is taken care of by applying the Nash unit hydrograph concept. Base-flow is computed using an ARIMA (1,1,0) model in which it is assumed that the actual base-flow is a function of previous base-flows.

Taking the above into account, prior to the calibration of the rainfall-runoff models, observed discharges were divided in surface runoff and base-flow. This division was made based on observed rainfall and the depletion curve of the corresponding observed discharge hydrograph. As explained hereafter, the division in surface runoff and base-flow was used in determining the model parameters.

The following model parameters are required for the rainfall-runoff models simulations:

- ψ : Ratio of area producing surface runoff to the total catchment area.
- f_{min} : Minimum infiltration capacity [mm/hour].
- f_{max} : Maximum infiltration capacity [mm/hour].
- k_b : Decay factor used in determining the actual infiltration capacity [hours].
- k_n : Storage coefficient of the Nash cascade reservoir [hours].
- n_n : Number of Nash cascade reservoirs.
- alpha(1,i): ARIMA (1,1,0) coefficient used in computing base-flows

In case of Muskingum routing (i.e. only applied for Lippe Level 3):

- K : Storage-time constant of a particular river stretch [hours].
- x : Weighting factor ($0 < x < 0.5$).

Hereafter, the methodology applied in determining the model parameters is explained. For the actual applied values, reference is made to the sections in which the calibration and validation results of the rainfall-runoff models are discussed.

i. Model parameter ψ:

$\psi = 0$ refers to an area not producing any surface runoff at all (for instance a catchment of which the outflow is completely stored in a reservoir), while $\psi = 1$ refers to a catchment of which its entire area is contributing to the surface runoff. Prior to the calibration, ψ values for each catchment were determined taking into account the presence of reservoirs.

ii. Model parameters f_{min}, f_{max}, k_b, k_n and n_n:

The model parameters f_{min}, f_{max}, k_b, k_n and n_n were determined by fine-tuning the surface runoff computed by the rainfall-runoff model to the surface runoff determined by the division of observed discharges into surface runoff and base-flow.

iii. Model parameters alpha(1,1) to alpha(1,i):

The model parameters alpha(1,1) to alpha(1,i) were determined using the base-flow determined by the division of observed discharges into surface runoff and base-flow. Values of alpha(1,i) were determined by minimizing Eq. 9.1.

$$\sum \{ Q_{b,\mathrm{alpha}(1,i)}(t) - Q_{b,\mathrm{determined}}(t) \}^2 \qquad (9.1)$$

where:

$$Q_{b,\mathrm{alpha}(1,i)}(t) = \{1 + \mathrm{alpha}(1,i)\} * Q_{b,\mathrm{determined}}(t - i * dt) - \mathrm{alpha}(1,i) * Q_{b,\mathrm{determined}}(t - \{i+1\} * dt) \qquad (9.2)$$

in which:

dt = time step (i.e. six hours).
alpha (1,i) = ARIMA coefficient for determining the base-flow at t=t on basis of the base-flow at t=t-i*dt and the base-flow at t=t-(i+1)*dt.
$Q_{b,alpha(1,i)}$ (t) = computed base-flow using the ARIMA(1,1,0) model at t=t.
$Q_{b,determined}$ (t) = determined base flow by dividing observed discharges into surface runoff at t=t and base-flow at t=t.

In accordance with the required forecasting time-horizons for the rainfall-runoff models (see subsection 8.2.2), for the Sieg values for alpha(1,1) to alpha(1,8) and for the Lippe values for alpha(1,1) to alpha(1,10) were determined. It is to be mentioned that in general for $i > 3$, values for alpha(1,i) became equal to zero. This is considered to be due to the fact that base-flows more than 18 hours ahead are not only functions of previous base-flows but are also influenced by the rainfall, which occurs within this 18 hour time-span (see also subsection 8.1.3).

iv. Muskingum parameters K and x:

Muskingum routing is only incorporated in the Lippe Level 3 rainfall-runoff model. The Muskingum parameters K and x were determined using the surface runoff at the upstream and downstream station, which were established by the division of observed discharges into surface runoff and base-flow. Corrections for lateral inflow of surface runoff in between the upstream and downstream station, were made by substracting this lateral inflow of surface runoff from the downstream station in proportion to its established surface runoff. The Muskingum parameters K and x were obtained by matching the routed surface runoff hydrograph with the for lateral inflow corrected surface- runoff hydrograph at the downstream station.

9.3 Calibration and validation for Sieg Level 1.

In this section the calibration and validation results for Sieg Level 1 are discussed. Sieg Level 1 concerns the modelling of the entire river Sieg basin (i.e. 2,832 km^2) as a whole. Calibration and validation is done by comparing computed and observed discharges at Menden. Muskingum routing was not required.

The Sieg Level 1 was calibrated for Period no. 5 and validated for Periods no. 7, no. 8 and no. 12. In the validation the same model parameters were applied as established in the calibration. The parameter ψ (the ratio of area producing surface runoff to the total catchment area) was determined taking into account the presence of the Breitenbach-talsperre, the Obernautalsperre, the Wahnbachtalsperre, the Genkeltalsperre, the Agger-talsperre and the Wehltalsperre with a combined command area of 189.57 km^2, which is equal to $(189.57/2,832)*100\% \cong 7\%$. Hence for the Sieg basin as a whole a value of 0.93 was used for the model parameter ψ. For the calibration and validation results, the values of the model parameters f_{min}, f_{max}, k_b, k_n , n_n and alpha(1,i) as well as for the indicators (explained in subsection 8.2.4), reference is made to Figs. 9.1 to 9.5.

Forecasted discharges at Menden provide a good match with observed discharges at Menden for the calibration Period no. 5 and the validation Period no. 7. The match between forecasted discharges and observed discharges at Menden for the validation Period no. 8 and for the Period no. 12 (especially) is not that good as for the Period no. 5 and Period no. 7. In Fig. 9.5. the results of the validation for Period no. 12 is shown using a slightly increased value for the model parameter f_{min} (i.e. 0.40 instead of 0.30), resulting in a far better match with observed discharges.

The model parameter f_{min} refers to the minimum infiltration capacity. It is to be mentioned that soil conditions due to snow cover, frost etc., most likely may vary per flood event (or even during a flood event), allowing for the use of a different value for f_{min} in Period no. 12. However, the use of a larger value for f_{min} in Period no. 12 may also refer to the overestimation of areal rainfall in this period. Concluding it can be remarked that satisfactory calibration and validation results were obtained for Sieg Level 1.

9.4 Calibration and validation for Sieg Level 2

9.4.1 Description and schematization of Sieg Level 2

Sieg Level 2 (see section 5.1 and Fig. 5.1) refers to a division of the river Sieg basin into three sub-basins, viz:

- The Middle/Upper Sieg basin, having an area of 1,889 km^2,
- The Agger basin, having an area of 785 km^2, and
- The Lower Sieg basin, having an area of 158 km^2.

The following rated river gauging stations were used in calibrating and validating Sieg Level 2, viz:

- *Siegburg*, measuring the outflow of the Middle/Upper Sieg basin,
- *Lohmar*, measuring the outflow of the Agger basin, and
- *Menden*, measuring the combined outflow of the Middle/Upper Sieg, Agger and Lower Sieg basins.

No Muskingum routing was applied in the Sieg Level 2 rainfall-runoff model, since:

- the distance from Lohmar to Menden amounts to 6.7 km., and
- the distance from Siegburg to Menden amounts to 8.3 kilometres only,

resulting in travel-times, which are small compared to the time-step used.

9.4.2 Calibration and validation results of Sieg Level 2

The Sieg Level 2 (as for Sieg Level 1) rainfall-runoff was calibrated for Period no. 5 and validated for Periods no. 7, no. 8 and no. 12. In the validation the same model parameters were applied as established in the calibration. The parameter ψ (the ratio of area producing surface runoff to the total catchment area) for each subbasin was determined taking into account the presence of reservoirs, viz:

- *Middle/Upper Sieg basin (ψ=0.94):*

  The Breitenbachtalsperre, the Obernautalsperre and the Wahnbachtalsperre are located in the Middle/Upper Sieg basin. Except for other purposes, these three reservoirs are used for flood mitigation. Their combined command area amounts to 103.13 km^2, which is equal to (103.13/1,889)*100% $\cong$ 6% of the total catchment area of the Middle/Upper Sieg. Hence for the Middle/Upper Sieg basin a value of 0.94 was used for the model parameter ψ.

- *Agger basin (ψ=0.89):*
  The Genkeltalsperre, the Aggertalsperre and the Wehltalsperre are located in the Agger basin. However, only the Aggertalsperre and the Wehltalsperre have potentials for flood mitigation. The combined command area of these two reservoirs amounts to 86.44 km^2, which is equal to (86.44/785)*100% ≅ 11%. Hence for the Agger basin a value of 0.89 was used for the model parameter ψ.
- *Lower Sieg basin (ψ=1.00):*
  There are no reservoirs in the Lower Sieg basin. A value for ψ equal to unity was, therefore, applied.

For the calibration and validation results, the values of the model parameters f_{min}, f_{max}, k_b, k_n, n_n and alpha(1,i) as well as for the indicators (explained in subsection 8.2.4), reference is made to Figs. 9.6 to 9.19.

As for the Sieg Level 1 rainfall-runoff model, forecasted discharges at Menden provide a good match with observed discharges at Menden for the calibration Period no. 5 and the validation Period no. 7. The match between forecasted discharges and observed discharges at Menden for the validation Period no. 8 and for the Period no. 12 (especially) is not that good as for the Periods no. 5 and no. 7. In Fig. 9.10 the results of the validation for Period no. 12 is shown using an increased value for the model parameter f_{min} (i.e. 0.70 instead of 0.40 for the Middle/Upper Sieg basin), resulting in a far better match with observed discharges. As mentioned in the discussion on the Sieg Level 1 modelling results, f_{min} refers to the minimum infiltration capacity and may vary per flood event due to different soil conditions. Concluding it can be remarked that satisfactory calibration and validation results at Menden were obtained for Sieg Level 2 as well. In Figs. 9.11 to 9.14 the calibration and validation results for the station Lohmar on the Agger, and in Figs. 9.15 to 9.19 the calibration and validation results for the station Siegburg on the Sieg are given.

9.5 Calibration and validation for Lippe Level I

Hereunder the calibration and validation results for Lippe Level 1 are discussed. Lippe Level 1 concerns the modelling of the entire river Lippe basin (i.e. 4,783 km^2) as a whole. Calibration and validation is done by comparing computed and observed discharges at Schermbeck. Muskingum routing was not required.

The Lippe Level 1 was calibrated for Period no. 9 and validated for Periods no. 7, no. 8 and no. 10. In the validation the same model parameters were applied as established in the calibration. The parameter ψ (the ratio of area producing surface runoff to the total catchment area) was determined taking into account the presence of the Aabachtalsperre, the Talsperre Hullern and the Stevertalsperre Haltern, having a total command area of 1,546.26 km^2, covering nearly (943.11/4,783)*100% ≅ 20% of the Lippe catchment The Talsperre Hullern and the Stevertalsperre Haltern are cascade reservoirs, which are mainly used for dinking water purposes and have a limited storage capacity only. Nevertheless, a value of 0.80 for the model parameter ψ was adopted for the entire river Lippe basin.
For the calibration and validation results, the values of the model parameters f_{min}, f_{max}, k_b, k_n , n_n and alpha(1,i) as well as for the indicators (explained in subsection 8.2.4), reference is made to Figs. 9.20 to 9.24.

Forecasted discharges at Schermbeck provide a good match with observed discharges at Schermbeck for the calibration Period no. 9 and the validation Period no. 7. The match between forecasted discharges and observed discharges at Schermbeck for the validation Period no. 8 (especially) and for the Period no. 10 is not that good as for the Periods no. 7 and no. 9. In Fig. 9.22. the results of the validation for Period no. 8 is shown using a slightly increased value for the model parameter f_{min} (i.e. 0.40 instead of 0.20), resulting in a better match with observed discharges. The model parameter f_{min} refers to the minimum infiltration capacity. It is to be mentioned that soil conditions due to snow cover, frost etc. most likely may vary per flood event, allowing for the use of a different value for f_{min} in Period no. 8. However, the use of a larger value for f_{min} in Period no. 8 may also refer to the overestimation of areal rainfall in this period. Concluding it can be remarked that satisfactory calibration and validation results were obtained for Lippe Level 1.

9.6 Calibration and validation for Lippe Level 3

9.6.1 Description and schematization of Lippe Level 3

Lippe Level 3 (see section 5.2 and Fig. 5.2) refers to a division of the river Lippe basin into four sub-basins, viz:

- The Upper Lippe basin, having an area of 1,396 km^2,
- The Middle Lippe basin, having an area of 1,929 km^2,
- The Stever basin, having an area of 948 km^2, and
- The Upper Lippe basin, having an area of 510 km^2.

The following rated river gauging stations were used in calibrating and validating Lippe Level 3, viz:

- *Lippstadt2*, measuring the outflow of the Upper Lippe basin,
- *Leven*, measuring the combined outflow of the Upper Lippe and Middle Lippe basins,
- *Haltern*, measuring the combined outflow of the Upper Lippe, Middle Lippe and Steverbasins,
- *Schermbeck*, measuring the combined outflow of the Upper Lippe, Middle Lippe, Stever and Lower Lippe basins (i.e. the entire Lippe basin)

Muskingum routing was applied to the following river Lippe stretches, viz:

- *Lippstadt2 to Leven*, covering a distance of 102.7 km, and
- *Haltern to Schermbeck*, covering a distance of 30.9 km.

Please note that no Muskingum routing was applied for the stretch from Haltern to Leven, since the length of this stretch amounts to 12 km. only. The travel time of a flood wave in this reach are compensated for by the Muskingum routing from Lippstadt2 to Leven and the Muskingum routing from Haltern to Schermbeck.

9.6.2 Different forecasting time-horizons within Lippe Level 3

The aim of the Lippe Level 3 rainfall-runoff model is to forecast discharges at Schermbeck 60 hours in advance (see subsection 8.2.2). Incorporating Muskingum routing for the stretches from Lippstadt2 to Leven (18 hours travel-time) and from Haltern to Schermbeck (6 hours travel-time) results in different forecasting time-horizons requirements for the individual subbasins, viz:

- Discharges at Lippstadt2 need to be forecasted only 36 hours in advance in order to correspond to 60 hours in advance at Schermbeck, since the travel-time from Lippstadt2 to Schermbeck amounts to 24 (=18+6) hours. Hence the outflow of the Upper Lippe basin is to be forecasted for only 36 hours in advance.
- Discharges at Haltern need to be forecasted only 54 hours in advance in order to correspond to 60 hours in advance at Schermbeck, since the travel-time from Haltern to Schermbeck amounts to 6 hours. Hence the outflow of the Middle Lippe basin and the Stever basin are to be forecasted for only 54 hours in advance.

In the Lippe Level 3 rainfall-runoff model the above explained differences in required forecasting time-horizons were taken into account.

9.6.3 Calibration and validation results of Lippe Level 3.

The Lippe Level 3 (as for Lippe Level 1) rainfall-runoff model was calibrated for Period no. 9 and validated for Periods no. 7, no. 8 and no. 10. In the validation the same model parameters were applied as established in the calibration. The parameter ψ (the ratio of area producing surface runoff to the total catchment area) for each subbasin was determined taking into account the presence of reservoirs, viz:

- *Upper Lippe basin (ψ=0.98):*
  There is only one reservoir, i.e. the Aabachtalsperre, located in the Upper Lippe basin. Except for dinkwater, this reservoir is also used for flood mitigation. The command area of this reservoir amounts to 34.8 km^2, which is equal to $(34.8/1,396)*100\% \cong 2\%$ of the total catchment area Upper Lippe. Hence for the Upper Lippe basin a value of 0.98 was used for the model parameter ψ.
- *Middle Lippe basin (ψ=1.00):*
  There are no reservoirs in the Middle Lippe basin. A value for ψ equal to unity was, therefore, applied.
- *Stever basin (ψ=0.90):*
  Two cascade reservoirs (i.e. the Talsperre Hullern upstream and the Stevertalsperre Haltern downstream) have been constructed on the river Stever. These two cascade reservoirs cover nearly the entire river Stever catchment. These two reservoirs are, however, mainly used for drinkwater purposes. Taking into account that their combined storage volume amount to 13% of the annual flood volume of the river Stever, a value for the parameter ψ of 0.90 was used.
- *Lower Lippe basin (ψ = 1.00):*
  There are no reservoirs in the Lower Lippe basin. A value for ψ equal to unity was, therefore, applied.

For the calibration and validation results, the values of the model parameters f_{min}, f_{max}, k_b, k_n, n_n and alpha(1,i) as well as for the indicators (explained in subsection 8.2.4), reference is made to Figs. 9.25 to 9.43. In the Muskingum routing the following parameters were applied, viz: from Lippstadt2 to Leven: K = 18 hours and x = 0.15, and from Haltern to Schermbeck: K = 6 hours and x = 0.10.

Forecasted discharges at Schermbeck provide a good match with observed discharges at Schermbeck for the calibration Period no. 9 and the validation Period no. 7 [in case instead of the calibration values, for the Stever basin f_{min} = 0.14 and for the Middle Lippe basin f_{min} = 0.25 is applied (see Fig. 9.26); taking the calibration values for f_{min} provides less good results (see Fig. 9.25)]. The match between forecasted discharges and observed discharges at Schermbeck for the validation Period no. 8 and for the Period no. 10 is not that good as for Period no. 7 and no. Period no. 9. As already was mentioned before soil conditions due to snow cover, frost etc. most likely may vary per flood event, allowing for the use of a different values for f_{min} (i.e. the minimum infiltration capacity) in Period no. 7. However, the use of different values for f_{min} in Period no. 7 for the Stever and Middle Lippe basin may also refer to the underestimation of areal rainfall in this period. Concluding it might be remarked that satisfactory calibration and validation results can be obtained for Lippe Level 3 in case different values for the model parameter f_{min} are applied.

9.7 Justification for not incorporating a snow-melt module

Only limited information on snow in both the Sieg basin and Lippe basin is available for calibrating and validating a snow-melt module. In addition as already stated in subsection 2.1.2 (i.e. second paragraph), there are no clear examples of a significant contribution of snow-melt on the generation of flood peaks.

For the Sieg basin snow data is available at the station Bad-Marienberg, located in the Nister basin (i.e. Middle/Upper Sieg); and the stations Bonn-Friesdorf and Koln-Wahn, located near the Lower Sieg (see Fig. 9.44), while for the Lippe basin snow data is only available at the station Bad-Lippspringe (see Fig. 9.44), located in its upper catchments areas. From this available snow data it can be concluded that:

1. In general the snowfall in the river Lippe basin is much smaller than the amount of snowfall in the river Sieg basin.
2. In general snowfall occurs in the upper catchment areas only, indicating that the contribution of snow-melt to the discharges at the inflow point with the river Rhine will be rather limited.
3. Snowfall occured in the upper catchment areas of both the river Sieg basin and the river Lippe basin in the periods used for the validation and calibration of the rainfall-runoff models.

Further on the rainfall-runoff model for the river Sieg was *calibrated* for **Period no. 5**: February 1984 and *validated* for **Period no. 7**: January - February 1986, **Period no. 8**: December 1986 - January 1987 and **Period no. 12**: February - March 1990. For the Sieg Level 1 and the Sieg Level 2 calibration and validation results, reference is respectively made to Figs. 9.1 to 9.5 and Figs. 9.6 to 9.19. For the occurrence of snowfall, reference is made to Fig. 9.45. In Periods no. 5, 7 and 8 more or less the same amount of snowfall was observed at Bad- Marienberg in the Nister basin, while less snowfall was observed at this station during period no. 12. The calibration results for period no. 5 and the validation results for period no. 7 can be considered as very good, while the validation results for period no. 8 and no. 12 are of less quality.
In order to improve the quality of Sieg Level 2 simulation for period no. 12, the value for f_{min} (minimum infiltration capacity) was to be increased for the Middle/Upper Sieg catchment (see Figs. 9.9 and 9.10; and Figs. 9.18 and 9.19). This is not in accordance with the observation at Bad-Marienberg that there was only a limited amount of snow-cover in the Middle/Upper Sieg catchment, implying that rainfall can not have been stored in the snow-layers, which would have resulted in an increased value for f_{min}. The reason why the value for f_{min} was to be increased for period no. 12 is not clearly understood, it might refer to an overestimation of the areal rainfall for the Middle/Upper Sieg catchment or to different soil conditions in the Middle/Upper Sieg catchment for Period no. 12. Concluding it can be stated that from the calibration and validation results for the river Sieg no evidence can be derived for the justifiying the incorporation of a snow-melt module in the rainfall-runoff model.

Considering the facts that:

- Only limited data is available for calibrating and validating a snow-melt module,
- Snowfall usually refers to a small part of the catchments only, and hence the contribution to the peak discharges is minimal, and
- The Sieg rainfall-runoff model, without having a snow-melt module incorporated, provides acceptable calibration and validation results, especially if fine-tuning with the parameter f_{min} is done,

justifies the decision not to include a snow-melt module in the FLORIJN rainfall-runoff model.

9.8 Reflections on Level 1 and Level 2/3 model results.

The division of the Sieg and Lippe basin into sub-basins (i.e. Sieg Level 2 and Lippe Level 3) did not result in a significant improvement of calibration and validation results as compared to Sieg Level 1 and Lippe Level 1 (see sections 9.3 to 9.6 and Fig. 9.1 to 9.43).

The advantage of dividing the river Lippe basin into four subbasins is the fact that:

- Forecasted rainfall for the Upper Lippe is only required 36 hours in advance, and
- Forecasted rainfall for the Middle Lippe and Stever is only required 54 hours in advance,

for making a forecasting corresponding to a forecast of 60 hours in advance at Schermbeck. It is, however, to be mentioned that area-wise, the Upper Lippe only contributes 29.2% to the discharges at Schermbeck. In addition peak discharges, generated by the Upper Lippe catchment are dampened on the river Lippe while travelling towards Schermbeck.

In Fig. 9.41 it can be seen that the discharges at Lippstadt2 are overestimated considerably for Period no. 8. However, this overestimation hardly effects the validation results at Schermbeck for Period no. 8 (see Fig. 9.27). Hence the advantage of having a longer lead-time appears to be not that significant.

The river Sieg, comprises of a dendritic network of tributaries. Hence there is not much scope for increasing forecasting time-horizons by a further subdivision of the river Sieg basin into subbasins. Please note that due to the lack of data at the discharge station Betzdorf a further subdivision of the Sieg basin could not be materialized (see also subsection 5.3.1).

In real-time flood forecasting of the Sieg Level 2 and Lippe Level 3 rainfall-runoff models, areal rainfall for more areas and discharges at more river gauging stations are to be collected (and screened) in order to update these models.

Taking the above arguments into account it appears to be not really worthwhile to try to improve the flood forecasting capability of the rainfall-runoff models by a further division of the river Sieg and river Lippe catchments into subbasins, having a maximum area of 500 to 1,000 km^2.

10 Sensitivity analysis of Sieg and Lippe rainfall-runoff models

In this Chapter the results of a sensitivity analysis on the Sieg and Lippe rainfall-runoff models are discussed. A time-step of 6 hours was used in forecasting the outflows of the Sieg and Lippe basins respectively 48 and 60 hours in advance using the same updating procedure as applied in real-time flood forecasting (see subsection 8.2.3).

The aim of the sensitivity analysis is to determine the influence (sensitivity) of certain parameters on the computational results of the Sieg and Lippe rainfall runoff-models, i.e on the magnitude and timing of the discharges flowing into the river Rhine. The results of the sensitivity analysis are of importance for the interpretation of computed discharges during real-time flood forecasting.

The sensitivity analysis for the Sieg rainfall-runoff model was carried out using **Period no. 5**: February 1984 (i.e. used in calibration) and **Period no. 12**: February - March 1990 (i.e. used in validation), while the sensitivity analysis for the Lippe rainfall-runoff model was done using **Period no. 7**: January - February 1986 (i.e. used in validation) and **Period no. 9**: February- March 1987 (i.e. used in calibration).

10.1 Scope of the sensitivity analysis

The sensitivity analysis was carried out for the Sieg Level 1 rainfall-runoff model (i.e. 2,832 km^2) and the Lippe Level 1 rainfall-runoff model (i.e. 4,783 km^2) only. With Level 1 is refered to as the rainfall-runoff models in which the entire catchment is lumped, meaning that no division into subbasins are made.

The sensitivity analysis comprised of variation in model parameters; variations in forecasted rainfall; and the difference in using *off-line* (or LUA-NRW) or *on-line* (or DWD) areal rainfall data.

10.1.1 Sensitivity to model parameters

The rainfall-runoff models comprise of the following model parameters, viz:

- ψ: Ratio of area producing surface runoff to the total catchment area,
- $f_{min:}$ Minimum infiltration capacity [mm/hour],
- f_{max}: Maximum infiltration capacity [mm/hour],
- k_b: Decay factor used in determining the actual infiltration capacity [hours],
- k_n: Storage coefficient of the Nash cascade reservoir [hours],
- n_n: Number of Nash cascade reservoirs, and
- alpha(1,i): ARIMA coefficient used in computing base-flows.

The model parameters ψ, f_{min}, f_{max} and k_b refer to the Horton-type of infiltration model, determining the amount of precipitation resulting in surface runoff. From earlier sensitivity analysis (Boks Econsult, 1997), it was concluded that the sensitivity to the model parameters f_{max} and k_b is small as compared to the model parameter f_{min}. The parameter ψ depends on the catchments geography and is, therefore, unlikely to change during real-time flood forecasting.

The model parameters k_n and n_n refer to the Nash-cascade, which takes care of the timely-distribution of the surface runoff. The parameters k_n and n_n also depend on the catchments geography (i.e. the slopes, density of natural streams etc.) and are, therefore, also unlikely to change during real-time flood forecasting.

The model parameters alpha(1,i) refer to the ARIMA(1,1,0) model which tries to relate the base-flow at a certain point in time to observed (i.e. established) baseflows in the past. In reality the base-flow at a certain point in time is not only a function of base-flows observed in the past, but depends also on the intemediate rainfall. This is considered to be the main reason for the poor results of the ARIMA(1,1,0) model.

Taking the above into account it was decided to conduct the sensitivity analysis with respect to model parameters by varying the value for the minimum infiltration capacity (i.e. f_{min}) only. For the results of this sensitivity analysis, reference is made to section 10.2.

10.1.2 Variations in forecasted rainfall

Rainfall forecasts in Germany are made by the Deutscher Wetterdienst. In consultation with the client it was decided to analyse the sensitivity of the rainfall-runoff models for erroneous forecasted rainfall as follows:

- *$t \leq 24$ hours in advance:*
  Overestimation and underestimation of areal rainfall, respectively expressed as +20% and -20% of *off-line* (or LUA-NRW) areal rainfall.
- *$24 < t \leq 48$ hours in advance:*
  Overestimation and underestimation of areal rainfall, respectively expressed as +40% and -40% of *off-line* (or LUA-NRW) areal rainfall.
- *$48 < t \leq 60$ hours in advance:*
  Overestimation and underestimation of areal rainfall, respectively expressed as +60% and -60% of *off-line* (or LUA-NRW) rainfall.

With *off-line* (or LUA-NRW) areal rainfall is refered to as areal rainfall, which is determined using rainfall data collected by the Landesumweltamt Nordrhein-Westfalen. It is to be mentioned that *off-line* (or LUA-NRW) areal rainfall was also applied in calibrating and validating the rainfall runoff models. For the results of the sensitivity analysis regarding erroneous forecasted rainfall, reference is made to section 10.2.

10.1.3 Use of *off-line* or *on-line* areal rainfall data

In calibrating and validating the rainfall-runoff models, use was made of *off-line* (or LUA-NRW) areal rainfall. In Chapter 7 spatial relationships between *off-line* (or LUA-NRW) areal rainfall and point-rainfall, observed at KL-climatic stations operated by the Deutscher Wetterdienst (DWD), were established. Areal rainfall, computed using observed rainfall at DWD KL-climatic stations and the established spatial relationships is refered to as *on-line* (or DWD) areal rainfall.

By comparing discharges computed using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall, a two-fold assessment is achieved, viz:

1. To assess the applicability of *on-line* (or DWD) areal rainfall for forecasting the outflows of the rivers Sieg and Lippe into the river Rhine, and
2. To assess the sensitivity of computed discharges refering to possible errors in the timely-distribution of areal rainfall as well.

For the difference in results by using *off-line* (or LUA-NRW) areal rainfall or *on-line* (or DWD) areal rainfall, reference is made to section 10.3.

10.2 Sensitivity for the minimum infiltration capacity.

10.2.1 Sieg Level 1, Period no. 5 & Period no. 12.

In the calibration (using Period no. 5) of the Sieg Level 1 rainfall-runoff model a value for the minimum infiltration capacity (i.e. f_{min}) of 0.30 was established. In the sensitivity analysis for the minimum infiltration capacity (hereafter refered to as the f_{min} sensitivity analysis), values for f_{min} of 0.10, 0.20, 0.30, 0.40 and 0.50 were applied. The f_{min} sensitivity analysis for the Sieg Level 1 rainfall-runoff model using *off-line* (or LUA-NRW) areal rainfall for period no. 5 and period no. 12 are respectively depicted in Figs. 10.1a to 10.1b and Figs. 10.2a to 10.2b. In these figures distinctions between 24 hours (Figs. a.) and 48 hours (Figs. b.) in advance forecasted discharges at Menden are made. In Tables 10.1a to 10.1b and Tables 10.2a to 10.2b, the evaluation indicators discussed in subsection 8.2.4 as well as the values of the other model parameters are given.

From the above mentioned figures it can be seen that the computed discharges at Menden can vary significantly due to the application of different values for the model parameter f_{min}. For the range of applied f_{min} values (i.e. from 0.10 to 0.50) the magnitude of the peak discharges may vary about 20%, while the timing of the peak discharge might differ more than 12 hours with respect to observed discharges at Menden. Different values for the errors in the magnitude and time of peak discharges yield for the 24 hours and 48 hours in advance forecasted discharges.

It is to be mentioned that forecasted discharges at Menden sometimes even become negative (see Figs. 10.1b to 10.2b) for small f_{min} values. Due to the too-low value of f_{min}, the computed surface runoff near the peak-discharge become too large, resulting in a too-large peak-discharge and hence a negative discharges on the reclining tail of the hydrograph (see for instance Q_pred_t=48_fmin=0.1 in Fig. 10.1b). Before elaborating this phenomena in more detail, first the method in which the 48 hours in advance forecasted discharge is computed in FLORIJN is explained (see also section 8.1):

$$Q_{tot,for}(t+48) = Q_{b,for}(t+48) + Q_{d,for}(t+48) \tag{10.1}$$

where:

$$Q_{b,for}(t+48) = \{1 + alpha(1,8)\} * Q_{b,\text{determined}}(t) - alpha(1,8) * Q_{b,\text{determined}}(t-6) \quad (10.2)$$

$$Q_{b,\text{determined}}(t) = Q_{tot,obs}(t) - Q_{d,\text{determined}}(t) \quad (10.3)$$

in which:

alpha(1,8)	=	ARIMA coefficient for determining the base-flow at t=48 hours on basis of the base-flow at t=t and t=t-6 (Please note that the time-step is 6 hours)
$Q_{b,determined}(t)$	=	Determined base-flow at t=t, obtained by substracting the computed surface runoff at t=t [i.e. $Q_{d,determined}$ (t)] from the observed discharge at t=t [i.e. $Q_{tot,observed}$ (t)]
$Q_{b,for}(t+48)$	=	Base-flow forecasted 48 hours in advance
$Q_{d,determined}$ (t)	=	Surface runoff computed at t=t on basis of observed rainfall.
$Q_{d,for}(t+48)$	=	Surface runoff forecasted at t=t+48 on basis of forecasted rainfall.
$Q_{tot,obs}(t)$	=	Observed total discharge at t=t.
$Q_{tot,for}(t+48)$	=	Forecasted total discharge at t=t+48.

In case the surface runoff near the peak discharge [i.e. $Q_{d,determined}$ (t)] becomes larger than the observed total discharge [i.e. $Q_{tot,observed}$ (t)] due to a too-low f_{min} value, the determined base-flow [i.e. $Q_{b,determined}(t)$] become negative. From Eq. 10.2 it can be seen that the 48 hours in advance forecasted base-flow [i.e. $Q_{b,for}(t+48)$] will become negative as well. Since usually rainfall decreases on the reclining tail of the hydrograph, the 48 hours in advance forecasted surface runoff [i.e $Q_{d,for}$ (t+48)] will be neglectable. Hence the fact that the 48 hours in advance forecasted base-flows become negative will also result in the fact that the 48 hours in advance forecasted total discharge [i.e. $Q_{tot,for}(t+48)$] becomes negative (see Eq. 10.1). The fact that the 48 hours in advance forecasted base-flow becomes negative is due to the concept of base-flow modelling applied in FLORIJN rainfall-runoff model and is to be considered as ***physically impossible***.

Further on it is to be mentioned that applying a too-high f_{min} value, results in a relatively too-low surface runoff [i.e. $Q_{d,determined}$ (t)] and that hence the base-flow [i.e. $Q_{b,determined}(t)$] following from Eq. 10.3 becomes ***unrealistic high***, meaning that the magnitude of the increase in base-flow over a particular time-step is too-large considering the physical processes involved. It will be obvious that a relatively too-large determined base flow at t=t will result in two-large 48 hours in advance forecasted base-flow [i.e. $Q_{b,for}(t+48)$] as well, and hence in a too-large 48 hours in advance forecasted total discharge.

Concluding it can be stated that the computed discharges at Menden (inflow point in the river Rhine) are considerably sensitive to the actual f_{min} value applied in the computation. It is advised to check in real-time flood forecasting wether a ***physically-realistic*** value for f_{min}

is used by comparing the computed surface runoff's against observed discharges and assess wether the increase in base-flows remains realistic.

10.2.2 Lippe Level 1, Period no. 7 & Period no. 9

In the calibration (using Period no. 9) of the Lippe Level 1 rainfall-runoff model a value for the minimum infiltration capacity (i.e. f_{min}) of 0.20 was established. In the sensitivity analysis values for the minimum infiltration capacity (hereafter refered to as the f_{min} sensitivity analysis), values for f_{min} of 0.01, 0.10, 0.20, 0.30 and 0.40 were applied. The results of the f_{min} sensitivity analysis for the Lippe Level 1 rainfall-runoff model using the LUA-NRW areal rainfall data for period no. 7 and period no. 9 are respectively depicted in Figs. 10.3a to 10.3c and Figs. 10.4a to 10.4c. In these figures distinctions between 24 hours (Figs. a.), 48 hours (Figs. b.) and 60 hours (Figs. c) in advance forecasted discharges at Schermbeck are made. In Tables 10.3a to 10.3b and Tables 10.4a to 10.4b, the evaluation indicators discussed in subsection 8.2.4 as well as the values of the other model parameters are given.

From the above mentioned figures it can be seen that the computed discharges at Menden can vary significantly due to the application of different values for the model parameter f_{min}. For the range of applied f_{min} values (i.e. from 0.01 to 0.40) the magnitude of the peak discharges may vary about 25%, while the timing of the peak discharge might differ more than 18 hours with respect to observed discharges at Schermbeck. Different values for the errors in the magnitude and time of peak discharges yield for the 24 hours, 48 hours and 60 hours in advance forecasted discharges.

As discussed under subsection 10.2.1, too-low f_{min} values result in physically-impossible negative 48 hours in advance forecasted total discharges (see Q_ped_t=60_fmin=0.01 in Fig. 4.4c) and too-low f_{min} values result in too-large base-flows. Regarding the application of realistic f_{min} values during real-time flood forecasting yields the same advice as given in section 10.2.1.

10.3 Results of rainfall sensitivity analysis

For a description of the applied overestimation and underestimation of LUA-NRW areal rainfall in the rainfall sensitivity analysis, reference is made to subsection 10.1.2. The rainfall sensitivity analysis aims at establishing variations in computed discharges due to errors in forecasted rainfall. Therefore erroneous rainfall was used in the real-time forecasting phase, while the correct *off-line* (or LUA-NRW) areal rainfall data was used in the updating procedure of the rainfall runoff model. For more information on the applied updating procedure, reference is made to subsection 8.2.3.

10.3.1 Sieg Level 1, Period no. 5 & Period no. 12

In the rainfall sensitivity analysis for Sieg Level 1, Period no. 5, the same model parameters were used as established in the calibration of the Sieg Level 1 rainfall-runoff model. In the rainfall sensitivity analysis for Period no. 12, however, a different value for f_{min} was used, i.e. f_{min}=0.40 instead of f_{min}=0.30. A different value for f_{min} in the rainfall sensitivity analysis for Period no. 12 was used, because a value of f_{min}=0.40 provides a better match between observed and forecasted discharges (see Figs. 9.4 and 9.5).

The results of the rainfall sensitivity analysis for the Sieg Level 1 rainfall-runoff model for period no. 5 and period no. 12 are respectively depicted in Figs.10.5 and 10.6. In Tables 10.5 and 10.6, the evaluation indicators discussed in subsection 8.2.4 as well as the values of the other model parameters are given.

From the above mentioned figures it can be seen that the computed discharges at Menden can vary significantly due to the applied differences in forecasted rainfall. The magnitude of the peak discharges may vary about 50%, while the timing of the peak discharge might differ more than 6 hours with respect to observed discharges at Menden. Different values for the errors in the magnitude and time of peak discharges yield for the 24 hours and 48 hours in advance forecasted discharges.

10.3.2 Lippe Level 1, Period no. 7 & Period no. 9

In the rainfall sensitivity analysis for Lippe Level 1, Period no. 7 and Period no. 9, the same model parameters were used as established in the calibration of the Lippe Level 1 rainfall-runoff model. The results of the rainfall sensitivity analysis for the Lippe Level 1 rainfall-runoff model for period no. 7 and period no. 9 are respectively depicted in Figs. 10.7a to 10.7b and Figs. 10.8a to 10.8b. In Tables 10.7 and 10.8, the evaluation indicators discussed in subsection 8.2.4 as well as the values of the model parameters are given.

From the above mentioned figures it can be seen that the computed discharges at Schermbeck can vary significantly due to the applied differences in forecasted rainfall. The magnitude of the peak discharges may vary about 70%, while the timing of the peak discharge might differ more than 6 hours with respect to observed discharges at Schermbeck. Different values for the errors in the magnitude and time of peak discharges yield for the 24 hours, 48 hours, and 60 hours in advance forecasted discharges.

10.4 Differences in using *off-line* or *on-line* areal rainfall

10.4.1 Sieg Level 1, Period no. 5 & Period no. 12

The *off-line* (or LUA-NRW) and the *on-line* (or DWD) areal rainfall for the Sieg catchment for Period no. 5 and Period no. 12 are respectively depicted in Figs. 10.9 and 10.10. Visual inspection of these two figures leads to the conclusion that the relation between *off-line* (or LUA-NRW) areal rainfall data and *on-line* (or DWD) areal rainfall data is not that good. Correlation diagrams for Period no. 5 and Period no. 7 are shown in Fig. 10.11. The correlation coefficients for Period no. 5 and Period no. 12 respectively amount to 0.37 and 0.65 only. The relative difference (i.e. according to LUA-NRW data) between *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall for Period no. 5 and Period no. 12 respectively amount to 16.5% and 21.3%. It is to be mentioned that in making the correlation diagrams the constant rainfall (see Figs. 10.9 and 10.10) in the *on-line* (or DWD) areal rainfall were set equal to zero.

The *on-line* (or DWD) areal rainfall for the Sieg basin was computed using the rainfall data of the KL-climatic stations Bad-Marienberg and Koln-Wahn, respectively having a correlation coefficient with *off-line* (or LUA-NRW) areal rainfall of 0.84 and 0.74, which are considered to be moderate correlations coefficients only. It can be concluded that the spatial relationships established in Chater 7 do not result in a good estimate for the areal rainfall in the Sieg basin. It is anticipated that a more dense network of DWD rainfall stations might be required in order to estimate more accurately the areal rainfall in the Sieg basin. For details on the difference between LUA-NRW and DWD areal rainfall, reference is made to section 3.1.

The results of the comparison between using *off-line* (or LUA-NRW) areal rainfall data and *on-line* (or DWD) areal rainfall data applying the calibration values for the model parameters for Period no. 5 and Period no. 12 are respectively shown in Figs. 10.12 and 10.15. It is to be mentioned that for Period no. 12 a value of f_{min}=0.40 was used instead of the calibration value, since in the validation for Period no. 12 a better match between observed and computed discharges was obtained. In Tables 10.9 and 10.14, the evaluation indicators discussed in subsection 8.2.4 as well as the values of the model parameters are given. From Figs. 10.12 and 10.15 it might be observed that in general the match between using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall is not that good. The magnitude of the peak discharges may vary about 25% while the timing of the peak discharges might differ more than 36 hours with respect to observed discharges at Menden. Different values for the errors in the magnitude and time of peak discharges yield for the 24 hours and 48 hours in advance forecasted discharges. The fact that 48 hours in advance forecasted discharges become negative (see Q_pred_t=48_based on DWD rainfall&fmin=0.30 in Fig. 10.12) is due to the fact that the *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall are out of phase. Due to a relative too-large *on-line* (or DWD) areal rainfall on 10-02-1984, a too-large surface runoff is computed, resulting in a negative determined base-flow, which in return results in a negative 48 hours in advance forecasted base-flow on 12-02-1984 (see also subsection 10.2.1). Concluding it can be mentioned that the use of *on-line* (or DWD) areal rainfall does not provide that accurate estimates of the discharges at Menden. In addition it can be mentioned that the correct timing of the areal rainfall is of importance for the correct forecast of discharges at Menden as well.

It has been tied to obtain a better match between discharges computed at Menden using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall by adjusting the value for the model parameter f_{min} (i.e. minimum infiltration capacity). The results of these trials are for Period no. 5 and Period no. 12 are respectively shown in Figs. 10.13 to 10.14 and Figs. 10.16 to 10.17. In Tables 10.10 to 10.11 and 10.13 to 10.14 the evaluation indicators discussed in subsection 8.2.4 as well as the values of the model parameters are given. From the figures mentioned above it might be concluded that the match between using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall slightly improves for Period no. 5 (i.e. compare Figs. 10.12 to 10.14) in case f_{min}=0.5 is applied, while for Period no. 12 the best match is obtained for f_{min}=0.40 is applied. It is, however, to be mentioned that by manipulating with the value of model parameter f_{min} not all discrepancies between *on-line* (or DWD) areal rainfall and *off-line* (or LUA-NRW) areal rainfall can be compensated for.

10.4.2 Lippe Level I, Period no. 7 & Period no. 9

The *off-line* (or LUA-NRW) and *on-line* (or DWD) areal rainfall for the Lippe catchment for Period no. 7 and Period no. 19 are respectively depicted in Figs. 10.18 and 10.19. Visual inspection of these two figures leads to the conclusion that the relation between *off-line* (or LUA-NRW) areal rainfall data and *on-line* (or DWD) areal rainfall data is better than for the Sieg basin but still not that good. Correlation diagrams for Period no. 5 and Period no. 7 are shown in Fig. 10.20. The correlation coefficients for Period no. 7 and Period no. 9 respectively amount to 0.89 and 0.79. The relative difference (i.e. according to LUA-NRW data) between *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall for Period no. 7 and Period no. 9 respectively amounts to 41.0% and 27.4%. It is to be mentioned that in making the correlation diagrams the constant rainfall (see Figs. 10.18 and 10.19) in the *on-line* (or DWD) areal rainfall were set equal to zero.
The *on-line* (or DWD) areal rainfall for the Lippe basin was computed using the rainfall data of the KL-climatic stations Bad-Lippspringe, Bad-Sulzuflen, Bocholt, Dusseldorf, Essen, Guetersloh, Kahler-Asten and Munster, respectively having a correlation coefficient with LUA-NRW areal rainfall of 0.78, 0.75, 0.63, 0.71, 0.77, 0.84, 0.77 and 0.82. It can be concluded that the spatial relationships established in Chapter 7 result in a better estimate for the areal rainfall in the Lippe basin with respect to the timing of the rainfall than was the case for the Sieg basin. However, the volume of areal rainfall as compared to the *off-line* (or LUA-NRW) areal rainfall is systematically overestimated by the *on-line* (or DWD) areal rainfall. The reason for this are not clearly understood. For details on the difference between *off-line* (or LUA-NRW) and *on-line* (or DWD) areal rainfall, reference is made to section 3.1.

The results of the comparison between using *off-line* (or LUA-NRW) areal rainfall data and *on-line* (or DWD) areal rainfall data applying the calibration values for the model parameters for Period no. 7 and Period no. 9 are respectively shown in Figs. 10.21 and 10.24. In Tables 10.15 and 10.18, the evaluation indicators discussed in subsection 8.2.4 as well as the values of the model parameters are given. From Figs. 10.21 and 10.24 it might be observed that in general the match between using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall for the reproduction of the peak discharges is acceptable. The magnitude of the peak discharges vary about 26% while the timing of the peak discharges differs less than 9 hours with respect to observed discharges at Schermbeck. Different values for the errors in the magnitude and time of peak discharges yield for the 24 hours, 48 hours and 60 hours in advance forecasted discharges. Concluding it can be mentioned that the use of *on-line* (or DWD) areal rainfall provides a reasonable accurate estimates of the discharges at Schermbeck with respect to the reproduction of peak discharges.

It has been tied to obtain a better match between discharges computed at Schermbeck using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall by adjusting the value for the model parameter f_{min}. The results of these trials are for Period no. 7 and Period no. 9 are respectively shown in Figs. 10.22 to 10.23 and Figs. 10.25 to 10.26. In Tables 10.16 to 10.17 and 10.19 to 10.20 the evaluation indicators discussed in subsection 8.2.4 as well as the values of the model parameters are given. From the figures mentioned above it might be concluded that the match between using *off-line* (or LUA-NRW) areal rainfall and *on-line* (or DWD) areal rainfall for Period no. 7 does not improve by the use of different value for f_{min}, while the match for Period no. 9 by using a value of f_{min}=0.3 instead of 0.20 results in a considerable improve of the reproduction of the magnitude of the peak discharge while the accuracy of the timing of the peak discharge comes about 6 hours later. It is, however, to be mentioned that by manipulating with the value of model parameter f_{min} not all discrepancies for the lower peaks (period from 17-03-1987 to 31-03-1997, see Figs. 10.25) between *on-line* (or DWD) areal rainfall and *off-line* (or LUA-NRW) areal rainfall can be compensated for. These discrepancies are considered to refer to erroneous areal rainfall data

10.5 Summary of sensitivity results

The following can be concluded from the sensitivity analysis, viz:

1. *Variations in the model parameter f_{min}:*
   The applied variations in the model parameter f_{min} (i.e. minimum infiltration capacity) resulted in differences of upto 25% in the magnitude of computed peak discharges and difference in the timing of the peak-discharge of about 18 hours.
2. *Overestimation or underestimation of forecasted rainfall*
   The applied overestimation or underestimation of forecasted rainfall (i.e. upto +/- 60% for 48-60 hours in advance) resulted in differences of upto 70% in the magnitude of computed peak discharges. Since the timing of the rainfall was not altered, the difference in the timing of the peak-discharge remained limited to 6 hours only.
3. *Use of on-line areal rainfall instead of off-line areal rainfall:*
   a. Spatial relationships:
      The spational relationships between rainfall observed at DWD stations and areal rainfall established using rainfall observed at LUA-NRW stations for the Sieg catchment are of less quality than for the Lippe catchment. It is considered that this might be due to the fact that the density of DWD stations per square kilometer for the Lippe catchment is larger than for the Sieg catchment. In addition it is considered that the DWD stations available for the Sieg catchment might be less representative (orographic effects) for establishing areal rainfall than the available DWD stations for the Lippe catchment. It is to be mentioned that for both Period no. 7 and no. 9 the on-line (or DWD) areal rainfall is larger than the off-line (or LUA-NRW) areal rainfall.

   b. ***Comparison of discharges according to off-line and on-line areal rainfall:***
      The applied on-line (or LUA-NRW) and off-line (or DWD) areal rainfall data resulted in differences upto 25% in the order of magnitude of the computed peak discharge and difference in the timing of the peak-discharge of about 36 hours for the Sieg (i.e discharges at Menden). For the Lippe (i.e. discharges at Schermbeck) the differences in magnitude of the computed peak discharge was only 26%, while the difference in the timing of the peak-discharge remained within 9 hours only. In general it can be stated that the match for the Lippe was better than for the Sieg. It was tried to improve the results for the Sieg Level 1 rainfall runoff model by varying the model parameter f_{min}, however this did not turn out to be very fruitfull. For the Lippe a slight improvement for Period no. 9 was obtained by varying the value of f_{min}. It is to be mentioned that deviations to obvious erroneous rainfall data can not be corrected for by the parameter f_{min}, especially if it refers to an error in the timing of the areal rainfall.

Varying model parameters can result in negative forecasted total discharges or in unrealistic high increases in base-flow over a time-step. These phenomena's are related to the method used in FLORIJN rainfall-runoff model concept for forecasting the base-flows several hours in advance (see subsection 8.1.3). In order to avoid this it is advised to check the surface runoff against total observed discharges during real-time flood forecasting.

11 Aspects in real-time flood forecasting

In this Chapter following aspects of importance in flood forecasting are discussed:
- Weather forecasts by the Deutscher Wetterdienst (DWD),
- Updating the rainfall-runoff models, and
- Choice of precipitation data for making forecasts.

11.1 Weather forecasts by the DWD

In Germany weather forecasts are made by the Deutscher Wetterdienst (DWD) taking into account rainfall at the DWD synoptic/KL-climatic stations (see subsection 3.1.2) and the simulation results of physically-based meteorological models (Majewski, 1994). At present the DWD uses a global spectral model (GM) for large-scale forecasts, a regional model ("Europa-Model",EM) for synoptic and meso-α scale, and a high-resolution meso-β scale model ("Deutschland-Modell",DM) as the main short range weather forecasting tool for Germany. In Fig. 11.1 (i.e. Fig. 1b in Majewski) the extent and raster (or embedded grids) of both the Europa-Model and the Deutschland-Model are depicted. In Fig. 11.2 (DM raster) depicts in more detail the gridpoints of the Deutschland-Model covering the river Rhine basin.

Presently the DWD makes forecasts for 48 hours in advance at all gridpoints, which are shown in fig. 10.2. The forecasts are given as mm precipitation and % snow, i.e. 2.0 mm / 100 % means that there is expected snow with a water-equivalent of 2.0 mm. The Deutschland-Model is operational since about four years, which means that there are yet no long series for calibration and verification. At present areal forecasts for the Sieg and Lippe basin are available at the DWD as well.

Weather forecasts are made twice a day, i.e. at 00:00 hours (UTC) and 12:00 hours (UTC). In the (near) future, forecasts are anticipated to be made at 06:00 and 18:00 hours (UTC) as well. Hence in the (near) future forecasts will be made four times a day (i.e every 6 hours).

According to information from the DWD, four synoptic stations will not be part anymore of the forecasting network ('Messnetzkonzept 2000') in the near future, being: Gueterloh, Laarbruch, Bocholt and Bonn-Hardthohe. The omission of these four stations will have no implication for the areal distributed weather forecast, since the Deutschland-Model is based on a regular grid.

11.2 Updating the rainfall-runoff models

For updating the rainfall-runoff models the following discharge data (upto the point-in-time on which the next forecast will start) is required:
- *Sieg Level 1:*
  Observed discharges at the station Menden on river Sieg,

- *Sieg Level 2:*
  Observed discharges at station Menden on the river Sieg, station Lohmar on river Agger and station Siegburg on river Sieg,
- *Lippe Level 1:*
  Observed discharges at the station Schermbeck on river Lippe.
- *Lippe Level 3:*
  Observed discharges at station Schermbeck on river Lippe, station Haltern on river Lippe, station Leven on river Lippe and station Lippstadt2 on river Lippe.

The discharge data is to be collected from the concerning Staatliches Umweltamt (StUA).

Further on areal rainfall upto the point-in-time on which the next forecast will start (hereafter refered to as *antecedent areal rainfall*) is required for updating the rainfall-runoff models.

- *Sieg Level 1:*
  Antecedent areal rainfall for the entire Sieg basin,
- *Sieg Level 2:*
  Antecedent areal rainfall for the Lower Sieg basin, the Agger basin and the Middle/Upper Sieg basin.
- *Lippe Level 1:*
  Antecedent areal rainfall for the entire Lippe basin,
- *Lippe Level 3:*
  Antecedent areal rainfall for the Lower Lippe basin, the Stever basin, the Middle Lippe basin and the Upper Lippe basin.

For a delineation of the river basins and the subbasins mentioned above, reference is made to Chapter 5.

Two method for determining the required antecedent areal rainfall are discerned, viz:

- *Collect observed LUA-NRW rainfall:*
  Collect on a real-time basis rainfall observed at the LUA-NRW stations used in the determination of the areal rainfall in Chapter 6 and compute the antecedent areal rainfall for the concerning river basins and subbasins using the observed LUA-NRW rainfall.
- *Spatial relationships & rainfall observed at DWD KL-climatic stations:*
  Collect observed rainfall at the DWD KL-climatic stations, which were used in establishing spatial relationships with the LUA-NRW areal rainfall and determine the antecedent areal rainfall for the concerning river basins and subbasins using the spatial relationships established in Chapter 7 and the rainfall observed at the DWD KL-climatic stations.

Taking into account the quality of the established spatial relationships between point-measurements at DWD KL-climatic stations and LUA-NRW areal rainfall (see Chapter 7 and section 10.4), preference might be given to collecting LUA-NRW observed rainfall, i.e. rainfall measured at stations operated by the Landesumweltamt Nordrhein-Westfalen.

In updating the rainfall-runoff models precipitation is to be divided into rainfall and snowfall. Since the influence of snow-melt on flood generation is considered to be neglectable, it was decided not to include a snow-melt module in the FLORIJN rainfall-runoff model (see section 9.7). Hence in updating only rainfall is to be entered in the rainfall-runoff model, while snowfall is to be considered as a loss of precipitation.

11.3 Choice of precipitation data for making forecasts

For making forecasts with the rainfall-runoff models only areal precipitation forecasts for the river basins and subbasins, which are already described in section 11.2, are required. These areal precipitation forecasts for a particular river basin or subbasin can be obtained from the precipitation forecasts of the gridpoints of the Deutschland-Model, which are located within the concerning basin or subbasin. The areal precipitation rainfall can be based on a simple (weighted) average of the gridpoints as the Deutschland-Model already takes into account the local conditions in the basins, such as topography.

As explained in section 11.2 also in forecasting a distinction is to be made between rainfall and snowfall. Only rainfall is to be entered in the rainfall-runoff models for making forecasts, while snowfall is to be considered as a loss of precipitation.

12 Concluding remarks & recommendations

Rainfall-runoff models were developed for the rivers Sieg and Lippe in Germany. From the validation and calibration results (see Chapter 9) it can be concluded that adequate forecasts of the discharges flowing into the river Rhine at Menden (Sieg) and at Schermbeck (Lippe) can be made using these models. Forecasts at Menden and Schermbeck respectively refer to 48 hours and 60 hours in advance. The areal rainfall used in calibrating and validating the models was based on rainfall data, observed by the Landesumweltamt Nordrhein-Westfalen (LUA-NRW). In this report the LUA-NRW areal rainfall is also refered to as *off-line* areal rainfall.

Interpretation of the modelling results lead to the conclusion that in the considered time periods, snow does not play an important role in flood generation (see section 9.7). Accordingly it was decided not to include a snow-melt module in the FLORIJN rainfall-runoff model. In real-time flood forecasting it is, however, important to make a distinction between forecasted rainfall and forecasted snowfall, this yields for both the updating and the forecasting phase (see sections 11.2 and 11.3).

For the Sieg and Lippe rainfall-runoff models were developed for the entire basin and for a division into subbasins, having a maximum area of 1,500-2,000 km^2. The division into subbasins did not result in a major improvement of the modelling results (see section 9.8). Sensitivity analysis were carried out with the rainfall-runoff models in which the entire basin is lumped. From these sensitivity analysis it was concluded that the rainfall-runoff models are sensitive to the value of the model parameter f_{min} (i.e. minimum infiltration capacity of the soil) and the correct timing of the areal rainfall. An overestimation or underestimation directly results in a porportional overestimation or underestimation of forecasted discharges at Menden or Schermbeck (see Chapter 10).

Spatial relationships between point-rainfall at KL-climatic stations, operated by the Deutscher Wetterdienst (DWD), and LUA-NRW areal rainfall were established. Although the results for the Lippe basin are slightly better than for the Sieg basin, it was concluded (see Chapter 7 and section 10.4) that these spatial relationships can provide moderate estimates for the areal rainfall in the Sieg and Lippe basins only. In real-time flood forecasting it is, therefore, advised to use in the updating phase of the rainfall-runoff models observed areal rainfall and to use in the forecasting phase the areal rainfall forecasted by the Deutschland Model (see Chapter 11). The quality of observed areal rainfall will depend on the number and spatial distribution of on-line available point-rainfall observations.

In FLORIJN base-flows are computed using an ARIMA(1,1,0) model, which considers base-flows to be a function of antecedent base-flows only. A physical-based ground-water model, relating non-effective rainfall to the recharge of the ground-water reservoir and hence to an increase of the base-flow, is not incorporated in FLORIJN. This omission imposes its limitations (see section 8.1.3). In real-time flood forecasting negative discharges might be forecasted as a result of this omission (see section 10.2). Taking the above into account it is advised to check in real-time flood forecasting wether the computed surface runoffs and computed increases in base-flows remain within physically realistic limits.

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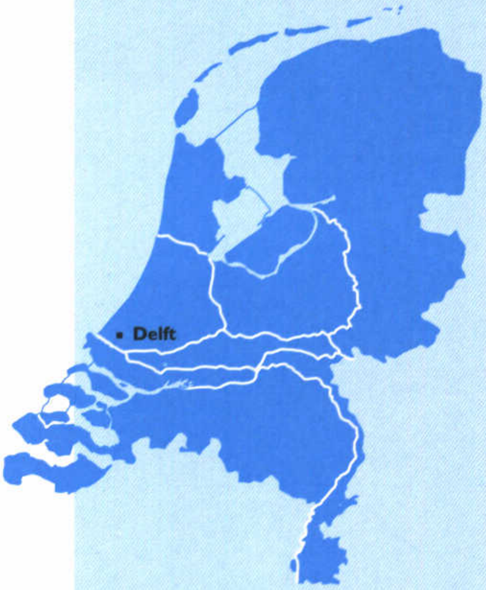

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