EFFECTS OF GRID RESOLUTION AND PRECIPITATION INTERPOLATION ON A MESOSCALE FLOOD FORECAST MODEL[1]

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SUMMARY

Due to frequent flooding within the watershed of the Moselle River (A ≈ 28,000 km²), the extension of flood forecast lead times to up to 48 hours represents one key measure of improved flood management. In order to reach this goal, a grid-based flood forecast model for the Moselle River was developed and refined by applying the program system LARSIM.

The first Moselle River model consists of 154 cells with an area of 14 km by 14 km for each cell. It is currently used as a real-time flood forecasting system for the German part of the Moselle River. Input data include hourly values of measured discharge (at 20 gauges), measured precipitation (at 50 rain gauges) and the 48-hour precipitation forecasts of the German Weather Service. In the event of a flood, measured data are automatically transmitted from France, Luxembourg, and Germany to the flood forecast center in Trier, Germany.

The second Moselle River model has a higher resolution with a grid cell size of only one square kilometer, resulting in about 28,000 grid cells. Additionally, the interpolation of precipitation has been improved by integrating information from historical precipitation events using geostatistical methods. Calculating 12-hour forecasts, the reliability of the new 1 km² grid model could be demonstrated.

A comparison of simulation results of the two models shows that the geostatistical interpolation procedure for measured precipitation does not improve results derived from the inverse-distance-method. Slightly improved results are obtained for the model with the denser grid, especially for smaller catchments and for the upstream regions. Furthermore, the model with the denser grid provides a vastly more flexible tool for flood management: it is capable of including spatial data with higher resolution (e.g., weather forecasts, radar) and has the potential for future flood warning for local flood events.

Keywords: flood forecasting model, geostatistical interpolation, grid size, LARSIM, Moselle

1. INTRODUCTION

The floods of 1993 and 1995 along the Rhine and the Maas rivers inundated entire cities and villages in France, Belgium, and Germany and led to the evacuation of several 100,000 people in the Netherlands. Due to the enormous damage, the secretaries of the environment of the respective countries signed a resolution with which the watershed commissions along the Rhine, the Moselle, the Saar, and the Maas River were assigned to plan integrated and internationally coordinated flood prevention measures.

In the watersheds of the Moselle and the Saar rivers, which cover parts of the countries France, Luxembourg and Germany (Figure 2-1(1)), transboundary co-operation started early, when the first international workgroup for flood prevention was founded in 1985. Two years later, an agreement was signed coordinating the information flow process during floods with the goal of installing a real-time transmission water level information system. In 1998, the International Commission for the Protection of the Moselle and Saar Rivers (IKSMS) set up the "Aktionsplan Hochwasser" (“Action Plan Floods”) (IKSMS, 1999) with the following objectives:

- Short-term optimization of monitoring systems and measuring devices.
- Improvement of disaster prevention plans.
- Extension of the forecast times for the Lower Moselle River to up to 12 hours until the year 2000 and of up to 24 hours until the year 2005.

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2. THE LARSIM MODEL

2.1 Overview

To extend forecast times up to 48 hours, a flood forecast model based on the program system LARSIM was established for the Moselle river basin (approx. 28,000 km²) on behalf of the Rhineland-Palatinate (a federal state of Germany) water authorities.
LARSIM (Large Area Runoff Simulation Model) is based on the river basin model FGMOD (Ludwig, 1982), which was developed for the systematic modelling of runoff generation and flood-routing. LARSIM can be applied both as a water balance model for continuous simulation and as an event-based flood forecast model. It is successfully used for operational flood forecasts in several German flood forecast centers.
If LARSIM is applied as a water balance model, the processes of interception, evapotranspiration and water storage in soils and aquifers are included besides runoff generation in the area and translation and retention in river channels (Bremicker, 2000). It is currently tested for the operational use in such a mode for the low and mean flow forecast for the Neckar River (Bremicker, Gerlinger, 2000).
Snow accumulation and snow melt can be considered in both model versions as well as artificial influences (e.g. storage basins, diversions or water transfer between different basins).

2.2 Model components

The program system LARSIM offers alternative subroutines for most stages of the rainfall-runoff process. Due to data limitation, the number of free model parameters required for the Moselle flood forecast model had to be kept to a minimum. As an operational flood forecast model, it only uses comparatively simple model components which are satisfying for practical purposes and for individual flood periods due to the possibility of on-line parameter adaptation:

- Calculation of areal rainfall similar to the gridpoint-procedure of the NWSRFS model, an inverse-distance method (U.S. Department of Commerce, 1972).
- Parallel storage models for subareas consisting of two linear storages (a fast and a slower storage) and a distribution of effective runoff to these storages by a threshold value (interflow index rate).
- Transformation of runoff in the interflow zone is simulated by a single linear storage. For direct runoff, a modified Clark model (Clark, 1945) is used where the shape of the subarea is approximated by a rectangle. The result is a triangle or a trapezoidal shape of the time-area-diagram. Retention constants for interflow and direct runoff are assumed proportional to the lag-times in subareas.
- Runoff coefficient function: runoff-dependent description of runoff coefficients (Ludwig, 1988). Runoff of the slower storage in the parallel storage model for the runoff is used as a soil moisture index. Variable runoff coefficients are derived from this index using a parabolic function, which is limited on both ends (minimal and maximal runoff coefficient).
- Flood routing procedure which accounts for nonlinear storage processes, especially for differences in runoff character between runoff in the main bed and the floodplain. Retention in channel subreaches is described by storage components, whose constants depend on inflow and outflow (Williams, 1969).

The modules for runoff predictions using the precipitation forecasts include:

- Warning model: before the beginning of the flood, when the discharge has not increased yet, fixed parameter values of the runoff coefficient function are used. These parameter values are determined for each gauge separately by analyzing historic flood events.
- Forecasting model: If the measured discharge shows a significant increase, the parameter values of the runoff coefficient function are determined from the current rainfall and runoff data. Differences between calculated and measured runoff are minimized using an adaptive optimization of the parameters of the runoff coefficient function by the Gauss-Marquardt procedure (Marquardt, 1963).
- Discrepancies between calculated and measured hydrographs are determined and calculation results for subsequent forecasts are corrected according to the analyzed error distribution by autoregressive models (ARIMA-correction) (Box, Jenkins, 1970).

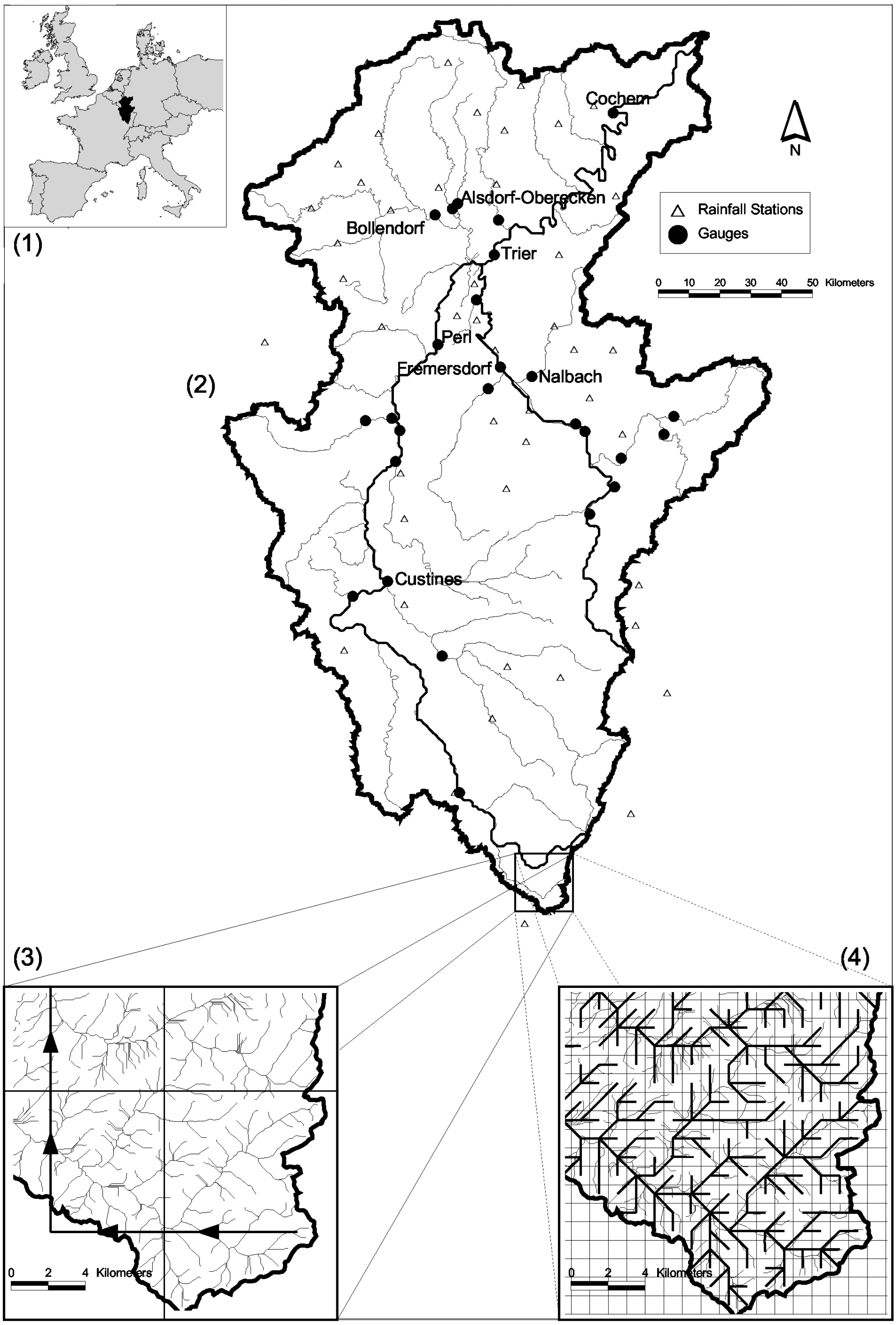

Figure 2-1: (1) Location of the Moselle basin in Europe
(2) Moselle basin and location of operationally used rainfall stations and water level gauges
(3) Example of 14 km by 14 km model grid and river network
(4) Example of the improved 1 km by 1 km model grid and river network

3. THE MOSELLE MODEL

3.1 The 14 km grid model of the Moselle river basin

In a first step, an event-based flood forecasting model with a coarse grid size of approximately 14 km by 14 km was established for the Moselle river basin (Figure 2-1(2)) (Gerlinger, Demuth, 2000). Input data for the runoff forecasts are the 48-hour precipitation forecasts which are computed by the German Weather Service (DWD) numerical weather prediction model (NWP) system for the whole Moselle basin.

The grid structure of this model was designed according to the horizontal resolution of the NWP-“Deutschland Modell” (“Germany model” of the DWD) to use a direct reference of precipitation forecast results on NWP nodepoints and model subarea grid cells. 154 grid-based subareas are used. Figure 2-1(3) shows a section of the 14 km by 14 km grid structure with the schematic graph of the subarea sequence according to the existing river network.

As input data for channel reaches information on their width and depth is needed for calculating the flood propagation in the river channel network. Since these data are not available for large parts of the river basin, they were estimated using a "hydraulic-geometry" assumption based on a statistical discharge index (Allen et al., 1994). Lengths and gradients of the river subreaches for the Moselle catchment were determined from topographical maps. From an existing flood routing model, more detailed system data was available for some channel reaches (Moselle downstream gauge Custines and Saar rivers) which was integrated in the model to substitute the approximate river geometry values.

At time, the model is operationally used in a test mode as a real-time flood forecasting system at the flood forecast center in Trier (Germany). First applications of the LARSIM model in the Moselle river basin for 24 hours flood forecasts have been successful. The predicted and measured discharges correspond quite well for the Lower Moselle River downstreams Perl. Input data for the continuous adjustment of the model are hourly values of water levels of 20 gauges and the precipitation measurements of 50 rain gauges transmitted automatically from France, Germany and Luxembourg to Trier (Figure 2-1(2)).

3.2 The 1 km grid model of the Moselle river basin

Improvements in the model performance were expected from a more detailed 1 km by 1 km grid. The grid size was chosen to improve the forecasts especially for small basin parts and the Upper Moselle River.

A completely new model structure has been designed (Figure 2-1(4)) based on an analysis of a Digital Elevation Model (50 m grid). Length and gradients of the rivers were determined with the help of GIS tools. A recalibration of the model was done using six historical flood events. For the forecast of precipitation, a higher resolution grid is now used (“Lokal-Modell” of the German Weather Service, at time a 7.5 km by 7.5 km grid).

3.3 Forecast results

To show the quality of flood forecasts with the high resolution model, the runoff values for 12 hours forecasts are compared with the measured values on the example of historic flood events. To simulate the real-time forecast procedure, a time interval of 8 hours between forecast timepoints has been used. In this test, information on measured precipitation has been used for the forecasts to check the possible model performance without additional errors introduced through precipitation forecasts. For precipitation interpolation the geostatistical procedure was applied.

Figure 3-1 shows the 12-hour runoff forecast values in relation to the measured runoff values for the three largest historic flood events of this test. The upper diagram in Figure 3-1 displays results for a gauge with a small catchment and the lower diagram those for a gauge with a large catchment.

The quality of the forecasts for the large catchment is very high. Forecasts for the smaller catchment show greater differences between forecasted and measured runoff values. Nevertheless, the results for the smaller catchments represent a decisive improvement, mainly because simulations for catchments of this size could not be carried out with the 14 km by 14 km grid model.

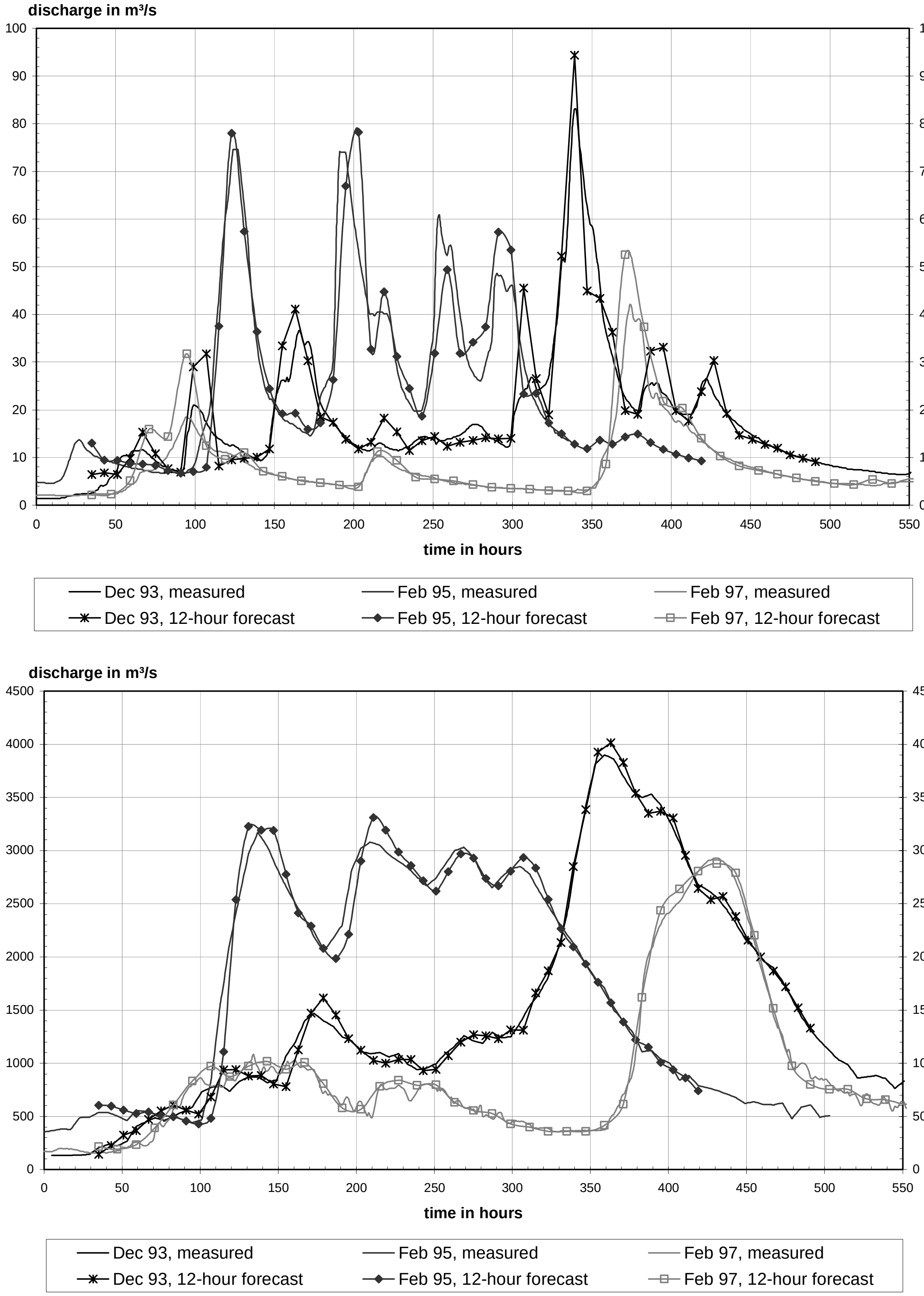

Figure 3-1: 12-hour forecast results for gauge Alsdorf/Nims (above; A = 264 km²) and for gauge Trier/Moselle (below; A = 23.857 km²)

4. INFLUENCE OF PRECIPITATION INTERPOLATION AND GRID SIZE

4.1 Criteria for the comparison

To compare the model performance, measured and calculated discharges for the gauges are compared by statistical measures (i.e., goodness-of-fit test) and additionally by visual comparison. A meaningful combination of several techniques should be employed for the model validation as well as for a thorough model assessment (Janssen, Heuberger, 1995).

Also, one should be aware of the fact that the various statistical measures for deviation typically highlight specific features of the flood hydrographs and therefore are no objective stand-alone values. The coefficient of determination, for instance, evaluates the degree of coincidence between the forms of hydrographs and can reach the maximal value of 1.0. It also equals 1.0 if measured and simulated hydrograph have the exact same form but differ by a constant value.

A more informative measure for the simulation quality is the "model efficiency" (Table 4-1) (Nash, Sutcliffe, 1970). The model efficiency measure reaches a value of 1.0 if measured and simulated valued are identical. However, it is important to notice that large single-peaked deviations from the mean of runoff values tend to increase model efficiency values thereby biasing the result.

Another reasonable statistical measure for flood simulation is the "hydrologic deviation" (Table 4-1) (Schultz, 1967). Values of the hydrologic deviation range from 0 % - 5 % ("good" results) to more than 15 % (not usable), with 10 % representing usable results (Schultz, 1967). This parameter is influenced by the hydrograph's peak value.

None of the statistical measures can claim to be the absolute truth while judging the quality of a model. Modeling characteristics like the data density and distribution or the modeling period etc. all affect the statistical output. Nevertheless, the various statistical measures allow relative comparisons between results of different simulation models or model runs, making them a valuable asset in model judgement.

Table 4-1: Model simulation measures "model efficiency" and "hydrologic deviation"

Model efficiency	Hydrologic deviation
$\frac{\left[\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2 - \sum_{i=1}^{N}\left(P_i - O_i\right)^2\right]}{\left[\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2\right]}$	$\frac{100}{{Q_{max}}^2 \cdot N}\sum_{i=1}^{N} 2 \cdot O_i \left\|O_i - P_i\right\|$
P_i and O_i denote the predicted value and observed value i; $\overline{O}$ the mean	

4.2 Influence of precipitation interpolation method on simulation results

Since the quality of flood forecasting models depends on the quality of their input parameters, the improvement of the interpolation of point measurements of precipitation (areal rainfall calculation) could lead to better simulation results, particularly as long as no radar data is available.

Due to the high variability of precipitation in space and time, modeling and interpolation of short-term precipitation is problematic and likely to be one of the largest sources for simulation errors. Essentially, the joint influence of atmospherical and orographical factors should be considered to estimate time-space distribution of precipitation adequately. Simple interpolation procedures as the Thiessen polygon or the inverse-distance method can produce errors (Goovaerts, 2000), which depend on the degree of precipitation heterogeneity during the actual flood.

Therefore an interpolation procedure for the hourly measured precipitation data was tested, which accounted for information from historical precipitation data and the relevant precipitation patterns (Hinterding, 2001).

In this interpolation procedure, a five-step procedure is performed to identify the typical precipitation patterns, yielding the so-called "background fields" necessary for the interpolation (Figure 4-1). A fuzzy set-type procedure based on a combination of geostatistical models has been chosen as mathematical basis for the interpolation.

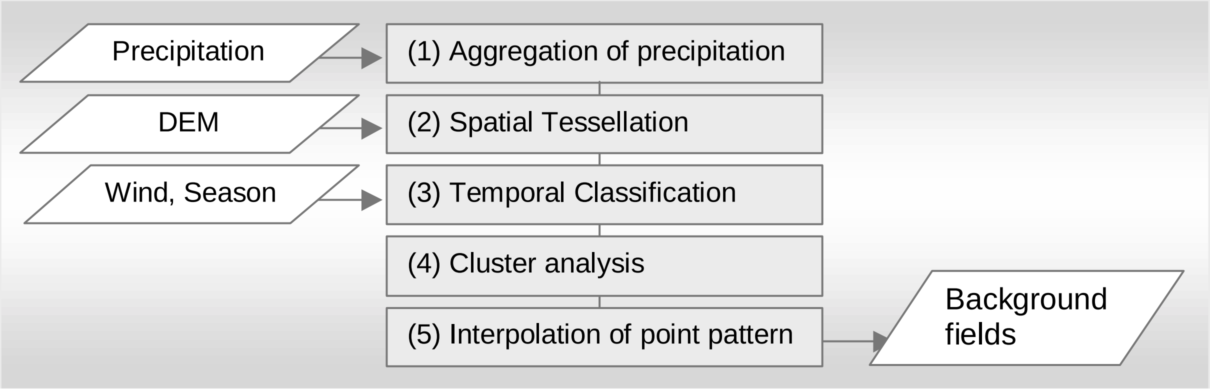

Figure 4-1: Identification of typical precipitation patterns (Hinterding, 2001)

For operational use, this interpolation procedure allows the estimation of the spatial distributions of precipitation with regard to the actual weather situation. It is installed at the flood forecast center in Trier for interpolating the measured and the predicted precipitation. It had also been applied to the catchment of the Nahe River and to the area of Rhineland-Palatinate.

To test the differences in runoff simulation quality, the geostatistical precipitation interpolation method and the inverse-distance-method were employed. The identical input data sets stemmed from six historical flood events. Simultaneously, the influences of different grid dimensions were examined (chapter 4.3). With regard to the interpolation of the precipitation data set for the higher resolution model, the remark should be made that the data was thinned by a factor of four (from ~ 28,000 data points to ~ 7000 data points) in order to save computing time.

To overlook the modeling results, Table 4-2 contains all values of the model efficiency parameter. Table 4-3 originates from a table similar to Table 4-2 but only summarizes the mean values of the hydrologic deviation parameter. For both tables, seven gauges with different orders of catchment size from different parts of the Moselle basin were selected (positions of the gauges see Figure 2-1(2)).

Runoff values for the gauge Alsdorf with the smallest catchment area cannot be simulated with the 14 km x 14 km model grid resolution. Model efficiency values and hydrologic deviation values for this gauge were consequently not incorporated for calculation of the mean values. This gauge was however used in Table 4-2 to demonstrate the possible high simulation quality with the 1 km x 1 km model.

Table 4-2 shows that the new interpolation method produces no improvements compared with the formerly used simpler method. In most cases, model efficiencies are approximately equal, in some cases even better with the simpler method. This tendency is independent of the chosen grid size dimension, but more marked in the simulation results of the model run with the coarser grid. The mean values of the hydrologic deviations (Table 4-3) display the same tendencies as the model efficiency values.

4.3 Influence of grid size on simulation results

The comparison of model simulation quality for the model runs with different grid sizes (Table 4-2) depicts that for gauges with small or intermediate catchment size (e.g., Nalbach, Bollendorf) and for gauges in the upper part of the Moselle River basin (e.g., Custines) the simulation quality increases when the high-resolution grid is used.

For gauges with intermediate and large catchment sizes in the lower parts of the Moselle River, only very small improvements result from the usage of the high-resolution model. This is not surprising since in these cases the low-resolution model already yielded very high model efficiency values.

The mean values for the hydrologic deviation parameter show the same tendency (Table 4-3). Especially for gauges with small to intermediate catchment size, lower values of the hydrologic deviation are reached. The mean values of the hydrologic deviation for results of the high-resolution model of about 7 % or less indicate “good” simulation results (Schultz 1967). The coarser model leads to simulation results for these gauges with mean values of up to 10 %.

Table 4-2: Model efficiencies of the Moselle model with different grid resolutions and interpolation procedures for 7 gauges

Grid resolution		1 km by 1 km grid							14 km by 14 km grid							Results comparison grid resolution ↓	
Interpolation procedure		Geostatistical interpolation															
Gauge	Area [km²]	Dec 93	Feb 95	Nov 96	Feb 97	Oct 98	Dec 99	Mean M1	Dec 93	Feb 95	Nov 96	Feb 97	Oct 98	Dec 99	Mean M2	M1-M2	(M1-M2)/M1 [%]
Alsdorf /Nims	264	0,94	0,94	0,68	0,94	-	0,60	0,82	-	-	-	-	-	-	-	-	-
Nalbach/Prims	712	0,95	0,92	0,77	0,88	0,79	0,83	0,86	0,88	0,83	0,71	0,72	0,78	0,79	0,79	0,07	8,4
Bollendorf/Sauer	3226	0,97	0,99	0,39	0,85	0,19	0,72	0,69	0,60	0,77	0,45	0,77	0,24	0,71	0,59	0,10	13,9
Custines/Mosel	6829	0,99	0,98	0,97	0,98	0,95	0,58	0,91	0,97	0,96	0,97	0,96	0,92	0,31	0,85	0,06	6,6
Fremersdorf/Saar	6983	0,98	0,98	0,97	0,98	0,96	0,97	0,97	0,97	0,98	0,96	0,98	0,94	0,96	0,97	0,01	0,9
Perl/Mosel	11522	0,99	0,99	0,84	0,98	0,94	0,97	0,95	0,98	0,98	0,87	0,97	0,90	0,97	0,95	0,01	0,7
Cochem/Mosel	27088	0,99	0,99	0,98	0,99	0,98	0,99	0,99	0,99	0,99	0,98	0,99	0,98	0,99	0,99	0,00	0,0
	Mean M3	0,98	0,98	0,82	0,94	0,80	0,84	0,89	0,90	0,92	0,82	0,90	0,79	0,79	0,85	0,04	4,5
Interpolation procedure		Inverse-Distance-Interpolation															
Gauge	Area [km²]	Dec 93	Feb 95	Nov 96	Feb 97	Oct 98	Dec 99	Mean M1	Dec 93	Feb 95	Nov 96	Feb 97	Oct 98	Dec 99	Mean M2	M1-M2	(M1-M2)/M1 [%]
Alsdorf /Nims	264	0,94	0,94	0,70	0,92	-	0,86	0,87	-	-	-	-	-	-	-	-	-
Nalbach/Prims	712	0,94	0,91	0,81	0,89	0,78	0,84	0,86	0,87	0,76	0,75	0,71	0,82	0,71	0,77	0,09	10,6
Bollendorf/Sauer	3226	0,98	0,98	0,58	0,91	0,36	0,77	0,76	0,75	0,90	0,66	0,94	0,41	0,72	0,73	0,03	4,4
Custines/Mosel	6829	0,99	0,98	0,97	0,98	0,96	0,76	0,94	0,97	0,96	0,96	0,96	0,94	0,53	0,89	0,05	5,7
Fremersdorf/Saar	6983	0,98	0,98	0,97	0,98	0,96	0,96	0,97	0,98	0,98	0,96	0,98	0,94	0,95	0,97	0,01	0,7
Perl/Mosel	11522	0,99	0,99	0,83	0,98	0,94	0,97	0,95	0,98	0,98	0,86	0,97	0,90	0,97	0,94	0,01	0,7
Cochem/Mosel	27088	0,99	0,99	0,98	0,99	0,98	0,98	0,99	0,99	0,99	0,98	0,99	0,98	0,98	0,99	0,00	0,0
	Mean M4	0,98	0,97	0,86	0,96	0,83	0,88	0,91	0,92	0,93	0,86	0,93	0,83	0,81	0,88	0,03	3,5
	M3-M4	0,00	0,00	-0,04	-0,01	-0,03	-0,04	-0,02	-0,02	-0,01	-0,04	-0,03	-0,04	-0,02	-0,03	← Results comparison inter-polation procedure	
	(M3-M4)/M3 [%]	0,0	0,3	-4,5	-1,2	-3,5	-4,3	-2,1	-2,8	-1,1	-4,7	-3,0	-4,8	-2,7	-3,1		

Table 4-3: Hydrologic deviation [%] of the Moselle model with different grid resolutions and interpolation procedures (means of 6 gauges according to Table 4-2)

	1 km by 1 km grid							14 km by 14 km grid							M1-M2	(M1-M2)/M1 [%]	Comparison model grid ↑
	Dec 93	Feb 95	Nov 96	Feb 97	Oct 98	Dec 99	M1	Dec 93	Feb 95	Nov 96	Feb 97	Oct 98	Dec 99	M2			
	Geostatistical interpolation																
M3	1,7	2,9	4,1	1,8	7,3	5,6	3,9	4,2	5,3	7,4	2,3	8,7	9,7	6,3	-2,3	-59,7	
	Inverse-Distance-Interpolation																
M4	1,6	3,1	3,9	1,6	6,8	5,3	3,7	3,7	4,4	7,7	1,9	7,7	9,0	5,6	-1,9	-50,5	
	0,1	-0,2	0,3	0,2	0,5	0,3	0,2	0,5	0,9	-0,3	0,4	0,1	0,7	0,7	M3-M4		
	5,1	-6,5	6,0	11,6	7,0	4,9	4,9	12,7	16,5	-3,7	17,0	11,5	6,7	10,4	(M3-M4)/M3 [%]		
	Comparison interpolation procedure ↑																
M (M1, M2, M3, M4): Means																	

5. CONCLUSION

The investigation shows that grid-type flood forecast models based on the program system LARSIM lead to valuable simulation and forecast results for gauges in the Moselle basin. Independent of the used precipitation interpolation method or the grid dimension, high values of model efficiency were obtained. Only a few simulations resulted in model efficiency values below 0.7. Analogously, values of hydrologic deviation are in most cases below 10 %. It is likely that data insufficiencies of measurements at the level gauges caused a major part of the few weak simulation results. The model simulations perform the best for gauges with large catchments. But also for relatively small catchments, reliable simulations and forecasts could be modeled using the high-resolution model.

On top of the improved simulation quality, the high-resolution model provides further advantages:

- Simulations for small catchments are possible as for instance at the gauge Nalbach/Prims, which could not be modeled using the coarser grid model structure.
- Additional points in the river network (gauges, catchments, or new forecast points) can now be incorporated easily and with great accuracy.
- Improvements through the use of the high-resolution model can further be expected by higher spatial resolution of precipitation measurements and next-generation precipitation forecast models.
- Perspectively, even short-term warnings with respect to local flood events as a consequence of convective storms seem possible.
- The 1 km x 1 km grid structure allows an adaptation of the model to a continuous water balance model which can be a realistic base for assessment of land use and/or climate changes as well as for large-scale high-resolution water quality modeling.

The geostatistical precipitation interpolation method did not result in a decisive improvement of simulation quality compared with the simpler inverse-distance-interpolation. However, more rainfall stations were available for the simulations compared to the operational use. And additionally, the loss of single stations in operational use has to be taken into consideration. Keeping this in mind, the geostatistical precipitation interpolation method might still be capable of outperforming the inverse-distance-interpolation and thereby increase the simulation quality in the operational use. Therefore, LARSIM is applied using the geostatistical interpolation method at the flood forecast center in Trier.

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