Pergamon

Phys. Chem. Earth (B), Vol. 26, No. 7-8, pp. 509–515, 2001

1464-1909/01/$ - see front matter

PII: S1464-1909(01)00042-9

Multi-Scenario Flood Modeling in a Mountain Watershed Using Data from a NWP Model, Rain Radar and Rain Gauges

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Received 15 May 2000; accepted 21 September 2000

Abstract The temporal and spatial distribution of precipitation is the key parameter for flood modelling. The study presents an evaluation of different meteorological data sources to assess their applicability and reliability for flood modeling. Apart from conventional rain gauge data, the information of the Numerical Weather Prediction Model SWISS MODEL (SM) and radar interpreted precipitation taken from the rain radar Fuerholzen, operated by the German Weather Service, has been available. They are used within the framework of an extended and GIS-structured TOPMODEL (Beven and Kirkby, 1979; Beven et al., 1994; Ludwig and Mauser, 2000), to perform model simulations and forecasts in the Ammer catchment for a hazardous flood event in 1999. The disaggregation and scaling of precipitation data, to meet the requirements of the hydrological model, is of specific interest. A variety of procedures to disaggregate NWP information for a hydrological application is presented, emphasizing the influence of the selected algorithm on the model result. Applying the SM and the rain radar data set, the calculated flood volume is overestimated within a range of 15 to 36%, while the rain gauge data set leads to an underestimated runoff volume of 13%. A sensitivity analysis shows a high variability in the spatial and temporal distribution of predicted and recorded precipitation and its consequent effect on the performance of the hydrological model. However, positive conclusions for future applications of a meteorological and hydrological model synergy can be drawn from the outcome of this study.

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1 Introduction

One of the major tasks in hydrology is to link recent progress in atmospherical and hydrological sciences to improve flood forecasting and control. The main objective of the EU-funded project RAPHAEL (Runoff and Atmospheric Processes for flood HAzard forEcasting and control) is to investigate the synergy of meteorological and hydrological models to address this issue in selected alpine testsites and testcases.

The presented study focuses on the 1999 „Whitsun flood" in the southern Bavarian Ammer catchment. The following key questions shall be addressed:

- What meteorological data sources are available for flood modeling and forecasting ?
- How can the data be processed and interpreted to meet the requirements for flood modeling on the catchment scale?
- What future perspectives can be derived from the study results ?

2 The Testcase

The study is performed in the Ammer watershed (709 km²). It is located in the Bavarian alpine forelands, characterized by physiogeographic heterogeneity in terms of topography (500 – 2200 m asl), landuse (50 % forested, 50 % agricultural use), soils (dominated by sandy loam and loam) and climate (1100 – 2000 mm of mean annual precipitation).

The "Whitsun flood" occurred during May 20th to May 23rd 1999 in Southern Germany. On account of preceding rainfall and snowmelt, the soils in the Ammer watershed were mostly saturated. A steady advective rainband caused a 48h period of excessive rainfall, delivering the highest intensities ever recorded in the area (138.7 mm on May 21st at gauge Hohenpeissenberg). The meteorological conditions enforced additional snowmelt up to regions of higher altitude. The combination of these effects resulted in a hazardous flood event, with the recorded stages along the Ammer corresponding to a bicentennial flood.

3 The enhanced TOPMODEL

Runoff and stream discharge is modeled with an enhanced GIS-structured version of the conceptual TOPMODEL approach (Beven and Kirkby, 1979). Numerous applications and model developments have emerged from the TOPMODEL (Beven, 1997), investigating and emphasizing on very different aspects, such as sensitivity analysis (Franchini et al., 1996; Bruneau et al., 1995), distributed input data (Saulnier et al., 1998), validation methods (Seibert, 1999) and uncertainty (Beven, 1993), leading to a wide international distribution of the model concept. However, few applications have dealt with the influence of the spatial variability of precipitation on the model performance (Obled et al. 1994).

The extended TOPMODEL establishes a GIS-structured interface to the physically based SVAT-model PROMET (PRocess-Oriented Multiscale EvapoTranspiration Model) (Mauser and Schädlich, 1998), to utilize spatially distributed information on evapotranspiration and snowmelt. PROMET calculates the actual evapotranspiration (based on the Penman-Monteith equation (Monteith, 1965)) as a function of water availability due to precipitation, radiation balance, physical soil characteristics and the physiological regulation mechanisms of heterogeneous plantstands. It also incorporates a two-layer snow module, which describes accumulation and melting processes in a snow cover according to energy balance terms (Todini, 1996; Taschner et al., 1998). PROMET hence provides additional water balance terms, i.e. evapotranspiration and snowmelt, for the TOPMODEL in a spatially distributed sense, where the modelled snow water equivalent is of specific interest for the presented case study. The PROMET derived soil moisture pattern and quantities are used to initialize the soil storage for the TOPMODEL application. Saturation excess and return flow is calculated, introducing a temporally and spatially dynamic index approach. The evapotranspiration-soil-topographic index α_{ET} takes into account the seasonal variability of plant activity by means of transpiration, rooting and surface roughness and its influence on the variable contributing area to surface runoff. The α_{ET} is calculated by Eq. (1), where A is the upslope area per unit contour length, ET_{coeff} is a dynamic evapotranspiration coefficient, K_S is the local saturated hydraulic conductivity and $\tan\beta$ is the local surface slope. The ET_{coeff} is determined as a spatially distributed evapotranspiration regime, resulting from dividing pixelwise evapotranspiration for a given timestep by its annual mean, for which data is taken from long-term PROMET simulations.

$$\alpha_{ET} = \ln\left(\frac{A}{ET_{coeff} \cdot K_S \cdot \tan\beta}\right) \qquad \text{(Eq. 1)}$$

The most important formulae describing the water fluxes in the TOPMODEL application are summarized below, where the areal storage deficit of the unsaturated zone S_m is calculated as a function of the areal percolation rate r and the recession parameter m, which is derived from long-term hydrograph analysis, with i_A being the number of raster elements in the catchment (Eq. 2). The local storage deficit S_i, and hence the saturation remnant, is determined through relating the deviation of the local index value α_{ET} to its areal mean γ (Eq. 3). Baseflow Q_B is modelled accordingly, with l being the number of river channel segments in each watershed (Eq. 4).

$$S_m = -\frac{m}{i_A}\sum_{i=1}^{i_A}\left(\ln r + \ln\frac{A_i}{ET_{coeff} \cdot K_S \cdot \tan\beta_i}\right) \qquad \text{(Eq. 2)}$$

$$S_i = S_m - m \cdot \left(\ln\frac{A_i}{ET_{coeff} \cdot K_S \cdot \tan\beta_i} - \gamma\right) \qquad \text{(Eq. 3)}$$

$$Q_B = \sum_{i=1}^{n} l_i \cdot \left(ET_{coeff} \cdot K_S \cdot \tan\beta_i\right) \cdot e^{-\frac{S_i}{m}} \qquad \text{(Eq. 4)}$$

Hortonian type flow is computed using the Green-Ampt infiltration model, described by Eq. (5), with f being the infiltration rate, the porosity Φ, the effective soil suction S_f, the initial water content θ_i and the accumulated infiltration amount F.

$$f = K_S \left[1 + \left((\Phi - \theta_i) \cdot \frac{S_f}{F}\right)\right] \qquad \text{(Eq. 5)}$$

A detailed description of the presented hydrological model concept is given in Ludwig and Mauser (2000) and Ludwig (2000). The model is performed on a 100 m grid with an hourly timestep.

4 Processing of precipitation data

The accessible precipitation data needs to be furtherly processed to meet the 100 m scale requirement of the hydrological model. All data were transformed to a uniform geometric projection (UTM).

Conventional rainfall measurements are available from 10 continuously recording gauges of the German Weather Service (DWD). These data are aggregated to hourly precipitation sums and have to be transformed from point measurements to a 100 m grid. After correcting the station measurements using a temperature and wind-speed dependent algorithm (Schulla, 1997), a linear regression trend analysis with elevation is performed, creating a timestep-specific trend level. In order to reproduce the measured values, only the residuals are interpolated using a squared

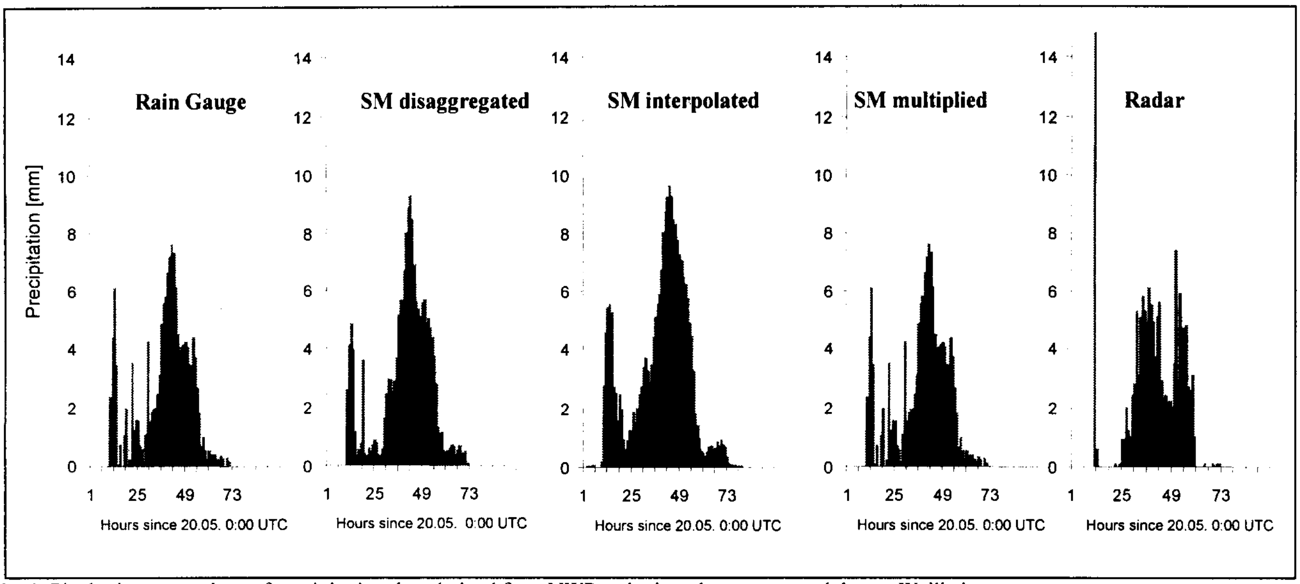

Fig. 1: Pixel-wise comparison of precipitation data derived from NWP and rain radar to measured data at Weilheim

inverse distance function and are added to the formerly calculated trend level.

The rain radar interpreted precipitation was provided on a 1 km grid, derived from radar measurements of the DWD-station Fuerholzen. The data is corrected by the German Aerospace Center (DLR), accounting for beam blockage and non-standard drop size distribution. A simple disaggregation was performed, duplicating each grid value to a 100m grid. The temporal resolution of 1 hour was created by averaging aggregated 15 min values.

The SM 96h-forecast data was provided by the Swiss Meteorological Institute (SMI) over a large domain in a 14 km grid and a temporal resolution of 1 hour, where each grid value represents the mean rainfall over a 196 km² area. For this application, the SM was initialized by the boundary conditions provided from DWDs' Europa Modell. The 14 km data were transformed to the required model grid using different interpolation schemes and disaggregation procedures:

- simple disaggregation, duplicating the data up to the required resolution (referenced as SM-multiplied)
- bilinear interpolation between 14 km pixel centers (SM-interpolated)
- disaggregation of data by distributing 14 km rainfall over a smoothed surface, supposing that highest rainfall intensities occur at the highest elevation (SM-disaggregated)

5 Data analysis

In a first step, a pixel-wise analysis of precipitation data is performed, comparing extracted rainfall intensities of the various data sources to the measurements at raingauge Weilheim for a 96h-period (Fig. 1). Reasonable agreement can be detected in temporal sequence, whereas the intensities vary considerably depending on the chosen data set and disaggregation scheme. Table 1 shows the statistical result of the pixel-wise data comparison. The coefficient of determination R^2 and the Root Mean Square Error RMSE are used as the objective functions to describe the data correlation:

Table 1: Pixel-wise comparison of precipitation

Recorded precipitation at Weilheim Σ = 147.5 mm				
	SM-disaggregated	SM-interpolated	SM-multiplied	DWD Rain Radar
R^2	0.69	0.64	0.65	0.28
RMSE (mm)	1.40	1.96	1.37	2.28
Σ (mm)	172.2	222.4	147.9	142.2

Secondly, the spatial distribution of 96-h aggregated precipitation is compared (Fig. 2, Table 2). While all of the images show a positive southbound gradient of areal precipitation, remarkable differences in its intensity become evident. Distinct maximums of rainfall amount in the southwestern part of the catchment are provided by both NWP model and rain radar.

Table 2: Areal precipitation [mm] over a 96-h period

	Mean	Minimum	Maximum
Rain gauge	162	143	199
SM multiplied	202	139	308
SM interpolated	220	147	302
SM disaggregated	195	142	307
Rain Radar	207	21	543

In comparison to measured data, NWP model and rain radar deliver significantly higher areal means, whereas especially the maximum values drastically surplus the

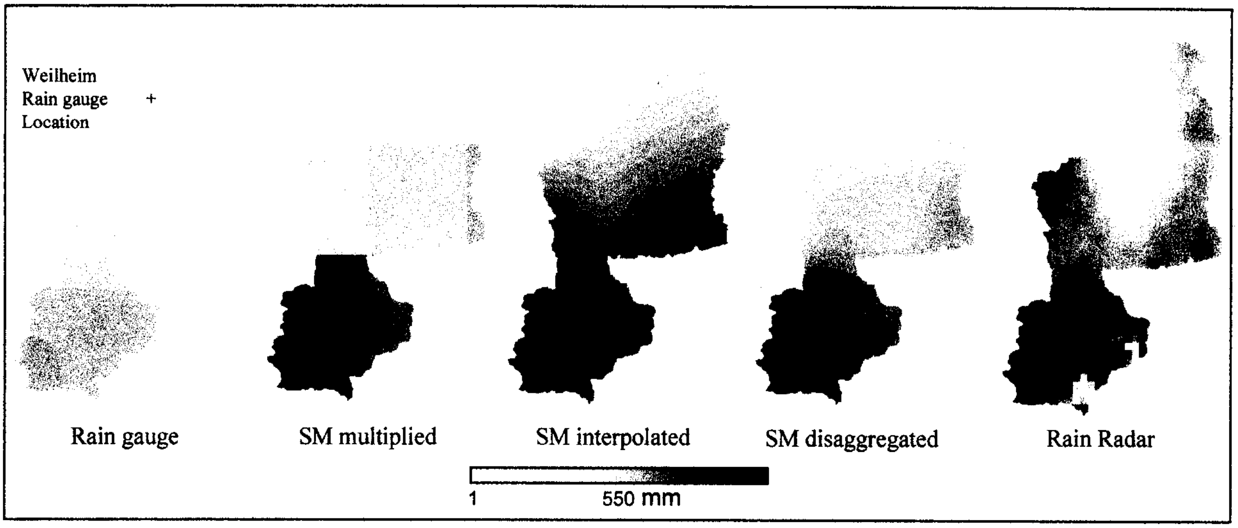

Fig. 2.: Areal precipitation in the Ammer watershed (709 km²) over a 96-h period

measured values. In particular, the rain radar provides an extremely high variance, which can be explained by effects of ground cluttering and beam blockage at the alpine ridges.

6 Model results

Hydrological simulations are performed employing the different meteorological data sources. Since parameter retrieval for the TOPMODEL application in the Ammer watershed was performed in an earlier study on long-term water-balance simulations no further calibration was performed (Ludwig 2000). To describe the efficiency of model performance comparing modelled (Q_m) to gauged stream discharge (Q_g), the Nash-Sutcliffe (1970) efficiency criterion ε is used as objective function (Eq. 6):

$$\varepsilon = 1 - \frac{\sum_{i=1}^{n}\left(Q_{m_i} - Q_{g_i}\right)^2}{\sum_{i=1}^{n}\left(Q_{g_i} - \overline{Q_g}\right)^2} \qquad \text{(Eq.6)}$$

The modelled runoff using interpolated raingauge data delivers the best approximation of the recorded hydrograph at streamgauge Weilheim ($\varepsilon = 0.89$), keeping in mind that on account of levee breaks along the Ammer a higher actual runoff volume and peak has to be assumed (Fig. 3).
The deviations of model results to measured discharge in terms of runoff peak (%), runoff volume (%) and peak time displacement (h), along with the efficiency ε are summarized in Table 3.
The general overestimation of the simulated runoff peak using SM data can be related to an overestimation of precipitation amount for 20 May 1999, leading to an unrealistic decrease of soil water deficit advancing the flood event. These divergent initial conditions result in an early rise and a general surplus of modelled flood discharge. The temporally delayed maximum in discharge simulated using the rain radar data is caused by an additional precipitation

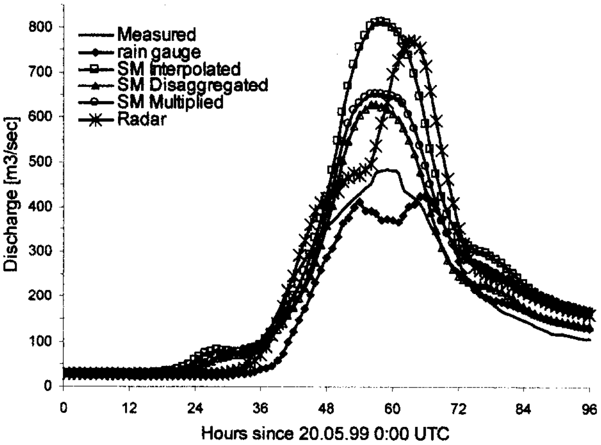

Fig. 3.: Modelled and measured hydrographs at the streamgauge Weilheim referring to the Whitsun flood using different precipitation input

Table 3: Multi-scenario hydrograph characteristics

Deviation to measured runoff	Peak flow [%]	Runoff volume [%]	Peak Time [h]	efficiency ε
Rain gauge	-9	- 13	- 6, + 6	0.89
SM multiplied	+ 25	+ 17	- 2	0.82
SM disaggregated	+ 21	+ 15	- 3	0.83
SM interpolated	+ 57	+ 36	- 1	0.66
Rain Radar	+ 51	+ 29	+ 8	0.61

maximum along with an extreme overestimation of precipitation in the southernmost alpine region, related to difficulties in ground clutter-corrections. The remarkable twin peak hydrograph, modelled by using the rain gauge data set, reflects the actual meteorological situation. Supplemental analysis performed on METEOSAT imagery by

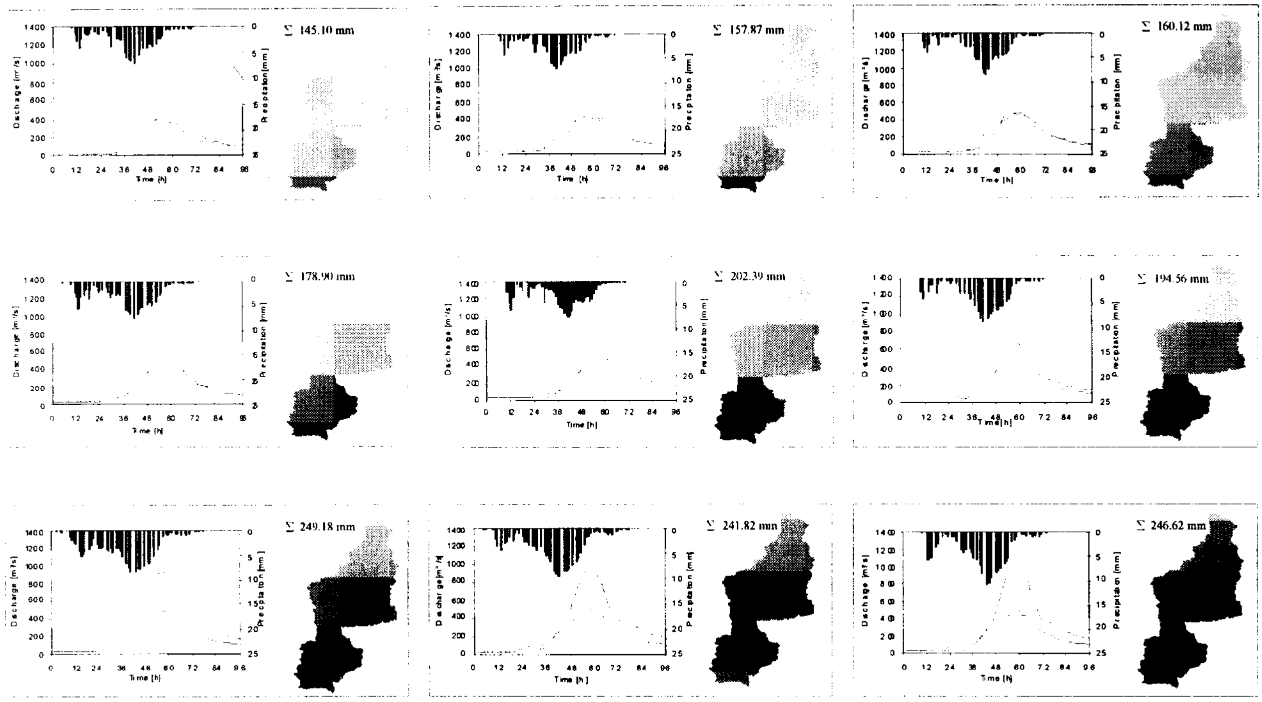

Fig. 4: Adjacency shift of NWP modelled precipitation fields for flood sensitivity analysis

Bendix et al. (2000) emphasizes the double maximum character of precipitation evolution during the Whitsun flood event. Measured discharge can only give an approximation of the actual runoff volume, since the tremendous water level exceeded the valid stage-discharge relationship and continuous levee leakages additionally falsified the recordings. The reliability of runoff model performance in this study is supported by comparable results of the IFFS model based on the same set of rainfall inputs (Bach et al., 2000).

Sensitivity analysis

To account for a possible inexact spatial basin coverage of the meteorological domain, a one-pixel dislocation is being allowed and hence an adjacency shift of the modelled mesoscale precipitation field is performed. Surveying a larger domain of NWP model data, a significant precipitation gradient can be detected approaching the Alps. Consequently, shifting the rainfields north results in a basin-wide increase of areal precipitation, while shifting south provides greater similarity to the interpolated rain gauge data (Fig. 4).

The areal shifting of predicted rainfall patterns is consequently reflected in the modelled hydrographs (Fig. 4). An obvious overestimation of the flood is modelled applying the southern rainfields, no distinctive deviations occur using the eastern and western neighbor, while the application of the northern rainfields show an improved correspondence of measured and modelled runoff with $\varepsilon = 0.93$. Especially the starting values of modelled precipitation correlate better to the measurements in terms of volume and hence provide a more realistic approximation of remaining soil storage capacity preceding the major flood event.

7 Discussion

Since hydrological models have shown their principle capability to simulate floods up to a reasonable degree of certainty in numerous applications, the question remains upon the accuracy of precipitation data. Until now, all of the available data sources are far from being perfect for flood modeling at the catchment scale.

Conventional rain gauging lacks accuracy on account of several well-known, but hardly quantifiable error-sources, such as wind turbulence, evapotranspiration or wetting. Correction-algorithms can only counteract these systematical errors based on empirically determined coefficients, which are generally not transferable in time and space. The application of the rain gauges data in this study result in an underestimation of the flood volume and peak, presuming the assignment of unrealistic correction parameters. Nevertheless, due to the reasons mentioned above an unambiguous explanation cannot be given.

Rain radars provide images of spatially distributed rainfall intensities at a high temporal and reasonable spatial resolution. However, these intensities are provided in coarse intervals, due to high uncertainties in the reflectivity equations. The exact knowledge about the actual drop size distribution or even the phase of precipitation is generally not available and hence requires complex correction procedures. In the presented application, problems emerge from the relatively far distance (~ 80 km) of the radar and the beam blockage at the alpine ridges, resulting in a unrealistic precipitation maximum of 550 mm and minimum of 1mm

The mesoscale meteorological models are basically the only data source to provide long-term rainfall forecasts in full spatial coverage and high temporal resolution over a large domain. Disadvantages for hydrological catchment applications descend from the very coarse spatial resolution, which makes disaggregating and downscaling of rainfall data necessary and hence introduces an additional error source. Furtherly, the model accuracy largely depends on the initializing boundary conditions of models working at even larger scales (Benoit et al., 1997). The complex physics, simulated in the meteorological models, requires sophisticated algorithms and high computer-power, which only few institutions are capable of providing at the operational level.

8 Conclusion

No matter how good physically based and spatially distributed hydrological models are in terms of process description, they still depend on the accuracy of its input data. In this investigation, different data sources have been tested for their applicability in flood modeling.

The presented interface of meteorological and hydrological models for flood analysis shows promising results and offers perspectives for future applications in real time flood forecasting. However, a larger variety of meteorological situations must be examined in order to evaluate the reliability of such a model synergy. Due to the limitations in range and view angle, the application of rain radar is critical for this testsite, since radar beam obstruction and ground cluttering cannot be prevented in rugged terrain.

In addition to ongoing research on dynamical and statistical downscaling of meteorological data (Murphy, 1999; Wilby and Wigley, 1997), further investigations need to be performed in order to develop more advanced methods to disaggregate and downscale NWP information for hydrologic applications at the catchment scale, focussing on subgrid parameterizations to represent orographic storage or luff/lee effects. Surface-atmosphere interactions have to be thoroughly analysed to develop directly coupled meteo-hydro-models.

The procedure of rainfield shifting can be generally applied upon NWP data when used for flood modeling, to provide a raw estimate of model results variability due to the spatial input variability, and hence giving information for flood forecasting within a certain range of reliability.

An incorporation of online-connected rain gauges, rain radar and remote sensing measurements within the meteorological model runs (providing continuous update information) will be an important step towards more accurate rainfall predictions. Coupled meteo-hydro-models can then develop to become an useful tool for flood warning services even at the catchment scale.

Acknowledgements

Research for this study has been funded by the EU within the framework of the RAPHAEL project. The valuable contributions of all RAPHAEL partners are gratefully acknowledged. The meteorological station data were generously supplied by the DWD. Special thanks go to Peter Binder and Pirmin Kaufmann of the SMI and Peter Meischner and Martin Hagen from DLR for providing the SM results and the rain radar data. The Bavarian Water Authority is kindly acknowledged for providing the stream gauge measurements. Special thanks also go to Keith Beven for sharing the basic TOPMODEL codes.

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