

# **Einsatz gekoppelter Modelle und Wetterradar zur Abschätzung von Niederschlagsintensitäten und zur Abflussvorhersage**

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# Abstract

Floods remain one of the most frequent and devastating natural hazards worldwide. Flood forecasting systems provide an early warning tool to contribute to the reduction of ecologic and economic losses. In the second half of August 2005, heavy rainfall hit the northern part of the Alps, causing Century floods in Switzerland, Austria, and Germany. Water levels in rivers and lakes reached record heights. This event caused heavy damage in these countries, people were forced to evacuate their homes and infrastructure was affected. Due to the extremely fast response of river runoff to precipitation events, early flood warning in Alpine catchments can only be achieved by mid-range precipitation forecasts through numerical weather prediction (NWP). This data can be applied to hydrological models to give flood forecasts.

The quality of hydrological modeling is limited due to the restricted availability of high resolution temporal and spatial input data such as temperature, global radiation, and precipitation. One of the main problems of hydrological modeling is to determine areal (and spatially distributed) rainfall fields, which are the most important input source to hydrological models. On the one hand, station data provide exact point information on rainfall. To estimate areal precipitation, statistical methods need to be applied. Interpolation of station data leads, depending on the method applied and the density of rainfall stations, to huge differences in areal precipitation and its spatial distribution (NEUMANN 2005). On the other hand, radar data provide good spatial information (rainfall patterns) whereas the quantification of rainfall intensities using a so called Z/R-relationship is still a not fully solved problem. Therefore, adjustment techniques using measured rainfall data have been developed which face the problem of representativeness of a point information for the area covered by the radar.

The goals of this case study were to

- build and test a one-way-coupled meteorology-hydrology flood forecasting system and
- to adapt a Z/R-relationship to compute rainfall intensities  $R$  using radar data  $Z$  (reflektivities).

This study was undertaken in the Ammer catchment in the southern Bavarian Alps and

alpine forelands. The catchment size is  $709 \text{ km}^2$  up to the inflow into Lake Ammersee. The highest elevation is  $2185 \text{ m asl}$  (Kreuzspitze) in the Ammergau Alps, the outflow into Lake Ammersee is the lowest part within the catchment ( $533 \text{ m asl}$ ). Due to the complex orography and heterogeneity in topography, the catchment is characterised by big north-southerly differentiations in soils, land use, and climate. Long term mean annual precipitation in the northern part of the catchment is around  $1100 \text{ mm/yr}$  while the southern part with the summits of the Ammer Alps receives more than  $2000 \text{ mm/yr}$ . Maximum precipitation is in summer. The mean annual temperature is around  $7-8 \text{ }^\circ\text{C}$  in the alpine forelands and  $4.5 \text{ }^\circ\text{C}$  in the southern part of the catchment. The work focuses on the period summer 2001 to minimize uncertainties in the hydrological modeling and radar data processing due to snowfall. Within the basin, six river gages were available for this study. Geographical input data (elevation from interferometric ERS-data and digital maps, land use from Landsat-TM fuzzy logic classification, and soil classes from Bavarian Bodenquetekarte) were obtained from the RAPHAEL Project (RAPHAEL, 2000) in which the runoff and atmospheric processes for flood hazard forecasting and control was investigated.

## Adaptation of a Q-Z/R-relationship using observed river discharge data

Using radar data to estimate rainfall intensities is accompanied by basic difficulties such as clutter, shielding, variations of Z/R-relationships, beam-resolution and attenuation. Instead of accounting for all errors involved separately, a robust Z/R-relationship is estimated in this study for the short range (up to  $40 \text{ km}$  distance) of the radar using inverse hydrological modeling for a continuous period of three months in summer 2001. River gage measurements from five catchments are used to estimate areal precipitation and finally Z/R-relationships using the water balance simulation model WaSiM (SCHULLA 1997). The calibration of the model was performed with meteorological station data. It was done in such a way that the parameters have been iteratively calibrated one after another. The parameters *drainage density*, which effects the interflow single linear storage, and the *recession constant for interflow single linear storage* are jointly calibrated because they both affect the simulation of interflow.

The German Weather Service-Project RADOLAN (2004) investigated and established an operational method to adjust radar rainfall intensities online using ground-based

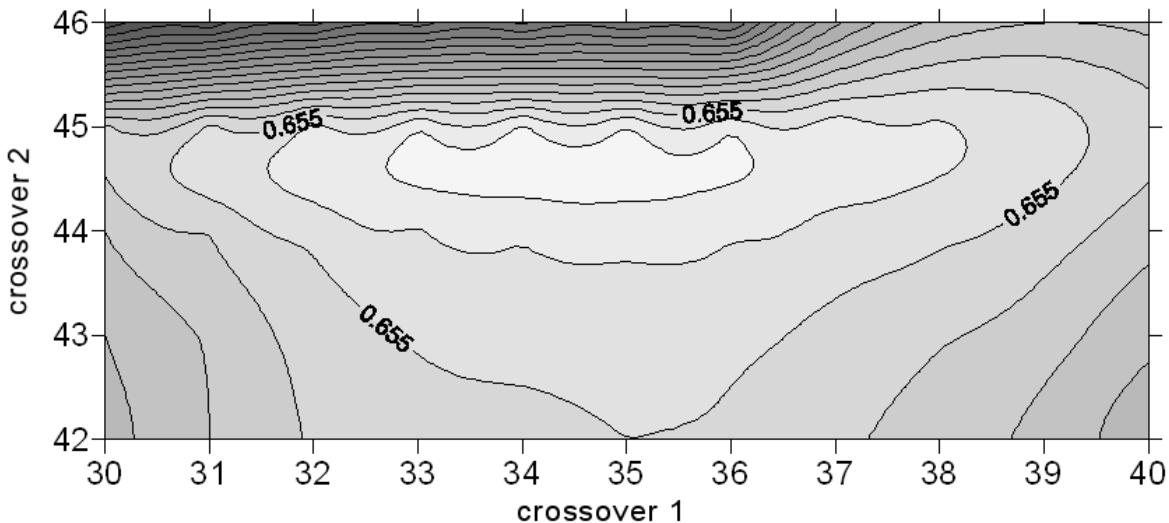
point measurements of rainfall. As intermediate step, the overall Z/R relationship was differentiated into three piecewise linear parts depending on the absolute reflectivity values. A simplified version of this improved Z/R-relationship for three reflectivity ranges with

$$\begin{aligned} Z &= 125R^{1.4} &< 36.5 & \text{dBZ} \\ Z &= 200R^{1.6} & 36.5 \dots 44 & \text{dBZ} \\ Z &= 77R^{1.9} & > 44 & \text{dBZ} \end{aligned}$$

was applied to calculate rainfall intensities using the data from the radar at Meteorological Observatory Hohenpeissenberg. This device has the advantage of being installed at 988 m asl on top of Mount Hohenpeissenberg, therefore ground clutter is reduced to a minimum. Attenuation has been neglected because the radar device is situated next to the Ammer catchment. The new approach chosen in this study is to estimate parameters  $a, b$  and the crossovers  $c_1, c_2$  between the three parts via comparison of observed runoff  $Q_{obs}$  and radar data driven simulated runoff  $Q_{sim}$ . The optimisation problem can be formulated with mean observed discharge  $\overline{Q_{obs}}$  as

$$1 - \frac{\sum_{i=1}^n (Q_{obs} - Q_{sim}[R(Z, a_j, b_j, c1, c2)])^2}{\sum_{i=1}^n (\overline{Q_{obs}} - Q_{sim}[R(Z, a_j, b_j, c1, c2)])^2} \stackrel{!}{\rightarrow} \min$$

for each branch  $j=(1,2,3)$  of the split Z/R-relationship and for every subcatchment. In each optimization step, two parameters have been optimised at the same time. Fig. 0.1 gives an intermediate result of the calibration at river gage Obernach. Therefore, the

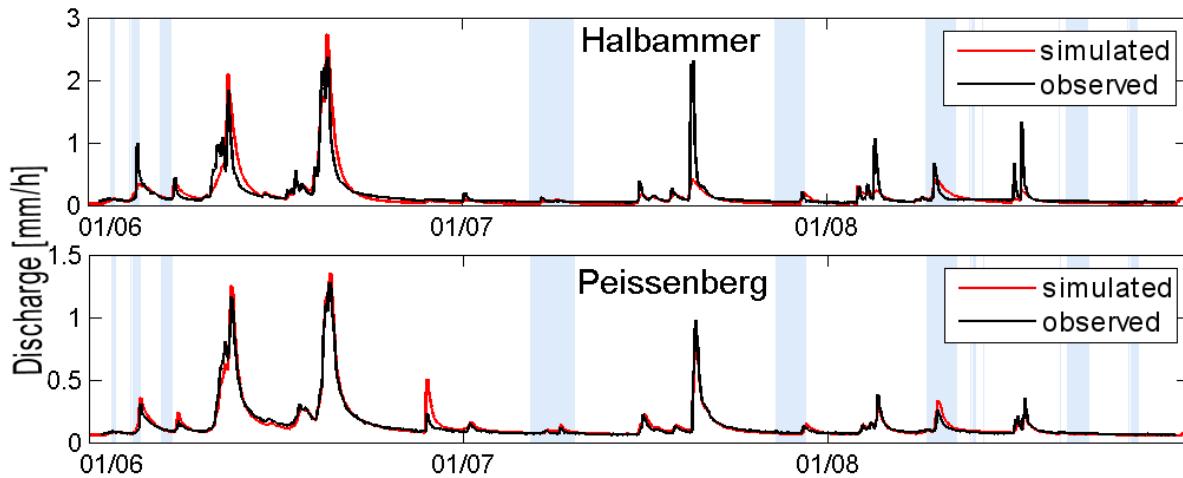


**Figure 0.1:** Effect of changing the two crossovers between the three Z/R-relationships on the Nash-Sutcliffe Efficiency at river gage Obernach. Line distance: 0.001 NS.

crossovers c1 and c2 have been varied and 55 WaSiM runs have been performed. The parameter estimation was applied on five subcatchments. It was repeated using different starting values for two times and resulted finally in:

$$\begin{array}{lll} Z = 104R^{1.48} & <36 & \text{dBZ} \\ Z = 131R^{1.57} & 36 \dots 44.5 & \text{dBZ} \\ Z = 73R^{1.63} & >44.5 & \text{dBZ} \end{array}$$

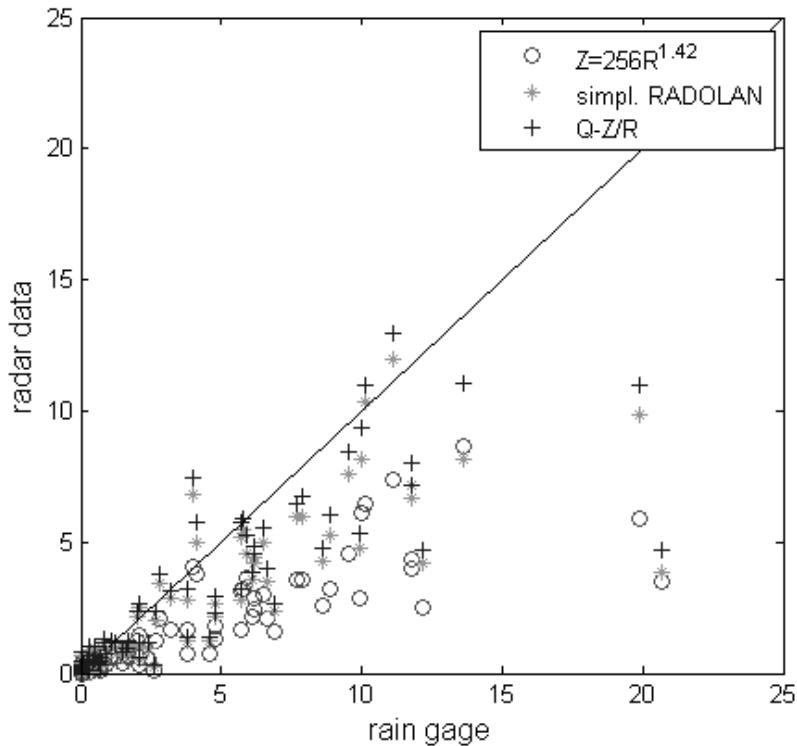
Fig. 0.2 shows the simulated river runoff with the new found Q-Z/R-relationship for river gages Halbammer and Peissenberg. Concerning the spatial pattern and absolute



**Figure 0.2:** River discharge at gages Halbammer and Peissenberg, simulated using the new found Q-Z/R relationship. Timeframes in which radar data was not available are marked in light blue.

values of the three month rainfall sum estimated with radar data and rain gage data, it could be shown that locally big differences occur.

A validation of the adjusted Q-Z/R-relationship was done using 14 rain gages. The estimated radar rainfall intensities showed good agreement with the ground measurements. Fig. 0.3 shows a comparison of station observations to differently estimated radar rainfall intensities. Nevertheless, rainfall intensities  $\geq 10 \text{ mm/7h}$  are mostly underestimated. The new found method allows to include data of small rainfall intensities in the adjustment process whereas the calibration methods using rain gage data are limited to rainfall intensities  $> 1 \text{ mm/h}$ . Additionally, the Q-Z/R-method overcomes the problem of representativeness of a rain gage for the area covered by the radar. Furthermore, it could be shown that radar rainfall data can be successfully applied over a three-month period in continuous hydrological simulations. It must be noted that dividing the traditional one-piece Z/R-relationship into three piecewise linear parts in the RADOLAN



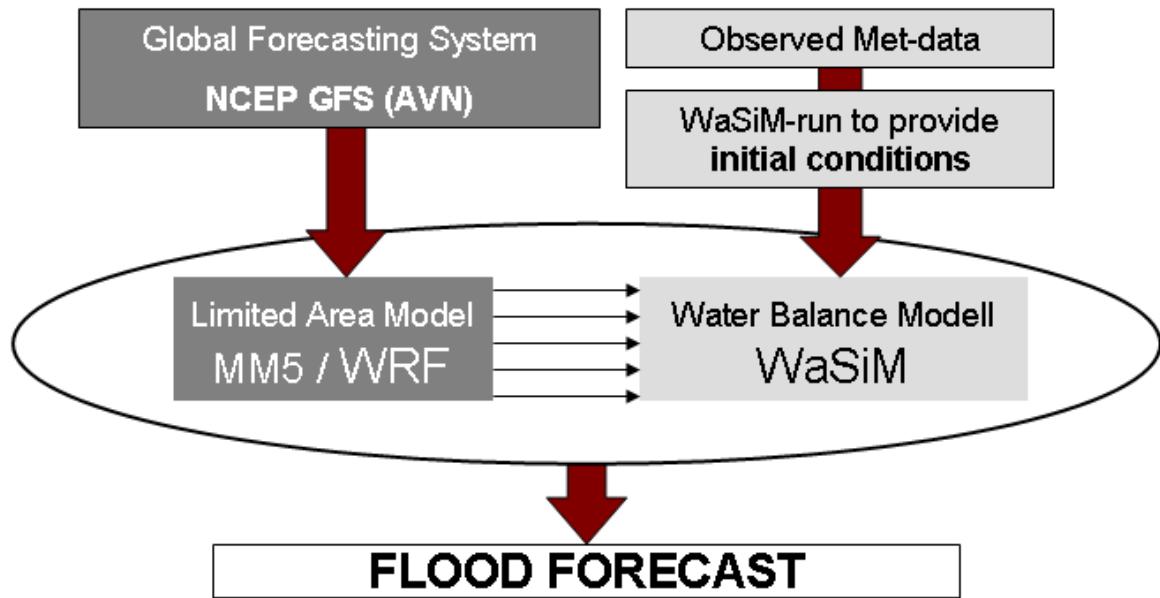
**Figure 0.3:** Comparison of rain gage at Bad Kohlgrub to differently estimated radar rainfall intensities: Z/R-relation of the German Weather Service, simplified version of the three-part RADOLAN (2004) relationship and adjusted Q-Z/R relationship.

project was already a big step forward for radar based hydrological simulations. The final adjustment using observed river discharge (Q-Z/R-relationship) reduced the underestimation of the RADOLAN method compared to rain gage measurements.

## Design and test of a one-way coupled meteorology-hydrology model system

A Flood Forecasting System was designed in a one-way coupling strategy. Therefore, meteorological high resolution forecast data from the Weather Research and Forecast (WRF, Skamarock et al. 2005) was extracted, transformed and passed to the water balance simulation model WaSiM. One-way coupling means that during the model runs there is no interaction between the models. An interface extracts NWP output data and transforms it to WaSiM input data. Fig. 0.4 gives an overview of the flood forecast system. WaSiM is mainly used because of its capability to store soil moisture, snow coverage and storage in river channels at the end of a model run. These are calculated driving the hydrological model with observed meteorological station data. This way, initial storage values are updated parallel to the weather forecast simulations and the

interplay between snow melt, soil conditions and precipitation can be accounted for. It



**Figure 0.4:** Overview over the early flood warning system.

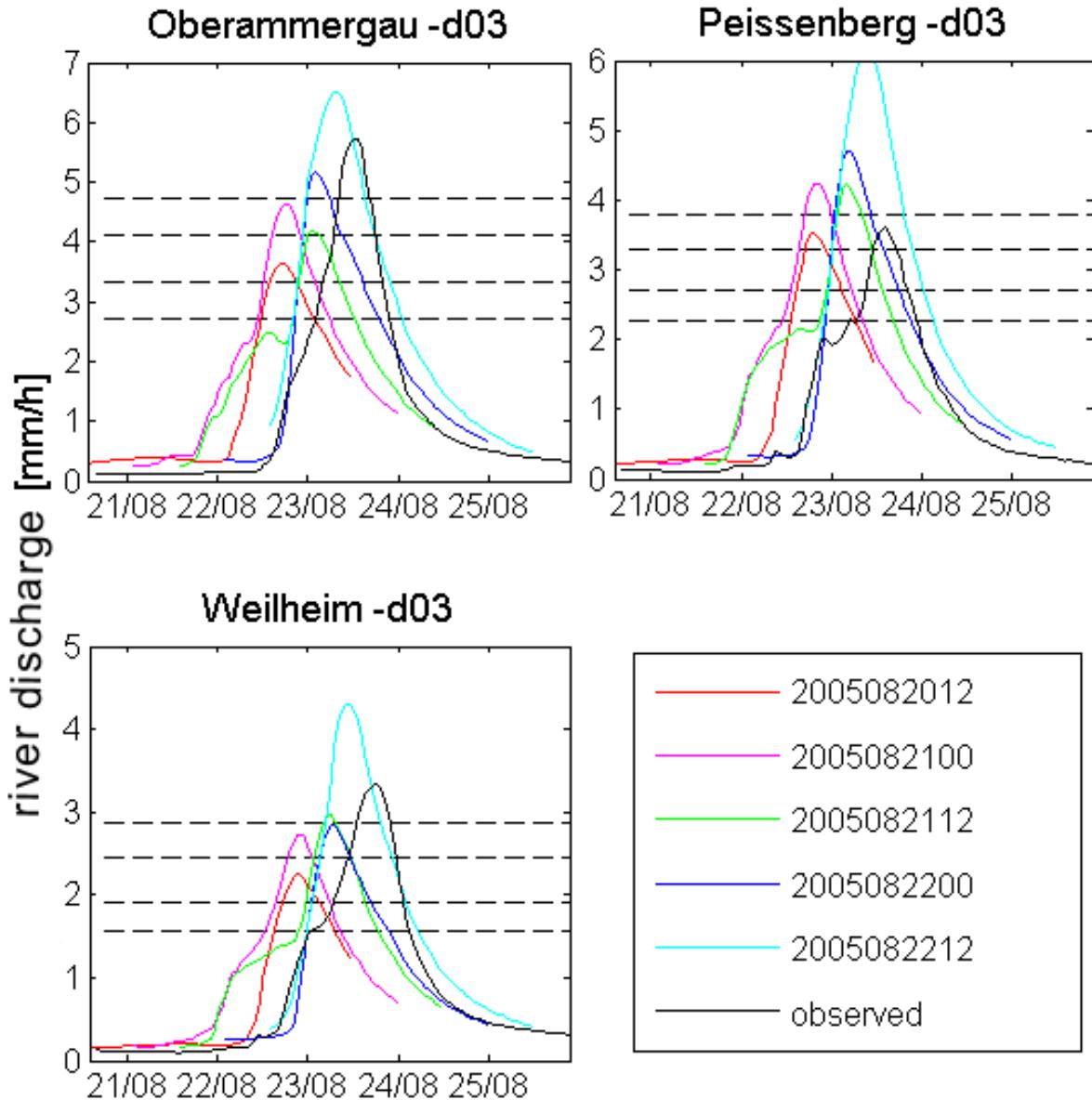
emerged that the calibration of the hydrological model based on data of summer 2001 was not useful to simulate a Century flood. Therefore, a recalibration was performed using data for the year 2005, including the flood event in August.

To investigate the sensitivity of the NWP and the coupled model system, the weather forecast was evaluated using

- GFS analysis and forecast data,
- different parameterizations for
  - gridscale precipitation,
  - cumulus precipitation and
  - planetary boundary layer,
- different Land Surface Models and
- Digital Elevation Models.

Furthermore, the effect of horizontal model resolution of the four WRF-domains (54, 18, 6 and 2 km) and timestep of model output on different efficiency criteria have been investigated. For the flood event in August 2005, five 12h-shifted initial times (3-1 days

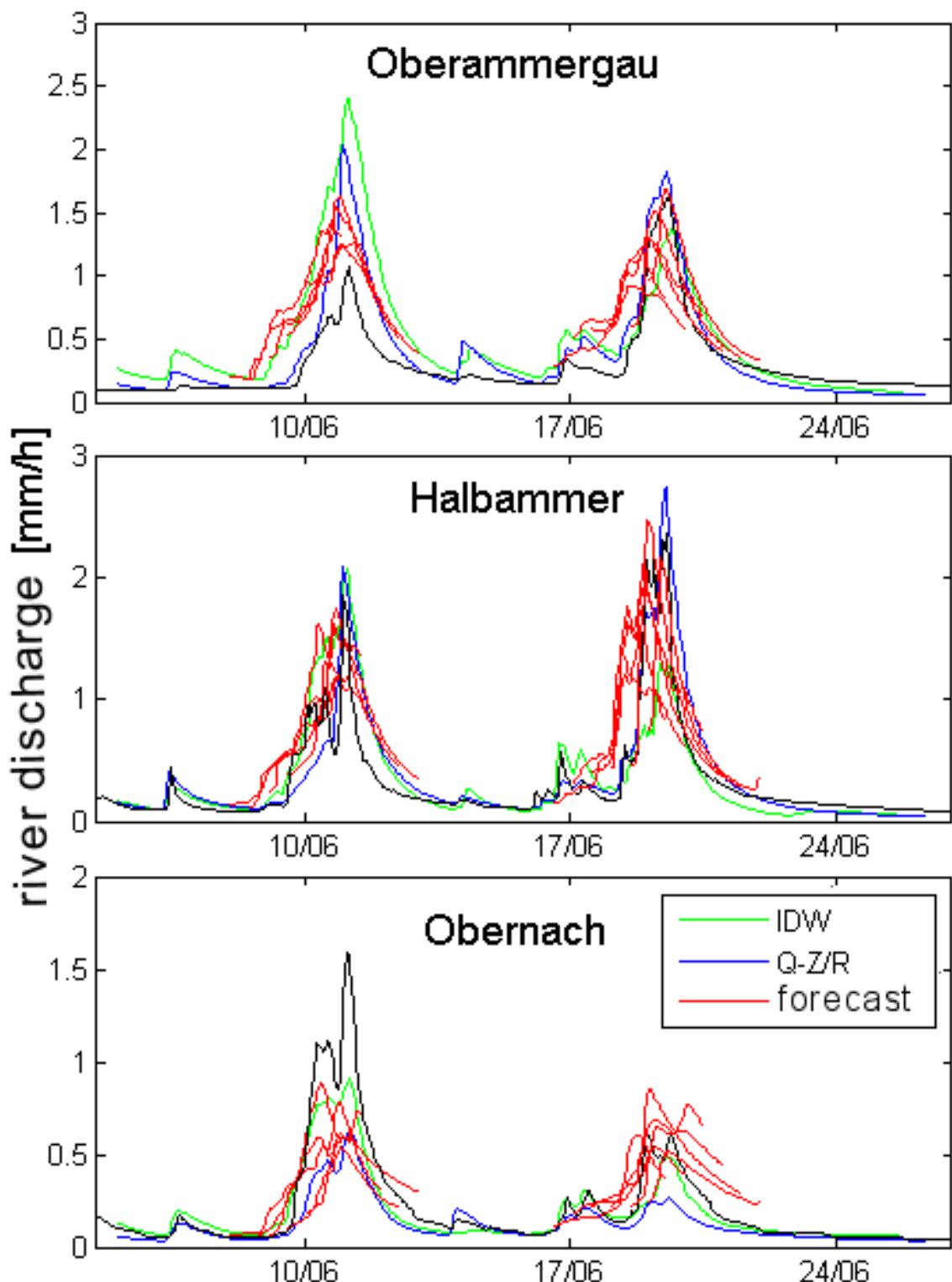
in advance of maximum river discharge) for the runoff forecast have been applied to investigate the effective advance warning time. The result is show in Fig. 0.5.



**Figure 0.5:** Time evaluation of the flood forecast (WRF@6km-WaSiM) for the event in August 2005, dotted lines: Hq10, Hq20, Hq50 and Hq100.

Eleven river discharge forecasts for two events in June 2001 have been performed to validate the model system. For this period of time, hydrological simulations based on interpolated rain gages and based on radar rata have been available. These overall hydrological simulation results are shown in fig. 0.6 for the subcatchments Oberammergau, Halbammer and Obernach.

The huge number of performed flood forecasts could be used for *ensemble predictions*. Each of the forecasts is available in four WRF-domains, five different model setups have



**Figure 0.6:** WaSiM simulation results based on 11 flood forecasts, interpolated rain gage data, and radar data (Q-Z/R-relationship).

been applied. Shifting of the simulation results north-, south-, west-, and eastwards (amount  $1 \times$  horizontal model resolution) to account for spatial uncertainties results in a total of 100 weather forecasts for the flood forecasts. Nevertheless, an *ensemble* strategy is not recommended because most of the forecasts led to underestimations of precipitation and river discharge.

Recapitulating it could be shown that observed river discharge data can be used to adjust a Z/R-relationship to estimate rainfall intensities from radar data. On the other hand, radar data driven hydrological simulations showed good results over a continuous three-month period in summer 2001.

The coupled meteorology-hydrology flood forecast system allows effective warning against floods 48 hours in advance for the Ammer catchment. Nevertheless, it was not possible to simulate the exact point of time and the exact value of the maximum runoff.

This work was partially performed under the framework of the Centre of Numerical Environmental Simulation at the University of Augsburg and funded by the Bavarian High Tech Initiative.

# Zusammenfassung

In der vorliegenden Studie wurden zwei Zielsetzungen verfolgt: (1) die Realisation und der Test eines gekoppelten Meteorologie-Hydrologie Abflussvorhersagesystems und (2) die Ableitung einer Z/R-Beziehung zur Berechnung von Niederschlagsintensitäten  $R$  aus Radarreflektivitäten  $Z$ . Die Studien wurden im Ammereinzugsgebiet mit einer Fläche von  $609 \text{ km}^2$  bis zum Pegel Weilheim in Südbayern durchgeführt. Gemessene Abflussdaten wurden genutzt, um mit Vorwärtsimulationen des hydrologischen Modells WaSiM flächendifferenzierte, stündliche Niederschlagsfelder abzuschätzen. Dazu wurden die Koeffizienten einer dreiteiligen Z/R-Beziehung so lange verändert, bis ein Minimum des Nash-Sutcliffe-Kriteriums, basierend auf Abflussbeobachtung und -simulation über einen dreimonatigen Zeitraum, erreicht wurde. Die so kalibrierte ***Q-Z/R-Beziehung*** hat in der Validierung mit Niederschlagsstationsdaten gute Ergebnisse gezeigt, hohe Niederschlagsintensitäten werden allerdings unterschätzt. Die Vorteile der hier erstmalig angewandten Methode im Vergleich zu Aneichungsverfahren an Stationsdaten sind die Möglichkeit, auch Daten geringer Niederschlagsintensitäten nutzen zu können und die Ausschaltung des Problems der Repräsentativität einer Punktmessung für eine umgebende Fläche. Es konnte außerdem gezeigt werden, dass Radarniederschlagsdaten erfolgreich über einen dreimonatigen Zeitraum in kontinuierlichen Abflusssimulationen eingesetzt werden können.

Der ***Aufbau eines Hochwasservorhersagesystems*** wurde durch die Ein-Wege-Kopplung des meteorologischen Modells WRF mit dem hydrologischen Modell WaSiM realisiert. Es wurden umfangreiche Studien auf Basis der Vorhersagen des Augusthochwassers 2005 durchgeführt. Dazu zählen die Auswirkungen unterschiedlicher GFS-Eingangsdaten, Höhenmodelle und Parametrisierungen für grid- und subgridskaligen Niederschlag, Planetarische Grenzschicht und den Stoff- und Energieaustausch zwischen Erdoberfläche und Atmosphäre. Der zeitliche Verlauf der Hochwasservorhersage wurde durch fünf 72-stündliche Wettervorhersagen mit jeweils um zwölf Stunden versetzte Initialisierungszeitpunkte bis einen Tag vor dem Erreichen der maximalen Pegelstände untersucht. Dabei hat sich gezeigt, dass mit dem gekoppelten Modellsystem Extremereignisse modelliert werden können. Die Validierung erfolgte mit 13 Vorhersagen für zwei Abflussereignisse im Sommer 2001. Es konnte gezeigt werden, dass das Abflussvorhersagesystem die effektive, 48-stündliche Hochwasservorwarnung im Ammereinzugsgebiet ermöglicht. Die Vorhersage des exakten Zeitpunktes und der Abflussmenge des Hochwasserscheitels kann mit den heute verfügbaren Methoden jedoch nicht erreicht werden.