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Assessing the predictive ability of the spatially distributed conceptual AFFDEF model for a mesoscale catchment

TAPASH DAS[1], GRETA MORETTI[2], ANDRÁS BÁRDOSSY[1] & ALBERTO MONTANARI[3]

1 *Institute of Hydraulic Engineering, University of Stuttgart, Pfaffenwaldring 61, D-70569 Stuttgart, Germany*
tapash@iws.uni-stuttgart.de

2 *Ingenieurbüro Winkler und Partner GmbH, Schlossstrasse 59a, D-70176 Stuttgart, Germany*

3 *Faculty of Engineering, University of Bologna, Via del Risorgimento 2, I-40136 Bologna, Italy*

Abstract The spatially distributed grid based conceptual rainfall–runoff model AFFDEF is herein applied to a mesoscale catchment located in central Europe. The AFFDEF model was originally developed at University of Bologna, Italy. In this study, a simplified snow module based on the degree day approach was embedded in AFFDEF to simulate snow accumulation and snow melt processes. Also, in the modified model version, necessary modifications were undertaken to work with highly spatially-resolved meteorological forcing variables. The objective of this study is to investigate the predictive ability of the model at different spatial scales while calibrating the model at the outlet of the catchment. This approach enables the identification of the predictive ability of the model when applied to ungauged basins. The results show that the distributed model provides reliable simulation referring to ungauged river sections.

Key words distributed rainfall–runoff model; multi-site validation; predictive ability; ungauged basin

INTRODUCTION

The estimation of peak discharge for an assigned probability of exceedance (so called design flood, NERC, 1975) has become a central topic in applied hydrology. In fact, to reduce the flood risk posed by the increasing inundations and flash flood events that have occurred in the last decades, a reliable estimation of design flood is essential. This estimation supports the design of river engineering works and flood protection measures, especially in the case of ungauged or information-poor catchments. Also, rainfall–runoff models have been used in the framework of continuous simulations showing the ability of reproducing flood frequency distributions, even when dealing with data limited or ungauged catchments (Blazkova & Beven, 1997, 2002).

Lumped parameter models are quite difficult to apply to ungauged or information-poor basins. On the other hand, spatially distributed models are particularly suitable for ungauged basins, because such models are potentially able to produce river flows at any locations on the catchment river network. Nevertheless, it is not yet clear to what extent these models are able to simulate the river flow over a wide range of spatial scales.

The present work shows the application of a spatially distributed rainfall–runoff model, called AFFDEF, to assess its predictive ability when applied to ungauged basins. The model had proved its ability to provide reliable simulations at ungauged river sections through application in data-limited catchments (Brath *et al.*, 2003; Moretti & Montanari, 2003).

In the present study, the model was applied to a portion of the Upper Neckar catchment, located in the southwest of Germany, to simulate the river flows at different spatial scales. The model was calibrated utilizing the daily observed discharge at the outlet of the catchment. The simulated river flows were compared with the observed discharge at the outlet as well as at two internal gauging stations. This approach enables the identification of the predictive ability of the model when applied to ungauged basins.

To perform the analysis, a simplified snow module based on the degree day approach was embedded in the original version of the AFFDEF to simulate the processes of snow accumulation and snow melt. In addition, necessary modifications were undertaken to work with highly spatially resolved meteorological forcing variables.

FRAMEWORK OF THE ANALYSIS

Brief description of the rainfall–runoff model

AFFDEF (Brath *et al.*, 2003; Moretti & Montanari, 2005) is a spatially-distributed grid-based conceptual rainfall–runoff model, which enables continuous simulation of river flows at any time step. It is robust and thus applicable to a wide spectrum of real world case studies. The main characteristic of the model is that long simulation runs can be performed with short time steps and limited computational efforts. In addition, river flows can be computed at any location of the investigated catchment river network.

The model is raster-based, i.e. it discretizes the basin in square cells coinciding with the pixels of the Digital Elevation Model (DEM). The river network is automatically extracted from the DEM by applying the D-8 method (Tarboton, 1997). This allows the estimation of flow paths and contributing area to each cell.

The catchment hydrological response is determined by the composition of two processes of hillslope runoff and channel propagation along the river network. The interaction between soil, vegetation, and atmosphere is modelled by applying a conceptual approach which accounts for interception and evapotranspiration. In detail, two reservoirs are located in correspondence of each cell. The first reservoir simulates the interception operated by the vegetation cover. Once the interception reservoir is full of water, the excess rainfall that reaches the ground (reduced by the water that eventually accumulates as snow or evapotransporates) is divided into surface and subsurface flows according to the modified CN approach. Thus, it is possible to simulate the redistribution of soil water content during inter-storm periods. To this end, a linear infiltration reservoir is located at the soil level to collect the infiltrated water and generate surface flow. The bottom outflow from this reservoir is the subsurface flow. The capacities of the interception and infiltration reservoirs are computed as the product of the local soil storativity computed with the CN method (Soil Conservation Service, 1972) and a calibration parameter.

Surface and subsurface flows are propagated towards the basin outlet by applying the Muskingum-Cunge model with variable parameters, which are determined on the basis of the "matched diffusivity" concept (Orlandini & Rosso, 1996). The distinction between hillslope rill and network channel is based on the concept of constant critical support area (Montgomery & Foufoula-Georgiou, 1993).

Some of the model parameters have a well-defined physical meaning and can be estimated on the basis of *in situ* surveys ("Estimated" in Table 1); the remainder have to be optimized by calibration on the basis of some historical hydrometereological records ("Calibrated" in Table 1). The parameters of the model are assumed to be constant throughout the catchment. The Strickler roughness on the hillslope is allowed to vary in space only, according to the land cover class.

Description of the case study

The Upper Neckar catchment is located in southwest Germany. Figure 1 shows the study catchment area together with stream gauging station locations. The study area is selected up to the Horb gauging station, having an extension of 1200 km^2. The maximum and minimum elevations are 1000 and 390 m a.s.l., respectively. The mean annual precipitation is 1210 mm. The mean daily temperature is 7.8°C. Coniferous trees are the most dominant vegetation, especially in the western part of the catchment. The main stream length is around 61.5 km. The mean annual runoff at the outlet Horb is 14.87 m^3 s^{-1}.

The basic input elements for the model are precipitation and air temperature. The model can run with a time step coinciding with one of the observed precipitation, but submultiple time resolutions are also possible. The DEM, available with a resolution of 30 × 30 m, was resampled at 1 × 1 km spatial resolution, which is also the dimension of individual computational model grid. The map of the Curve Number (CN) is

Table 1 The AFFDEF model parameters and their values.

Parameter	Dimension	Method of estimation	Upper Neckar
Channel width/height ratio for the hillslope	–	Calibrated	92 949
Strickler coefficients for the N-classes of the roughness on the hillslope(a)	m$^{1/3}$ s^{-1}	Calibrated	5.01, 43.08, 6.12, 5.95
Channel width/height ratio for the channel network	–	Estimated	20
Maximum and minimum Strickler roughness for the channel network	m$^{1/3}$ s^{-1}	Estimated	6, 10
Constant critical source area	km^2	Estimated	21
Saturated hydraulic conductivity	m s^{-1}	Calibrated	0.01
Width of the rectangular cross section of the subsurface water flow	m	Calibrated	0.5
Bottom discharge parameter for the capacity of the infiltration reservoir	s	Calibrated	390 595
Multiplying parameter for the capacity of the infiltration reservoir	–	Calibrated	0.40
Multiplying parameter for the capacity of the interception reservoir	–	Calibrated	0.13

[a] N = 4 classes of land use were assumed in this application.

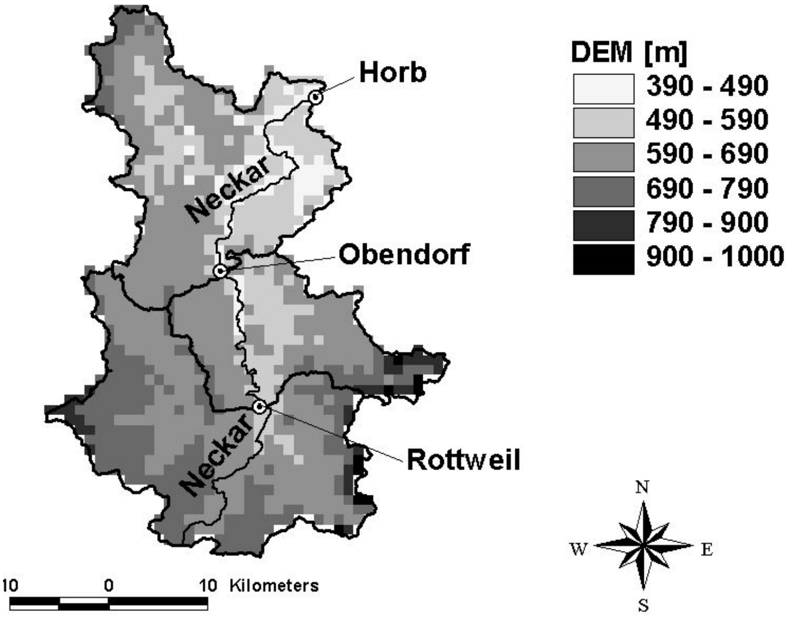

Fig. 1 Catchment study area and gauging station locations.

required as input to characterize the spatial pattern of the infiltration capacity of the drainage area. The value of the CN depends on the soil type and land use and was estimated with reference to the tables provided by the USDA (Soil Conservation Service, 1972). Also, the required information was extracted from a soil map (1:200 000 scale) and land use/land cover map (LANDSAT93 satellite images for the year 1992–1993) provided by the State Institute for Environmental Protection (LfU, Baden-Württemberg).

Daily mean discharge data for the outlet and the two internal gauging stations, namely Rottweil and Oberndorf (drainage area of 456 km^2 and 691 km^2, respectively), was also obtained from LfU, Baden-Württemberg. Daily precipitation and daily mean air temperature were obtained from the German Weather Service. The data obtained from the meteorological stations were basically point data, and there was a need to interpolate them in order to calculate areal values for each grid. The external drift kriging method (Ahmed & de Marsily, 1987) was chosen for interpolation so that orographic effect is taken into account by using the topography as an additional variable. This method was utilized to produce spatially distributed precipitation and temperature data at 1 × 1 km grid resolution. Because the temperatures show a fairly constant lapse rate, topographic elevation was used as the drift variable for interpolating the temperature. The rate at which precipitation change decreases with increase in elevation should be noted. The square root of the topographic elevation was assumed as a good approximation to account for such variation and it was used as the drift variable for precipitation.

Methodology

The model was automatically calibrated by means of the Shuffled Complex Evolution Algorithm (Duan *et al.*, 1993). The objective function to be minimized was the square difference between the observed discharge and the simulated discharge (*SDSO*):

$$SDSO = (q_s(t) - q_o(t))^2 \tag{1}$$

where $q_o(t)$ is observed daily discharge (m^3 s^{-1}) and $q_s(t)$ is simulated daily discharge (m^3 s^{-1}).

The model was calibrated utilizing daily discharge measured at the Horb basin outlet for the period of 15 June 1961 to 31 July 1962. Also, the simulated river flows were compared with the observed discharge at Horb and at the two internal gauging stations.

Finally, a set of simulations was carried out to investigate if the variation of the internal model time step may improve the performance of the model. Two sub daily time steps were considered, namely 6 h and 12 h. Also, the daily time series of precipitation data was disaggregated at the above mentioned time scales assuming equal distribution within the day, while the daily mean air temperature was kept constant throughout the day. The model was calibrated in both cases utilizing the daily discharge at the Horb basin outlet. Also, the results of the simulation were assessed for both calibration and validation period. The values of the calibrated parameters for the simulation with daily time step are listed in Table 1.

RESULTS

The simulation results were compared using the Nash-Sutcliffe coefficient R^2 (Nash & Sutcliffe, 1970) given as:

$$R^2 = 1 - \left(\frac{(q_s(t) - q_o(t))^2}{(q_o(t) - q_m)^2} \right) \tag{2}$$

where $q_o(t)$ is observed daily discharge (m^3 s^{-1}), $q_s(t)$ is simulated daily discharge (m^3 s^{-1}), and q_m is mean observed daily discharge (m^3 s^{-1}).

The relative accumulated difference and peak error were also computed to judge the performance of the model in maintaining the water balance and its estimation capacity for peak flow. Accordingly, the relative accumulated difference (*rel.acc.diff.*) was computed as shown below:

$$rel.acc.diff. = \frac{\sum q_s - \sum q_o}{\sum q_o} \tag{3}$$

where the peak error is equal to:

$$peakError = \frac{\overline{q}_{s(\max)} - \overline{q}_{o(\max)}}{\overline{q}_{o(\max)}} \tag{4}$$

where $\overline{q}_{s(\max)}$ is mean annual maximum simulated discharge and $\overline{q}_{o(\max)}$ is mean annual maximum observed discharge.

Tables 2 and 3 show the model performance for different simulation time steps in the calibration and validation period, respectively. It can be seen that the model was

Table 2 Model performance for different simulation time steps (calibration phase).

Simulation timestep	Horb R^2	*rel.acc. diff.*	*peak error*	Obendorf R^2	*rel.acc. diff.*	*peak error*	Rottweil R^2	*rel.acc. diff.*	*peak error*
Daily	0.826	–0.086	–0.077	0.728	–0.147	–0.256	0.705	0.029	–0.397
12 hours	0.829	–0.127	–0.040	0.724	–0.216	–0.205	0.712	–0.090	–0.370
6 hours	0.824	–0.129	–0.04	0.719	–0.221	–0.197	0.713	–0.087	–0.360

Table 3 Model performance for different simulation time steps (validation phase).

Simulation timestep	Horb R^2	*rel.acc. diff.*	*peak error*	Obendorf R^2	*rel.acc. diff.*	*peak error*	Rottweil R^2	*rel.acc. diff.*	*peak error*
Daily	0.711	–0.056	0.002	0.651	–0.037	–0.134	0.622	–0.097	–0.179
12 hours	0.705	–0.087	0.055	0.646	–0.094	–0.102	0.625	0.003	–0.160
6 hours	0.697	–0.081	0.055	0.640	–0.087	–0.099	0.622	0.013	–0.145

able to simulate river flows quite well both at the outlet and at the internal cross sections considered as ungauged. The Nash-Sutcliffe coefficient was comparatively low at the internal locations with respect to the Horb calibration section. The least value of Nash-Sutcliffe coefficient was obtained at Rottweil, which is the farthest gauging station from the calibrating one. Also, model performance was not improved by simulating river flows at sub daily simulation time steps.

Figure 2 shows the comparison between simulated and observed discharge at Horb produced with a daily time step for the maximum flood event that occurred during the validation period. It can be noticed that low flows and medium peak flows were estimated well, while higher peak flows were underestimated, especially during the late winter and spring. This may be due to an improper representation of snow accumulation and snow melting phenomena or the simplification adopted in the model to simulate water redistribution in the soil.

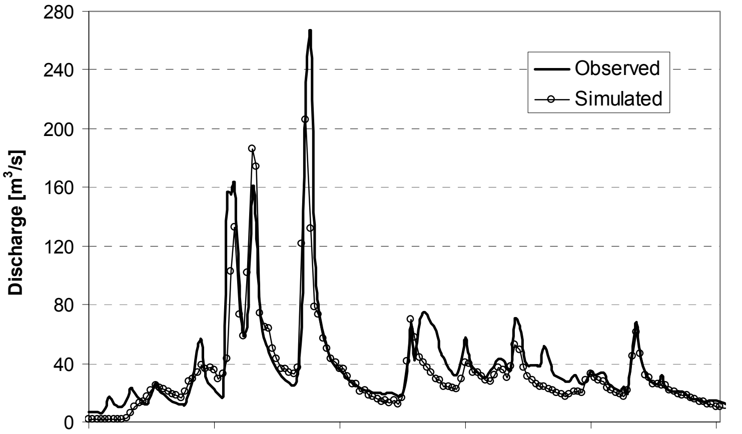

Fig. 2 Comparisons between simulated and observed discharge at Horb for the maximum peak registered in the validation period.

A detailed representation of the model performance corresponding to the internal river sections is provided in Fig. 3. From the scatter plots, it can be observed that good reproduction of low flows and medium peak flows was provided, while the points representing the higher peak flows diverge from the 45° line.

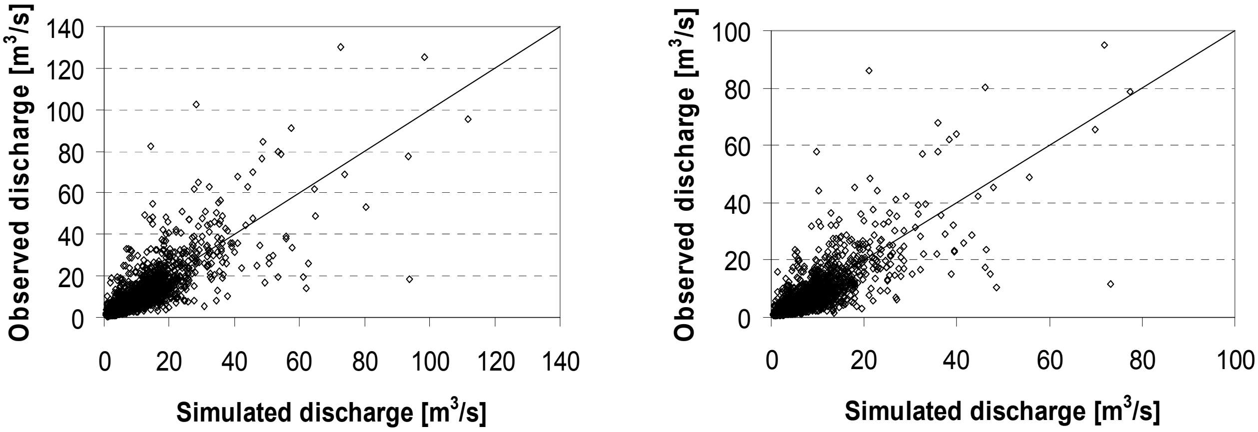

Fig. 3 Scatter plot of simulated and observed discharge in the validation period at (a) Obendorf and (b) Rottweil.

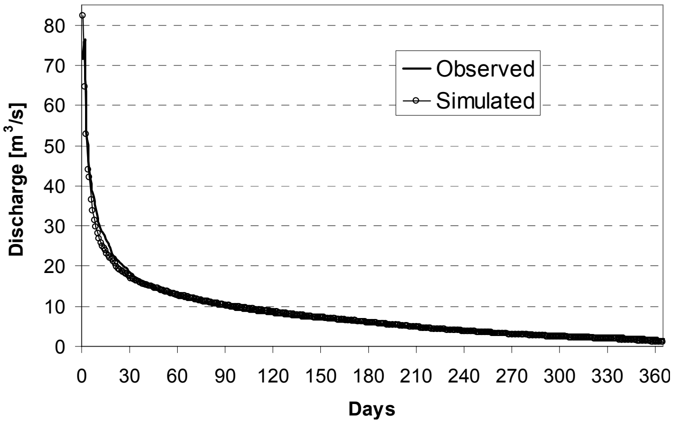

Fig. 4 Flow duration curves for the validation period at Obendorf.

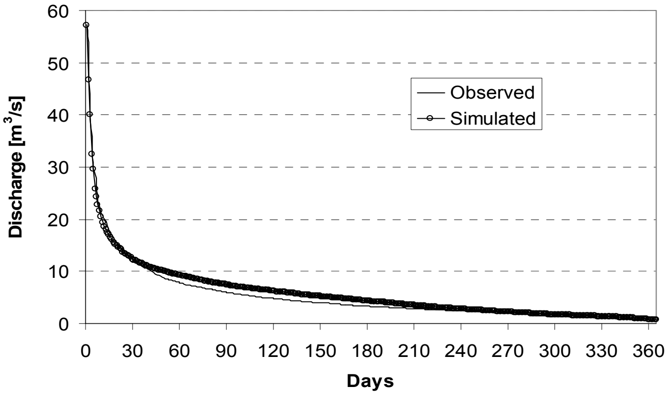

Fig. 5 Flow duration curves for the validation period at Rottweil.

Figures 4 and 5 show the flow duration curves at Obendorf and Rottweil, respectively. It can be concluded that the mean values of observed and simulated discharge matched relatively well.

CONCLUSIONS

The AFFDEF model was applied to a portion of Upper Neckar catchment to generate river flows in internal river sections considered as ungauged and, then, to assess its performance when applied for prediction in ungauged basins. The values of the goodness-of-fit indexes showed that the model was able to simulate river flows at different spatial scales with reasonably good results. In particular, the Nash-Sutcliffe coefficient for Rottweil, which is the farthest cross-section from the calibrating one, was equal to 0.622 for the validation period with daily time step. The good performance of the model is probably due to the spatial description of the characteristic of the catchment allowed by the model, and the spatial distribution of the main forcing input data. On the other hand, simulating the river flows with different sub daily simulation time steps did not improve the model performance in either the calibration or validation phases. To obtain improved performance, one probably needs a temporally highly resolved main forcing input data. The flow duration curves obtained at the internal river sections were well represented. The results of such modelling can be used for water resources planning purposes.

This research shows that spatially distributed rainfall–runoff models might be useful tools for computation of river flows on internal river sections, where historical discharge records are not available. Nevertheless, it is expected that the outcomes summarized above were influenced by the characteristics of the case study and the type of rainfall–runoff model that had been used. Similar experiments, carried out by considering different spatially distributed rainfall–runoff models and other case studies, may confirm the achieved results.

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