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Applying radar rainfall data in basin hydrological modelling

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Abstract To assess the advantage of basin-scale hydrological modelling gained from using radar rainfall data as input over the standard gauge measurements, this study applied the WSR-88D level III hourly radar rainfall data of the National Weather Service, USA, to simulate the basin hydrology of the Blue River basin using the physics-based hydrological model, DPHM-RS. To reduce the errors of radar rainfall data, the radar data are first re-sampled with respect to the gauge rainfall data of Oklahoma Mesonet by the statistical objective analysis (SOA) approach. Preliminary results show that adjusting the radar rainfall data by SOA improved the simulated runoff hydrograph.

Key words gauge rainfall data; hydrological modelling; radar rainfall data; statistical objective analysis

INTRODUCTION

To overcome the limitation of point measurements from raingauges, there is a growing interest in utilizing radar data for basin-scale hydrological modelling (Sun *et al.*, 2000). Since radar rainfall data are derived from radar echoes, there is also a need to analyse errors associated with precipitation estimated from different radar processing techniques (Borga, 2002). This study uses the WSR-88D level III hourly rainfall estimates supplied by the Hydrology Laboratory (HL) of the National Weather Service (NWS) office, USA, meteorological data of Oklahoma Mesonet, and a semi-distributed hydrological model, DPHM-RS developed by Biftu & Gan (2001).

Major sources of errors affecting the WSR-88D level III hourly rainfall estimates are radar electronic calibration, the *Z–R* relationship, rainfall attenuation, radar range effect, anomalous propagation, ground cluster, beam filling, and the radar sampling strategy (Austin, 1987), and techniques used to produce stage III data from stage II products, such as averaging the overlapping radar bins. In general, more spatially and temporally variable spring and summer convective rainfall is better represented by radar data than the sparse raingauges, while the less variable stratiform winter precipitation could be well captured by sparse raingauges (Stellman *et al.*, 2001). This study focuses on the following objectives:

(a) To assess the advantage of basin-scale hydrological modelling gained from using radar rainfall data as input over the standard input of gauge measurements in terms of basin subdivision and radar data resolution.
(b) To integrate radar rainfall fields with gauged rainfall data via a statistical objective analysis scheme as an effort to reduce errors in terms of storm type (i.e. convective and stratiform storms), and storm size.

DESCRIPTION OF STUDY SITE

The study site is the Blue River basin (BRB) of the South Central Oklahoma, where its stream gauging station is located at latitude 33°59′49″N and longitude 96°14′27″W, 1.6 km west of Blue, Oklahoma, USA (see Fig. 1). Its elevation ranges from 153 to 350 m a.m.s.l. and there is no impoundment on the Blue River. Woody savannah is the dominant vegetation cover, occupying almost 80% of BRB. The major soil group of BRB is clay loam mixed with sand or silt in some portions. The average annual precipitation ranges from about 400 mm in the extreme western panhandle to 1420 mm in the southeastern corner of the State (NOAA, 1977). In winter, Oklahoma lies in the southern range of the polar jet stream and the northern range of the subtropical jet stream, leading to extremely variable temperature, precipitation (rain, ice and snow), strong winds, and blizzard conditions. The January temperature ranges from a daytime high of 20°C to a nighttime low well below zero. The primary source of moisture is from the Gulf of Mexico. The Pacific Ocean off the coast of Mexico is a source of moisture under certain airflow patterns. Much of the spring precipitation results from large thunderstorms, many of which produce tornadoes and large hail. These severe storms occur as surface low-pressure and frontal systems develop when a transient upper-air trough approaching from the west interacts with warm, moist air from the Gulf of Mexico (Tortorelli, 1991). Further, important moisture sources include local and upwind land surfaces. Convective storms generally move eastward across the state to provide most spring and early summer rainfall. If intense thunderstorms repeatedly develop over the same terrain for several hours or days, localized flooding can be massive.

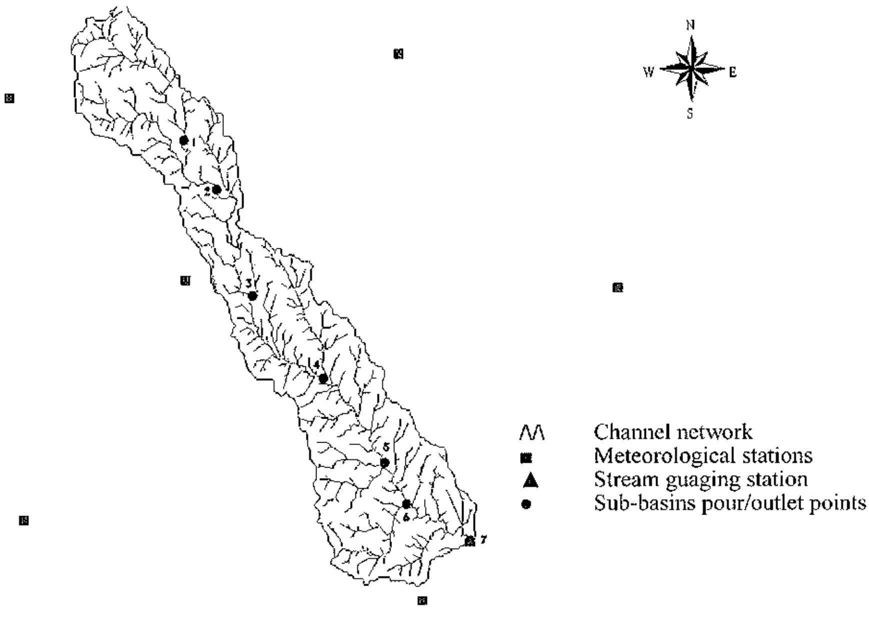

Fig. 1 Location map of Blue River basin indicating channel network, meteorological stations, streamflow gauging station, and sub-basins pour/outlet points.

RESEARCH METHODOLOGY

The research methodology comprises of the following:

(a) Assess the difference between the observed and the simulated runoff hydrograph of BRB by DPHM-RS model driven by: (a) gauge rainfall data; (b) radar rainfall data; (c) mean aerial precipitation (MAP) of gauged data; and (d) MAP of radar data, for convective (spring and summer) and stratiform (winter) storms.

(b) For the WSR-88D hourly stage III data produced via the global, conceptual processing technique of Krajewski (1997), a variation of the statistical objective analysis (SOA) scheme of Preira Fo *et al.* (1998) was applied to refine the radar rainfall data to better reflect local conditions by statistically re-sampling the WSR-88D stage III data (see Fig. 2) with respect to the tipping bucket measurements of Oklahoma Mesonet, and the adjusted radar data assessed as described in (a).

(c) At 4 × 4 km resolution, BRB can be covered by about 1024 cells of radar data (see Fig. 2). To gain an idea of the optimum radar data resolution based on storm types, repeat the tests of (a) at coarser resolutions, such as 8 × 8, etc., to 128 × 128 km.

(d) To study the effect of basin subdivision on the simulated hydrograph, BRB was subdivided into a number of sub-basins (e.g. see Fig. 3) and tests described in (b) were repeated to determine an optimum basin subdivision.

DESCRIPTION OF DATA

Radar rainfall estimates

The techniques used to derive operational WSR-88D hourly products are divided into three stages (Seo *et al.*, 1999). Stage I involves producing the Hourly Digital Precipitation (HDP) from individual radars of the National Weather Service (NWS) at a spatial resolution of approximately 4 km × 4 km, on a polar stereographic projection called the Hydrological Rainfall Analysis Project (HRAP) grid. Then, depending on what is the prevailing weather condition, a standard Z–R relationship ($Z = 300R^{1.4}$) or a tropical Z–R relation ($Z = 250R^{1.2}$) is used to convert the radar measured reflectivity (HDP) into a radar rainfall rate estimate, called a stage I product.

Stage II deals with the data quality control that consists of correcting the mean-field bias, the filling of missing values, and the removal of erroneous values of the hourly radar product (stage I). Bias is estimated from the difference between the rain-gauge-measured rainfall and the radar-derived values at the gauge's nine surrounding HRAP cells. This bias is computed for the non-zero gauge-radar pairs, with a minimum of three pairs used to calculate the mean field bias. The computed mean field bias is applied for the respective hour over the entire radar coverage area until a new set of gauge-radar pairs is obtained (Seo *et al.*, 1999). In the absence of at least three gauge-radar pairs for a given hour, the previous hour mean field bias is applied to the whole coverage.

If a gauge reports rainfall for a given hour while the radar data are missing, a maximum value at the gauge's site is assigned to all HRAP cells falling under the gauge's radius of influence. The gauge's radius of influence under the radar's umbrella

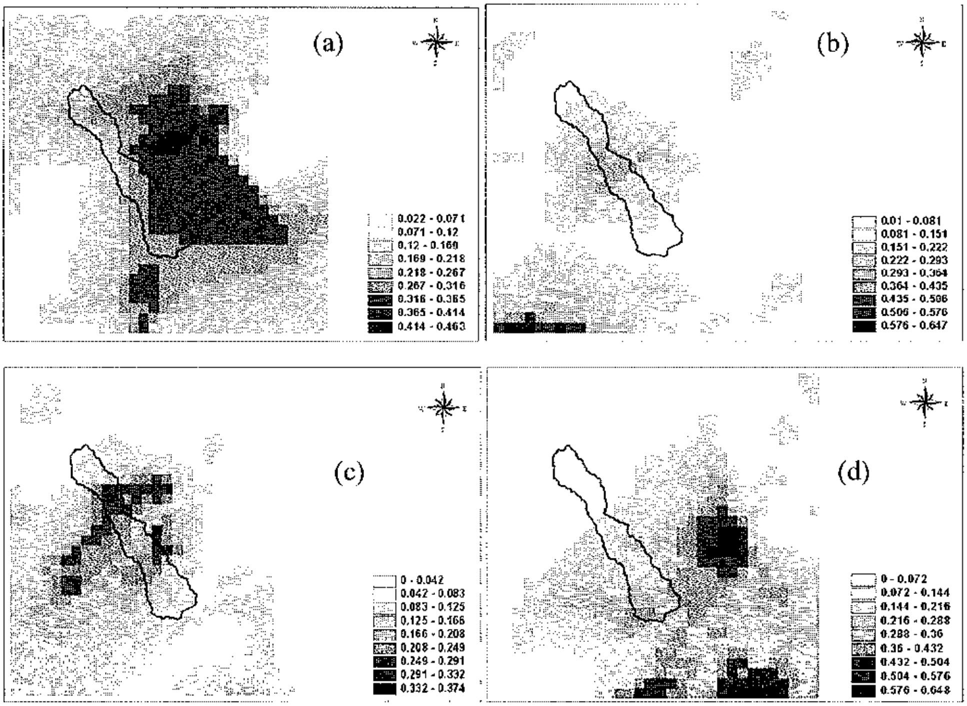

Fig. 2 Four episodes of radar rainfall (cm h^{-1}) occurring over BRB on 7 January 1998 at z-times (a) 00z, (b) 01z, (c) 02z, and (d) 03z.

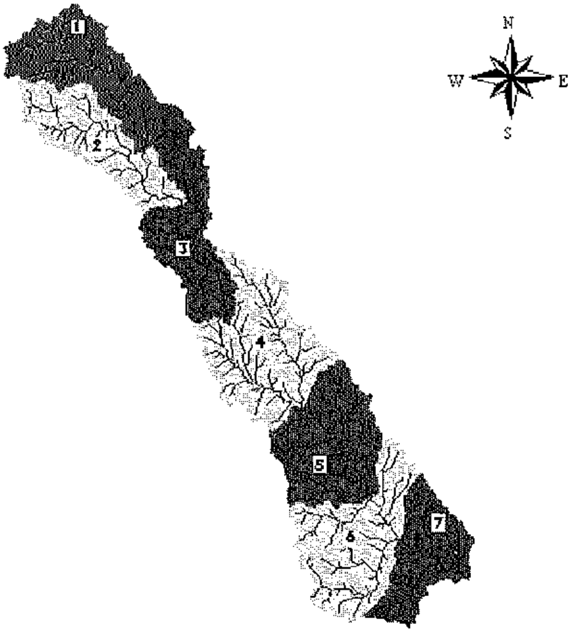

Fig. 3 Blue River basin sub-divided into seven sub-basins.

is typically two to three HRAP bins. On the other hand, for the case where radar data are available, but show rainfall over a gauge that reports zero, then the respective HRAP bin will be assigned a zero value. This process results to a stage II product.

In stage III, any erroneous gauge or radar data due to bright banding, ground clutter, or anomalous propagation are removed, followed by combining the individual stage II products from the respective radars within the area of coverage into a single mosaic. Specifically, for areas of overlapping radar coverage, the multiple values at a given HRAP grid are averaged. Pereira Fo *et al.* (1998) showed that this averaging, among other factors, leads to errors in the final stage III products of the WSR-88D network used for operational purposes (e.g. streamflow forecasting).

Land-use and terrain data

To drive the physics-based, DPHM-RS model of Biftu & Gan (2001) to BRB, the input data required are the topographic data, land-use/cover, soil data, meteorological data, channel cross-section, depth of groundwater table, and observed streamflow data. The land-use classes determined from the Arc/Info GIS for BRB consist of 78% woody savannah, 14% deciduous needle leaf forest, 4% evergreen needle leaf forest, 2% grasslands, 1% croplands, and 1% urban and built-up areas. Based on the 100 m × 100 m resolution DEM data, the basin was divided into seven sub-basins (Fig. 3). The slope, flow direction, flow accumulation, mean elevation, and topographic soil index of each sub-basin was also determined. Four dominant soil types were identified for BRB: loam, clay, sandy clay loam, and silty clay loam. Hourly hydroclimatic data such as air temperature, global solar radiation, relative humidity, wind speed, soil temperature, and gauge measured rainfall data were taken from the Oklahoma Mesonet. The hourly ground heat flux and net solar radiation were estimated within DPHM-RS.

STATISTICAL OBJECTIVE ANALYSIS (SOA) AND DPHM-RS

SOA scheme

As an effort to reduce errors in the stage III radar rainfall data described in the previous section, the radar precipitation data were re-sampled with respect to raingauge measurement using the SOA scheme originally developed by Gandin (1963) and modified by Pereira Fo *et al.* (1998). The SOA scheme exploits the strength of both systems, such that weather radar maps out the spatial details more accurately while raingauges measure the mean value of precipitation field more accurately than radars. By combining these two data sources we can potentially improve the rainfall estimates and consequently the estimated flow hydrograph.

SOA will be applied to the WSR-88D stage III radar rainfall data of BRB on a seasonal time series since we expect the correlation structure of rainfall fields to differ between seasons, e.g. winter in BRB is dominated by stratiform storms, while spring and summer are more subjected to convective storms. The proposed analysis equation used in SOA is:

$$R_a(x_j, y_j) = R_r(x_j, y_j) + \sum_{n=1}^{N} w_{jn}\left[R_g(x_n, y_n) - R_r(x_n, y_n)\right] \tag{1}$$

where $R_a(x_j,y_j)$ is analysed rainfall (mm) at grid point j; $R_r(x_j,y_j)$ is radar estimated rainfall (mm) at j; $R_g(x_n,y_n)$ is raingauge rainfall measurement (mm) at station n; $R_r(x_n,y_n)$ is radar estimated rainfall (mm) at station n; w_{jn} is *a posteriori* weight; N is the number of raingauge stations; and (x, y) are coordinates (km).

As a necessary condition to determine the weights, we need to assume that the raingauge measurement (observation) and radar measurement (background) errors are uncorrelated and unbiased. The expected analysis error variance is minimized by differentiating equation (1) with respect to each of the weights, w_{jn}.

Hydrological model (DPHM-RS)

A physics-based hydrological model (DPHM-RS) (Biftu & Gan, 2001), designed to assimilate data in a semi-distributed approach, is used to simulate streamflow of BRB. The model is divided into six components: interception, evapotranspiration (ET), soil moisture, subsurface flow, surface flow, and channel routing (see Fig. 4). ET from land and vegetation is modelled separately, exchanges of energy and water fluxes at the land–atmosphere interface are considered to be one-dimensional (vertical), and a kinematic response function is used to route surface and sub-surface runoff from each sub-basin to the stream and then via a network of stream channels to the basin outlet.

DISCUSSION

For any hydrological modelling based on gauge rainfall data, we expect some discrepancies between the simulated and observed runoff hydrographs because gauge data are point measurements that cannot adequately account for the spatial variability of rainfall fields. On the other hand, the use of spatial radar rainfall data alone could still lead to simulated hydrograph that usually suffer in terms of an underestimation in volume/peak runoff than in phase shift because radar captures the spatial variability of rainfall events well but tends to underestimate the mean rainfall in comparison to raingauges. We therefore expect the integration of radar and gauge rainfall data to improve the basin rainfall estimation and hence the resultant simulated hydrograph to agree better with the observed both in phase and in runoff volume. As this point, the effect of radar data resolution on the resultant simulated hydrograph is difficult to predict, but we may find the optimum data resolution to be something other than 4 km, and dependent on the climatic and hydrological regime of the river basin. We would expect more accurate results from using radar rainfall than gauge rainfall data, especially if the basin is dominated by convective (more highly variable in space and time) than stratiform (less variable) storms.

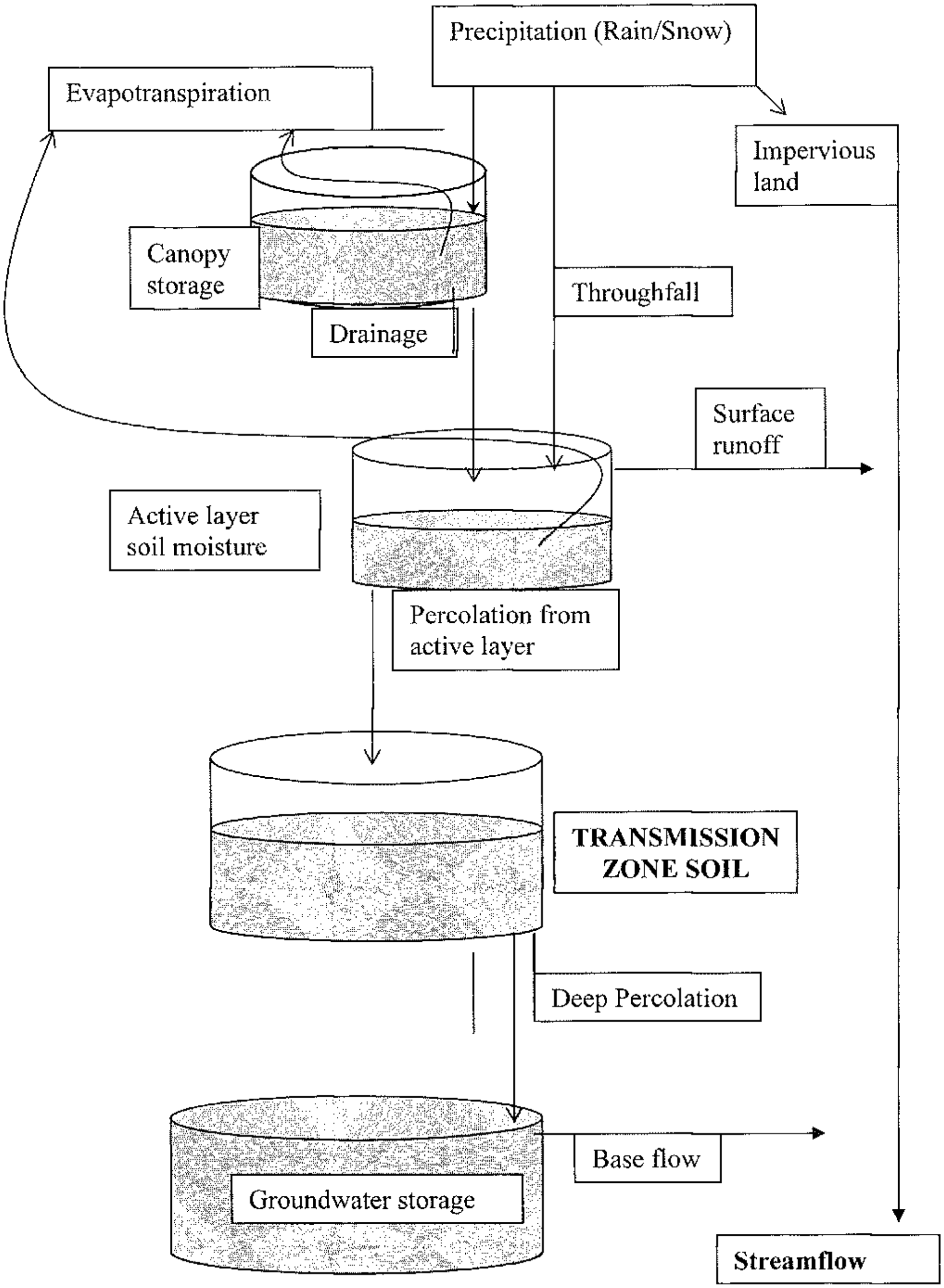

Fig. 4 A schematic diagram showing the major components of DPHM-RS.

PRELIMINARY RESULTS

The response function from a 1 cm effective rainfall (Fig. 5) for each of the seven sub-basins (Fig. 3) was derived using a kinematic wave equation. These response functions have a major influence on the final shape of the estimated basin outflow hydrograph because they are used to compute the actual surface runoff for each sub-basin. With 57 grids of radar rainfall data falling within the BRB, each sub-basin had an average of eight grids (ranging from 5 to 10 grids per sub-basin). The efficiency index (*Ef*) of Nash and Sutcliffe (1970) was used for statistical evaluation of model estimated hydrographs.

Generally the result (Fig. 6) shows that the model estimated hydrographs with gauge, radar, and radar adjusted (SOA) rainfall input forcing both failed to predict the second peak of the observed hydrograph. This can partly be attributed to the sub-division of the basin as evidenced by: (a) the sub-basin's response functions (Fig. 5);

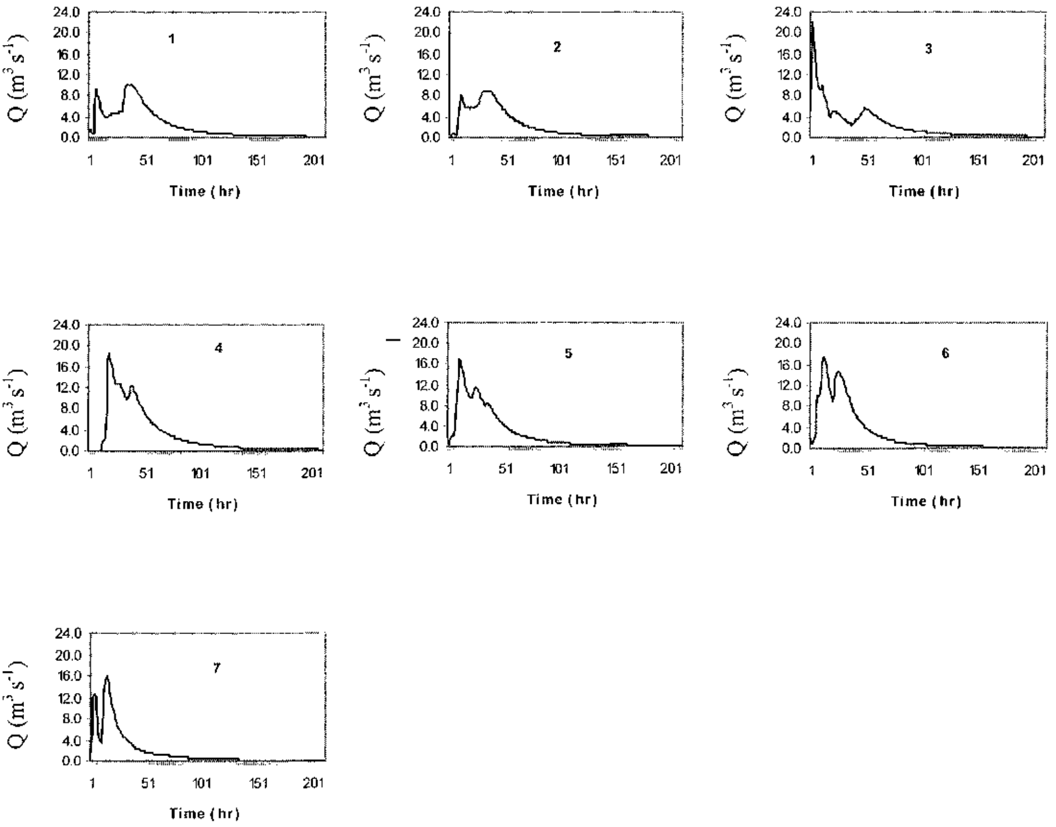

Fig. 5 Kinematic response (routing) function for each of the seven sub-basins of the Blue River basin (BRB).

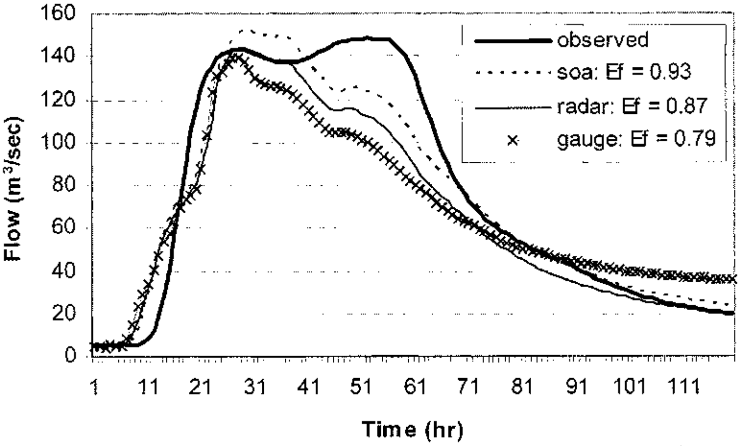

Fig. 6 Comparison of observed and estimated hydrographs for the period of 13–17 March 1995 using different rainfall estimation methods (*Ef* is the simulation efficiency of Nash & Sutcliffe, 1970).

(b) the DPHM-RS model structure, particularly the surface runoff component (Fig. 4); (c) spatial rainfall distribution for this particular rainfall event; and (d) magnitude and duration of the storm/flood event. This will be explored further by: (a) comparing the amount of average rainfall for each sub-basin to see if more rainfall was concentrated on sub-basins with a dominating single peak response function, namely 3, 4, and 5 (Fig. 5); (b) simulating a hydrograph for medium and small storm/flood events; and (c) combining sub-basins with similar response function among each other (e.g. 1 and 2) and with the observed hydrograph to allow them to have a large influence on the final outflow hydrograph which can lead us into obtaining an optimum subdivision of the basin.

Comparing the hydrographs simulated by the three rainfall forcings, namely, gauge, radar, and SOA shows that, SOA produced a better overall outflow hydrograph (*Ef* = 0.93), even though it overestimated the first peak of the observed hydrograph. The radar input rainfall predicted well the first observed peak but it systematically under-estimated the observed hydrograph thereafter, and hence its simulation efficiency (*Ef* = 0.87) was lower. The gauge estimated hydrograph (*Ef* = 0.79) was relatively poor, partly because not one raingauge (out of six) falls within BRB. The adjusted radar rainfall data produced a better hydrograph in both total volume and phase as compared to radar or gauge data alone because it combined the capability of radar to capture the spatial distribution of rainfall (resulting in better phase prediction of the hydrograph) and the more accurate mean rainfall recorded by raingauge. This is evident particularly at the tail part of the estimated hydrographs (Fig. 6) where the radar estimated hydrograph is much more in-phase with the observed hydroraph, followed by SOA and finally by the gauge data alone.

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