INTEGRATION OF WEATHER RADAR DATA INTO A RASTER GIS FRAMEWORK FOR IMPROVED FLOOD ESTIMATION

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Abstract

Weather radar data were used to estimate rainfall fields at 2-km resolution for a large flood event in 1999 in southeast Queensland, Australia, and subsequently integrated with a raster-based hydrologic model for runoff generation and flow routing. Gauge-based and radar-based temporal storm patterns are quite similar for the storm event. Considerable under-estimation of radar-based total rainfall occurred in relatively low rainfall areas. This bias cannot be removed without a spatially variable reflectivity-intensity relationship for the basin during the storm event. The hydrologic model works very well when calibrated against the measured hydrograph. Underestimation of peak discharge was noted for uncalibrated sites in other parts of the basin largely because of the bias in radar-based rainfall estimates.

Key Words: Subtropical, Brisbane, URBS, RAMS

Introduction

Accurate rainfall data with a sufficiently high spatial and temporal resolution are critical to short-term storm and flood forecasts. Use of weather radars can significantly improve the spatial resolution of rainfall data over a large area (> 1000km^2). Once calibrated against ground measurements, time series of rainfall fields can be input to hydrologic models for flood estimation and forecasting (Odgen *et al*., 2002). Thus, radar calibration and integration of estimated rainfall fields with runoff models are two crucial steps in hydrologic application of weather radars.

For the temperate region of Australia, weather radars have been calibrated at hourly intervals for selected storm events (Seed *et al.*, 2002). While the coefficient in the rainfall reflectivity-intensity (*Z*-*R*) relationship varied greatly between storm events, the agreement between gauge-based and radar-based measurements was quite encouraging. For tropical and subtropical regions of Australia, however, calibration of radar-based rainfall measurements has not yet been attempted for individual storm events at hourly intervals.

At present, Australian Bureau of Meteorology (BOM) operates the URBS rainfall-runoff model for flood warning purposes (Carroll, 1996; Malone, 1999). To implement the URBS model for flood estimation, a catchment is divided into a number of sub-areas. Rainfall total for a flood event was determined for each sub-area, and temporal storm patterns derived from pluviometers in the catchment were assigned to individual sub-areas. The size of sub-areas can vary widely both within a catchment and between catchments, and the number of pluviometers used is often much less than the number of sub-areas. Coupling radar data with the URBS model therefore would require re-sampling the rainfall data into these arbitrarily defined sub-areas. The advantage of having rainfall data with high spatial resolution is diminished in the re-sampling process.

The objectives of this study are 1) to calibrate a WSR74 S Band radar in the subtropical southeast Queensland for a large storm event; 2) to apply the calibrated rainfall field to a raster-based hydrologic model for runoff generation and flow routing. The hydrologic model operates at a spatial scale, both in resolution and extent, which is compatible with radar-based rainfall measurements.

Data and Method

This study is focused on the Brisbane River Basin in southeast Queensland, Australia. The basin area is 13,600 km^2. The climate is subtropical with a mean annual rainfall of about 934 mm (based on 110 years of rainfall data at Esk, near the centre of the basin), with 68 % of rain occurring in the summer half of the year (October – March).

The Queensland Regional Office of BOM in Brisbane operates a WSR74 S Band radar at Marburg (27.61°S, 152.54°E, 370 m a.s.l.), about 53 km west of Brisbane. The radar transmitted radiation with a wavelength of 10 cm and produced a beam with a 3 dB width of 1.7°. This radar was operated in a volume scan mode, collecting data from 15 elevation angles every 10 minutes. The data resolution was 1° in azimuth and 1000 m in range, to a maximum range of 256 km.

The CAPPI (constant altitude plan position indicator) reflectivity data used in this study were extracted from the raw data at a nominal elevation of 1.5 km and spatial resolutions of 2x2 km^2. Polar to Cartesian conversion was done by averaging the reflectivities returned from all the range bins falling within a given 2 km pixel. The beam angle that has its centre closest in elevation to 1.5 km is chosen for each pixel.

The URBS rainfall-runoff model has been calibrated by BOM for a number of flood events in the Brisbane River Basin. Large storm events were selected to calibrate radar-based rainfall fields for the period from 1999 to 2001. The February 1999 event was the largest of three flood events in the 3-year period. The spatially averaged rainfall total was nearly 200 mm for the event. Most of the rain occurred over a 3-day period (7-9 Feb), covering a wide area in southeast Queensland. 10-min reflectivity data for the event were aggregated into hourly rainfall intensity to calibrate with gauge measurements. Hourly radar-based data were extracted from those 2x2km^2 cells in which gauges were located. The following relationship between a reference rainfall intensity, R_o, and reflectivity, Z was used:

$$Z = R_o^{1.6} \qquad (1)$$

The exponent value of 1.6 was selected based on an investigation of the climatological *Z-R* relationship for the site (Fields *et al*., this symposium). The coefficient, A, to convert the reference rainfall intensity to predicted rainfall intensity, as in

$$R = AR_o \qquad (2)$$

was estimated using

$$A = \frac{\sum_{i=1}^{N}\sum_{j=1}^{M} G_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{M} R_{o\,ij}} \qquad (3)$$

where G_{ij} is ground-level measured rainfall intensity for gauge i, and time interval j., and N is the number of rain gauges and M the number of time intervals. Estimation of the coefficient A, using (3) ensures that there is no bias in the spatially averaged rainfall for the whole event. The quality of the radar-based rainfall field was assessed by comparing time series of the gauge-based and radar-based average rainfall intensity and total rainfall amount for the event.

Around 100 tipping bucket rain gauges were in operation during these storm events. The discrete tipping bucket data have been regularised at hourly or half-hourly intervals for the URBS model. Data from several gauges were discarded for calibrating the coefficient A in equation (3). Some were from duplicate or nearby stations, and others obviously contained incorrect data. Those gauges located within 10 km of the radar were also eliminated for calibration purposes because visual examination of the rainfall field showed that rainfall intensity was consistently low in the vicinity of the radar. Two gauges were not used for calibration because the radar-based estimates were unreasonably high (see also Fig. 2). In the end, gauge data for 55 rainfall stations were used for the Feb 1999 event.

A 2 km raster digital elevation model (DEM) was prepared from the original 9 second DEM to match the resolution of rainfall fields. Flow direction and accumulation, and slope were derived from the 2 km DEM with ArcGIS. Spatially distributed vegetation and soil data at the same resolution were also available for the catchment.

The radar-based runoff generation and flow routing model has two inter-related components: The first component simulates the soil moisture balance and runoff generation through either infiltration excess or saturation excess. The second component is based on kinematic wave approximation using an unconditionally stable routing algorithm. Either linear or non-linear storage-discharge relationships can be used. The initial spatial distribution of soil moisture deficit, *D*, is scaled by the topographic index used in TOPMODEL (Beven and Kirkby, 1979):

$$D \propto \ln\left(\frac{Ac}{L\tan\beta}\right) \qquad (4)$$

where *Ac* is the contributing area, *L* is contour width, and β slope angle. Only the minimum and maximum moisture deficits need to be specified for each model run. Grid size was used to represent the contour width. A spatially variable infiltration model of the form:

$$R_e = R - I_m \exp(-R/I_m)] \qquad (5)$$

where R_e is rainfall excess (mm/h), *R* rainfall intensity (mm), and I_m spatially averaged maximum rate of infiltration, was used to model infiltration excess. Equation (5) can be derived assuming that the maximum rate of infiltration follows an exponential distribution in space (Yu *et al.*, 1997). Yu *et al.* (1998) have shown that this infiltration model is superior to the constant loss and proportional loss models that have been widely used in engineering hydrology. More recently, Fentie *et al*. (2002) compared eight different approaches to estimate runoff rates. The method based on equation (5) out-performed all other models.

Kinematic wave approximation leads to a storage equation of the form:

$$\frac{dS}{dt} = I - Q \qquad (6)$$

where *S* is water in store, *t* time, *I* and *Q* are inflow and outflow, respectively. Unconditionally stable solution to (6), in discrete form, is

$$Q_i = \alpha Q_{i-1} + 0.5(1-\alpha)(I_{i-1} + I_i) \qquad (7)$$

where *i*, and *i*-1 indicate the current and previous time steps, respectively, and routing parameter, α, is given by

$$\alpha = \frac{K}{K + \Delta t} \qquad (8)$$

where *K* is the lag time and Δt the time interval (Yu *et al*., 1997). In the context of raster-based modelling framework, equation (9) can be re-arranged in the form:

$$\alpha = \frac{\sigma\lambda\Delta x}{\sigma\lambda\Delta x + v\Delta t} \qquad (9)$$

where Δx is grid size (m), *v* characteristic wave speed (m/s), and λ is the sinuosity (the actual distance over grid distance) and σ a dimensionless shape factor. σ = 1 for flow routing in directions across the grid, = 1.414 in the diagonal direction, and = 0.5611 for local inflow within each cell. A linear storage-discharge relationship is represented by a flood wave speed that is independent of discharge. A non-linear storage-discharge relationship can be formulated using the Manning's equation for overland and channel flows. Based on kinematic wave approximation, the non-linear relationship between flow rate and wave speed is given by:

$$v = \frac{5}{3}\left(\frac{\sqrt{s}}{n}q^{2/3}\right)^{3/5} \qquad (10)$$

where *q* is the unit discharge, i.e. discharge per unit flow width. It is worth noting that slope, infiltration parameter, I_m, Manning's *n*, channel width, and contributing area are spatially explicitly variables. Although not attempted in this paper, the infiltration and roughness parameters can potentially be calibrated as functions of measureable spatially explicit attributes such as land use, vegetation cover, and soil properties. The runoff generation and flow routing model is an integral part of a larger raster-based hydrologic modelling systems (RAMS). Other components of RAMS include rainfall erosivity mapping, and sediment generation and transport simulations (not presented in this paper).

The URBS rainfall and runoff model was implemented for flood forecasting purposes for 7 separate catchments in the Brisbane River Basin. Disparate initial loss amount and continuous loss rate values were used for different catchments. The initial loss amount varied from 20 to 110 mm, and the continuous loss from 1.5 to 2.93 mm/h for the event among the 7 catchments. Other parameters did not vary as much, and the exponent for the storage-discharge relationship was held constant for the 7 catchments. For this study, hydrographs at 18 locations from 4 of these catchments in the unregulated part of the Brisbane River Basin were considered. Hydrograph recorded at Gregor Creek (GS143009) was used to calibrate the following parameters for the entire basin: the minimum and maximum soil moisture deficit, D_{min} and D_{max}, the spatially averaged infiltration rate, I_m, and Manning's *n* value for the overland and channel flows. Although Manning's *n* can assume vastly different value for overland and channel flows. A constant value is applied for all cells in the Brisbane River Basin due to a lack of data to develop a spatially explicit relationship between catchment attributes and this roughness parameter at present. In addition, a sinuosity value of 1.5, and the following relationship between channel width and contributing area are assumed:

$$W = Ac^{0.5} \qquad (11)$$

where *W* is width in m, and *Ac* is the contributing area in km^2. Once calibrated, peak discharge and runoff volume were extracted for cells where the remaining 17 streamflow stations were located. These key runoff variables were compared with the recorded values for these sites to evaluate the model performance.

In this paper, Nash-Sutcliffe coefficient of efficiency, *E*, was used for all model comparison and assessment (Nash and Sutcliffe, 1970). A generic formula for *E* is:

$$E = 1 - \frac{\sum(P-O)^2}{\sum(O-\bar{O})^2} \qquad (12)$$

where *O* and *P* are observations and model predictions, respectively; and over-bar indicates the average and the summation is over all the observations. Root mean squared error (RMSE) is also presented. A generic formula for RMSE is:

$$RMSE = \sqrt{\frac{1}{N}\sum(P-O)^2} \qquad (13)$$

where *N* is the number of observations, and *O* and *P* are defined above.

Results

The total gauge-based rainfall varied from 54 mm to 515 mm for the February 1999 event. The coefficient *A* determined using equation (3) was 0.0534. Average rainfall intensity for the 55 rain gauges is shown in Fig. 1. This was a fairly prolonged event (> 3 days) consisting of at least 6 peaks in rainfall intensity. Predicted average rainfall intensity using the calibrated coefficient shows a similar storm pattern (Fig. 1). The agreement between observed and predicted average rainfall intensity is very good, although the intensity tends to be under-predicted at high intensities. The radar-based peak intensity (8.2 mm/h) is less than the observed peak intensity (10.8 mm/h). The Nash-Sutcliffe's coefficient of efficiency was 0.91 for the predicted spatially-averaged intensities. RMSE was 0.63 mm/h for the event, or 5.8% of the gauge-based peak intensity.

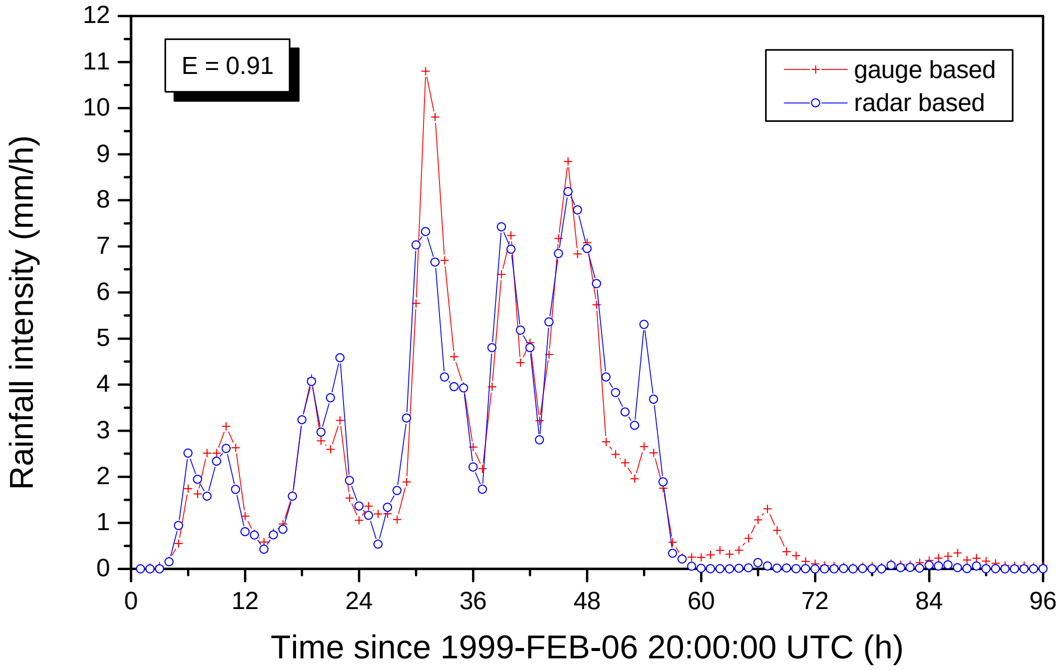

Fig. 1 Time series of spatially-averaged rainfall intensity. Measured intensity was based on 55 tipping bucket rain gauges. Predicted were averaged intensity values for cells in which rain gauges were located. Rainfall for the first 4 days was 192.6mm.

Gauge-based and radar-based event totals do not compare nearly as well as the result for temporal intensity patterns (Fig. 2). The *E* value was only 0.16. There is considerable bias in the radar-based rainfall estimates. Radar-based rainfall total is systematically higher than gauge rainfall to the north of the radar where the gauge rainfall was the highest. In areas of relatively low rainfall to the west and southwest, the radar-based rainfall estimates were considerably less than the gauge totals. The RMSE for event totals was 98 mm, or 51% of the average rainfall for the Feb 1999 event. It is worth stressing that this bias cannot be removed by adjusting the *A* value for the event unless the coefficient is allowed to vary spatially. The bias in the radar-based rainfall estimates has important implications for the hydrologic modelling results presented below.

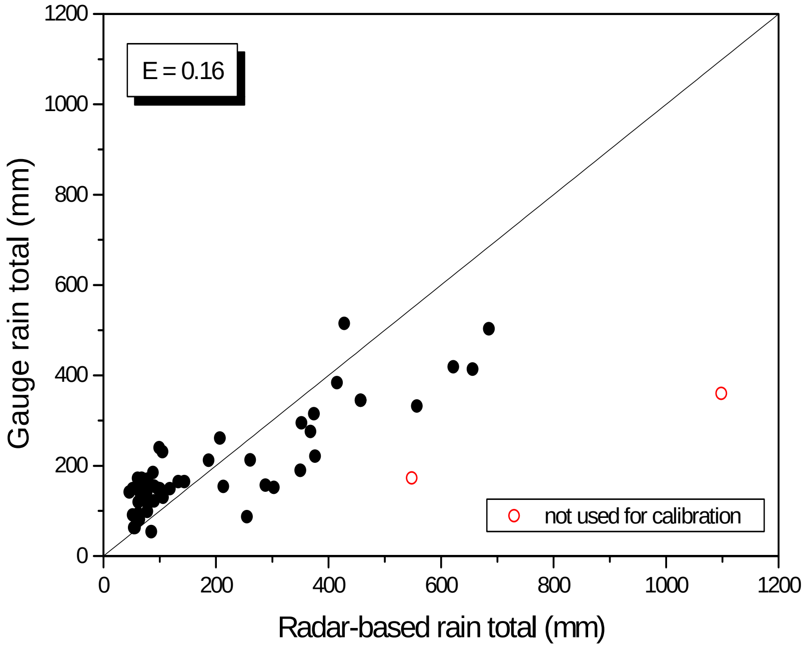

Fig. 2 A comparison of radar-based and gauge-based rainfall total for the February 1999 event.

Fig. 3 shows the calibrated hydrograph for 160 hours for the Feb 1999 flood event at the Gregor Creek gauging station in the upper Brisbane River Basin. The fit was excellent. It can be seen from Fig. 3 that the calibrated hydrograph using radar-based rainfall estimates is just as good as that generated with the URBS model. Following parameter values were manually determined:

$$D_{min} = 50\text{mm},\ D_{max} = 80\text{mm},\ I_m = 19.5\ \text{mm/h},\ n = 0.3.$$

To validate the integrated hydrologic model, predicted and recorded peak discharges were compared for 17 other sites in the unregulated part of the Brisbane River Basin. Fig. 4 shows that modelled peak discharge compares reasonably well with the measured peak discharge for sites located upstream from the calibration site. For sites located in other parts of the basin, there is nearly an order of magnitude under-estimation of the peak discharge. This under-estimation in peak discharge occurs in relatively low rainfall areas where radar-based rainfall was considerably less the gauge rainfall totals (see Fig. 2). The overall model efficiency for the 17 sites is 0.77, and RMSE was 310 m^3/s, or about 70% of the mean peak discharge for the 17 uncalibrated sites.

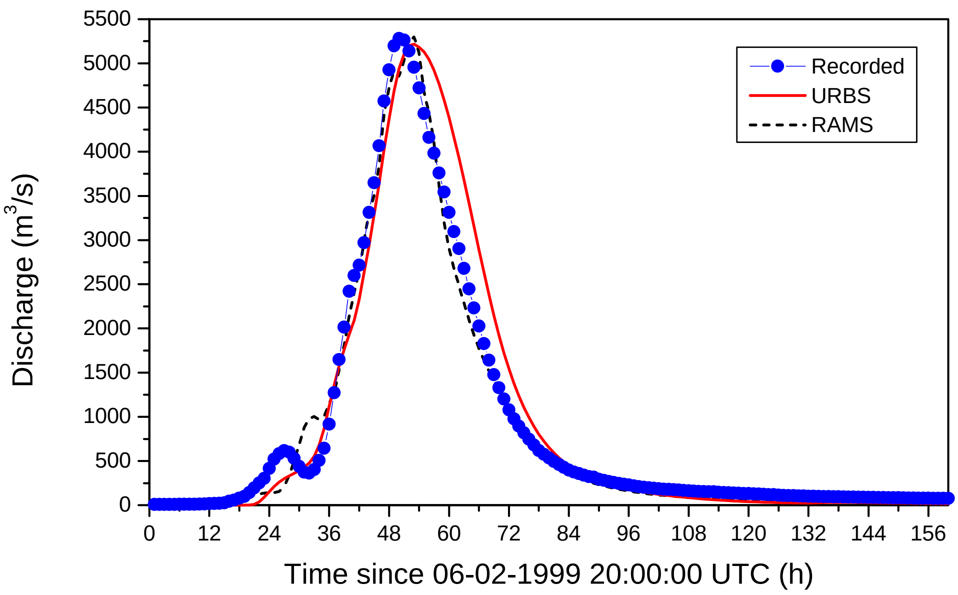

Fig.3 Recorded and calibrated hydrographs at Gregors Creek (GS143009) for the Feb 1999 flood in the upper Brisbane catchment.

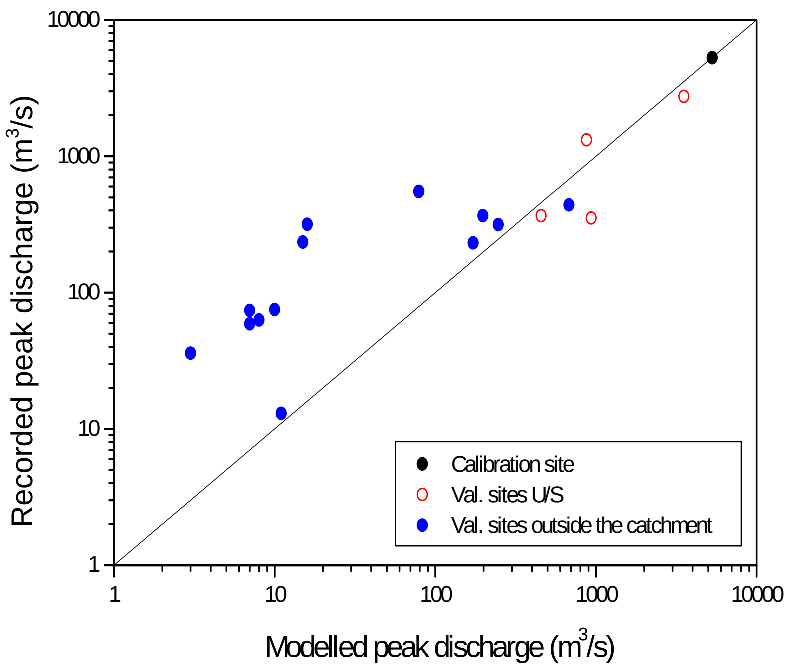

Fig. 4 Modelled and recorded peak discharge at 18 stream gauging stations in the Brisbane River Basin.

Discussion

Compared to conventional rainfall-runoff routing models relying on conceptual storage-discharge relationships for flood estimation, a raster-based model presented in this paper has the advantage and the potential of having spatially explicit representation of catchment attributes such as catchment topography, channel morphology, soils, vegetation, and land use. It also allows a seamless integration with rainfall fields estimated using weather radars at the same spatial scale. A critical input to the runoff generation and flow routing model is the spatial distribution of total rainfall. The bias noted in radar-based rainfall estimates indicates that the *Z-R* relationship may assume different sets of parameter values for different parts of the basin during the same storm event. It is sensible, therefore, to consider adjusting the coefficient *A* spatially for a better representation of the spatial rainfall distribution for flood forecasting purposes.

Conclusion

A raster-based runoff generation and runoff model was integrated with radar-based estimates of rainfall fields for the Brisbane River Basin (>10^4 km^2) having a subtropical climate. Testing and application of this approach for flood estimation have shown that gauge-based and radar-based temporal storm patterns are quite similar for a large storm event in February 1999. Under-estimation of radar-based total rainfall is considerable in low rainfall areas for the event, and over-estimation occurred in high rainfall areas. The bias in rainfall estimates cannot be removed without a variable *Z-R* relationship for the basin for the same storm event. The integrated weather radar-hydrologic model works very well when calibrated against measured hydrographs. Considerable underestimation of peak discharge occurred for uncalibrated sites in other parts of the Brisbane River Basin largely because of the bias in radar-based rainfall estimates.

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