Assessment of rainfall observed by weather radar and its effect on hydrological simulation performance

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Abstract Since the mid-20th century, using radar to measure rainfall has been deployed in many countries. The advantage of radar is that it can measure rainfall amounts and intensities over large areas during a storm. Therefore, this method has attracted the attention of meteorologists and hydrologists. However, radar rainfall measurement is an indirect method that can cause errors due to the signal transformations and the nature of the observed target. To improve the accuracy of radar rainfall measurement, it must be calibrated by using simultaneous recording gauge rainfall data. A case study on estimating the areal rainfall on Can Dang watershed, a drainage contributing area of Dong Nai River basin, by the Nha Be weather radar station in Ho Chi Minh City was undertaken. The effect of radar rainfall was assessed by means of applying the DHI NAM conceptual model. The results of the calibration and verification periods show that the radar rainfall provides a better hydrological simulation performance against that of the gauge data.

Key words hydrological simulation performance; radar rainfall

INTRODUCTION

Rainfall is the primary input into the hydrological cycle of watersheds and large river basins. While rainfall is the key source of water for people, excessive rainfall amounts can also lead to flooding. It is necessary, therefore, that hydrologists and watershed managers know how to measure rainfall and analyse the measurements that are obtained.

The most common method of measuring rainfall is to use gauges, typically cylindrical containers 20.3 cm (8 inches) in diameter. Three types of gauges in general use are the standard gauge, the storage gauge, and the recording gauge: (1) Standard or nonrecording gauges are often used because of economy, such gauges should be read periodically, normally every 24 h, at the same time each day. (2) Storage gauges have the same size opening as standard gauges but have a greater storage capacity, usually for 1525–2540 mm of rainfall; these gauges can be read periodically, for example, once a week, once a month, or seasonally. (3) Recording gauges including weighing and tipping-bucket types, allow for continuous measurement of rainfall but have a higher cost. The data observed by gauges are point rainfall values, which have to be extrapolated to get the mean depth of rainfall on a watershed, which is often required in many hydrologic investigations. Several methods are used in deriving this value. The three most common are the arithmetic mean, the Thiessen polygon, and the isohyetal methods.

Flood forecasting requires estimates of rainfall occurring in “real time”, meaning as it falls to the Earth’s surface, or shortly thereafter. Radar provides qualitative estimates of rainfall amounts and intensities over large areas during a storm, provided that radar coverage is sufficient. Radar senses the backscatter of radio waves caused by water droplets and ice crystals in the atmosphere. The area of coverage and relative intensity of rainfall can be estimated up to a distance of 250 km. Radar echoes can often be correlated with measured rainfall, but this calibration is hampered by ground barriers, raindrop size, distribution of rainfall, and other storm factors resulting in large errors (Sauvageot, 1994). Therefore, to improve the accuracy of radar rainfall measurement, it must be calibrated by using simultaneous measurement of gauge rainfall data.

Since the mid-20th century, using radar to measure rainfall has been used in many countries. Vietnam, at present, has a radar network including seven stations and planned to be developed to 15 stations by the year 2020. The advantages of rainfall measurement by radar are that it covers a wide area, and it is rapid as well as accurate in defining the rainfall location; thus this method is widely applied by meteorologists and hydrologists. In recent years many water resources studies related to flood control, irrigation, hydropower, domestic and industrial uses have used hydrologic studies of the rainfall–runoff relationship, which require accurate measurements of rainfall on a watershed.

This research presents a case study on determining rainfall by the Nha Be weather radar station for the Can Dang watershed, a drainage contributing area of the Dong Nai River basin in southeast Vietnam. To assess the accuracy of radar rainfall measurement, the DHI NAM rainfall–runoff model is used to examine its efficiency on hydrological simulation performance.

MATERIALS AND METHODS

Studied area description

The Can Dang watershed covering an area of 617 km^2 is located within 11°31′17″–11°51′53″N latitude and 105°58′45″–106°11′15″E longitude. The watershed of the River Ben Da is a drainage contributing area of the Dong Nai River basin in southeast Vietnam. Elevation within the watershed ranges from 10 m at the outlet to 204 m amsl at the top of the watershed divide. It has a tropical climate, with the mean annual values of precipitation, evapotranspiration and runoff depth of 1800 mm, 1195 mm and 605 mm, respectively, from the record period 1978–2010.

There is one hydro meteorological station at the outlet of watershed to measure water level, discharge and rainfall data. The discharges from gauging have just been observed a few times, and then based mainly on the Q–H relations to fill the data all the year. The rainfall has been measured by the standard gauge that is read every 24 h at 07:00 h each day.

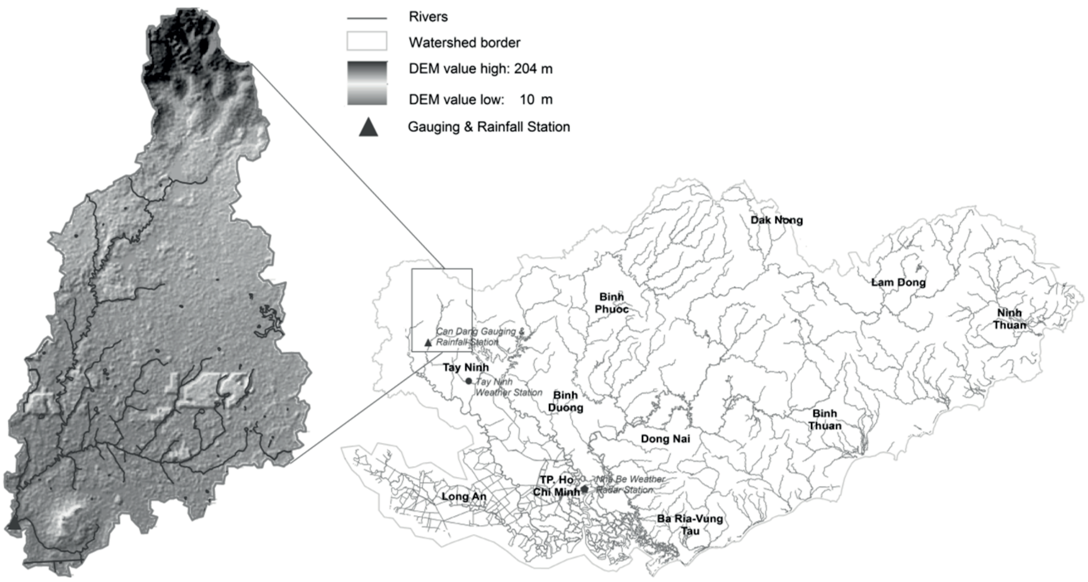

Fig. 1 Location of the Can Dang watershed in the Dong Nai River basin.

METHODOLOGIES AND DATA PROCESSING

The rainfall on the Can Dang watershed can be derived from the radar's signal at the Nha Be weather radar station. This station was established in 2005 at 10°39′35″N latitude and 106°43′40″E longitude, Long Thoi ward, Nha Be district, Ho Chi Minh City (see Fig. 1). Radar is of the type DWSR-2500C (Doppler Weather System Radar) manufactured by Enterprise Electronics Corporation (USA). It is capable of volume scan and wind speed measurements in a certain range. The radar's antenna has abilities to scan azimuth 360° and elevation angle from –2° to 90°. The radar when using C band (4–8 cm and 4–8 GHz) can reach to a maximum radius of 480 km, however its data should be used within 240 km (50%) to ensure reliability. The software EDGE 4.0 runs under LINUX 8.3 for displaying weather data and controlling weather systems. The radar has been operated 24/24 h with process configuration files of 10 minutes.

From products of the radar volume scan data such as PPIz (Plan Position Indicator for precipitation), CAPPI-1km (Constant Altitude Plan Position Indicator 1 km), PCP-1h (Precipitation 1 h), and then using EDGE software, rainfall data can be determined in the grid at 1 × 1 km resolution. Rainrate R is derived from the corrected intensity Z moment using the Marshall-Palmer equation (DRS-WS, 2004):

$$Z = A \times R^b \tag{1}$$

where the constants A and b are operator definable with values $A = 200$ and $b = 1.6$.

To improve the accuracy of radar rainfall measurement, it must be calibrated by using simultaneous gauge rainfall data, namely taking the gauge rainfall as a standard, then comparing with the values on the rain radar map. The radar rainfall data are often lower than the rainfall data measured on the ground, so therefore radar data need to be corrected by factor F as follows:

$$F = \frac{1}{N}\sum_{i=1}^{N} G_i / R_i \tag{2}$$

where G_i is rainfall intensity measured on ground (mm h^{-1}), R_i is radar rainfall intensity (mm h^{-1}), and N is the number of occurrences in various stages.

For this study area, correcting the radar rainfall was based on the gauge data at the Tay Ninh station being about 100 km distant from the Nha Be station (see Fig. 1), which uses a recording gauge for continuous measurement of rainfall.

To assess the efficiency of radar rainfall data in hydrological simulation, the rainfall–runoff model NAM is used. NAM is a traditional hydrological modelling system of the lumped conceptual type operating by continuously accounting for the moisture contents in four mutually interrelated storages. NAM was originally developed at the Technical University of Denmark and has been modified and extensively applied by Danish Hydraulic Institute (DHI) in a large number of engineering projects covering all climatic regimes of the world. Furthermore, NAM has been transferred to more than 100 other organizations worldwide as part of DHI's MIKE 11 generalized river modelling package (DHI, 2004).

The NAM application for this test is executed for the flood events: September 2008 for calibration and October 2010 for verification with hydro meteorological input data as follows:

(1) The daily rainfall data are derived from the radar's output at the Nha Be station and observed at the Can Dang station. In addition, the hourly radar rainfall data are also used to show in more detail their effect and validation.
(2) The potential evapotranspiration data were estimated directly by the Penman-Monteith method according to daily meteorological data (mean temperature, relative humidity, sunshine hour and wind speed) at the Tay Ninh weather station, land cover data at 30' resolution and vegetation-related parameters based on AVHRR (Advanced Very High Resolution Radiometer) and LDAS (Land Data Assimilation System) information (Nghi & Lanh, 2009).
(3) The hourly observed discharges at the Can Dang station covering an area of 617 km^2.

Model simulation performance is evaluated by following criteria:

(1) Coefficient of mass residual:

$$BIAS = \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} C_i}{\sum_{i=1}^{N} O_i} \times 100\% \tag{3}$$

(2) Model efficiency coefficient (Nash & Sutcliffe, 1970):

$$R^2 = \frac{\sum_{i=1}^{N}(O_i - O)^2 - \sum_{i=1}^{N}(C_i - O_i)^2}{\sum_{i=1}^{N}(O_i - O)^2} \tag{4}$$

where N is the total number of the observations; O_i and C_i are the observed and computed values of *ith* observation, respectively; and O is the mean of observed values.

In addition to these statistical measures, the reliability of model outputs is judged through the graphical presentations of the computed and observed values.

RESULTS AND DISCUSSION

The Can Dang watershed is located 120–150 km from the Nha Be weather radar station; it means that the study area is within the radius of reliable radar data exploitation (see Fig. 1). The radar rainfall, theoretically, can be derived each 10 minutes at 1 × 1 km resolution. However, due to not having software to exploit the radar data, all the calculations were done manually, the radar rainfall was extracted every 1 hour in the grid at 6 × 6 km resolution. Therefore for the recorded gauge data from 2008 to 2010 measured at the Tay Ninh station, the correction factor F in equation (2) was defined to calibrate radar rainfall on the Can Dang watershed. The results of F values for three rainfall intensity ranges are shown in Table 1. Finally the hourly and daily corrected radar rainfall on the Can Dang watershed was determined for September 2008 and October 2010.

Table 1 Corrected factor to calibrate radar rainfall in Can Dang watershed.

Rainfall intensity stages (mm h^{-1})	0.2–2.5	2.5–7.5	>7.5
Number of occurrences, N	128	46	17
Corrected factor, F (%)	1.12	1.67	2.43

In fact, using only one raingauge does not achieve the most accurate correction result, but at present there are no other recording gauges in the Can Dang study watershed and surrounding area. However, F is quite sensitive as it depends on intensity, duration, and rainfall type, as well as formation mechanisms. However, the estimation of F values in this research was mainly interested in rainfall intensity. Table 1 shows differences between the rainfall intensity measured at the surface and the radar. The threshold of rainfall intensity from 0.2 to 2.5 mm h^{-1} the radar rainfall is just 10% smaller than the gauge data, while from 2.5 to 7.5 mm h^{-1} and notably >7.5 mm h^{-1} the difference is quite large. The reason for this is because the radar at the Nha Be station is using C band with a wavelength of 5.6 cm, so the reflectance energy is decreased during heavy rainfall.

The suitability of the radar rainfall data on the Can Dang watershed was assessed by applying the NAM conceptual hydrological model. NAM was used to simulate two flood events at the watershed outlet occurring during 1–30 September 2008 for calibration and 10–26 October 2010 for verification.

The calibration procedures adopted the “trial and error” method. The graphical and numerical performance criteria such as *BIAS* (%) and model efficiency coefficient R^2 were used as important guidance for the hydrologists when deciding upon the set of parameter values which they assessed to be optimal. As these decisions inevitably depend on the personal experiences and judgements of hydrologists, it may be argued that this procedure adds an undesirable degree of subjectivity to the results. By applying the standard calibration procedure of which the hydrologists had comprehensive experience, the results may be seen as typical results from the different modelling systems, when using standard engineering procedures for data collection, model construction, and calibration.

In terms of comparison between the daily radar rainfall and the gauge inputs, the performance measures of the model calibration and validation are summarized in Table 2, which shows the numerical criteria of the overall water balances, *BIAS* and efficiency coefficient R^2.

The results show that while the model calibration performances are quite good and have no significant difference in efficiency coefficient between the radar rainfall (0.915) and the gauge (0.897), the model verification result in the case of gauge rainfall input is unreliable even though *BIAS* is less than 10%. One reason for this behaviour lies in the different hydro-climatic conditions of the calibration and validation periods, i.e. rainfall is a random variable, so the gauge rainfall measured at the outlet cannot represent the entire watershed with an area of 617 km^2; and the “good” gauge data in September 2008 are lucky and just occurred in unusual circumstances.

Generally, the radar rainfall provides a better model performance in terms of the efficiency coefficient against that of the gauge data in both the simulation periods.

Table 2 NAM performance under various rainfall input in the periods September 2008 and October 2010.

Rainfall input data	Efficiency coefficient, R^2		Coefficient of mass residual, *BIAS* (%)	
	Calibration	Verification	Calibration	Verification
Daily radar	0.915	0.787	0.1	–9.5
Daily gauge	0.897	0.511	0.0	+7.2
Hourly radar	0.959	0.906	0.0	+0.8

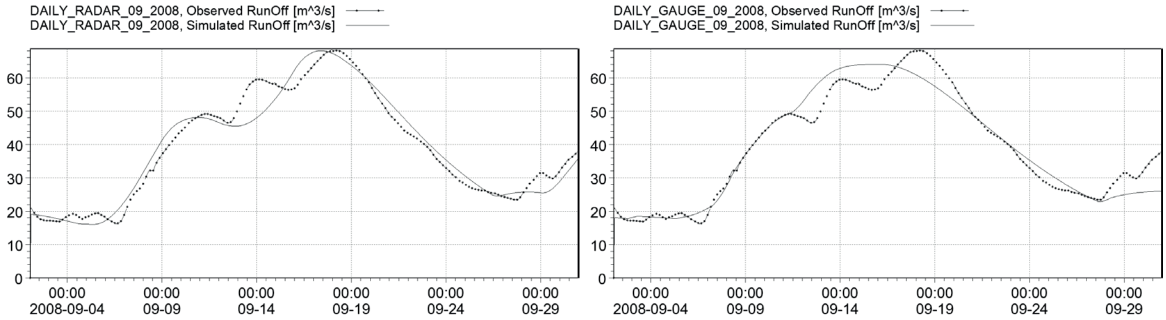

Fig. 2 Model calibration results using daily radar and gauge rainfall inputs in September 2008.

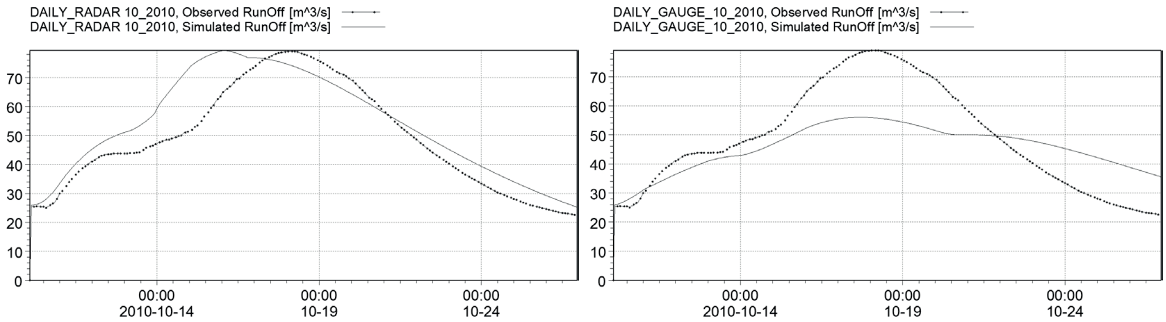

Fig. 3 Model verification results using daily radar and gauge rainfall inputs in October 2010.

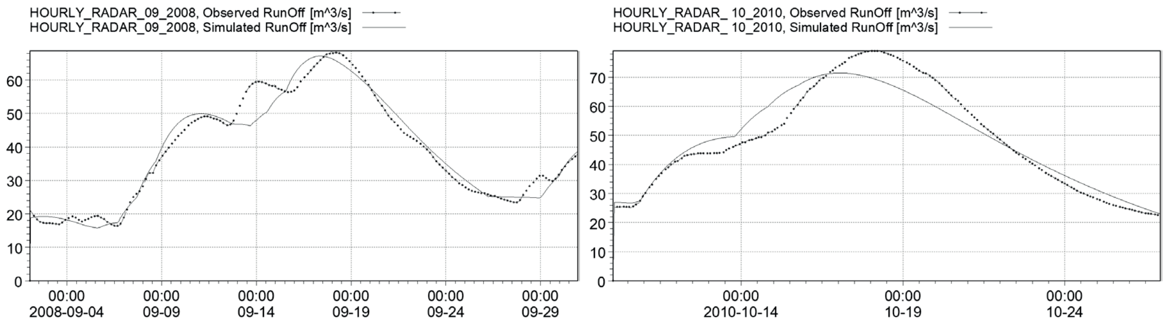

Fig. 4 Model calibration and verification results using hourly radar rainfall inputs.

Figures 2 and 3 present the simulated and observed hydrographs of flood events occurring in September 2008 and October 2010 at the Can Dang watershed outlet; they attest to the conclusions derived based on the above numerical criteria.

Besides using the daily data to have an identical comparison, the NAM model was set up with hourly radar rainfall input. Model simulation performances are very impressive, namely R^2 equals 0.959 and 0.906; and BIAS is smaller, down to 1% in both calibration and verification periods (see

Table 2). Visually, Fig. 4 also shows that shape and timing of the observed and simulated hydrographs agree for the most part of the two periods. These results once again confirm and show the increase of efficiency of the radar rainfall on hydrological simulation responses.

CONCLUSIONS

Rainfall is a key input into studies in hydrology and water resources and therefore should be developed to be as accurate as possible in space and time.

For this study, the rainfall on the Can Dang watershed was derived from the radar output at the Nha Be station and corrected by the recording gauge data at the Tay Ninh station. The data were extracted every 1 hour in the grid at 6 × 6 km resolution. Subsequently, by means of applying the NAM conceptual hydrological model, the radar rainfall effect on hydrological simulation performance was assessed. The results show that the radar rainfall provided a better model performance in comparison with the gauge data. In terms of the inputs of hourly radar rainfall, NAM had results with R^2 values greater than 0.9 and *BIAS* smaller than 1%, as well as reproducing the observed hydrographs accurately with the simulated hydrographs.

Radar is evidently a powerful technique to measure rainfall and has potential and a big future, particularly in remote areas or in areas where increased spatial or time resolution is required. However, the radar rainfall measurement is an indirect method; the radar rainfall needs to be corrected by the recording gauge data in terms of a correction factor *F*. In fact the *F* value varies and depends on various rainfall characteristics; in this study it was based on limited data (only one recording gauge station outside study area) and only considered rainfall intensity in three stages, namely 0–2.5, 2.5–7.5 and >7.5 mm h^{-1}. Therefore, to receive more reliable and accurate data, *F* should be determined in detail and according to constraints such as intensity, duration, and rainfall type as well as formation mechanisms. In Vietnam the meteorological monitoring network is still very poor and scattered; for example the Dong Nai River basin where topographic change is quite large the density of rainfall stations with reliable data is just 1 per 1000 km^2. From this study, a recommendation can be inferred as follows: the recording raingauge network should be expanded and upgraded.

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