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Rainfall-runoff modeling using Doppler weather radar data for Adyar watershed, India

S. JOSEPHINE VANAJA, B. V. MUDGAL and *S. B. THAMPI

Centre for Water Resources, Anna University, Chennai, India

**India Meteorological Department, Chennai, India*

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e mail : josephine.vanaja@yahoo.com

सार – जल विज्ञानिक मॉडलों लिए वर्षा एक महत्वपूर्ण निवेश है इसलिए यह आवश्यक है कि अच्छी मात्रा में वर्षा हो। वर्षामापी से किसी स्थान विशेष की वर्षा का मापन होता है जबकि रेडार से वर्षा की मात्रा का तत्काल इलैक्ट्रोमैग्नेटिक बैकस्कैटर (पश्च प्रकीर्णन) चित्र प्राप्त होता है जिसे अल्गोरिथ्म के माध्यम से वर्षा की मात्रा में बदल दिया जाता है। यह प्रमाणित हो गया है कि आकाशीय वर्षा का रेडार से मापन वर्षामापी संजाल के मापन से बेहतर है, खास तौर पर दूरदराज़ के क्षेत्रों में जहाँ वर्षामापियों की संख्या अपर्याप्त है और दूर संवेदी उपग्रह से प्राप्त वर्षा आँकड़े भी स्टीक नही होत हैं। भारत के चेन्नै भाहर में अड्यार वाटरशेड के लिए रेडार से प्राप्त वर्षा आँकड़ों के आधार पर वर्षा रनऑफ माडुलन तकनीक को परिश्कृत करने के लिए शोध किया जा रहा है। वर्षा रनऑफ प्रक्रियाओं का अनुकरण करने के लिए एक जल विज्ञानिक मॉडल जिसे हाईड्रोलोजिक इंजिनियरिंग सेन्टर– हाईड्रोलोजिकमॉडलिंग सिस्टम (HEC-HMS) कहते हैं, का उपयोग किया गया है। अडयार वाटरशेड डॉप्लर रेडार स्टेशन से 100 कि. मी. की त्रिज्या वाले क्षेत्र में है इसलिए इस क्षेत्र का चयन शोध के लिए किया गया है। चक्रवाती तूफान जाल की घटना जो 4 - 8 नवम्बर, 2010 की अवधि में हुई, को इस अध्ययन के लिए चुना गया है। इस अवधि के आँकड़े सांख्यिकीय विभाग और चक्रवात संसूचन रेडार केन्द्र चेन्नै, भारत से प्राप्त किए गए हैं। इससे प्राप्त परिणामों से पता चला है कि वर्षामापी स्टेशनों से प्राप्त वर्षा की तुलना में डॉप्लर रेडार से अंशाकित आँकड़ों के उपयोग से किया गया वर्षा का पूर्वानुमान अधिक है।

ABSTRACT. Precipitation is a significant input for hydrologic models; so, it needs to be quantified precisely. The measurement with rain gauges gives the rainfall at a particular location, whereas the radar obtains instantaneous snapshots of electromagnetic backscatter from rain volumes that are then converted into rainfall *via* algorithms. It has been proved that the radar measurement of areal rainfall can outperform rain gauge network measurements, especially in remote areas where rain gauges are sparse, and remotely sensed satellite rainfall data are too inaccurate. The research focuses on a technique to improve rainfall-runoff modeling based on radar derived rainfall data for Adyar watershed, Chennai, India. A hydrologic model called 'Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS)' is used for simulating rainfall-runoff processes. CARTOSAT 30 m DEM is used for watershed delineation using HEC-GeoHMS. The Adyar watershed is within 100 km radius circle from the Doppler Weather Radar station, hence it has been chosen as the study area. The cyclonic storm Jal event from 4-8 November, 2010 period is selected for the study. The data for this period are collected from the Statistical Department, and the Cyclone Detection Radar Centre, Chennai, India. The results show that the runoff is over predicted using calibrated Doppler radar data in comparison with the point rainfall from rain gauge stations.

Key words – Rain gauge, Radar rainfall, Z-R relationship, Rainfall-Runoff model, HEC-HMS model.

1. Introduction

Precipitation is a significant input for hydrologic models; so, it needs to be quantified precisely. The measurement with rain gauges gives the rainfall at a particular location; with an assumption that it is uniform over an area. With this presumption, many hydrological models were developed and the prediction of the surface-water potential was done. The results were not concurrent with the observed data due to spatial and temporal variations in rainfall.

Research had been carried on the Upper Bernam river basin, Malaysia on rainfall-runoff modeling based on radar derived rainfall data. The results concluded that the watershed river flow can be better anticipated by using the radar derived rainfall data over the conventional rain gauge data (Waleed *et al*., 2009). A study was done using the Width Function Instantaneous Unit Hydrograph (WFIUH) model for the Treja river basin, Italy (Lopez *et al*., 2005). The results proved that the radar rainfall data can improve hydrograph reconstruction significantly. Ezio (2001) conducted a case study on the upper Reno river close to Casalecchio, near Bologna (Italy), with several rain gauges and one C-band Doppler meteorological radar and stated that weather radar based rainfall estimates has a wide range of possible applications. Many researchers concluded that meteorological radars have several advantages over the conventional rain gauges, since a single site is able to obtain coverage over a vast area with high temporal and spatial resolution (Eloise and Peter 2011; Mikayla and Paul 2005; TSMS, 2005; Meischner, 2004; Borga 2002; Wyss *et al*., 1990).

Research had been carried out in various countries using radar derived rainfall data. However, there are limited studies in India to utilize the weather radar products for hydrological purposes. The present challenge in India is the utilization of Doppler Weather Radar (DWR) products for hydrological purposes similar to the rainfall-runoff models, flood forecasting, flood zone mapping and research & development activities.

This study focuses on deploying the radar derived rainfall data to predict the surface runoff of Adyar watershed, using HEC-HMS model. As well, the research analyzes and proposes the prospects of using radar based rainfall-runoff estimation for Adyar watershed, Chennai, India.

2. Case study

The Chennai basin group rivers, which are situated between latitudes 12° 30' 00" to 13° 35' 00" N and longitudes 79º 15' 00" to 80º 22' 30" E and is located in the northern part of Tamil Nadu, India. The Chennai basin comprises of eight watersheds such as Adyar, Araniyar, Cooum, Gummidipoondi, Kosasthalaiyar, Kovalam, Nagari and Nandhiyar.

The Adyar watershed is a low-lying, flat, and slightly undulating terrain with a general slope of 3-5° toward the E-ENE direction. The study area falls under the semi-arid tropical region; consequently, it has high temperature and high humidity. Average monthly minimum and maximum temperatures are about 19 ºC and 42 ºC respectively. The mean relative humidity is about 67.27%, while the mean wind velocity is 4.84 km/hour. Average sunshine hours/day is 7.25, and the average annual rainfall is about 1200 mm.

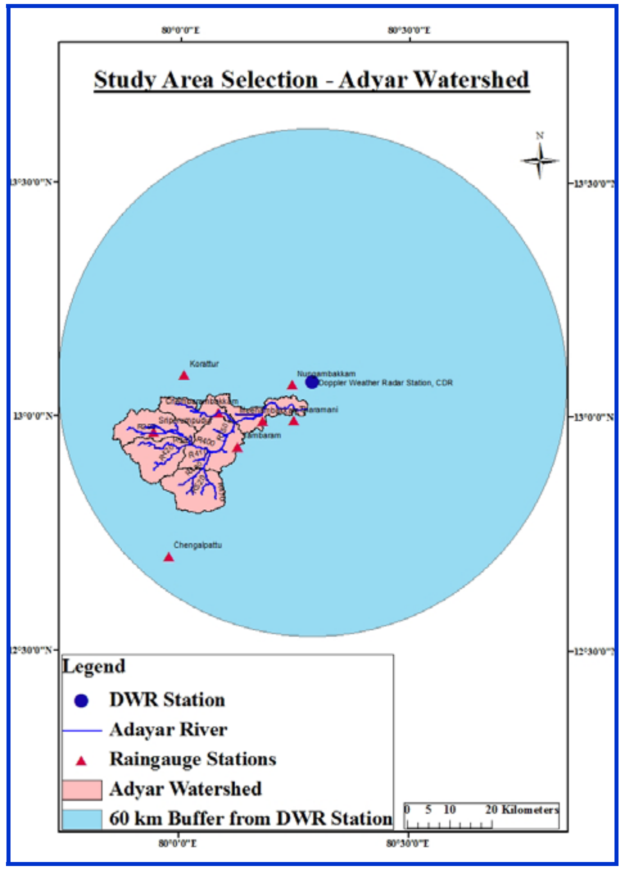

Fig. 1. Study area and rain gauge stations

India Meteorological Department (IMD) has installed one S-Band Doppler Weather Radar at Cyclone Detection Radar Centre (CDR), Chennai. The DWR derived products such as Surface Rainfall Intensity (SRI) and Precipitation Accumulation (PAC) are available only for 100 km radius circle from the DWR station, Chennai. The Adyar watershed is within 100 km radius from DWR station, hence it has been chosen as the study area. The aerial extent of this study area is 631.79 km^2 (Fig.1).

3. Data and methodology

The Adyar watershed is delineated using CARTOSAT 30 m Digital Elevation Model (DEM). Geographic Information System (GIS) pre-processing is done using HEC-Geo Hydrological Modeling System (HEC-GeoHMS) software. It uses ArcGIS tools such as ArcView and the Spatial Analyst extension, to develop a number of hydrologic modeling inputs for the HEC-HMS model. Parameters such as initial abstraction, curve

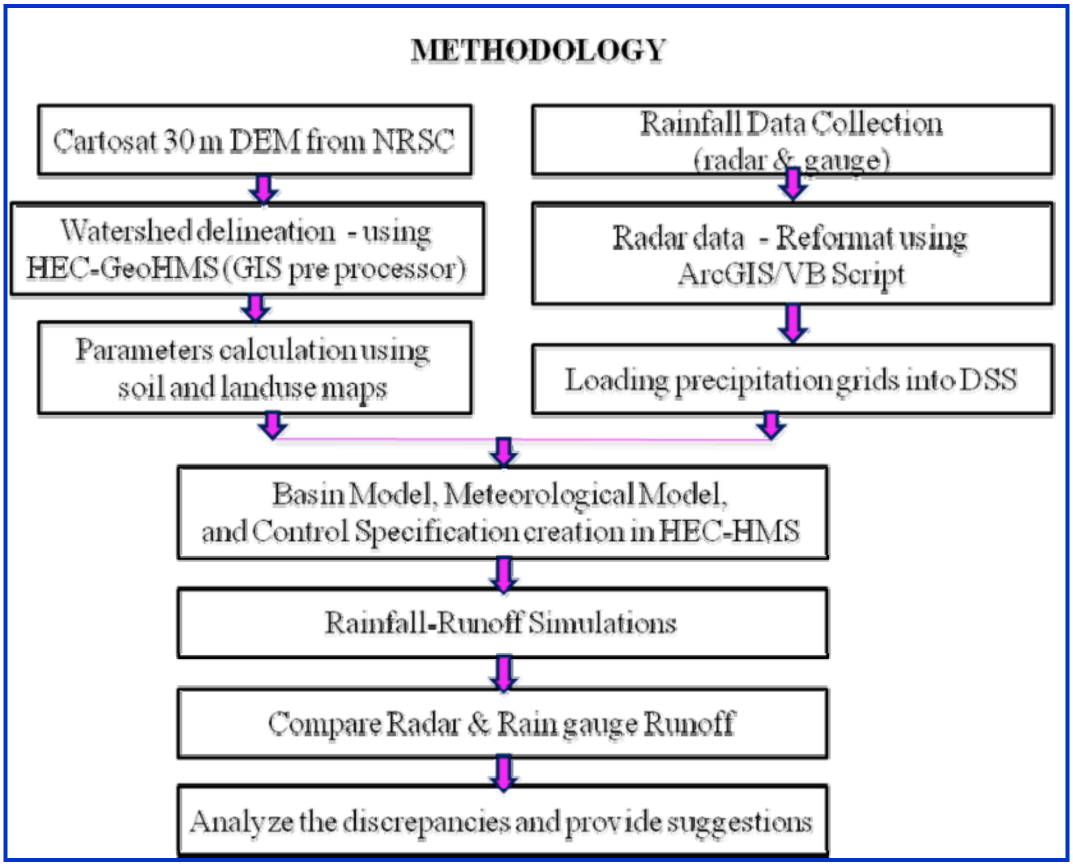

Fig. 2. Framework of research methodology

TABLE 1

Radar and rain gauge rainfall data from 4-8 November, 2010

Rain gauge stations	Nungambakkam	Tharamani	Meenambakkam	Tambaram	Chembarambakkam	Korattur	Sriperumpudur	Chengalpattu
Radar data (mm)								
4 Nov 2010	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.90
5 Nov 2010	0.00	0.00	1.00	1.00	0.00	1.00	0.00	0.00
6 Nov 2010	2.90	2.20	10.00	2.60	16.60	0.00	1.00	2.20
7 Nov 2010	19.30	20.90	17.00	19.70	14.30	17.40	11.90	26.70
8 Nov 2010	9.60	13.50	10.00	36.90	31.80	6.80	18.90	37.59
Sum	**31.80**	**36.60**	**38.00**	**60.20**	**62.70**	**25.20**	**31.80**	**71.39**
Rain gauge data (mm)								
4 Nov 2010	1.80	0.00	4.80	1.00	5.00	13.00	0.00	73.00
5 Nov 2010	3.80	0.00	0.00	0.00	5.00	6.00	0.00	0.00
6 Nov 2010	3.80	0.00	5.00	8.00	12.00	0.00	0.00	0.00
7 Nov 2010	22.80	23.80	21.40	11.20	12.00	5.00	8.20	11.40
8 Nov 2010	47.80	40.80	44.80	49.00	49.00	37.00	53.00	79.20
Sum	**80.00**	**64.60**	**76.00**	**69.20**	**83.00**	**61.00**	**61.20**	**163.60**

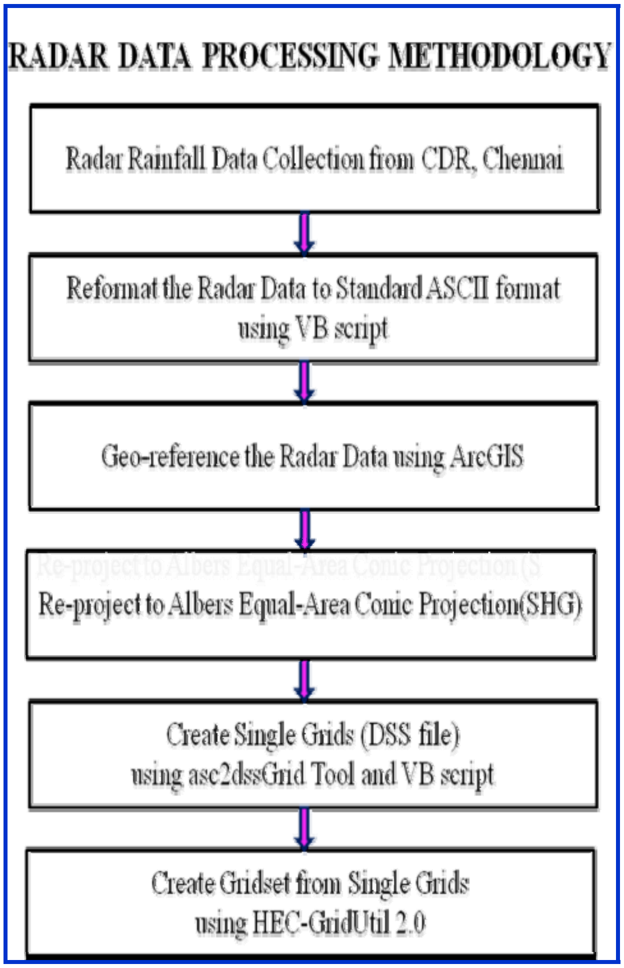

Fig. 3. Radar data processing methodology

number, percentage of impervious area, lag time, Muskingum K, and Muskingum X are calculated using Adyar soil and land use maps. Fig. 2 illustrates the framework of research method.

3.1. *Rain gauge rainfall data*

Based on the hydro-meteorological features of the watershed, the rain year in India is divided into southwest monsoon period spanning from June to September (four months), and Northeast monsoon period spanning from October to December (three months), Winter period spanning from January to February (two months) and Summer period spanning from March to May (three months).

There are eight rain gauge stations in and around the Adyar watershed, of which two are automatic rain gauges. The annual rainfall in the Adyar watershed varies from 2111 mm to 753 mm. The watershed receives more

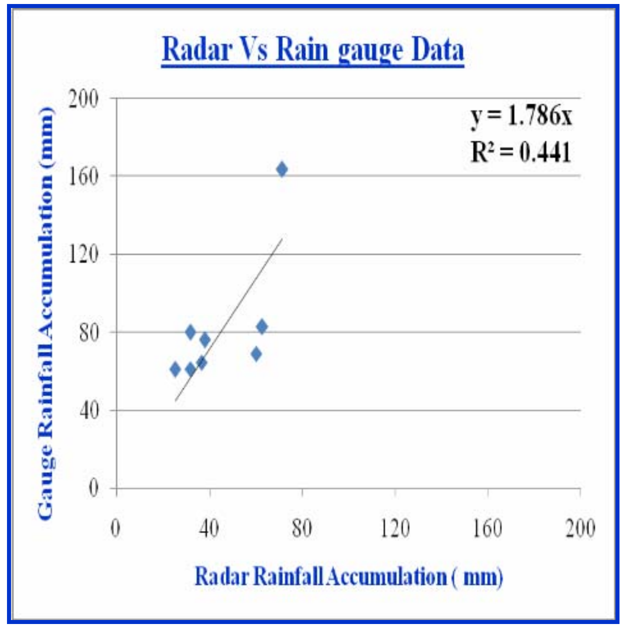

Fig. 4. Radar rainfall calibration model (original values)

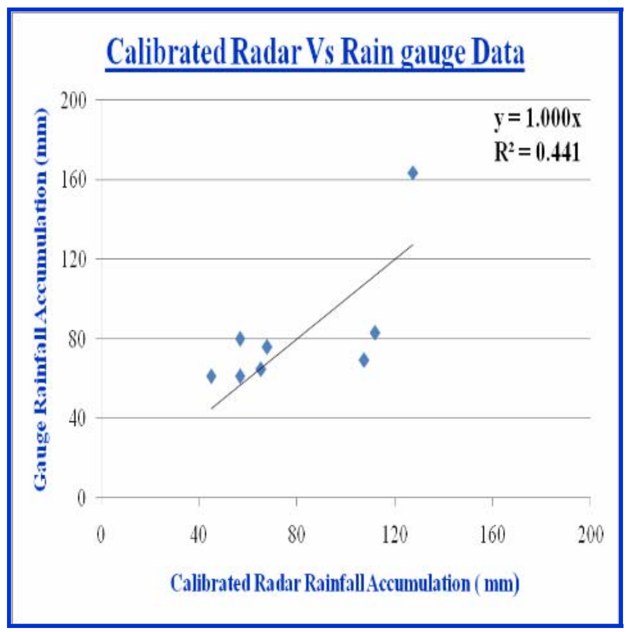

Fig. 5. Radar rainfall calibration model (calibrated values)

rainfall in the northeast monsoon, and it varies from 1171 mm to 274 mm. Southwest monsoon rainfall varies from 776 mm to 263 mm; winter rainfall varies from 307 mm to 0 mm, and summer rainfall varies from 399 mm to 0.90 mm (Chennai Basin Report, 2007).

India receives a significant amount of rainfall from cyclonic storms. During 2010, four cyclonic storms such

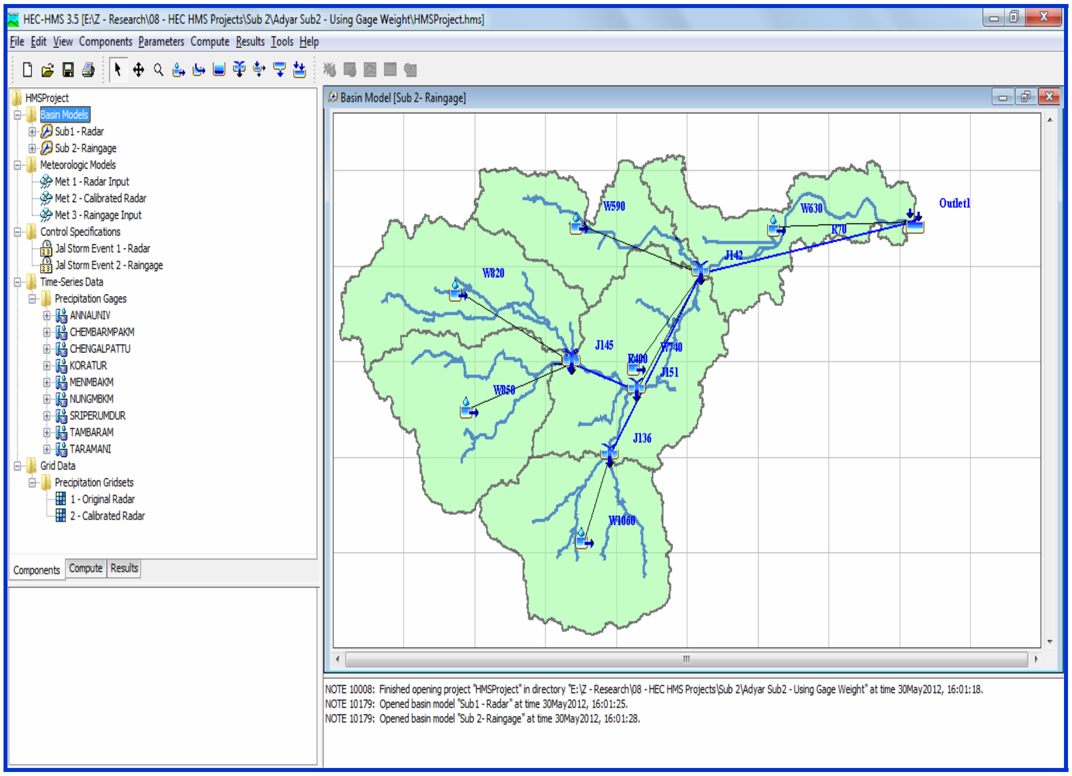

Fig. 6. Basin model of Adyar watershed in HEC-HMS model

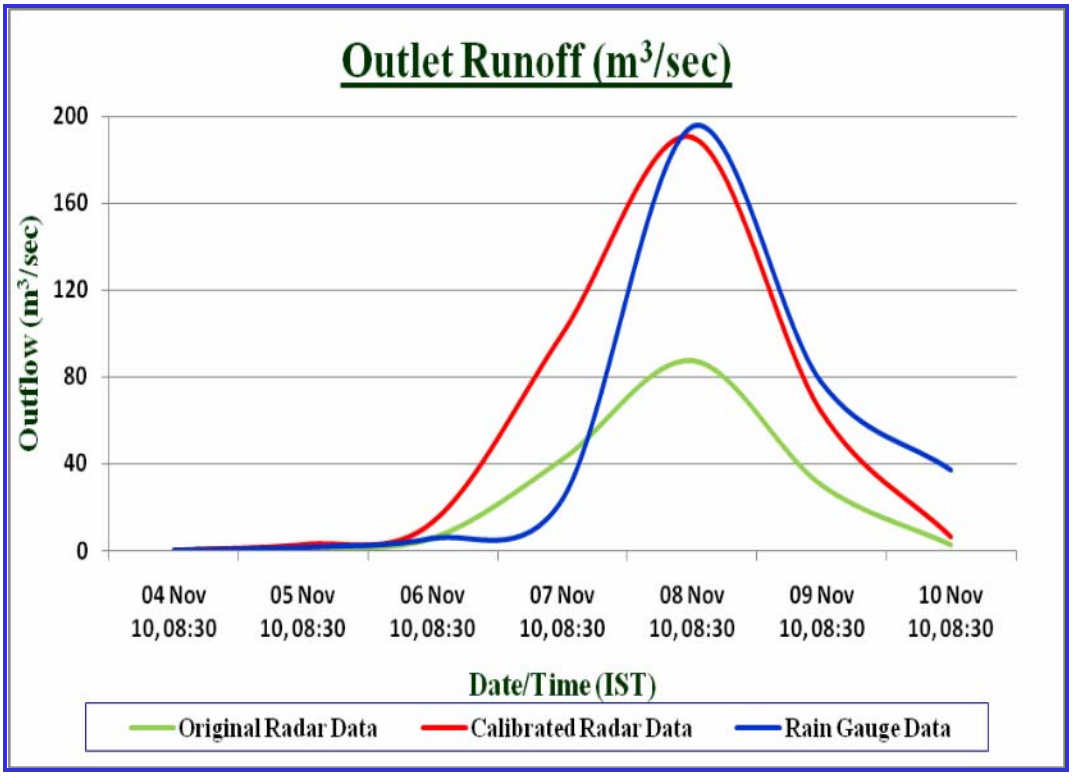

Fig. 7. Runoff at the Adyar watershed outlet

as Laila, Phet, Giri, and Jal formed over the Indian seas. Cyclone Jal brought heavy rains to the Bay of Bengal and the south-eastern coast of India (Chennai) in early November 2010 (Annual Climate Summary Report, 2010). The cyclonic storm Jal event from 4-8 November, 2010 period is selected for the study.

The rain gauge data for this period is collected from the State Ground and Surface Water Resources Data Centre, Tharamani, Chennai. Table 1 shows the radar and rain gauge rainfall data for the study period.

3.2. *Radar rainfall data*

The relationship between the rainfall rate and the reflectivity will be affected by the geography, seasonal variation, and the climatological conditions of the area. So, it is impossible to derive a universal Z-R Relationship (Sen *et al*., 2009). The DWR operating at CDR, Chennai uses the following Z-R Relationship for the SRI computation; PAC is calculated as a second-level product based on the SRI (National Seminar Report, 2010).

$$Z = 267\ R^{1.345} \qquad (1)$$

SRI images are obtained at every 15-minutes interval; PAC is an accumulation of the SRI products per day to provide the cumulative 24 hours rainfall. The SRI and PAC at 500 m resolutions are used for the runoff estimation. The radar rainfall data is collected from CDR, Chennai. Software tools have been developed for reformatting the radar data into the format required by the HEC-HMS model, and the radar data processing methodology is elucidated in Fig. 3.

3.3. *Radar rainfall adjustment procedures*

The weather radar does not measure rainfall directly; it acquires instantaneous snapshots of electromagnetic backscatter from rain volumes that are then converted to rainfall via algorithms (Lopez *et al*., 2005). So the radar data requires adjustment prior to using it as the input to any model. Fig. 4 shows the scatter plot between original radar data and rain gauge data. A trend line is drawn to study the correlation between two different inputs and obtained the linear trend equation $y = 1.786x$ with correlation coefficient 0.441, *i.e*., Rain gauge data = 1.786 * radar data. Hence the radar rainfall calibration factor for the study area is identified as 1.786.

The adjustment of radar data is obtained by matching the accumulation of rain gauge rainfall data and radar rainfall data in the study area. The estimated radar derived rainfall data is adjusted by multiplying the original value by the calibration factor. Fig. 5 shows the scatter plot between calibrated radar data and rain gauge data with linear trend equation $y = 1.000x$ and correlation coefficient is 0.441.

3.4. *HEC-HMS rainfall runoff model*

HEC-HMS program is designed for surface water hydrology simulation. It can be adapted to fit almost any watershed. It includes all the components of the hydrologic cycle like precipitation, evaporation, infiltration, surface runoff, and base flow. Basin models, meteorological models and control specifications are the main components used for simulation runs.

The basin map is used to visualize a basin model component. Using HEC-GeoHMS inputs, basin model is created in the HEC-HMS. Sub-basins in the basin model are the elements that receive precipitation and other meteorological inputs. Excess rainfall is estimated using Soil Conservation Service-Curve Number (SCS-CN) method. SCS Unit Hydrograph transform method converts excess precipitation into runoff at the sub-basin outlet. The routing method deals movement of the water in the reach. The Muskingum routing method is popular and relatively simple to use for stream flow (Tewolde and Smithers, 2006); hence, it has been selected. Fig. 6 shows the basin model of Adyar watershed in HEC-HMS.

Meteorological model deals all the atmospheric conditions over the watershed. It is defined with type of precipitation analysis like gridded precipitation for radar rainfall and Thiessen polygon (Gage weight) for rain gauge rainfall input. Control specifications are lightweight components, and it is to control when the simulation start and stop and what time interval is used in the simulation.

A simulation run consists of one basin model, meteorological model, and control specifications, and it calculates the rainfall-runoff response. Three simulations are executed using rain gauge rainfall, original radar rainfall and the calibrated rainfall data and results are stored in the output Data Storage System (DSS) file for analysis.

4. Results & discussion

The common way of assessing the accuracy of radar rainfall estimation is through the comparison of radar data with observations from automatic rain gauge networks. Eight rain gauges are available in the study area; however, only two rain gauges (Nungambakkam and Meenambakkam) are automatic. Hence all the eight rain gauges are considered for radar rainfall comparison and model calibration. The radar derived rainfall calibration factor is computed as 1.786 for Adyar watershed. Radar derived rainfall calibration model is successfully developed. It is found that, the discrepancy between rain gauge rainfall and radar rainfall is reduced to 3% after calibration from 46% before calibration.

Fig. 7 represents the results of simulation runs using rain gauge data, original radar data and calibrated radar data. Calibrated radar and rain gauge results are compared at the outlet of the Adyar watershed and difference in the peak outflow is 2.46% and total outflow is 13.67%. Simulation using calibrated radar data shows a slightly higher total outflow. The discrepancy might be due to the consideration of spatial and temporal variations in rainfall in the watershed.

5. Conclusions

Research investigates the feasibility of using DWR rainfall data for the hydrological purpose in Chennai watersheds. Radar rainfall data is converted into standard ASCII format using VB Script and then geo referenced. Software tools are created to convert the radar grid into Data Storage System to use in HEC-HMS model. It is observed that CDR provided original radar rainfall data is under estimating the rainfall by 50% for the study period. Therefore, radar derived rainfall calibration model is successfully developed by comparing radar rainfall with the rain gauge rainfall data.

Radar outflow pattern matches the observed outflow. The research concludes that DWR products available at CDR, Chennai can be used for hydrological purposes such as runoff estimation, flood forecasting, flood zone mapping, and Research and Development activities because of the benefits of their spatial and temporal information content.

6. Future research recommendations

DWR station is applying unique Z-R relationship for all the seasons and types of rainfall. Hence the present Z-R relationship may not be appropriate. Automatic recording rain gauges must be used for precise radar calibration. Since the study area has inadequate automatic rain gauges, both recording as well as non recording rain gauges are considered for radar calibration. Recently, IMD has installed ten automatic rain gauge stations in and around Chennai. It will assist for accurate radar calibration.

Research will be extended to simulate rainfall-runoff for the entire watersheds in Chennai basin to assist the policy and decision makers for better planning and development activities, especially in remote areas where rain gauges are sparse.

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Abbreviations

CDR	Cyclone Detection Radar Centre
DEM	Digital Elevation Model
DSS	Data Storage System
DWR	Doppler Weather Radar
GIS	Geographic Information System
HEC-GeoHMS	Hydrologic Engineering Center-Geo Hydrologic Modeling System
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modeling System
IMD	India Meteorological Department
PAC	Precipitation Accumulation
SCS–CN	Soil Conservation Service-Curve Number
SRI	Surface Rainfall Intensity
WFIUH	Width Function Instantaneous Unit Hydrograph
Z-R	Radar measured reflectivity - Rainfall rate