Improved Watershed Runoff Estimation Using Radar-Derived Rainfall in Peninsular Malaysia

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Abstract: In traditional hydrologic and water resource applications, rain gauges are the commonly used rainfall measuring device. Normally these rain gauges are installed at convenient locations. Rain gauges provide direct rainfall measurements over small areas. Malaysia is a humid tropical country with more than 60% of land area covered with forest. Hence, using rain gauges to determine the spatial distribution of watershed rainfall may not be the best technique. Weather radar provides measurements of rainfall over large area at high spatial resolution and frequent intervals. These characteristics make weather radar a useful system for rainfall estimation. The main objective of this study was to develop a technique to improve the performance of hydrological models to estimate runoff more accurately using radar-derived rainfall data incorporating GIS. The six weather radar stations (Subang, Alor Setar, Butterworth, Kluang, Kota Bharu and Kuantan) available in the Peninsular Malaysia were considered in this study. Radar-derived rainfall data was implemented to generate more representative rainfall distribution maps. Hence, considerable improvements were found in the watershed runoff estimation using radar rainfall compared to the available rain gauges.

Keywords: Virtual Rainfall Stations; Rational Method; KnowledgeGRID Malaysia; AgriGRID

1. INTRODUCTION

Rainfall is the primary source of fresh water for most areas of the world. It is vitally important to quantify it accurately. Knowing the amount of rainfall that occurred, floods, land slides, works and projects for the development and protection of water resources can be better designed and managed.

At present, there are essentially three basic systems for providing rainfall measurements for use in hydrological applications. Conventional ground based telemetric rain gauges, weather radar system, which is of growing importance in recent decades, and the third potentially useful measurement system is based upon the analysis of clouds shown by geo-stationary satellite images (Milford and Dugdale, 1989).

The cost of operating and maintaining a large number of automated rain gauges to represents spatial rainfall variability is expansive. Hence, weather radar that covers much larger areas has become the most attractive instrument for monitoring rainfall especially in an operational context. Radar has higher probability to detect rainfall; it can almost see any rainfall event within large extent, while a gauge can only see rainfall occurring within 1 m^2 of the gauge location (Wang et al., 2008).

Deriving accurate areal rainfall estimates from observations is an essential prerequisite for successful hydrological modeling. The quality of the radar-derived rainfall can be significantly improved with the aid of ground measurements (rain gauges measurements).

This study focuses on a technique to improve the rainfall-runoff modeling by improving the rainfall data derived from raw weather radar data. The radar-derived rainfalls were used as inputs in hydrological model for better runoff estimation for a watershed having low density rain gauges network.

1.1 Rainfall estimation by radar

Radar for meteorological purposes was recognized soon after its invention, due to two fundamental advantages associated with measurements made using radar. Firstly, radar can be used to estimate the distributions of precipitation amounts over areas as large as 50,000 km^2. Secondly, radar allowed the detection of rain events, which would not have been detected by the rain gauges earlier. These advantages improved the accuracy of weather forecasts and led to reduction in damage to property and the loss of life due to storms (James et al., 1993).

Marshall and Palmer (1948) found that the relationship between the signal reflected by the radar (*Z*) in a unit of measurement dB's (decibels) and precipitation rate (*R*) in units of (mm/hr), commonly termed as *Z-R* relationship is given by equation (1).

$$Z=aR^b \quad (1)$$

Where Z is the radar reflectivity (mm^6/m^3), R is the rainfall rate (mm/hr), a and b are fitting coefficients (Bedient and Huber, 2002; Doviak and Zrnic, 1993).The values of a generally vary from 100 to 2000 depending on the type of precipitation and precipitation rate to explain, hence the size of precipitation too. Values of b vary from 1 to 2.

The primary advantage of radar observations of precipitation compared to traditional rain gauge measurements is their high spatial and temporal resolution and large areal coverage. Unfortunately, radar data require vigorous quality control before being converted into precipitation products that can be used as input to hydrologic models (Sharif et al., 2002).

1.2 Radar rainfall calibration

In hydrological applications of weather radar rainfall some adjustment may be required for the collected radar data, based upon various factors, to match it with the ground truth. This is termed as the calibration of the radar. Generally radar rainfall calibration has done with the help of rain gauges data.

The systematic difference (‘bias’) between radar rainfall and rain gauge rainfall can be progressively removed using information provided by rain gauges. This is performed through an adjustment factor that is estimated as the ratio of the accumulated rain gauge rainfall, G, and the accumulated radar rainfall, R. The simplest method of bias correction is to multiply the radar rainfall values by calibration factor (G/R) (Chumchean et al. 2006).

1.3 Radar-derived rainfall in hydrological modeling

Deriving accurate areal rainfall estimates from observations is an essential prerequisite for successful hydrological modeling and its application (Cole and Moore, 2008). The statistical objective analysis technique enables a local correction of the radar measurements by using rain gauge data, which leads to an immense improvement of the quality of the radar precipitation quantification.

Therefore, the original structure of the radar-derived rainfall distribution is preserved, while the precipitation sums are adjusted to the ground truth (Gerstner and Heinemann, 2008).

The performance of distributed and physically based hydrologic models depends greatly on the quality of the input data. The most important input is rainfall because such models are very sensitive to it (Julien and Moglen, 1990).

Sun et al. (2000) implies that the use of radar data, together with observations from surrounding gauges, to estimate rainfall would be more effective for flood forecasting in real time than using catchment-based gauge data alone.

2. METHODOLOGY

2.1 Weather radar stations available in Peninsular Malaysia

Six weather radar stations are available in Peninsular Malaysia (Figure 1). It belongs to the Malaysian Meteorological Department (MMD). They are mainly for meteorological rainfall estimation and forecasting. The MMD provides maps of radar-derived rainfall estimated from S-band conventional pulse radar station using 3D-Rapic Program.

2.2 Radar-derived rainfall calibration

The hydrological data such as rainfall, river discharge and water levels were obtained from the department of Irrigation and Drainage (DID). For each radar station, the nearest automatic rain gauge stations available in Peninsular Malaysia were identified. Data from 24 rain gauges (Figure 1) operated by DID and located within a 100 km range from the radar location were used for radar rainfall comparisons and calibration.

In this study the ratio method was used to assess the ratio between radar-derived rainfall data and the rain gauge data. The radar rainfall estimated from all radar stations available in Peninsular Malaysia were multiplied by the ratio factor such that radar estimated rainfall values are approximately equal to the gauge rainfall values (Stellman et al., 2001).

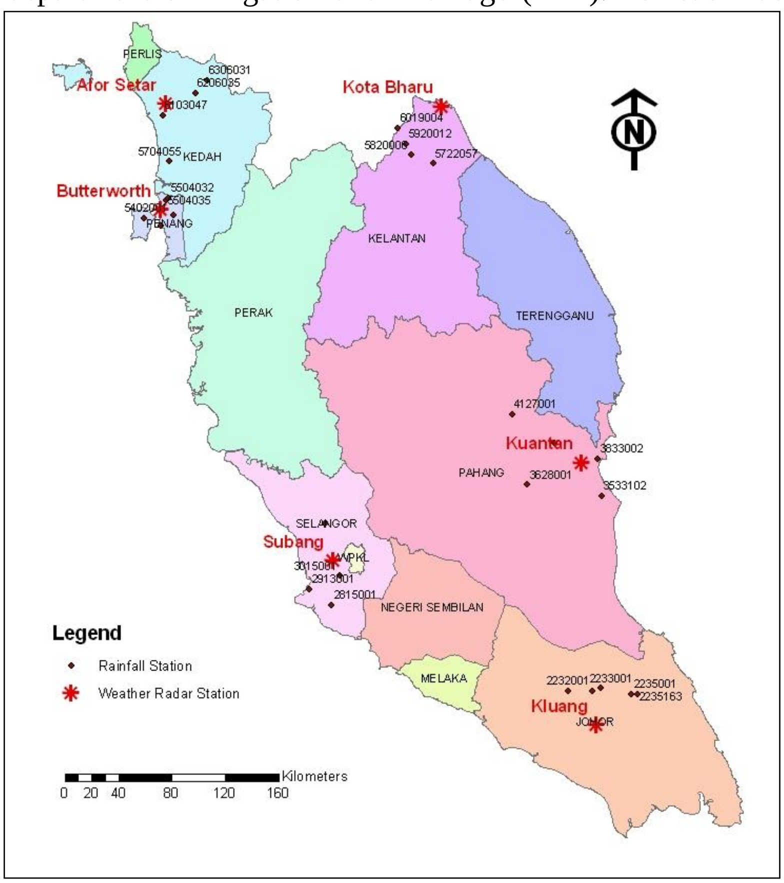

Figure1. Location Map of Radar Stations Available in Peninsular Malaysia

2.3 Implementations of radar-derived rainfall

Many implementations using radar-derived rainfall can be highly performed such as, civil infrastructure design, irrigation water management, landslid assessment, watershed management, rainfall variability mapping and flood forecasting operations.

In this study, for the implementations of radar rainfall, the Upper Bernam River Basin (UBRB) was considered as study area. The study area is located in southeast Perak and northeast Selangor, Malaysia, between 3° 36´ 23´´ to 3° 47´ 55´´ North and 101° 30´ 53´´ to 101° 39´ 33´´ East . The total upper basin area is 1108 km^2.

UBRB is the main source of irrigation water supply for 20,000 ha rice granary. This gave the basin its importance in irrigation water supply (Figure 2).

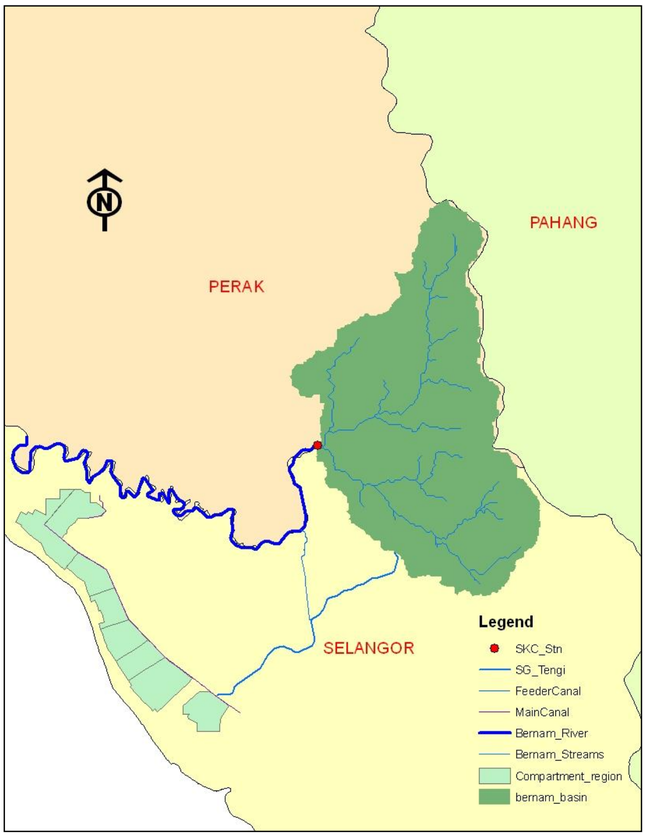

Figure 2. Location Map of the Upper Bernam River Basin

With limited number of rain gauges available in the watershed of UBRB (Figure 3), the rainfall distribution map generated could not represent the real situation of rainfall variability. Therefore, virtual rainfall stations were created uniformly in the study area. The rainfall amounts for these stations can be estimated from weather radar.

The distribution of virtual rainfall stations depends on the size of the watershed area. The bigger the watershed area the bigger is the spacing between the virtual stations. For the study area of UBRB, 10 km spacing between the virtual rainfall stations was considered (Figure 4), due to the large size of the watershed i.e. greater than 1100 km^2.

Rational model was used to estimate surface runoff using the model interface available in Watershed Modeling System software (WMS 8.0).

Two types of rainfall data were used for runoff estimation:

1. Rainfall data measured in rain gauges
2. Rainfall data estimated from weather radar
   - 2.1 Original radar-derived rainfall data
   - 2.2 Calibrated radar-derived rainfall data

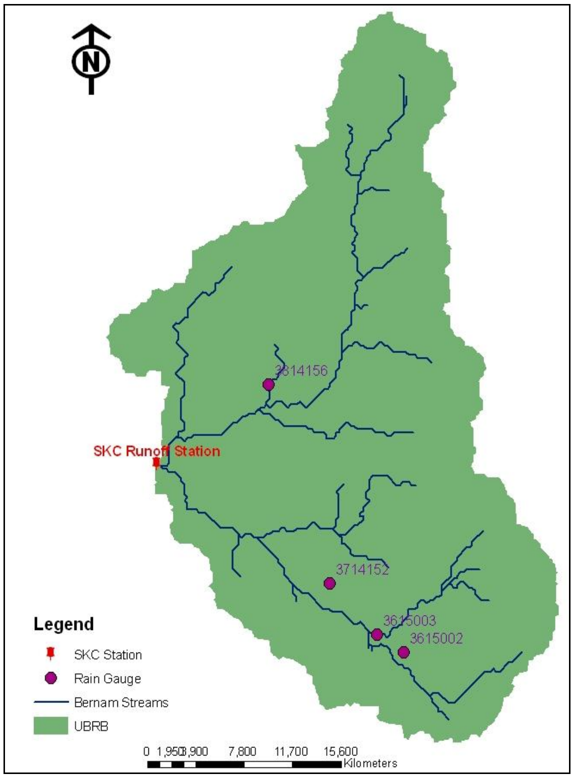

Figure 3. Location Map of the Rain Gauges Available in the UBRB

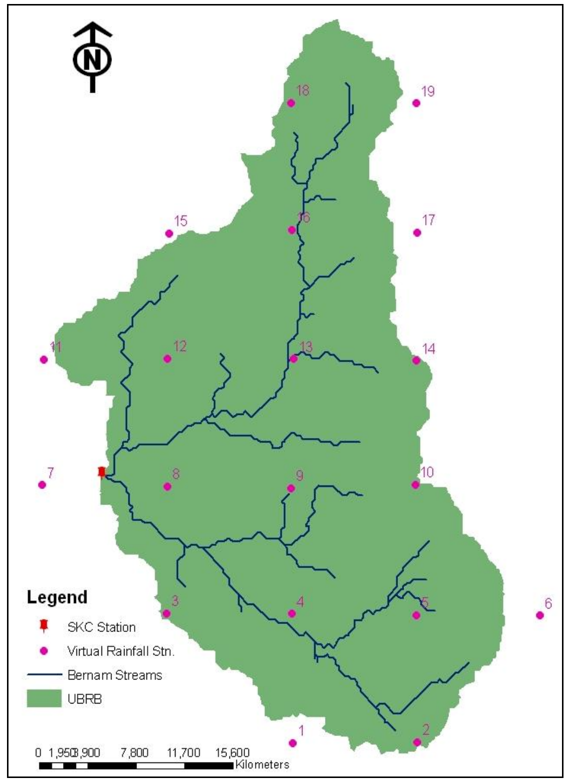

Figure 4. Virtual Rainfall Stations Created in the UBRB

3. RESULTS AND DISCUSSION

In this study, a new computer program called RaDeR©ver1.0 was successfully developed using Visual C++. RaDeR©ver1.0 is a single windows interface program. The program estimates radar-derived rainfall using meteorological raw radar data available at the Malaysian Meteorological Department (MMD).The RaDeR©ver1.0 program performs fast estimation more than 100 times of 3D-Rapic Program used by MMD.

The RaDeR©ver1.0 was developed for the AgriGRID portal under the KnowledgeGRID Malaysia initiative of MOSTI. Therefore, the program was modified to be suitable with the Linux environment, auto-raw radar rainfall data entry and multiple locations rainfall reports generation.

3.1 Development of radar-derived rainfall calibration models

For each radar station, specific radar-derived rainfall calibration models were developed. These models were developed based on the original and adjusted radar-derived rainfall data with gauge rainfall data. The radar-derived rainfall calibration method involves two steps:

1. Adjustment of radar-derived rainfall rates
2. Determination of radar-derived rainfall calibration factors

For the radar-derived rainfall rates estimated (e.g. 7.5, 11.5, 17.8, 27.3, 42.1 and 64.8 mm/hr), the corresponding gauge rainfall values observed were collected. The average of the observed gauge rainfall values were used to find the adjusted radar-derived rainfall rate. According to these averages, the suitable adjustments required for the estimated radar-derived rainfall rates were determined as given in Table 1.

Graphical method in term of scattered plots between the radar-derived rainfall data and the gauge rainfall data were used to perform the linear regression in order to develop the radar-derived rainfall calibration models.

Table 1. Adjustments of radar rainfall rates for different video levels

Video level	Original radar rainfall rate (mm/hr)	Adjusted radar rainfall rate (mm/hr)
6	7.5	4
7	11.5	7
8	17.8	12
9	27.3	15
10	42.1	20
11	64.8	25

The suitable ten minutes radar-derived rainfall calibration factors for each radar station are given in Table 2. The original ten minutes estimated radar-derived rainfall data should be adjusted as in Table 1 before using the radar rainfall calibration factor (R_{Cf}).

Table 2. Ten minutes radar-derived rainfall calibration factors (R_{cf}) for the radar stations

Radar station	Ten minutes radar-derived rainfall calibration factors, R_{Cf}
Alor Setar	0.9313
Butterworth	0.7248
Kluang	0.5722
Kuantan	0.6782
Kota Bharu	0.8282
Subang	0.8772

3.2 Watershed runoff estimation

Selected rainfall events were supplied to the model to estimate the runoff at the outlet point (SKC Bridge) for both wet and dry seasons. The observed flow data were used during the model calibration phases. The Subang radar station was used to estimate the rainfall for the virtual rainfall station created in the UBRB.

Using rational equation, the surface runoff values were estimated based on different rainfall inputs. The direct runoff values calculated after base flow separation from the observed runoff were used for model estimations comparison and evaluation.

The estimated runoff results using the three types of rainfall inputs (i.e. gauge rainfall, original and calibrated radar-derived rainfall) for different rainfall events that occurred in 2006 are shown in Figure 5.

It is clear that the runoff estimation was improved using the calibrated radar-derived rainfall data compared to using gauge rainfall or original radar rainfall. Using radar rainfall data for runoff estimation generally gave reasonable values, while gauge rainfall data gave overestimation in most of the cases.

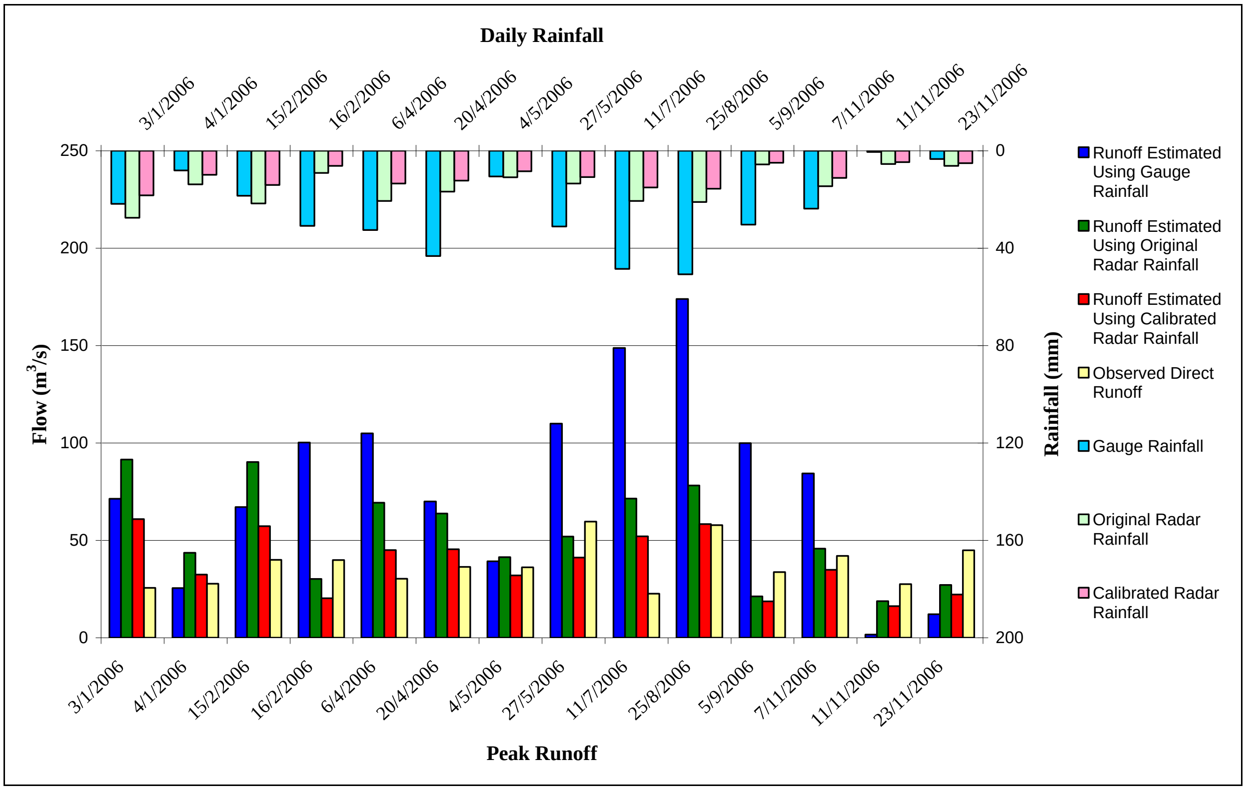

Figure 5. Comparisons between Measured and Estimated Runoff Using Different Rainfall Inputs

The statistical criteria used for runoff model evaluation show that (Table 3), the calibrated radar-derived rainfall used for runoff estimation performed best, with the average values of the *MAE* and *RMSE* being 80% better for some of the events. Taking the Theil's *U*, *E* and R^2 as measures, the total percentage improvement in runoff error using radar compared to rain gauge is 65, 70 and 50% respectively.

Table 3. Results of statistical criteria used for model performance evaluation

Statistical test	Runoff estimated using		
	Gauge rainfall	Original radar rainfall	Calibrated radar rainfall
MAE	**49.53**	**11.51**	**9.20**
RMSE	**59.81**	**12.84**	**11.66**
***U* Theil's**	**0.45**	**0.15**	**0.16**
Model efficiency (*E*)	**-44.06**	**0.42**	**0.69**
R^2	**0.47**	**0.74****	**0.84*****

The conclusion here is that due to the limited number of rain gauges in the study area (four rain gauges only), rainfall estimates sometimes failed to account for the spatial structure of the rainfall distribution i.e. insufficient rain gauge observations were available to capture the intense rainfall centers, which cause major errors in runoff estimation.

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5. CITATION AND REFERENCES

Bedient, P.B., and Huber, W.C., (2002). Hydrology and Flood Plain Analysis. Prentice Hall. Upper Saddle River, New Jersey.

Chumchean, S., Seed, A., and Sharma, A., (2006). Correcting of real-time radar rainfall bias using a Kalman filtering approach. Journal of Hydrology (317): 123-137.

Cole, S.J., and Moore R.J., (2008). Hydrological modeling using raingauge- and radar-based estimators of areal rainfall. Journal of Hydrology (358): 159-181.

Doviak, R.J., and Zrnic, D.S., (1993). Doppler Radar and Weather Observations. Academic Press, 562.

Gerstner, E.M, and Heinemann, G., (2008). Real-time areal precipitation determination from radar by means of statistical objective analysis. Journal of Hydrology (352): 296- 308.

James, W.P., Robinson, C., and Bell, J.F., (1993). Radar-assisted real-time flood forecasting. Journal of Water Resources Planning and Management, ASCE, 119 (1): 32-44.

Julien, P.Y, and Moglen, G.E., (1990). Similarity and length scale for spatially varied overland flow. Water Resources Research, 26 (8): 1819-1832

Marshall, J.S., and Palmer, W.McK., (1948). The distribution of raindrops with size. Journal of the Atmospheric Sciences, 5 (4): 165-166.

Milford, J.R, and Dugdale, G., (1989). Estimation of rainfall using geostationary satellite data. Applications of Remote Sensing in Agricultural Sciences. London.

Sharif, H.O., Ogden F.L., Krajewski W.F., and Xue M., (2002). Numerical Simulations of Radar Rainfall Error Propagation. Water Resources Research, 38 (8).

Stellman, K.M., Fuelberg, H.E., Garza, R., and Mullusky, M., (2001). An examination of radar and rain gauge–derived mean areal precipitation over Georgia watersheds. American Meteorological Society 16 (1): 133-144.

Sun, X., Mein, R.G, Keenan, T.D, and Elliott, J.F., (2000). Flood estimation using radar and rain gauge data. Journal of Hydrology (239), 4-18.

Wang, X., Hongjie, X., Sharif, H., and Zeitler, J., (2008). Validating NEXRAD MPE and stage III precipitation products for uniform rainfall on the Upper Guadalupe River Basin of the Texas Hill Country. Journal of Hydrology (348): 73-86.