

Comparison between the TRMM Product and Rainfall Interpolation for Prediction in Ungauged Catchments

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Abstract: Several satellite rainfall products are commonly used for data-scarce catchments because of their extensive coverage together with applicable spatial and temporal resolutions. Although satellite rainfall products have limited accuracy, in data-scarce situations they may be preferable to interpolating between raingauges. Various previous studies focus on assessing the performance of different satellite-based rainfall products in sparsely gauged regions but few make the comparison with interpolated rainfall. This paper aims to evaluate the performance of the Tropical Rainfall Measurement Mission (TRMM) product and a customised rainfall interpolation technique using the case study of the upper Ping River basin, Thailand, both in terms of rainfall rates at different time resolutions and also in terms of rainfall-flow indices.

The two methods of rainfall estimation data being assessed are TRMM_3B42 version 6 with a spatial resolution of 0.25 x 0.25 degrees; and interpolated rainfall based on the combination of lapse rate and inverse distance weighting (IDW) averaged over the same 0.25 x 0.25 degree grid squares.

As a baseline for comparing the performance in selected grids, rainfall from multiple gauges within selected 0.25 x 0.25 degree grids is averaged and assumed to represent the true spatially averaged rainfall over that grid. The gauges used for this baseline estimate are excluded from the spatial interpolation and the TRMM calibration. In total, 49 ground gauges are available.

The analysis reveals that interpolating gauged rainfall causes less error than using calibrated TRMM products both for the case of estimating spatial rainfall over a grid and for estimating rainfall-flow indices including runoff coefficient and rainfall-runoff elasticity. However, the accuracy of the TRMM products is not necessarily unacceptable and could be useful for estimating spatial rainfall for catchments with fewer or poorer quality raingauges.

Keywords: TRMM; rainfall interpolation; areal rainfall; ungauged.

1 INTRODUCTION

Rainfall is a key input to hydrological models and its estimation can have a critical effect on accuracy of hydrological studies. Rainfall data have traditionally been obtained from raingauges. While these can give very good accuracy at the location of the gauge, inaccuracies arise when estimating rainfall between them (Garcia et al. [2008]). Although in some regions, ground-based radar has been used to assist

in spatial interpolation of rainfall for many decades, it was not until 1990s that satellite-based rainfall estimates have made spatial estimation widely possible.

Several satellite rainfall products are commonly used for data-scarce catchments, where the raingauge network is coarse or its data of poor quality, because of the extensive spatial coverage provided by satellites together with applicable spatial and temporal resolutions. However, the satellite rainfall products have limited accuracy caused by, for example, the difficulty of calibrating a reliable relationship between the raw satellite signals and the actual rainfall. There are a considerable number of previous studies evaluating the performance of single or different satellite-based rainfall products over an area relative to baseline gauged estimates (i.e. Ward et al. [2011]; Asadullah et al. [2008]; Sorooshian et al. [2000]). However, few of these assess the satellite products relative to the alternative of interpolating between sparsely spaced gauges in the practical context of a catchment hydrological analysis.

Also, there have been few published studies of the applicability of satellite-derived rainfall to water resources studies in the monsoon-dominated climates of Thailand. The most comprehensive published study is that of Chokngamwong and Chiu [2007] who compared the Tropical Rainfall Measurement Mission (TRMM) 3B42 V5 and V6, and 3B43 V5 and V6 products to gauged rainfall over the whole of Thailand at the spatial resolution of 1 x 1 degree. The TRMM 3B43 V6 yielded the best performance statistics for monthly analysis over Thailand with bias -0.6 mm/month, mean average error 7.5 mm/month, and RMSE 72 mm/month. Their analysis concluded that both versions of TRMM products are deficient in capturing heavy rainfall event but applying a scaling factor between 0.2 and 2 could be used to compensate for this weakness. Using the 5-day average of the outputs of either the V5 or V6 TRMM products was considered appropriate for large-scale water resources applications. However, the sub-basin scale studies that are now necessary in Thailand (Visessri et al., 2011) require TRMM to be assessed at a finer resolution.

As a result, this paper aims to evaluate the performances of the TRMM 3B42 V6 product and a customised rainfall interpolation technique using the case study of the upper Ping River basin in northwest Thailand. The objectives are identifying the difference between two rainfall estimation methods and recommending the better approach for the purpose of estimating runoff coefficients and other relevant rainfall-flow indices.

2 STUDY CATCHMENT

The Ping River basin is in the northwest of Thailand, lying between latitude 17.0°-19.8°N and longitude 98.0°-99.5°E (Figure 1). The approximate catchment area is 25,370 km². Most parts of the basin are mountainous and much of the rest has undulating and rolling hills, but the mid-basin consists of the Ping River plain as shown in Figure 1. The climate of the upper Ping basin is tropical and mainly characterised by two monsoons, the southwest and northeast monsoons. The southwest monsoon defines the rainy season between mid May to mid October and the northeast monsoon causes the winter season between mid October to mid February. The transition between the two monsoons is the summer (dry) period.

3 DATA SETS

3.1 Raingauge Dataset

Daily rainfall measured by 49 ground gauges from 1998-2006 was obtained from the Royal Irrigation Department of Thailand (RID), Department of Water Resources (DWR), and the Thai Meteorological Department (TMD). The raingauge network is

sparse and not uniformly distributed as shown in Figure 1. Raingauges are relatively densely located in the middle of the basin but widely scattered near the basin's border. To use as a baseline for comparing the performance of interpolated rainfall and TRMM product, gauged rainfall is spatially averaged within each of the most densely gauged 0.25 x 0.25 degree grid squares. Five grid squares (shown in Figure 1 using a red grid border), which each have 3-5 gauges, are used in this paper as benchmark grids. The average gauged rainfall over each of these grids represents an approximation of the true spatially averaged rainfall over that grid, though the accuracy is limited by inadequate sampling of raingauges as well as potential bias due for example to wind effects.

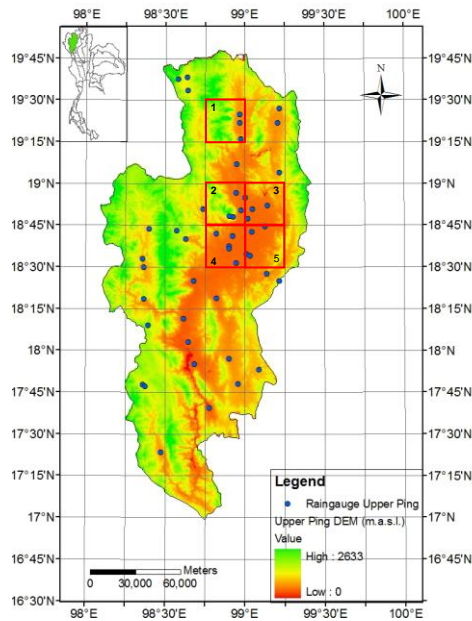


Figure 1 The terrain of the Upper Ping River basin and the distribution of raingauges over 0.25 x 0.25 degree grid squares

3.2 Interpolation of Raingauge Data

Point gauged rainfall is interpolated over the entire basin with monthly temporal and 0.05 x 0.05 degree spatial resolutions. To take into account both the effects of distance from the nearest gauge and elevation on the interpolated values of rainfall at an ungauged point, a customised rainfall interpolation technique is introduced. Firstly the monthly rainfall lapse rate (monthly rainfall gradient with respect to elevation, λ) is calculated by regressing monthly rainfall against gauged elevations:

$$R_{os} = R_{og} + \lambda(h_s - h_g) \quad (1)$$

where R_{os} is observed rainfall at sea level
 R_{og} is observed rainfall at gauged level
 h_s is elevation at sea level ($h_s = 0$)
 h_g is elevation at gauged level

Using this equation, the observed rainfall from all gauges is then made homogeneous to mean sea level equivalents. Subsequently, inverse distance weighting is applied to R_{os} to account for decreasing correlation of rainfall between sites with distance between sites. The final interpolated values are obtained by converting the interpolated rainfall at sea level back to gauged level, again through equation (1). An example of using lapse rate for temperature interpolation can be found at Mirshahi [2010]. For this study catchment, the combination of lapse rate

and inverse distance weighting was found to outperform other interpolation methods, i.e. Thiessen polygons, kriging, linear regression with elevation and/or distance. The average of the 0.05 x 0.05 degree interpolated rainfall data over a 0.25 x 0.25 degree grid square allows comparison with the benchmark grids and the TRMM estimates. The gauges within the benchmark grids were omitted from the interpolation.

3.3 TRMM 3B42 Version 6 Algorithm

The rainfall measuring equipment for TRMM comprises the Precipitation Radar, TRMM Microwave Imager, and Visible Infrared Scanner. TRMM 3B42 V6 merges the TRMM data with other sources to produce daily rainfall at 0.25 x 0.25 degree spatial resolution. Firstly, 3-hourly infrared estimates are merged with the calibrated microwave estimates and other satellite products including GMS, GOES-E, GOES-W, Meteosat-7, Meteosat-5, and NOAA-12. Then the 3-hourly merged-infrared precipitation is summed over a calendar month to combine and calibrated using monthly ground-gauged data. The same calibration coefficients are assumed to apply to the 3-hour estimates, and the final product of TRMM 3B42 is the accumulation of the 3-hour 0.25 x 0.25-degree data over each day.

Table 1 Data used in this study

Product	Spatial resolution	Duration
Raingauges	point	Jan 1998- Dec 2006
Benchmark grid-averaged raingauges	Averaged over 0.25° x 0.25°	Jan 1998- Dec 2006
Interpolated raingauge data	0.05° x 0.05°, then scaled up to 0.25° x 0.25°	Jan 1998- Dec 2006
TRMM 3B42 V6	0.25° x 0.25°	Jan 1998- Dec 2006

4 ANALYSIS PROCEDURE AND RESULTS

4.1 Assessment of TRMM 3B42 V6 at Daily and Monthly Scales

The daily and monthly assessment of TRMM estimates relative to the five benchmark grids is performed through equations (2) to (6). The probability of detection (POD) and false alarm rate (FAR) are measures of how well TRMM detects wet days. These are calculated only for the daily time step. High POD, 0.91-0.94, and low FAR, 0.10-0.15 over the 5 benchmark grid squares, suggest that TRMM is highly capable of capturing rainfall occurrence. There is no clear spatial pattern in FAR but the lowest POD for grid squares 1 and 2 (Figure 1) can be associated with the large mountainous area where satellite signals may not represent the rainfall mechanisms (i.e. McCollum et al. [2000]; Dinku et al. [2011]) so that the detection of daily rainfall is deteriorated.

$$\text{POD} = \frac{H}{H+M} \quad (2)$$

$$\text{FAR} = \frac{FA}{H+FA} \quad (3)$$

where H = Number of days when both gauges and TRMM record rainfall
 M = Number of days when gauges record rainfall but TRMM does not
 FA = Number days when TRMM records rainfall but gauges do not

The performance of the TRMM product at estimating rainfall amounts is evaluated both using daily data and monthly aggregation of the data. For this evaluation, bias, mean absolute error (MAE) and correlation coefficient (r), as defined in equations (4), (5) and (6), are used.

$$\text{Bias} = \frac{[\sum(x-y)/n]}{\text{mean}(y)} \times 100 \quad (4)$$

$$\text{MAE} = \frac{[\sum[\text{abs}(x-y)]/n]}{\text{mean}(y)} \times 100 \quad (5)$$

$$r = \frac{(n\sum xy - \sum x \sum y) / \text{sqrt}[(n\sum x^2 - (\sum x)^2)(n\sum y^2 - (\sum y)^2)]}{\quad} \quad (6)$$

where x = TRMM estimate of rainfall depth over a grid
 y = Gauged rainfall depth averaged over a grid
 n = Number of days (or months)

By comparing the time series of TRMM estimates to those of the benchmark grid-averaged raingauges, this study agrees with the statement of Chokngamwong and Chiu, [2007] in that TRMM cannot accurately measure high rainfall rates. The TRMM product often fails to capture rainfall amounts over 350 mm/month. This may be caused by infrequent sampling frequency so that the satellite misses short storms (Ward et al. [2011]). Figure 2 indicates that the aggregation of daily TRMM estimates to monthly estimates reduces the discrepancy between the TRMM estimates and ground-gauged rainfall. This is due to the effect of error averaging from a finer to coarser time scale.

Figure 2 also shows that the long-term bias in rainfall (%Bias) at each of benchmark grids is small, ranging between approximately -15% and +7%. The %Bias is smaller for grid squares 3, 4, and 5 where the terrains are relatively flat and have a good distribution of raingauges leading to the true grid-averaged rainfall being better represented by the grid-averaged raingauges. The heterogeneity of terrain within the grid squares is considered to have a stronger influence on long-term bias than the number of raingauges within the grid squares.

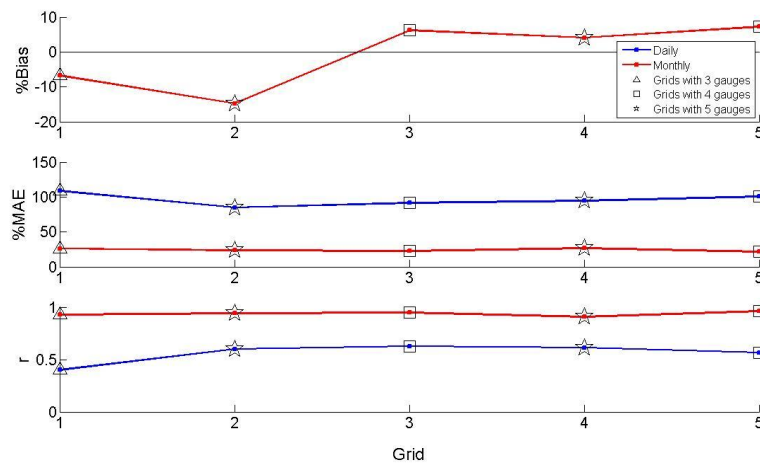


Figure 2 Comparison of daily and monthly performance for TRMM estimates

Although the TRMM product has already merged the satellite data with some ground-gauged data, there is potential benefit in additional calibration of the TRMM data against regional data sets (Asadullah et al. [2005]). Therefore, the TRMM daily estimates are adjusted through linear regression against gauged rainfall (excluding the benchmark gauges) and then aggregated to monthly time steps. To assess the ability of the TRMM product to represent seasonal scale variability, the monthly TRMM estimates are further aggregated into seasonal rainfall. Figure 3 shows that the TRMM estimates overpredict rainfall amounts in summer but underpredict during winter

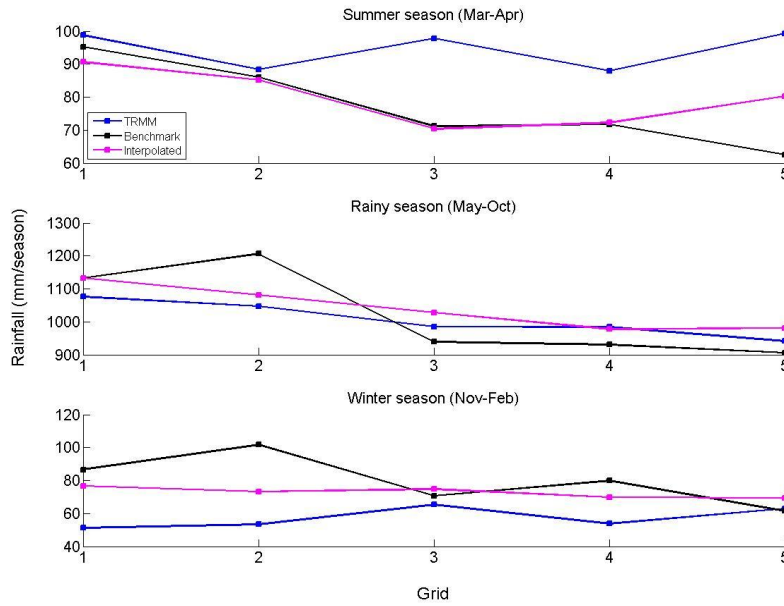


Figure 3 Seasonal rainfall amount estimated based on TRMM and interpolated raingauge data

4.2 Comparison of TRMM 3B42 V6 and interpolated raingauge data at a monthly scale

The main purpose of this section is to assess the best method for estimating gridded rainfall in sparsely gauged areas as represented by the case study. The gauges falling in the benchmark grids are excluded from the TRMM calibration and interpolation so that they can be used for independent performance comparison. Figure 4 indicates the similar pattern of errors produced by TRMM and interpolation but the latter (with a grid-averaged MAE of approximately 19 mm/month) outperforms TRMM (with a grid-averaged MAE of approximately 24 mm/month) in estimating areal rainfall over the benchmark grids.

The monthly rainfall from a randomly selected raingauge in each benchmark grid square is also included in this analysis to investigate how much of the error is associated with lack of rain gauges to provide the benchmark estimate (on the assumption that using a random single gauge will in general give a poorer grid-average estimate than using all available gauges). Using a randomly selected raingauge gives a grid-averaged MAE approximately 10 mm/month different from that using all gauges. This indicates that the number of gauges used for the benchmark estimate is important influence on the apparent accuracy of both estimation methods.

The spatial rainfall obtained from TRMM and interpolated raingauge data are used to calculate the runoff coefficient and rainfall-runoff elasticity. This is relevant because these and other indices must be estimated for all the sub-basins as part of a wider water resources study (Visessri et al. [2011]). Rainfall-runoff elasticity is defined in equation (7). This is implemented over all 44 basins with reasonable quality flow observations. The true values of rainfall-flow indices over all these sub-basins are not known, nevertheless the runoff coefficient and rainfall-runoff elasticity calculated based on the spatially averaged rainfall from all raingauges located within each sub-basin is used as a comparison. All three rainfall estimation methods - TRMM products, interpolated rainfall and gauge-averaged rainfall - yield plausible values of runoff coefficients (Figure 5). The spatial variability of the runoff coefficients over sub-basins obtained from all methods is similar but TRMM gives lower runoff coefficients than the other two methods. This is believed to be caused by the underestimation of winter rainfall as shown in Figure 3. Figure 6 shows that

TRMM produces higher rainfall-runoff elasticity than the interpolated rainfall because of the small seasonal variability in wet and dry rainfall as shown in Figure 3, supporting the previous finding that the TRMM has limited ability to measure high rainfall rates, resulting in the over-estimate of rainfall-runoff elasticity.

$$\text{Rainfall-runoff elasticity} = \frac{[(WF-DF)/DF]}{[(WR-DR)/DR]} \quad (7)$$

Where
 WF = Streamflow in wet period (May-Oct)
 DF = Streamflow in dry period (Jan-Apr and Nov-Dec)
 WR = Rainfall in wet period (May-Oct)
 DR = Rainfall in dry period (Jan-Apr and Nov-Dec)

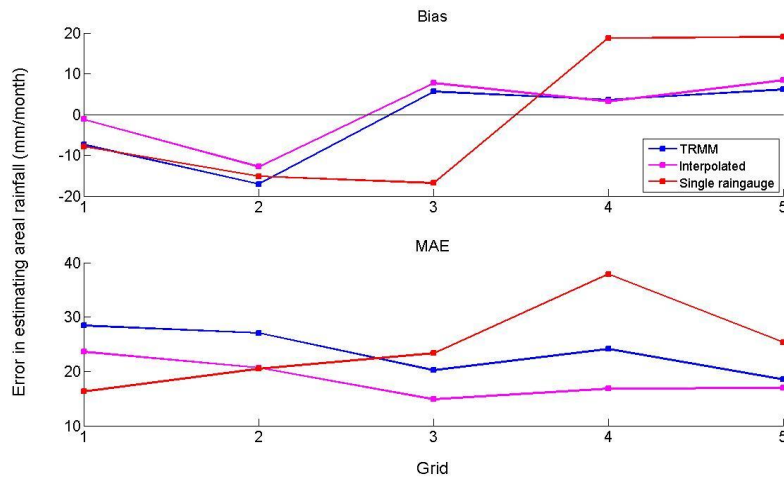


Figure 4 Error of areal rainfall estimates based on TRMM, interpolated raingauge data and a point raingauge

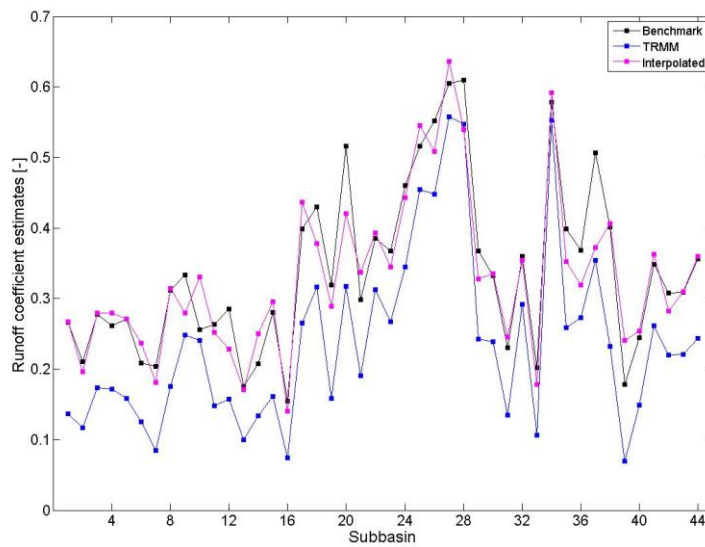


Figure 5 Runoff coefficient estimates based on TRMM and interpolated raingauge data

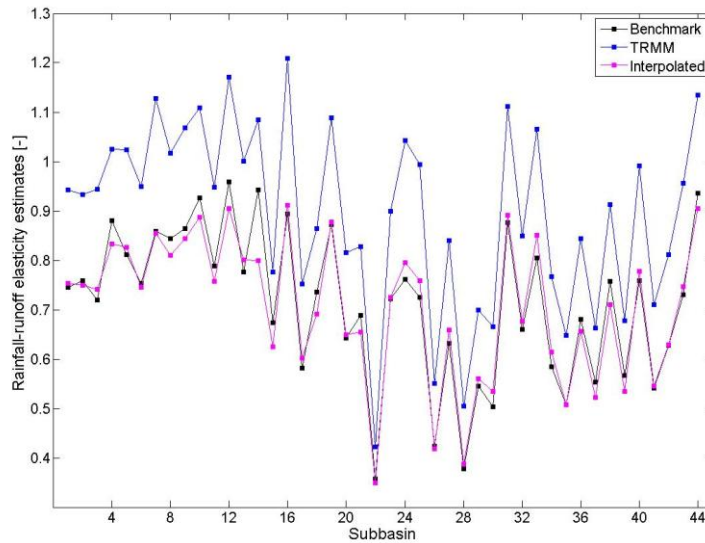


Figure 6 Rainfall-runoff elasticity estimates based on TRMM and interpolated raingauge data

5 DISCUSSION AND CONCLUSION

The analysis indicates that interpolating gauged rainfall causes less error than using the calibrated TRMM product for estimating spatial rainfall over a grid. The monthly bias and mean average error for TRMM estimates obtained from this study are significantly larger than that of Chokngamwong and Chiu [2007]. This is believed to be because the errors (in both gauged and TRMM estimates) found in the the 2007 study were averaged out more because larger grid boxes of 1 x 1 degree were used.

This paper suggests that the use of lapse rate with inverse distance weighting to interpolate relatively sparse ground-gauged data is generally more accurate than using TRMM at 0.25 x 0.25 degree, daily to seasonal scales. However, this is not necessarily applicable to all other case studies because the TRMM product could be useful for estimating spatial rainfall for catchments with an even more sparse raingauge network, and for catchments with lower data quality.

The paper also illustrated that the biases in rainfall estimation, in particular in the winter season in this case, have the potential to introduce significant error in rainfall-flow indices that are used in water resources modelling.

The main limitation of this paper is that the conclusion is drawn based on a small number of benchmark grid squares, and even though these were relatively densely gauged, it could be argued that much of the error is associated with that in the benchmark estimates. However, the consistency of results in Figures 1-6 supports the general conclusion that in this case the interpolation of ground-gauged estimates is better than using TRMM. The challenge for future research is to improve the estimation of rainfall in complex terrain, especially in mountainous areas.

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