Evaluation of satellite precipitation products for extreme flood events: case study in Peninsular Malaysia

Eugene Zhen Xiang Soo, Wan Zurina Wan Jaafar, Sai Hin Lai, Tanvir Islam and Prashant Srivastava

ABSTRACT

This study aimed at evaluating the three advanced satellite precipitation products (SPPs), i.e. CMORPH, TRMM 3B42V7 and PERSIANN, against the ground observation to evaluate their performance in detecting rain, capturing storms and rainfall pattern during 2014–2015 extreme flood events at three different river basins in Peninsular Malaysia (Kelantan, Langat and Johor river basins). Several spatial interpolation methods, including Arithmetic Mean, Thiessen Polygon, Inverse Distance Weighting, Ordinary Kriging and Spline were applied on the ground observations to transform the point-based precipitation into areal precipitation. Slight variations in the interpolated values were found, but overall it was comparable. Based on the daily rainfall data for the duration of 62 days, this study found that all SPPs performed with acceptable accuracy, as shown by the Kelantan river basin; however, these SPPs did not estimate accurately for Langat and Johor river basins. Overall, TRMM and CMORPH outperformed PERSIANN for the Langat and Johor river basins. In conclusion, all SPPs were capable of predicting heavy rainfall during the northeast monsoon and the level of accuracy is promising for the northern part of Peninsular Malaysia. However, as for the rest of the region, careful consideration should be given when applying the SPPs.

Key words | extreme flood, Malaysia, rainfall interpolation, satellite precipitation products

INTRODUCTION

Flooding is one of the most common natural disasters that occur in the world (Scofield & Kuligowski 2003; Khan et al. 2011; Seyyedi et al. 2014). This disaster eventually disrupts the quality of life and economic growth in a country and can result in severe damage and loss of properties, and occasionally loss of human lives. Many researchers, climatologists and hydrologists have tried to collect climatic information throughout water resources management for identifying trends in the statistics of historical stream flow or other hydro climatic variables (Easterling et al. 1999; Moazami et al. 2013). Precipitation is one of the fundamental components of the climate system and of the global water cycle (Gu et al. 2010; Kidd & Huffman 2011; Kucera et al. 2013; Hou et al. 2014) and it is also an important input required for water resource management, hydrologic and ecologic modeling, recharge assessment, and irrigation scheduling (Su et al. 2008; Mair & Fares 2010; Behrangi et al. 2011; Jiang et al. 2012). It is difficult to determine the amount of rain that falls across the world as the temporal and spatial distribution of rainfall is not even (Gu et al. 2010).

A rain gauge is one of the most common weather measurements for providing precipitation data. This instrument directly measures precipitation and has been the only available information from which to derive long records of reference precipitation over many years (Yilmaz et al. 2005; Tapiador et al. 2012). While rain gauges provide
rainfall measurements at individual points, it is of more interest for hydrologic engineers to know rainfall amounts over an area. Such an area can be a small drainage basin, a watershed, or a large river basin (Habib et al. 2012; de Coning 2013). Also, in many regions of the world, including developing countries, oceans and mountains are ungauged (Collischonn et al. 2008; Behrangi et al. 2011). Apart from that, the instruments do malfunction and back-up systems may not always provide accurate data (Strangeways 2004). Rain gauges may also underestimate true precipitation due to significant bias arising from coarse spatial resolution, location, wind, and mechanical errors (Groisman & Legates 1994; Yilmaz et al. 2005; de Coning 2013). Precipitation can also be estimated using weather radar due to its continuous spatial coverage (Habib et al. 2012) but it has difficulties in hardware calibration (Yilmaz et al. 2005). The area covered by weather radar is still limited, the precipitation can be undetected or the rate can be underestimated as the distance from the radar increases (Scofield & Kuligowski 2003; Gu et al. 2010; Diederich et al. 2015). Moreover, the accuracy of the reflectivity values can be influenced by fixed targets such as ground clutter, beam block or anomalous propagation (de Coning 2013; Diederich et al. 2015).

Precipitation estimated from weather satellites is useful in any hydrological applications due to their extensive spatial coverage and finer space and time resolutions (Tian et al. 2009; Moazami et al. 2013). This estimation can be useful for sparse data and ungauged basins in some developing areas (Moazami et al. 2015), or regions such as oceans and mountains where rainfall data cannot be obtained from any resources (de Coning 2013). Various new global high resolution satellite precipitation products (SPPs) have been operationally available, including the National Oceanic and Atmospheric Administration Climate Prediction Center morphing technique product (CMORPH) (Joyce et al. 2004), the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis products (TMPA) (Huffman et al. 2007), the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) (Hsu et al. 1997; Sorooshian et al. 2000), and the Global Satellite Mapping of Precipitation (GSMaP) (Kubota et al. 2007). These SPPs have provided quasi-global high-temporal (≤3 h) and spatial (≤0.25) resolution precipitation maps.

Numerous studies evaluating the performance of weather satellites have varied according to location, season, topography, climatology, and so on (Dinku et al. 2008; Moazami et al. 2013; Tan et al. 2015; Jiang et al. 2016; Luo et al. 2017). In Malaysia, Varikoden et al. (2010) and Semire et al. (2012) evaluated the TRMM 3B42V6 daily and monthly data respectively in Malaysia and found that 3B42V6 performs well over Malaysia with about 15% error bias at monthly scale. Later, Tan et al. (2015) found that CMORPH, TRMM and PERSIANN satellite products performed better in the northeast monsoon compared to the southwest monsoon. These products also showed better performances in eastern and southern Peninsular Malaysia (Kelantan, Terengganu, Pahang and Johor) and in the north of East Malaysia (Sabah), which receives higher rainfall during the northeast monsoon. Poor performances occurred in the western and drier Peninsular Malaysia.

In China, Xue et al. (2015) evaluated two versions of TRMM 3B42 (V6 and V7) products in the mountainous Wangchu Basin of Bhutan using rain gauge data. The results showed that the TRMM 3B42V7 product was better compared to the 3B42V6 product in precipitation accuracy and could serve as input to distributed hydrological modelling in that study area. Jiang et al. (2012) evaluated the performance of near real time satellite products, i.e. CMORPH and two models of TMPA satellite – 3B42V6 and 3B42RT – from 2003 to 2008 in the Mishui Basin in South China. They found that the 3B42V6 satellite underestimated the rainfall precipitation by about 4%, while the other two underestimated by about 40%. Later, Jiang et al. (2016) evaluated the latest version of TRMM 3B42V7 with CMORPH over 12 years (2000–2011) in two different latitude basins of China and found that both satellite products overestimated precipitation over the high-latitude Laoha river basin and underestimated for the low latitude Mishui Basin. Chen et al. (2014) evaluated the performance of CMORPH and PERSIANN products during flood events in Beijing, China in July 2012. The results showed that both CMORPH and PERSIANN were not comparable to the dense rain gauge observations. CMORPH overestimated the daily accumulated rainfall, whereas PERSIANN underestimated the daily accumulated rainfall.

Gottschalck et al. (2005) evaluated the performance of PERSIANN and TRMM 3B42RT over the Continental
United States (CONUS), and found that both PERSIANN and 3B42RT overestimated precipitation over the central CONUS and western mountains during the spring and summer. However, during the fall and winter months PERSIANN underestimated precipitation in the western mountains and 3B42RT overestimated it. Later on, Tian & Peters-Lidard (2007) furthered the work by evaluating CMORPH over the CONUS and found that there was an underestimation over the northeast during the summer months, but a severe overestimation over the central CONUS and mountain west during the summer and spring months.

Some researchers evaluated the performance of SPPs by point to pixel comparison (Hughes 2006; Ghaju & Alfredsen 2012; Bajracharya et al. 2015) and some of that evaluated the precipitation at basin scale by implementing rainfall interpolation methods. None of the researchers evaluated which interpolation method is suitable to compare with the grid-based satellite estimations. Most of the researchers used the inverse distance weighting (IDW) technique to interpolate the rain gauge data and evaluated the performance of TRMM 3B42 by direct comparison of the mean rainfall (Collischonn et al. 2008; Tan et al. 2015; Tuo et al. 2016). Liu et al. (2012, 2015) used the Thiessen Polygon (TP) method to convert the point-based rain gauge observations to areal precipitation. Akbari et al. (2011) used the Kriging method on the existing gauge network to explain the storm pattern over the Klang watershed and to compare with TRMM rainfall estimation.

The present study attempts to evaluate the performance of three SPPs (CMORPH, TRMM 3B42V7 and PERSIANN) at three selected river basins (Kelantan, Langat and Johor) in Peninsular Malaysia during the 2014–2015 flood events. The scope of this study differs from most other studies (for example, Liu et al. 2015) in that the evaluation of the SPPs during the extreme events was applied to the three river basins that are located at different geographical locations. The December 2014–January 2015 event was chosen due to its being the worst flood that occurred in Kelantan, followed by Johor. During this period, Peninsular Malaysia experienced the northeast monsoon, thus the Kelantan river basin was the worst affected as it was directly influenced by the monsoon. As for Johor, even though the location is towards the south, the bad weather also affected this area and Peninsular Malaysia as a whole. It was said that climate change was the main factor. The inclusion of Langat river basin in this study is due to its geographic location towards the west of Peninsular Malaysia. Thus, this research investigates the capability of satellite rainfall by taking into account river basins from different geographic locations, i.e. the west coast of Peninsular Malaysia. Also, note that in this study, a comparative evaluation on various rainfall interpolation methods used to transform the point-based rain gauge data to areal precipitation was performed. The purpose of this evaluation is to determine the most suitable method for the rain gauge observations to compare with the grid-based satellite estimations. Moreover, this study presents the rain detection and capturing storm ability of every SPP over three river basins. The case study specifications including the datasets are discussed in the next section, followed by a description of the implemented methods for evaluating the SPPs. The results are then discussed, and the final section draws the conclusions of this research and provides recommendations for future studies.

STUDY AREA AND DATASETS

Description of the study area

At the end of 2014, an extreme flood event hit several countries such as Indonesia, Malaysia, Thailand and Philippines where heavy rains fall due to the southeast monsoon blowing across the South China Sea, making the sea warmer than usual. In Malaysia, extreme floods that occurred on 15 December 2014–3 January 2015 are considered to be the worst flood events in decades. During this event, most of the rivers in Kelantan, Pahang, Perak and Terengganu reached dangerous levels. More than 200,000 people were affected and 21 people were killed due to this natural disaster (Akasah & Doraisamy 2015). In this study, three river basins were chosen mainly based on their history of great flood, variations in basin size and different geographic locations. As shown in Figure 1, Kelantan, Langat and Johor river basins are located at the northern, western and southern parts of Peninsular Malaysia, respectively. Further explanation on these study areas is discussed in the following section.
Kelantan river basin

Kelantan river basin, as shown in Figure 2(a), is one of the major basins in Malaysia which is located at the northeastern part of Peninsular Malaysia at latitudes 4°40’ N to 6°12’ N and longitudes 101°20’ E to 102°20’ E. The maximum length and breadth of the catchment are 150 and 140 km, respectively. The river is about 248 km long and drains an area of 13,100 km², occupying more than 85% of the State of Kelantan. The basin has an annual rainfall of about 2,500 mm, much of which occurs during the north-east Monsoon between mid-October and mid-January. The mean annual temperature at Kota Bharu is 27.5°C with mean relative humidity of 81%. The mean flow of the Kelantan River measured at Guillemard Bridge (5.76° N, 102.15° E) is 557.5 m³/s. The entire basin contains large areas of tropical forested mountains, lowland forest and limestone hills. Currently, there are many activities involving land use changes from lowland forest to vegetation and urban areas. In terms of climate, the southwest and northeast monsoons hit Peninsular Malaysia annually (Tangang et al. 2007; Sow et al. 2011). The northeastern monsoon produces heavy rains and thunderstorms between November and March. From May to September, another inter-monsoon comes from the southwest and hits places like Kelantan, bringing the most rainfall to the study area. During the 2014–2015 flood events, Kelantan was the most seriously affected state and it had the most evacuees with more than 20,000 people (Akash & Doraisamy 2015).

Langat river basin

Langat river basin, as shown in Figure 2(b), covers the state of Selangor and Negeri Sembilan and also a portion of the Federal Territory of Putrajaya, Kuala Lumpur and Klang, and Petaling Jaya district. The basin has a total catchment area of about 2,350 km². The larger part of the basin, totaling 1,900 km², occupies the south and southeastern parts of the state of Selangor. The basin is located between latitudes 1°30’–2°10N and longitudes 103°20’–104°10E. There are three major tributaries, i.e. Langat River (the main river), Semenyih River and Labu River. The Langat River has a total length of about 180 km, draining from the main range (Banjaran Titiwangsa) at the northeast of Hulu Langat District in a south-southwest direction into the Straits of Malacca. Both the Langat River and the Semenyih River originate from the hilly and forested areas in the western slope of Banjaran Titiwangsa, northeast of Hulu Langat. This water catchment is important as it provides raw water supply and other amenities to approximately 1.2 million people within the basin.
Important built-up areas served include towns such as Cheras, Kajang, Bangi, Government Centre of Putrajaya and others. There are two reservoirs (Semenyih and Hulu Langat) and eight water treatment plants (four of which operate 24 hours), which provide clean water to the users after undergoing treatment. In terms of climate, high rainfall and high humidity occur at various periods throughout the year. The mean areal annual rainfall of this basin is 1994.1 mm. The highest recorded monthly rainfall was about 327.1 mm, occurring in November (i.e. during the northeast monsoon), while the lowest was 97.6 mm in June (i.e. during the southwest monsoon).

Johor river basin

Johor river basin, as shown in Figure 2(c), is located in the southern part of Peninsular Malaysia, located between latitudes 1°30’–2°10’ N and longitudes 103°20’–104°10’ E. The catchment covers four districts of Johor State: Kota Tinggi, Kluang, Kulai Jaya and Johor Bahru. It has a surface area of about 1,652 km². The main river, Johor River, is 122.7 km long and originates from Gunung Belumut (the second-highest mountain in Johor) in the north of the basin. The river flows in a north–south direction and then south–west into the Strait of Johor. This basin is covered mostly by rubber and oil palm plantation. This catchment has an average annual rainfall of 2,500 mm. Like the Kelantan river basin, the climate in Johor river basin is a tropical monsoon climate, divided into the northeast monsoon (November–February), and the southwest monsoon (May–August) (Tangang et al. 2007; Sow et al. 2011). Flooding events frequently occur in December when the highest rainfall and peak streamflow are recorded.

Description of the datasets

Rain gauge network

Daily rainfall data collected from 1 December 2014–31 January 2015 (62 days) at 50 operating rain gauge stations in Kelantan river basin, 28 stations in Langat river basin and 18 stations in Johor river basin were analysed. All data were collected from the Department of Drainage and Irrigation (DID), Malaysia. Table 1 represents examples of selected stations with detailed information including station name, district, river, latitude and

![Figure 2](https://iwaponline.com/jwcc/article-pdf/10/4/871/640732/jwc0100871.pdf)
longitude for the three river basins. Figure 2 shows the distribution of rain gauge network for all three river basins. For Kelantan river basin, as shown in Figure 2(a), most of the rain gauge stations are installed at lower elevations in the northern portion of the basin, while only a few stations are found at the southeastern portion of the basin. For Langat river basin, as shown in Figure 2(b), the rain gauges are almost equally distributed. More stations are concentrated at latitudes 3°00′–3°15′ N and longitudes 101°45′–102°00′ E, but not many stations were found at the southeastern portion of the basin. Not many rain gauge stations are active during the selected event in Johor River Basin; in fact some grids are found with only one station, as shown in Figure 2(c).

CMORPH

The CMORPH product (Joyce et al. 2004) is a pure SPP using only satellite infrared information about the spatial and temporal evolution of rain clouds and not the rainfall estimates themselves. This product provides precipitation for the spatial coverage of 60°N–60°S. In the latest CMORPH Version 1.0, bias correction was conducted by adjusting the satellite estimates against a daily rain gauge analysis and can be accessed from ftp://ftp.cpc.ncep.noaa.gov/precip/global_CMORPH. Three spatial and temporal resolutions can be selected: 8 km–30 min, 0.25°–3 hourly, and 0.25°–daily. In this study, the 0.25°–daily bias-corrected Version 1.0 CMORPH data were used.

TRMM

The TMPA (TRMM Multisatellite Precipitation Analysis) was produced by the National Aeronautics and Space Administration (NASA). This product is a combined microwave-infrared precipitation product (Huffman et al. 2007), providing precipitation for the spatial coverage of 50°N–50°S at the latitude–longitude resolution. The latest version of this product, 3B42V7, can be freely downloaded from Goddard Earth Sciences Data and Information Services Center (http://mirador.gsfc.nasa.gov). In this study, the daily aggregated TRMM 3B42V7 observations at a spatial resolution of 0.25° were analyzed.

PERSIANN

The PERSIANN product estimates the rainfall rate from satellite observations by combining the infrared and passive microwave data using the artificial neural network function (Hsu et al. 1997; Sorooshian et al. 2000). This product can provide precipitation data for the spatial coverage of 60°N–60°S. In this study, the bias-corrected PERSIANN data were downloaded from www.ngdc.noaa.gov/. These data maintain the total monthly precipitation estimation

<p>| Table 1 | Examples of rain gauge stations used in study |</p>
<table>
<thead>
<tr>
<th>River basin</th>
<th>ID</th>
<th>Station Name</th>
<th>District</th>
<th>River</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelantan</td>
<td>4721001</td>
<td>Upper Chiku</td>
<td>Gua Musang</td>
<td>Sg. Nenggiri</td>
<td>04°45′55″</td>
<td>102°10′25″</td>
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<td></td>
<td>4819027</td>
<td>Gua Musang</td>
<td>Gua Musang</td>
<td>Sg. Galas</td>
<td>04°52′45″</td>
<td>101°58′10″</td>
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<tr>
<td></td>
<td>5320038</td>
<td>Dabong</td>
<td>Kuala Krai</td>
<td>Sg. Galas</td>
<td>05°22′40″</td>
<td>100°00′55″</td>
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<tr>
<td></td>
<td>5719001</td>
<td>Kg. Durian Daun (Lawang)</td>
<td>Tanah Merah</td>
<td>Sg. Jelok</td>
<td>05°46′50″</td>
<td>101°58′05″</td>
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<tr>
<td></td>
<td>5823001</td>
<td>Ibuk Bekalan Tiga Daerah</td>
<td>Pasir Putih</td>
<td>Sg. Semerak</td>
<td>05°51′50″</td>
<td>102°20′40″</td>
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<tr>
<td>Langat</td>
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<td>Sg. Langat</td>
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<tr>
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<td>Sg. Semenyih</td>
<td>03°04′43″</td>
<td>101°52′50″</td>
</tr>
<tr>
<td></td>
<td>3118105</td>
<td>Batu 14, Hulu Langat (Balai Polis)</td>
<td>Hulu Langat</td>
<td>Sg. Langat</td>
<td>03°06′41″</td>
<td>101°48′59″</td>
</tr>
<tr>
<td></td>
<td>3218101</td>
<td>TNB Pansun</td>
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<td>Sg. Langat</td>
<td>03°12′34.7″</td>
<td>101°52′33.1″</td>
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<tr>
<td>Johor</td>
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<td>Sek. Men. Bkt. Besar di Kota Tinggi</td>
<td>Kota Tinggi</td>
<td>Sg. Johor</td>
<td>01°45′50″</td>
<td>103°43′10″</td>
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<td>1738131</td>
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<td>Sg. Sebol</td>
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<td>103°38′15″</td>
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with GPCP (Global Precipitation Climatology) (Huffman et al. 2001), at a spatial resolution of 0.25° and daily temporal resolution.

**METHODS**

**Interpolation of rain gauge precipitation**

Rain gauge measurement is considered as a point precipitation measurement and it cannot represent the volume of precipitation falling over a given catchment area. Therefore, spatially distributed dense rain gauges are crucial as a true representation of the precipitation in the area. However, a very dense spatially distributed rain gauge is often difficult to find in most countries. When a limited number of rain gauges are compared to the satellite products, a point-to-grid precipitation is insufficient for the large variability of rain gauge associated with the spatial and temporal resolution of satellite products. Therefore, conversion to a gridded surface from rain gauge data at the same resolution of satellite products. Therefore, conversion to a grid representation of the precipitation in the area. However, a spatially distributed dense rain gauges are crucial as a true measurement and it cannot represent the volume of precipitation falling over a given catchment area. Therefore, spatially distributed dense rain gauges are crucial as a true representation of the precipitation in the area. However, a very dense spatially distributed rain gauge is often difficult to find in most countries. When a limited number of rain gauges are compared to the satellite products, a point-to-grid precipitation is insufficient for the large variability of rain gauge associated with the spatial and temporal resolution of satellite products. Therefore, conversion to a gridded surface from rain gauge data at the same resolution of satellite products.

The performance of SPPs with respect to rain gauge datasets comprises of quantitative and categorical indexes. The quantitative indexes are used to measure the accuracy of rainfall amount or intensity, whereas the categorical statistics are used to measure the skill in detecting the occurrence of rain events.

**Quantitative evaluation indexes**

Six quantitative evaluations were used in this study to measure the differences between the satellite products and rain gauge datasets: the coefficient of determination ($R^2$), coefficient of Pearson Correlation ($CC$), bias, mean absolute error ($MAE$), root mean square error ($RMSE$) and normalized $NRMSE$. $CC$ explains the relationship between the actual values of two variables (independent and dependent) while $R^2$ measures how well the independent variable explains the dependent variable in a regression. Both values range between 0 (no correlation) to 1 (perfect correlation). Bias describes the degree to which the observed value is overestimated or underestimated. The $MAE$ represents the average magnitude of the error. $RMSE$ indicates how closely the satellite observation predicts the measured values and $NRMSE$ evaluate the reliability of SPPs. Equations (1)–(6) below show the aforementioned quantitative evaluations:

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (S_i - G_i)^2}{\sum_{i=1}^{n} (S_i - \bar{S})^2} 
\]

\[
CC = \left[ \frac{\sum_{i=1}^{n} (G_i - \bar{G}) (S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n} (G_i - \bar{G})^2 \sqrt{\sum_{i=1}^{n} (S_i - \bar{S})^2}}} \right]^2 
\]

\[
Bias = \frac{\sum_{i=1}^{n} (S_i - G_i)}{\sum_{i=1}^{n} G_i} \times 100\% 
\]

\[
MAE = \frac{\sum_{i=1}^{n} |S_i - G_i|}{n} 
\]

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (S_i - G_i)^2}{n}} 
\]

\[
NRMSE = \frac{RMSE}{G} 
\]
where $S$ and $G$ represent satellite/gridded and gauge precipitation, respectively, and $n$ is the total number of measurement, $i$ is the index of data, $\bar{S}$ is the average value of $S_i$ and $\bar{G}$ is the average value of $G_i$.

### Categorical evaluation indexes

Five categorical evaluation indexes were used including the accuracy ($ACC$), probability of detection ($POD$), false alarm ratio ($FAR$), critical success index ($CSI$) and Heidke Skill Score ($HSS$), accessed to discriminate between rain/no-rain events (days). $ACC$ represents the level of agreement between the satellite estimate and the rain gauge precipitation data. $POD$ measures how far SPPs correctly detected rainfall for all the actual occurrences of rainfall detected by the rain gauges. $FAR$ measures how often SPPs detected rainfall when actually there was no rainfall. $CSI$ measures the fraction of a gauge’s precipitation that was correctly detected by the SPPs. $HSS$ measures the fraction of correct SPP estimates without considering random matches. The equations used to calculate these quantities have all been given by Mashingia et al. (2014). Equations (7)–(11) below show the formulas of the aforementioned categorical statistics. The quantities $A$, $B$, $C$ and $D$ are computed based on the contingency table (Table 2), where $A$ represents hits (event forecast to occur, and did occur); $B$ represents false alarm (event forecast to occur, but did not occur); $C$ means misses (event forecast not to occur, but did occur); $D$ is known as correct negative (event forecast not to occur, and did not occur) and $n$ is the sum of $A$, $B$, $C$ and $D$.

**Accuracy:**

$$ACC = \frac{A + D}{n}$$  \hspace{1cm} (7)

**Hit Rate/Probability of detection:**

$$POD = \frac{A}{A + C}$$  \hspace{1cm} (8)

**False Alarm Ratio:**

$$FAR = \frac{B}{A + B}$$  \hspace{1cm} (9)

**Critical Success Index:**

$$CSI = \frac{A}{A + B + C}$$  \hspace{1cm} (10)

**Heidke Skill Score:**

$$HSS = \frac{2(A \cdot D - B \cdot C)}{(A + C) \cdot (C + D) + (A + B) \cdot (B + D)}$$  \hspace{1cm} (11)

$ACC$, $POD$, $FAR$, and $CSI$ range from 0 to 1, with 1 being the perfect score for $ACC$, $POD$, and $CSI$ and 0 being the perfect score for $FAR$. The $HSS$ ranges from $-\infty$ to 1, with 1 being a perfect score, 0 meaning no skill, with negative $HSS$ indicating that the forecast is worse than the gauge observation.

### RESULTS AND ANALYSIS

**Evaluation of various interpolation methods for rain gauge observations**

During extreme floods, the highest amount of rain over the Kelantan river basin was observed on 17 December 2014 at 205.72 mm/day. On the other hand, for the Langat and Johor river basins, the highest total amount of rainfall over the basin was 37.45 mm/day on 22 December 2014 and 49.31 mm/day on 25 December 2014, respectively. From this rainfall data, we can observe the highest rainfall pattern that hit these three basins in response to time. As the northeast monsoon season brought in rainfall from the north towards the west and south, the first hit was on the 17th (Kelantan) followed by 22nd (Langat) and 25th (Johor).
This rainfall pattern seems to follow the northeast season circulation.

The analysis begins with the results from several interpolation methods such as AM, TP, IDW, OK and SP performed on rain gauge daily precipitation to produce mean areal precipitation. The purpose of this interpolation is to examine the spatial interpolation output when various interpolation methods are performed. Generally, this study found that the trend between five interpolation methods in computing the mean areal precipitation is somewhat similar for every basin. All interpolation methods performed based on rain gauge data exhibited a somewhat similar pattern with values quite close across all the methods, even though the results shown by Kelantan river basin for the highest rainfall performed by average method are slightly different from other methods, as shown in Table 3.

For each basin, four representative examples (TP, IDW, OK and SP) of 248 precipitation maps created are shown in Figure 3 (Kelantan river basin), Figure 4 (Langat river basin) and Figure 5 (Johor river basin). These precipitation maps are from the peak (highest rainfall) of the flood events. It should be noted that the map of the AM result is not shown as there is only one rainfall value and therefore no spatial variation. The precipitation map for Kelantan river basin shown in Figure 3 appears to be related to the geographic location of the area, whereby the higher precipitation values (280–350 mm/day) at the northern zone are due to direct exposure to the South China Sea. For Langat river basin (Figure 4), higher precipitation values (75–90 mm/day) were found at the southwestern part of the basin which is in the low elevation area and very near to the sea. Higher precipitation values (50–110 mm/day) were found at the northwestern part of the Johor river basin (Figure 5).

Table 3 | Highest areal rainfall of each interpolation method during 2014–2015 flood events

<table>
<thead>
<tr>
<th>River basin</th>
<th>AM</th>
<th>TP</th>
<th>IDW</th>
<th>OK</th>
<th>SP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kelantan</td>
<td>202.46</td>
<td>105.63</td>
<td>109.05</td>
<td>105.32</td>
<td>109.12</td>
</tr>
<tr>
<td>Langat</td>
<td>37.45</td>
<td>36.22</td>
<td>38.98</td>
<td>37.46</td>
<td>36.21</td>
</tr>
<tr>
<td>Johor</td>
<td>49.31</td>
<td>43.29</td>
<td>47.65</td>
<td>43.92</td>
<td>33.34</td>
</tr>
</tbody>
</table>

Figure 3 | Results of interpolation methods for daily mean precipitation of Kelantan river basin on 17 December 2014. (a) Thiessen polygon; (b) Inverse Distance Weighting; (c) Ordinary Kriging; (d) Spline.
Evaluation of SPP against interpolated rain gauge observations

In addition to the spatial representation of different interpolation methods, comparison between all interpolation methods against satellite products was performed by observing their daily temporal data. Figures 6–8 show daily temporal precipitation between the interpolated ground observations (i.e. AM, TP, IDW, OK and SP) and (a) CMORPH, (b) TRMM and (c) PERSIANN satellite
observations for the 2014–2015 flood events at Kelantan, Langat and Johor river basins, respectively.

For Kelantan river basin, the first and second highest rainfall occurred on the 16th and 22nd December 2014, given by all interpolation methods except the average method that reached nearly 150–200 mm/day. By comparing all five interpolation methods to the SPP (Figure 6), it was found that TRMM and CMORPH demonstrated the best performance as both of them captured the 16th December event quite comparably to the interpolation method with the exception of the average method. Conversely, the amount of rainfall given by PERSIANN was slightly lower, i.e. less than 50 mm/day, which implies the PERSIANN satellite performed poorly for the Kelantan region. For Langat river basin (Figure 7), all interpolation methods showed a somewhat good agreement, especially for the average method. A high rainfall value for Langat was found to occur three times, i.e. 20th December 2014, 22nd December 2014 and 8th January 2015 with a value of 30–40 mm/day. As in Kelantan, the SPP result for Langat showed that the CMORPH and TRMM outperformed the PERSIANN. This graphical result also showed that the TRMM overestimated. The interpolation methods performed on Johor river basin showed that all methods produced comparable results and
The highest rainfall (30–50 mm/day) occurred on the 26th December 2014 (Figure 8). The 30 mm/day rainfall was observed from the average method. The SPP result seemed not to be able to capture this event for Johor river basin as none of them could correctly measure the highest rainfall.

Figure 9 shows the scatter plots of averaged daily rainfall over all river basins for the three SPPs versus the rain gauge observations. The scatter plot further demonstrates the performance of SPP by comparing with each of the interpolation methods. For Kelantan river basin, the average method displays a slightly different pattern compared to the other methods. In addition, most of the data points are underestimated but are less scattered compared to other basins. For Langat river basin, the relatively scattered data points imply high variability in the SPP compared to all interpolation methods. Nevertheless, the TRMM shows good agreement as indicated by the square plots. A similar trend can also be observed for the Johor river basin as the data points for all SPPs are relatively scattered.

Details of the statistical performance of the SPP for all river basins and using all interpolation methods are tabulated in Table 4 and accompanied by graphs in Figure 10. This result shows that Kelantan river basin outperformed other river basins, followed by Langat and lastly Johor river basin as indicated by the three SPPs and based on all interpolation methods. Kelantan river basin is the largest
basin, followed by Langat and Johor river basins. It is geographically located near to the South China Sea and is directly and highly influenced by the northeast monsoon that brings heavy rainfall to this region. The SPP results in this study are actually in accordance with the movement of the rainfall circulation of the northeast monsoon, the circulation of which starts from the South China Sea towards the west and south of Peninsular Malaysia. An investigation of the SPP performance during the southwest monsoon season is suggested as the general monsoon circulation is opposite to the northeast monsoon and will take into consideration the river basins that are situated in various parts of Peninsular Malaysia.

The $R^2$ given by all SPPs in Kelantan is relatively high, above 0.6, which implies that all SPPs actually perform better regardless of any interpolation methods. As we move further towards western, i.e. Langat river basin, the SPP performance is slightly lower compared to the previous basin and it is found that the TRMM and CMORPH are able to perform with an accuracy of approximately 50–60%. PERSIANN, however, exhibited the poorest performance as compared to TRMM and CMORPH. The SPP performance

![Comparison of daily mean precipitation series between interpolated ground observations and (a) CMORPH, (b) TRMM and (c) PERSIANN satellite observations for the 2014–2015 flood events at Johor river basin.](image-url)

Figure 8
became worse as we moved down towards the south of the Peninsular Malaysia, which was consistent with the findings by Tan et al. (2015). As evidenced by Johor river basin, all SPPs performed poorly. In general, by comparing these three SPPs for the three basins, it can be concluded that the CMORPH and TRMM were able to capture the extreme event with acceptable accuracy compared to the PERSIANN.

In terms of bias error, underestimation of actual rainfall of about 30 to nearly 60% was shown by all SPPs for the Kelantan river basin, given by all the interpolation methods. According to Thiemig et al. (2012), the significant underestimation of the SPPs may be due to the poor ability in estimating heavy rain (>10 mm/day). However, the under or overestimation was found to be smaller for the Langat river basin, of which bias ranged up to 50% maximum for PERSIANN and 30% maximum for CMORPH. TRMM showed the lowest variability with less than 20%. As for Johor river basin, the variability was somewhat higher compared to the other basins. It is evident that TRMM and PERSIANN produce relatively high bias values of more than 80%. Conversely, CMORPH performs better with about up to 10% overestimation.

**Rain detection ability assessment**

This section discusses the capability of each SPP in detecting the precipitation rate using the categorical evaluation indexes, i.e. ACC, POD, FAR, CSI and HSS. The results are presented in Table 5 and Figure 11. This study used a 1 mm/day rainfall threshold to discriminate between a rainy or no-rain day. It is noticeable that the TRMM and PERSIANN performed better for all the categorical evaluation indexes for all river basins. Nevertheless, the differences in all categorical values for these two SPPs are relatively small compared to CMORPH. For example, TRMM gave the highest ACC with values varying from 0.790 to 0.839 for all basins. As for POD and FAR, the highest was shown by PERSIANN, i.e. POD from 0.846 to 0.962 and FAR from 0.149 to 0.390. TRMM also exhibited well in CSI and HSS. As the ACC and POD indexes denote a level of agreement and correctly detected rainfall, it is observed that the study area of Langat river basin has shown a better result based on these two indexes for all SPPs. As for the rest of the indexes, i.e. FAR, CSI and HSS, the best results are shown by Johor, Langat and Kelantan river...
basins, respectively. It can be assumed that the categorical indexes are unlikely to be influenced by the geographic location or size of the river basin. These factors are somehow difficult to determine in this case.

Capturing storm performance

In this section, the capability of every SPP in capturing storm performance using the HSS categorical index is further demonstrated. The rainfall threshold is increased in order to examine the ability of every SPP to capture the rain. Generally, the SPPs demonstrated poorer performance as the extreme precipitation threshold increased. The HSS decreased as the storm threshold increased. In Kelantan river basin (Figure 12(a)), TRMM exhibited the best performance as the HSS ranges from 0.4 to 0.9. For CMORPH and PERSIANN, when the storm threshold was reduced from or equal to 40 mm, the HSS values were larger than 0.5, implying that both satellites are capable of capturing moderate storms effectively. When the storm threshold was more than or equal to 50 mm, the HSS of CMORPH appeared unstable. As for PERSIANN, the HSS showed zero at the storm threshold of more than or equal to 70 mm.

In Langat river basin (Figure 12(b)), when the storm threshold was less than or equal to 11 mm, the forecast of TRMM and CMORPH satellites appeared better than the gauge observations as they showed positive HSS, ranging from 0.4 to 0.7. However, CMORPH does not perform

<table>
<thead>
<tr>
<th>Rainfall interpolation method</th>
<th>Kelantan river basin</th>
<th>Langat river basin</th>
<th>Johor river basin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMORPH</td>
<td>TRMM</td>
<td>PERSIANN</td>
</tr>
<tr>
<td>Arithmetic Mean</td>
<td>R²</td>
<td>0.909</td>
<td>0.908</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>0.954</td>
<td>0.953</td>
</tr>
<tr>
<td></td>
<td>BIAS (%)</td>
<td>−25.1</td>
<td>−31.6</td>
</tr>
<tr>
<td></td>
<td>NRMSE</td>
<td>0.531</td>
<td>0.415</td>
</tr>
<tr>
<td>Thiessen Polygon</td>
<td>R²</td>
<td>0.654</td>
<td>0.691</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>0.809</td>
<td>0.851</td>
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<tr>
<td></td>
<td>BIAS (%)</td>
<td>−54.3</td>
<td>−34.7</td>
</tr>
<tr>
<td></td>
<td>NRMSE</td>
<td>0.662</td>
<td>0.571</td>
</tr>
<tr>
<td>Inverse Distance Weighting (IDW)</td>
<td>R²</td>
<td>0.680</td>
<td>0.715</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>0.824</td>
<td>0.846</td>
</tr>
<tr>
<td></td>
<td>BIAS (%)</td>
<td>−53.1</td>
<td>−33.0</td>
</tr>
<tr>
<td></td>
<td>NRMSE</td>
<td>0.635</td>
<td>0.541</td>
</tr>
<tr>
<td>Ordinary Kriging</td>
<td>R²</td>
<td>0.653</td>
<td>0.689</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>0.808</td>
<td>0.830</td>
</tr>
<tr>
<td></td>
<td>BIAS (%)</td>
<td>−54.6</td>
<td>−35.2</td>
</tr>
<tr>
<td></td>
<td>NRMSE</td>
<td>0.646</td>
<td>0.547</td>
</tr>
<tr>
<td>Spline</td>
<td>R²</td>
<td>0.651</td>
<td>0.684</td>
</tr>
<tr>
<td></td>
<td>CC</td>
<td>0.807</td>
<td>0.827</td>
</tr>
<tr>
<td></td>
<td>BIAS (%)</td>
<td>−55.7</td>
<td>−36.8</td>
</tr>
<tr>
<td></td>
<td>NRMSE</td>
<td>0.677</td>
<td>0.589</td>
</tr>
</tbody>
</table>
well when the storm threshold is more than 11 mm, whereas TRMM does not perform well when the storm threshold is more than 15 mm. PERSIANN does not perform well compared to the other two satellites where the $HSS$ shows less than 0.4 when the storm threshold is more than 5 mm, and the results become worse as the storm threshold increases.

In Johor river basin (Figure 12(c)), all three satellites could not capture the storm as effectively as in Kelantan river basin. When the storm threshold was less than 20 mm, the $HSS$ values were larger than 0.4. CMORPH appeared unstable for storm thresholds of more than 12 mm. As for PERSIANN, the $HSS$ was around 0.35–0.5, however the performance worsened when the storm threshold was more than 20 mm and showed zero at storm thresholds more than or equal to 26 mm. The results show that none of the SPPs can be considered ideal for detecting extreme events. Although in the previous section on rainfall detection TRMM showed lower $POD$ compared to the PERSIANN product, low $POD$ of a product does not mean that the product could not detect the existence of rain. In fact, the product may have detected precipitation, but below the selected rainfall threshold (AghaKouchak et al. 2011).
CONCLUSION AND RECOMMENDATIONS

SPPs are gaining attention in the field of hydrology. These remotely sensed data have several advantages over traditional measurements, including higher spatial resolution and uninterrupted coverage and hence are beneficial over ungauged catchments, especially mountainous and oceanic regions. However, these satellite data are prone to systematic and random errors and have not yet been fully applied in Malaysia to investigate the spatial and temporal trends of precipitation. The present study attempted to investigate the performance of SPPs, i.e. CMORPH, TRMM and PERSIANN, during the northeast monsoon season in Peninsular Malaysia. This study was conducted on the three different river basins, i.e. Kelantan, Langat and Johor river basins situated in the northern, western and southern parts of Peninsular Malaysia. The northeast monsoon season brings in heavy rainfall in November–March and this monsoon circulates from the northern part towards the western and southern parts. Extreme events that occurred in December 2014–January 2015 were among the worst that hit Peninsular Malaysia and Kelantan and Johor river basins were the most affected regions owing to this event. SPPs have now become an indispensable alternative source of rainfall data, especially for regions with sparse rain gauge stations. The performance of SPP products in capturing rainfall events needs to be explored before it can be used in a wide variety of applications. Therefore, this study investigated these SPP products during extreme events and its main conclusions are as follows:

1. This study used daily observed rainfall data for a total of 62 days and applied several interpolation methods, i.e. AM, TP, IDW, OK and SP methods, to examine the effect of different spatial interpolation methods based on the observed data. Results indicate that the areal precipitation transformed by these interpolation methods gave slight variations in values but overall it is
comparable. Therefore, it can be concluded that no interpolation method was superior, as evidenced by the results.

(2) This study found that the TRMM, CMORPH and PERSIANN performed better during this extreme event as they show an acceptable accuracy in capturing high rainfall in Kelantan river basin. However, this performance decreased as the monsoon moved away towards the west and south, hitting Langat and Johor river basins. About 50–60% accuracy was obtained for the Langat and 30–40% for the Johor river basin, given by the TRMM and CMORPH. Conversely, PERSIANN shows poor accuracy for these two river basins. It is noted that all SPPs tend to overestimate or underestimate the actual rainfall. By comparing these three river basins, extreme events in Kelantan river basin were better captured by all SPPs compared to the other basins. This may be due to the geographic location, near to the South China Sea, which is directly exposed to heavy rainfall during the northeast monsoon.

Figure 11 | Rain detection capability of SPPs in (a) Kelantan, (b) Langat and (c) Johor river basins.
(3) The categorical indexes indicate that TRMM had a good level of agreement as denoted by ACC, whereas PERSIANN was better in correctly detecting rainfall, as denoted by POD. Langat river basin was found to be the best river basin with the highest ACC and POD for all SPPs. In general, the values of ACC and POD for all river basins computed by all SPPs were relatively close. Based on this study, it can be concluded that all SPPs were able to capture extreme events of heaviest rainfall with acceptable accuracy. As proven by this study, all SPPs work well for Kelantan; however, as the monsoon moves further away, the TRMM and CMORPH outperform PERSIANN.

Based on the conclusions derived above, it is important to highlight that spatial and temporal uncertainties may exist when comparing different SPPs with ground observations. Thus, bias-adjustment is suggested in order to improve the reliability of the estimation of SPPs. Therefore, this research could be furthered by continuing on the bias adjustment. Furthermore, it is suggested to investigate the performance of SPP during the southwest monsoon, of which the general

Figure 12 | The HSS of three SPPs (CMORPH, TRMM and PERSIANN) for in (a) Kelantan, (b) Langat and (c) Johor river basins.
monsoon circulation is opposite to the northeast monsoon, by applying it to the same river basins, which are situated in different parts of Peninsular Malaysia. It is also important to explore how good the SPP products are, focusing specifically on the highest storm of the 2014–2015 flood events on these river basins.

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