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# Probing on suitability of TRMM data to explain spatio-temporal pattern of severe storms in tropic region

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## Abstract

Spatial and temporal pattern of rainfall play an important role in runoff generation. Raingauge density influences the accuracy of spatial pattern and time interval influence the accuracy of temporal pattern of storms. Usually due to practical and financial limitation the perfect distribution is not achievable. Several sources of data are used to define the behavior of rainfall over a watershed. Raingauges station, radar operation and satellite sensor are the main source of rainfall estimation over the space and time. Recording raingauges are the most common source of rainfall data in many countries. However raingauge network has not adequate coverage in many watersheds spatially in developing countries. Therefore other global source of rainfall data may be useful for hydrological analysis such as flood modeling. This research assessed the ability of TRMM rainfall estimates for explain the Spatio-temporal pattern of severe storm over Klang watershed which is a hydrologically well instrumented watershed. It was experienced that TRMM rainfall estimates are 35 % less than actual data for the investigated events. Due to coarse temporal resolution of TRMM (3 h) compare to gauge rainfall (15 min), significant uncertainty influences identifying the start and end of storm event and consequently their resultant time to peak of flood hydrograph which is extremely important in flood forecasting systems. Due to coarse pixel size of TRMM data, watershed scale is important issue.

## 1 Introduction

Spatial and temporal pattern of rainfall plays important role in runoff generation. Several studies have shown that the spatial variability of rainfall is a major factor influencing flood formation in urban areas (Niemczynowicz, 1984; Watts and Calver, 1991; Obled et al., 1994; Bell and Moore, 2000; Faures et al., 2006). A number of studies specifically related to characterizing short-term rainfall properties have been carried out in Klang watershed (Niemczynowicz, 1987; Bacchi and Kottegoda, 1995; Desa and

Niemczynowicz, 1996). According to Desa and Niemczynowicz (1996) the areal extension of storms in Klang watershed is limited and there is no clearly preferred direction for the storm movement and propagation is chaotic in direction. Recording raingauges are the most common source of rainfall data that is used to define the areal extension of storms in many countries. However raingauge network has no adequate coverage in many watersheds especially in developing countries. Therefore other global source of rainfall data becomes attractive for hydrological analysis such as flood modeling. With the invention of TRMM data several researchers have tried to assess the ability of TRMM precipitation data. Recently, Varikoden et al. (2010, 2011) investigated the seasonal and diurnal distribution of rainfall in spatial and temporal domains over west Malaysia. They compared TRMM rain rate and rainfall data collected from the manual rain gauges for different topographical regions of Peninsular Malaysia and found that they agree well with a coefficient of determination ($R^2$) of 0.92 for east coastal station, 0.72 for south coastal station, 0.56 for highland station and 0.4 for west coastal station. They concluded that the TRMM rain rate data is enough to study the diurnal variation and spatial distribution of different intensity classes in different seasons. However they did not consider the spatio-temporal variations of storms and 3-hourly variation of TRMM estimates which have a significant influence on watershed response. The influence is evident in the different time-to-peak and shape of the correspondent flood hydrographs (Ball, 1994). This research focuses on the ability of TRMM rainfall estimates to explain spatio-temporal pattern of 3-hourly rainfall over hydrologically well instrumented Klang watershed which frequently effects with severe storms.

## 2 Materials and method

To make possible this comparison spatial distribution of storms has to be defined by utilizing interpolation technique. According to Earls and Dixon (2007) interpolated rainfall data and its accuracy is controlled by the spatial distribution of the rain gauges and the interpolation methods used that may or may not reflect reality. Estimating a smooth spatial distribution from noisy observations and constructing smoothed maps at locations with sparse data is performed based on geo-statistical method known as Kriging. Geo-statistics deals with spatial variability of regionalized variables (Gomez, 2007). Regionalized variables have an attribute value and a location in two or three dimensional space. According to Goovaerts (2000) geo-statistics is increasingly preferred because it allows the capitalization of the spatial correlation between neighboring observations to predict attribute values at un-sampled locations. Phillips et al. (1992), Haberlandt (2006), Paciorek and Schervish (2006) and Gomez (2007) have been shown that Kriging technique provides more reliable interpolation results than any other methods. Hence, GIS software such as ILWIS 3.4 has been fully adapted with GIS-base geo-statistical functions in a raster environment. Kriging method have been used in sevral regirnons to predict spatial distribution of rainfall. Goovaerts (2000) employed simple Kriging for rainfall interpolation in Portugal and found that ordinary Kriging yields more accurate prediction. Karamouz and Araghinejad (2005) applied the Kriging method to evaluate monthly regional rainfall in the central part of Iran. Thavorntam et al. (2007) indicated ordinary Kriging with spherical model performed better for interpolation of rainfall within the Thailand region. Akbari et al. (2008) conducted a research for spatial storm pattern Analysis using Kriging in Klang watershed. It was found that there is high variability of storms in space in the Klang watershed. It was also found that the effective influence range of rain gauges is about 6273 m, thus the effective radius of gauges is about 3136 m. Moreover; it was proven that Gaussian Smi-variogram model demonstrate slightly better estimation compare to Spherical and Exponential Semi-variogram models and propagates much lesser standard error at the effective influence range. Later Akbari et al. (2009) explained the effect of pixel size on the areal storm pattern analysis using Kriging and found out that the appropriate cell size for storm pattern analysis rage from 200 to 500 m in Klang watershed.

## 3 Study area

The study area is the upper Klang watershed located on the west coast of Peninsular Malaysia that encompasses the Federal Territory of Kuala Lumpur and parts of the state of Selangor (see Fig. 1). It is situated at 10°30′–10°55′ longitude and 3°–3°30′ latitude. The Klang river basin at the outlet showed in Fig. 1 covers area about 650 km$^2$. The elevation ranged from 20 m at the outlet to 1420 m upstream.

## 4 TRMM

The TRMM is a joint NASA/Japan satellite designed specifically to monitor rainfall and its associated latent heating in the tropics and subtropics (King et al., 2004). Although the sensors on TRMM have utility beyond the primary rainfall parameters, the TRMM science team has defined and developed a set of "standard products" that are critical to monitoring rainfall and its vertical structure. These standard products are processed by the TRMM Science Data and Information System (TSDIS). Radar sites located on Southern Florida, Australia (Darwin), Southeastern Texas, and the Marshall Islands are used for calibration and validation. Ground validation data are processed at Goddard Space Flight Center in cooperation with the TRMM ground validation team. According to Serafin et al. (2007) TRMM technology is now under development to operate in near future (2013) operate as a Global Precipitation Measurement (GPM) with the capability to measure rainfall depth from 2.5 to 250 mm. Further detail about the TRMM can be found in Adler et al. (2000) and Huffman and Bolvin (2007).

## 5 Gauge rainfall data

According to Kobold (2007) the number of rain gauges in the watershed should be densely enough to give proper areal extension. The US Army Corps of Engineers (USACE) related the gauge density for hydrologic modeling to watershed area (Vieux, 2004). The number of gauges, $N_g$, can be estimated from the following equation purposed by the USACE (1996):

$$N_g = 0.73 \times A^{0.33} \quad (1)$$

where $A$ is the watershed area in km$^2$ and $N_g$ is the number of gauges required for hydrologic modeling. According to this equation the number of raingauges required for hydrologic modeling in Klang watershed is about 6 raingauges. It is seen that gauge density in Klang watershed (one gauge per 24 km$^2$) is much more than gauge density suggested by USACE (one gauge per 113 km$^2$). However gauge density is still less than typical rain gauge density in urban watersheds recommended by Vieux (2004) which can be exceed one gauge per 10 to 20 km$^2$. Klang watershed has been well instrumented and equipped with rain gauges, water level and streamflow stations. Rainfall data were collected for 29 stations from DID Malaysia (see Fig. 1). All rainfall and stream flow stations visited within 3 days field survey and the coordinates were picked and mapped using Garmin GPSmap 76CSx. Missing records were found in 7 stations and remaining 22 stations were used for further analysis. General characteristics of used rainfall stations are listed in Table 1 and accumulated rainfall for investigated storms is provided in Table 2.

It is observed that some events have not recorded in all investigated stations. For example, rainfall event of 6 May 2002 did not catch in gauge 3016001. This can be due to technical problems in that gauge during the specific events. An attempt was made to recover missing records using nearby stations. But no significant correlation was found. The coefficient of variation (CV) was calculated to find the relatively uniform rainfall events. Four events with lower value of CV ware identified suitable for further analysis. Those are storm event of 6 May, 29 April, 11 June, and 21 December.

## 6 TRMM3B42 event

According to NASA (2009) the combined instrument rain calibration algorithm (3B-42) uses an optimal combination of 2B-31, 2A-12, SSMI, AMSR and AMSU precipitation estimates (referred to as HQ) to adjust IR estimates from geostationary IR observations. TRMM3B42 characteristics are provided in Table 3. 3-hourly TRMM Rainfall Estimate was downloaded from TRMM Online Visualization and Analysis System (TOVAS, accessible at: http://disc2.nascom.nasa.gov/Giovanni/tovas/TRMM_V6.3B42.2.shtml).

As mentioned horizontal resolution of TRMM data version 6 are $15' \times 15'$ or ~27.8 × 27.8 km. Considering Fig. 2, Klang watershed fall in 5 TRMM grids marked with 1, 3, 4, 5 and 6. TRMM V6 was downloaded in NetCDF format. This format can be read and manipulated with ArcGIS 9.3.

To evaluate the behavior of TRMM rainfall estimates with actual data, 3-hourly and total rainfall estimates of TRMM for the selected events were compared with gauge rainfall data in 6 cells (see Fig. 2). 3-hourly TRMM maps for the investigated events were mapped in Appendix 1. The value in each cell represents the amount of rainfall acquired within 3 h starting from 1.5 h before and 1.5 h after the specified time. To specify the hyetograph ordinates four pairs of digit is used. For example the first ordinate of TRMM hyetograph for event 6 May 2002 is shown with 06-06-05-02 which denotes the Time-Day-Month-Year respectively.

## 7 Results and discussion

Kriging method with Gaussian Smi-variogram model and 250 grid sizes were applied to four selected storm events to define the areal storms patterns (see Fig. 3).

18 recording raingauges contribute to interpolation for event 6 May and 19 recording raingauges for events 29 April, 11 June and 21 December. GIS tools were then used to calculate the weighted average rainfall for sub-watersheds. The average estimated rainfall in each sub-watershed was related to its center of gravity. Temporal pattern

of storms in each subwatershed is defined based on the nearest station to its center of gravity. This approach provide the necessary conditions to compare Flood runoff generated from ground-based rainfall data with storm derived from satellite imagery for a specific event. Temporal pattern of selected storms ware analyzed with 15 min time interval. As shown in appendix, it is seen that the storm duration and temporal distribution of investigated storms are irregular and demonstrates high degree of variation in space and time that effect the time-to-peak of flood hydrograph. For example as demonstrated in Table 4 and Figs. 4 and 5, peak discharge occurred on 17:45 p.m. LT at stream flow gauge 3116434 and 18:45 p.m. LT at gauge 3116430 with 1 h delay for event 29 April. However, time-to-peak of event 21 December occur at 21:15 p.m. at gauge 3116434 and 20:00 p.m. LT at gauge 3116430 with 1 h and 15 min earlier.

Coefficient of variation was used (see Table 5) to explain the temporal variation of storm events over Klang watershed.

As shown in Table 6 rainfall event of 29 April that demonstrate relatively lower degree of variation in time. Corresponding flood hydrograph is presented in Fig. 4. Flood hydrograph of events 6 May, 11 June and 21 December are presented in Figs. 5, 6 and 7 respectively.

## 8 Time adjustment

According to official TRMM web site (http://earth.nasa.gov/trmm/index.html) the mission time for TRMM is GMT also known as Coordinated Universal Time (UTC). Local time in Kuala Lumpur is equal to GMT + 8 h. Therefore time adjustment has to be made for TRMM events. However due to coarse temporal resolution of TRMM (3 h) compare to gauge rainfall (15 min), significant uncertainty influences identifying the start and end of storm event and consequently their resultant time to peak of flood hydrograph which is extremely important in flood forecasting systems.

## 9 Cell-base comparison

Comparison is made between the gauges rainfall (Gag.R) and TRMM rainfall (TRM.R) data. At first accumulated rainfall was calculated from TRMM data for flood events observed in 6-May, 29 April, 11 June and 21 December in each cell. Then grid map resultant from interpolation of actual rainfall events shown in Fig. 3 were crossed with the TRMM grid identifier map showed in Fig. 2. A weighted average rainfall for each cell was then calculated by using aggregation operation in ILWIS 3.4. Percent of error (PE) for TRMM prediction were calculated for four investigated storms as demonstrated in Table 6. It is found that rainfall estimates by TRMM algorithm are 37 % under estimate for investigated events.

## 10 Comparison of total rainfall

Total amount of rainfall for specified storms was calculated from both gauge data and TRMM estimates. High correlation coefficient of 0.99 is existed between the observed and TRMM estimates as shown in Table 7. However, negative bias indicates that TRMM rainfall data can estimate the total gauges rainfall by overall 35 % less than actual data. This result just explains the behavior of investigated storms and further research is needed to come out with regionalized conclusion which is beyond the focus of this research.

There is a close correlation ($r = 0.99$) between observed and TRMM estimates for the total rainfall depth. In spite of that, there is no significant correlation for temporal pattern of storms. In other word, as shown in Fig. 8 hyetograph derived from TRMM do not match with observed hyetographs of selected events except for event 6 May.

## 11 Sub-watershed comparison

To calculate the amount of rain that falls in each sub-watershed, the accumulated rainfall map resultants from Kriging interpolation for investigated flood events (see Fig. 3) were crossed with sub-watershed map. With the same way, accumulated TRMM estimates for the same events were crossed with sub-watershed map to calculate the amount of rain that falls in each sub-watershed resultants from TRMM estimates. As an example, Fig. 9 demonstrates operation involved for calculating the rainfall in each sub-basin. The procedure was repeated for three other events.

As it observed in Table 8 there is no significant correlation between two estimates.

## 12 Conclusions

From the spatial and temporal pattern analysis of rainfall over Klang watershed, it is evident that there is high variation of storm pattern in space and time. Existing gauge network can significantly explain the storm pattern over Klang watershed. Spatial and more importantly temporal patterns depicted by TRMM for investigated flood events do not explain the actual behavior of storms. It was revealed that TRMM rainfall estimates are 35 % less than observed data for the investigated events. Simultaneously with this study, Bitew and Gebremichael (2010) revealed that both CMORPH and PERSIANN-CCS which are TRMM products tend to underestimate severe storms by about 50 %. Due to coarse temporal resolution of TRMM (3 h) compare to gauge rainfall (15 min), significant uncertainty influences identifying the start and end of storm event and consequently their resultant time to peak of flood hydrograph which is extremely important in flood forecasting systems. In addition, Due to coarse pixel size of TRMM data, size of the watershed is important issue. As shown in Fig. 2, at the best condition, spatial variation of rainfall over the watersheds similar (in shape and area) to Klang can be defined with six values. Considering Eq. 1 indicates that proper areal precipitation for similar watershed is only achieved with TRMM grid when the watershed lays in six pixels. However, TRMM data can be considered as useful source of precipitation data for the regions with the sparse gauge network.

**Supplementary material related to this article is available online at: http://www.hydrol-earth-syst-sci-discuss.net/8/9435/2011/hessd-8-9435-2011-supplement.zip.**

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**Table 1.** General characteristics of rainfall stations located in and near to the Klang.

| No. | Station id | Local Name | State | Longitude | Latitude |
|---|---|---|---|---|---|
| 1 | 3216005 | Batu Dam | Kuala Lumpur | 101 40 48 | 03 15 36 |
| 2 | 3117080 | Bukit Antarabangsa | Selangor | 101 46 12 | 03 10 48 |
| 3 | 3016077 | Jalan 222 | Selangor | 101 37 48 | 03 05 24 |
| 4 | 3015001 | Jambatan Petaling | Kuala Lumpur | 101 39 36 | 03 04 48 |
| 5 | 3217102 | Jinjang | Kuala Lumpur | 101 39 36 | 03 13 48 |
| 6 | 3117070 | JPS Ampang | Kuala Lumpur | 101 45 00 | 03 09 00 |
| 7 | 3116004 | JPS Wilayah | Kuala Lumpur | 101 42 00 | 03 09 36 |
| 8 | 3217002 | Kelang Gates Dam | Kuala Lumpur | 101 45 00 | 03 13 48 |
| 9 | 3217004 | Kuala Seleh | Kuala Lumpur | 101 46 12 | 03 15 36 |
| 10 | 3116006 | Ldg Edinburgh | Kuala Lumpur | 101 37 48 | 03 10 48 |
| 11 | 3116074 | Leboh Pasar | Kuala Lumpur | 101 42 00 | 03 09 00 |
| 12 | 3117104 | Pandan Indah | Kuala Lumpur | 101 45 00 | 03 07 48 |
| 13 | 3016001 | Puchong Drop | Selangor | 101 36 00 | 03 01 12 |
| 14 | 3017105 | Seri Kembangan | Selangor | 101 43 12 | 03 00 36 |
| 15 | 3317001 | Sg. Batu Waterfall | Kuala Lumpur | 101 42 00 | 03 19 48 |
| 16 | 3117002 | Simpang Tiga | Kuala Lumpur | 101 43 12 | 03 15 00 |
| 17 | 3218101 | Stn. Jenaletrik Lln. Ponsoon | Selangor | 101 52 48 | 03 13 12 |
| 18 | 3217005 | Gombak Damsite | Kuala Lumpur | 101 42 00 | 03 13 48 |
| 19 | 3216001 | Kg. Sg. Tua | Kuala Lumpur | 101 40 48 | 03 16 12 |
| 20 | 3216004 | SMJK Kepong | Kuala Lumpur | 101 37 48 | 03 13 12 |
| 21 | 3317004 | Genting Sempah | Kuala Lumpur | 101 46 12 | 03 22 12 |
| 22 | 3016103 | Taman Desa | Kuala Lumpur | 101 40 48 | 03 06 00 |
| 23 | 3114114 | Kg. Berembang at Keramat | Kuala Lumpur | 101 44 24 | 03 10 12 |
| 24 | 3116003 | Pejabat JPS Malaysia | Kuala Lumpur | 101 40 48 | 03 09 00 |
| 25 | 3116005 | Sek. Ren. Taman Maluri | Kuala Lumpur | 101 38 24 | 03 12 00 |
| 26 | 3117101 | Kerayongvat Cheras Baru | Kuala Lumpur | 101 42 00 | 03 06 00 |
| 27 | 3117102 | Taman Miharja | Kuala Lumpur | 101 43 48 | 03 07 12 |
| 28 | 3217003 | Ibu Bekalan KM. 11 at Gombak | Kuala Lumpur | 101 42 00 | 03 14 24 |
| 29 | 3016102 | Taman Sg. Besi | Kuala Lumpur | 101 41 24 | 03 06 00 |

**Table 2.** Accumulated rainfall for investigated storm events on 2002.

| Gauge ID | 6 May 2002 R (mm) | 29 Apr 2002 R (mm) | 2 Jun 2002 R (mm) | 11 Jun 2002 R (mm) | 6 Sep 2002 R (mm) | 8 Oct 2002 R (mm) | 8 Nov 2002 R (mm) | 21 Dec 2002 R (mm) |
|---|---|---|---|---|---|---|---|---|
| 3015001 | 29.5 | 73 | 7 | 11 | 2 | 0.5 | 0 | 46 |
| 3016001 | 51 | 99 | 0 | 37 | 39 | 33 | 0 | 74 |
| 3016102 | 11.5 | 69.5 | 32.5 | 13.5 | 48 | 5.5 | 33.5 | 57.5 |
| 3016103 | – | – | – | – | 50 | 21.5 | – | – |
| 3116003 | 59.5 | 90 | 93.5 | 51.5 | 18 | 107 | 56 | 24.5 |
| 3116004 | 60.5 | 93 | 94 | 54 | 19 | 108 | 57 | 24 |
| 3116006 | 38.5 | 101.5 | 5.5 | 62.5 | 2 | 39.5 | 20.5 | 7.5 |
| 3116074 | 45.0 | 95 | 100 | 42 | 35 | 110 | 76 | 18 |
| 3117002 | 24.0 | 77 | 2 | 138 | 10 | 48 | 2 | 20 |
| 3117070 | 63.0 | 57 | 80 | 55 | 97 | 82 | 40 | 28 |
| 3117101 | 2.5 | 29 | 37.5 | 16.5 | 0 | 11 | 9 | 69.5 |
| 3117102 | 14.5 | 65.5 | 47.5 | 18.5 | 92 | 70 | 30.5 | 41.5 |
| 3117104 | 30.0 | 111 | 0 | 12 | 2 | 1 | 0 | 48 |
| 3216004 | 16.0 | 158 | 3.5 | 63 | 9.5 | 21 | 9.5 | 8.5 |
| 3216005 | 5.0 | 59 | 12 | 17 | 77 | 17 | 32 | 0 |
| 3217002 | 42.0 | 121 | 11 | 58.5 | 32.5 | 26 | 2 | 32.5 |
| 3217003 | 28.5 | 71 | 3 | 95.5 | 47 | 45 | 1 | 22.5 |
| 3217004 | 57.0 | 94.5 | 0 | 38 | 69 | 19 | 6 | 25 |
| 3217005 | – | – | – | – | 35 | – | – | – |
| 3317001 | 0.0 | 88 | 1.5 | 8.5 | 8 | 75 | 10.5 | 3 |
| 3317004 | 27.0 | 67.5 | 43 | 20 | 4 | 9.6 | 0 | – |
| 3217102 | – | – | – | – | – | 34 | 14 | 19 |
| Mean | 31.8 | 85.24 | 30.2 | 42.7 | 33.1 | 42.1 | 20 | 29.9 |
| Std | 20.5 | 27.87 | 36.2 | 33.1 | 30.4 | 36 | 22.7 | 21.2 |
| CV | 0.64 | 0.32 | 1.2 | 0.78 | 0.92 | 0.86 | 1.14 | 0.71 |

**Table 3.** TRMM3B42 Characteristics.

| Features | Specifications |
|---|---|
| Temporal Coverage | Start Date 1 Jan 1998; Stop Date: – |
| Geographic Coverage Latitude | 50° S–50° N; Longitude: 180° W–180° E |
| Horizontal Resolution | 0.25° × 0.25° |
| Temporal Resolution | 3-h |
| Average File Size | Compressed: ∼285 KB; Original: ∼4.5 MB |
| File Type | HDF, NetCDF, KMZ, ASCII |
| Product | Precipitation, range 0.0–100.00 mm |
| Mission Time | GMT |

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**Table 4.** Observed time-to-peak and peak runoff for selected flood events.

| Flood Event | $Q_{3116434}$ m$^3$ s$^{-1}$ | $T_{\text{peak}}$ | $Q_{3116433}$ m$^3$ s$^{-1}$ | $T_{\text{peak}}$ | $Q_{3116430}$ m$^3$ s$^{-1}$ | $T_{\text{peak}}$ |
|---|---|---|---|---|---|---|
| 6 May | 83.37 | 14:45 | 32.50 | 14:45 | 361.29 | 15:30 |
| 29 Apr | 40.48 | 17:45 | 61.22 | 16:45 | 154.55 | 18:45 |
| 11 Jun | 168.28 | 20:45 | 147.55 | 20:45 | 448.96 | 21:00 |
| 21 Dec | 23.33 | 21:15 | 47.27 | 21:30 | 121.46 | 20:00 |

**Table 5.** Temporal variations of selected storm events.

| Flood event | Number of stations | Accu. mean rainfall mm | rainfall duration (h) Mean | Std | CV |
|---|---|---|---|---|---|
| 6 May | 18 | 31.8 | 2.21 | 0.83 | 0.37 |
| 29 Apr | 19 | 85.4 | 7.61 | 1.37 | 0.18 |
| 11 Jun | 19 | 42.7 | 3.62 | 0.8 | 0.22 |
| 21 Dec | 19 | 29.9 | 1.68 | 1 | 0.59 |

**Table 6.** Cell-base comparison of observed rainfall with TRMM estimates.

| Cell id | 6 May | | | 29 Apr | | | 11 Jun | | | 21 Dec | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | TRM.R mm | Gag.R mm | PE % | TRM.R mm | Gag.R mm | PE % | TRM.R mm | Gag.R mm | PE % | TRM.R mm | Gag.R mm | PE % |
| 1 | 4.8 | 34.8 | −86 | 51.3 | 88.9 | −42 | 15.0 | 35.1 | −57 | 42.0 | 46.6 | −10 |
| 2 | 6.3 | 34.9 | −82 | 34.2 | 85.2 | −60 | 9.6 | 35.1 | −73 | 3.0 | 33.1 | −91 |
| 3 | 32.4 | 42.0 | −23 | 24.6 | 91.6 | −73 | 41.4 | 47.5 | −13 | 58.5 | 37.0 | 58 |
| 4 | 55.2 | 39.4 | 40 | 46.8 | 83.5 | −44 | 25.8 | 32.5 | −21 | 20.7 | 39.5 | −48 |
| 5 | 17.4 | 29.5 | −41 | 39.0 | 89.3 | −56 | 42.0 | 31.9 | 31 | 11.1 | 25.1 | −56 |
| 6 | 15.3 | 38.8 | −61 | 51.9 | 86.5 | −40 | 36.9 | 31.7 | 17 | 9.0 | 24.1 | −63 |
| Relative Bias | | | −42 | | | −53 | | | −19 | | | −35 |

TRM.R: TRMM rainfall estimate, Gag.R: gauge rainfall, PE: percent of error

**Table 7.** Comparison of total rain depth estimates of TRMM and gauges for the investigated events.

| Even | Total TRM.R mm | Total Gag.R mm | PE % |
|---|---|---|---|
| 6 May | 21.9 | 31.3 | −30 |
| 29 Apr | 41.3 | 84.0 | −51 |
| 11 Jun | 27.7 | 42.7 | −35 |
| 21 Dec | 22.4 | 29.4 | −24 |
| Relative Bias | | | −35 |
| Correlation coefficient | | | 0.99 |

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**Table 8.** Caparison the amount of rain that falling to the sub-watershed from gauge rainfall and TRMM rainfall estimates.

| SW | 6 May | | 29 Apr | | 11 Jun | | 21 Dec | |
|---|---|---|---|---|---|---|---|---|
| | Gag mm | TRM mm | Gag mm | TRM mm | Gag mm | TRM mm | Gag mm | TRM mm |
| s1 | 24.8 | 17.4 | 79.3 | 39.0 | 19.3 | 42.0 | 22.8 | 11.1 |
| s2 | 31.5 | 16.4 | 79.5 | 45.4 | 30.7 | 39.5 | 20.6 | 10.1 |
| s3 | 35.3 | 19.4 | 82.8 | 38.6 | 79.0 | 41.3 | 20.7 | 17.1 |
| s4 | 41.7 | 22.7 | 93.6 | 50.7 | 31.4 | 34.9 | 28.4 | 11.7 |
| s5 | 38.3 | 55.2 | 93.9 | 46.8 | 33.0 | 25.8 | 31.4 | 20.7 |
| s6 | 42.9 | 55.2 | 102.1 | 46.8 | 30.3 | 25.8 | 32.4 | 20.7 |
| s7 | 43.5 | 45.7 | 97.4 | 37.6 | 65.4 | 32.3 | 33.1 | 35.6 |
| s8 | 32.8 | 32.2 | 84.3 | 24.8 | 100.2 | 41.4 | 24.5 | 55.9 |
| s9 | 21.1 | 23.5 | 82.4 | 33.1 | 51.9 | 41.8 | 22.7 | 29.6 |
| s10 | 23.9 | 21.2 | 102.7 | 35.3 | 26.6 | 41.8 | 23.9 | 22.7 |
| s11 | 41.9 | 32.4 | 91.6 | 24.6 | 79.9 | 41.4 | 37.7 | 56.5 |
| s12 | 45.8 | 32.4 | 91.6 | 24.6 | 75.2 | 41.4 | 32.7 | 56.5 |
| s13 | 44.0 | 49.9 | 95.1 | 41.7 | 49.3 | 29.4 | 27.4 | 29.0 |
| s14 | 42.0 | 54.8 | 80.8 | 46.4 | 37.3 | 26.1 | 36.0 | 21.3 |
| s15 | 31.1 | 32.4 | 91.2 | 24.6 | 77.3 | 41.4 | 28.6 | 56.5 |
| s16 | 34.0 | 32.4 | 110.2 | 24.6 | 58.0 | 41.4 | 17.4 | 56.4 |
| s17 | 51.2 | 32.4 | 97.2 | 24.6 | 58.7 | 41.4 | 31.5 | 56.5 |
| s18 | 58.0 | 32.4 | 89.9 | 24.6 | 53.4 | 41.4 | 23.9 | 56.5 |
| s19 | 57.4 | 32.4 | 81.9 | 24.6 | 44.4 | 41.4 | 19.8 | 56.5 |
| s20 | 51.1 | 32.4 | 88.1 | 24.6 | 45.9 | 41.4 | 28.8 | 56.5 |
| s21 | 38.7 | 32.4 | 73.8 | 24.6 | 29.0 | 41.4 | 54.6 | 56.5 |
| s22 | 31.6 | 30.9 | 75.3 | 26.0 | 28.6 | 40.0 | 46.0 | 55.7 |
| s23 | 43.9 | 32.4 | 90.7 | 24.6 | 42.1 | 41.4 | 31.3 | 56.5 |
| s24 | 36.1 | 32.4 | 80.9 | 24.6 | 32.4 | 41.4 | 53.1 | 56.5 |
| s25 | 36.9 | 32.4 | 88.3 | 24.6 | 30.9 | 41.4 | 31.5 | 56.5 |
| s26 | 33.0 | 32.4 | 84.1 | 24.6 | 18.4 | 41.4 | 37.6 | 56.5 |
| s27 | 28.7 | 32.4 | 79.5 | 24.6 | 21.8 | 41.4 | 54.9 | 56.5 |
| s28 | 28.8 | 32.4 | 78.0 | 24.6 | 21.7 | 41.4 | 51.0 | 56.5 |
| s29 | 33.4 | 32.4 | 83.6 | 24.6 | 24.0 | 41.4 | 39.3 | 56.5 |
| s30 | 38.5 | 44.8 | 69.0 | 36.7 | 22.4 | 32.9 | 54.0 | 37.0 |
| s31 | 54.3 | 32.5 | 86.1 | 24.7 | 52.5 | 41.3 | 20.8 | 56.3 |
| s32 | 58.5 | 32.4 | 85.0 | 24.6 | 46.5 | 41.4 | 17.1 | 56.5 |
| s33 | 27.3 | 32.4 | 101.1 | 24.6 | 56.7 | 41.4 | 22.0 | 56.5 |
| Mean | 38.8 | 33.5 | 87.6 | 30.8 | 44.7 | 38.8 | 32.0 | 44.0 |
| STD | 10.0 | 9.8 | 9.2 | 8.8 | 20.9 | 5.2 | 11.4 | 17.5 |
| R | 0.3 | | 0.1 | | 0.2 | | 0.3 | |

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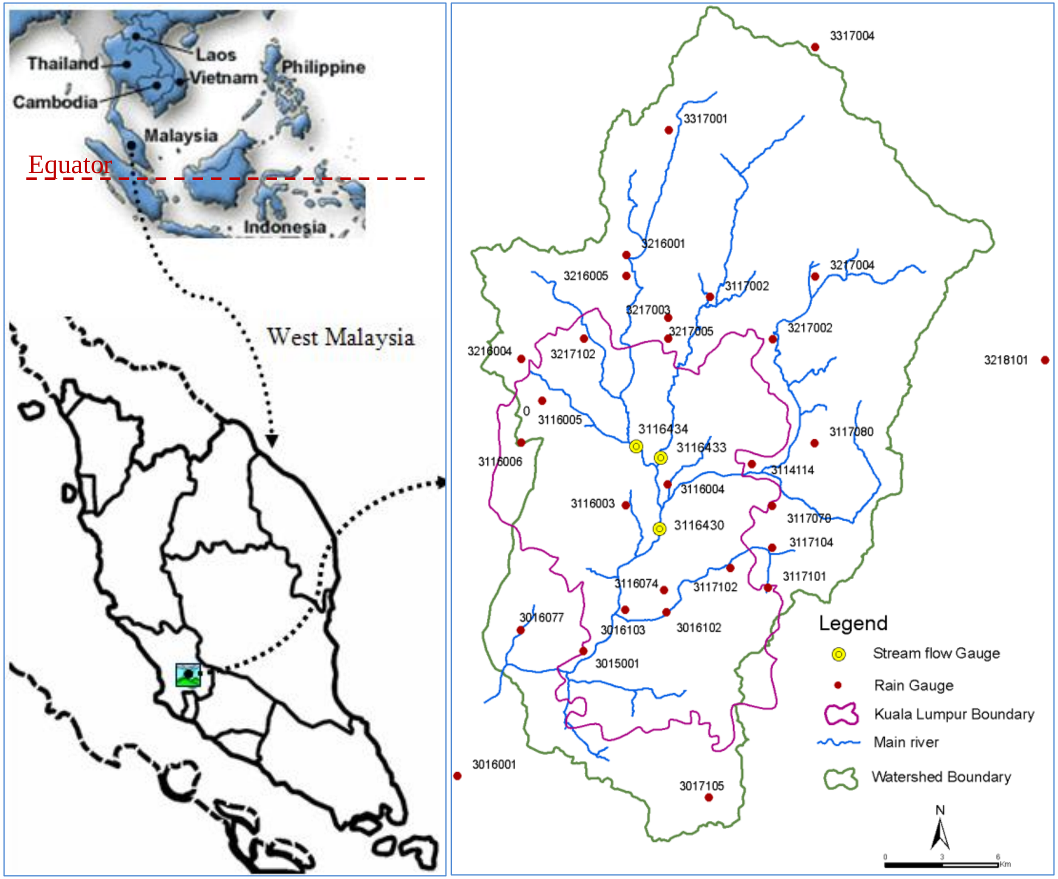

**Fig. 1.** Layout of the study area and used rainfall stations.

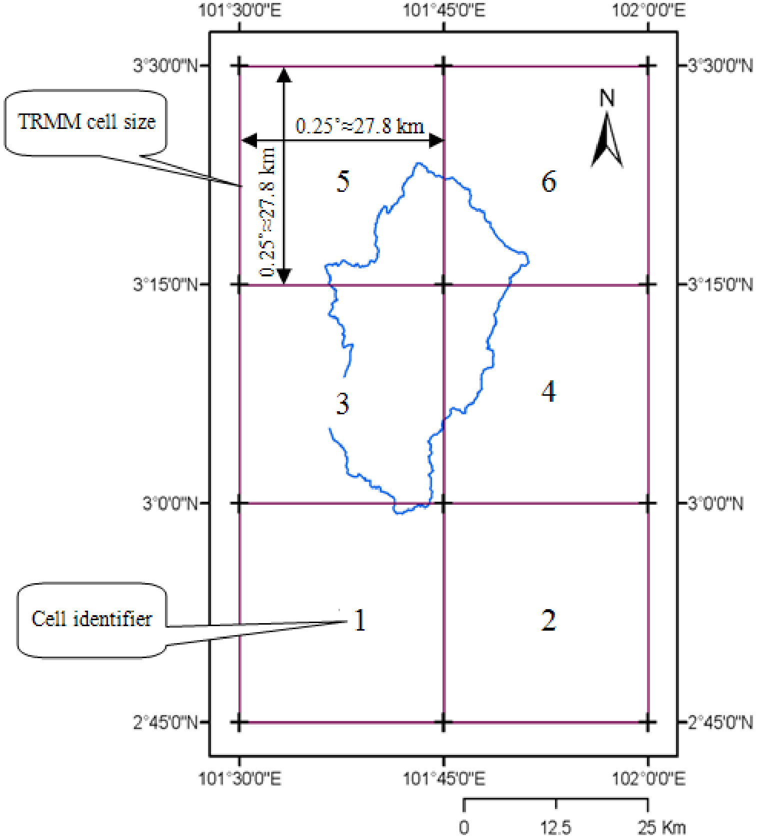

**Fig. 2.** TRMM grid map overlaid on Klang watershed.

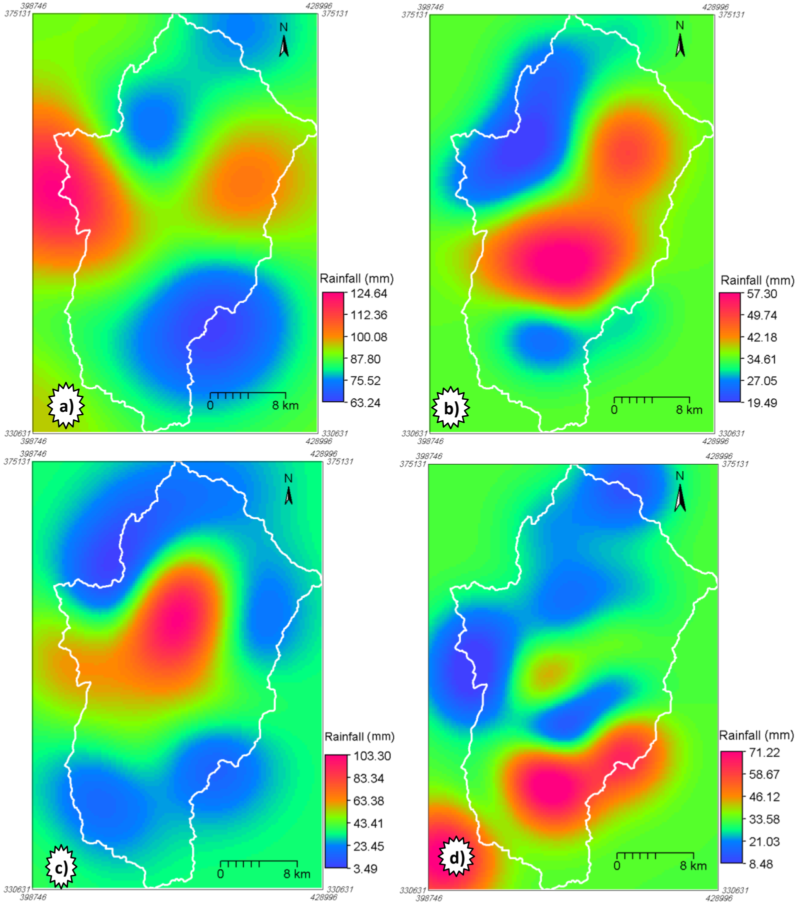

**Fig. 3.** Spatial distribution of rainfall events over Klang watershed using Kriging interpolation with Gaussian Smi-variogram model: **(a)** rainfall event 29 April 2002, **(b)** rainfall event 6 May 2002, **(c)** rainfall event 11 June 2002, **(d)** rainfall event 21 December 2002.

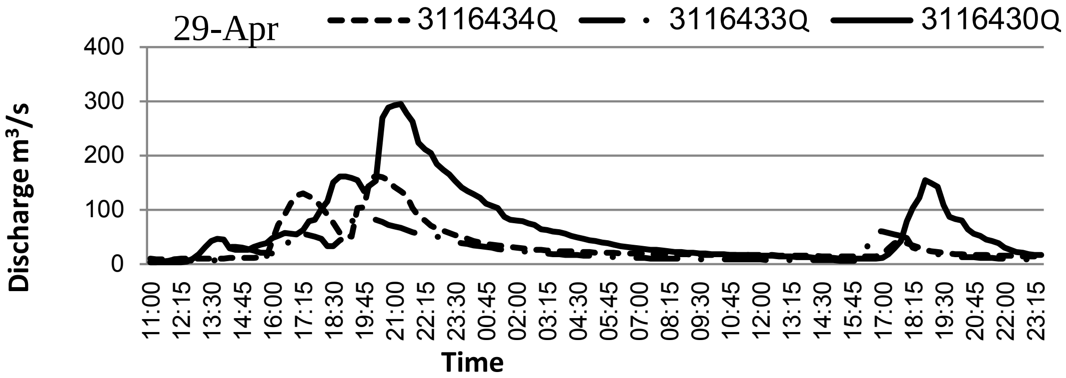

**Fig. 4.** Observed flood hydrograph resultant from storm event of 29 April 2002.

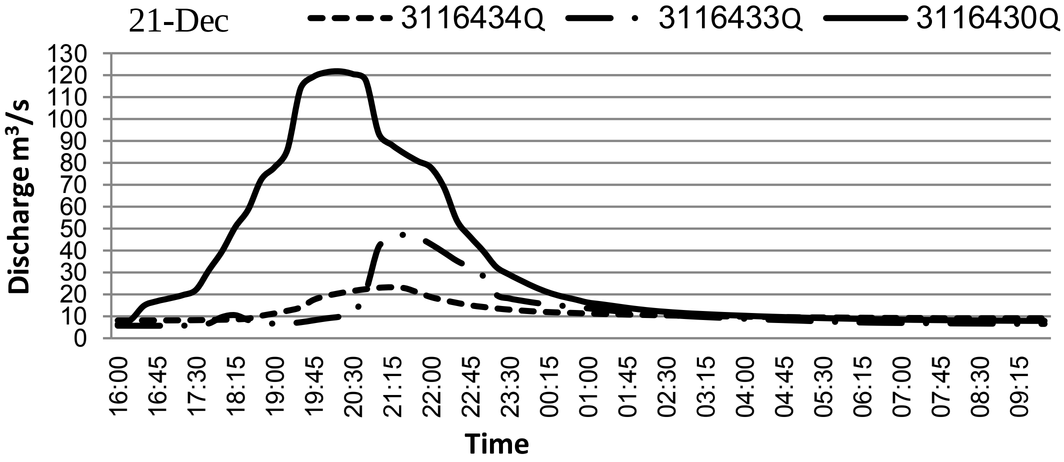

**Fig. 5.** Observed flood hydrograph resultant from storm event of 21 December 2002.

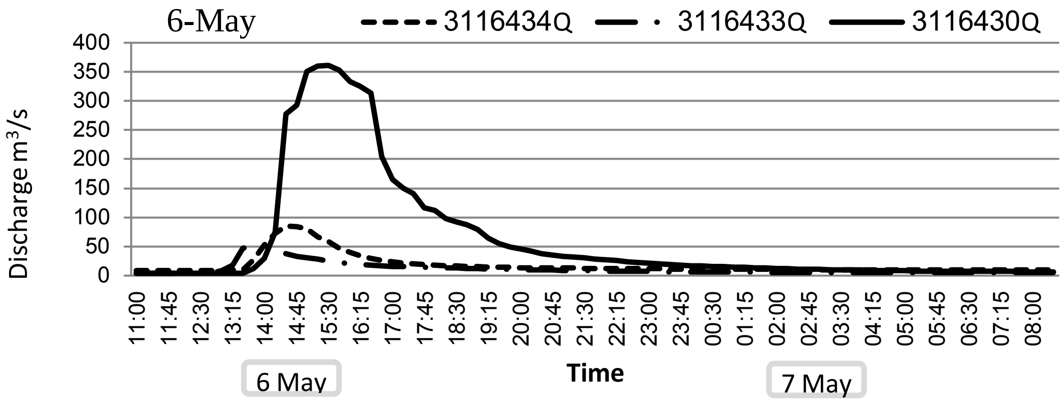

**Fig. 6.** Observed flood hydrograph resultant from storm event of 6 May 2002.

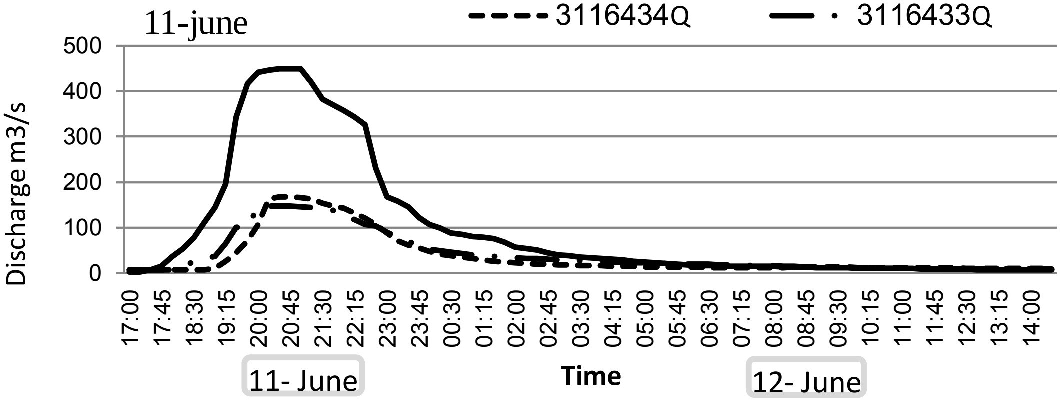

**Fig. 7.** Observed flood hydrograph resultant from storm event of 11 June 2002.

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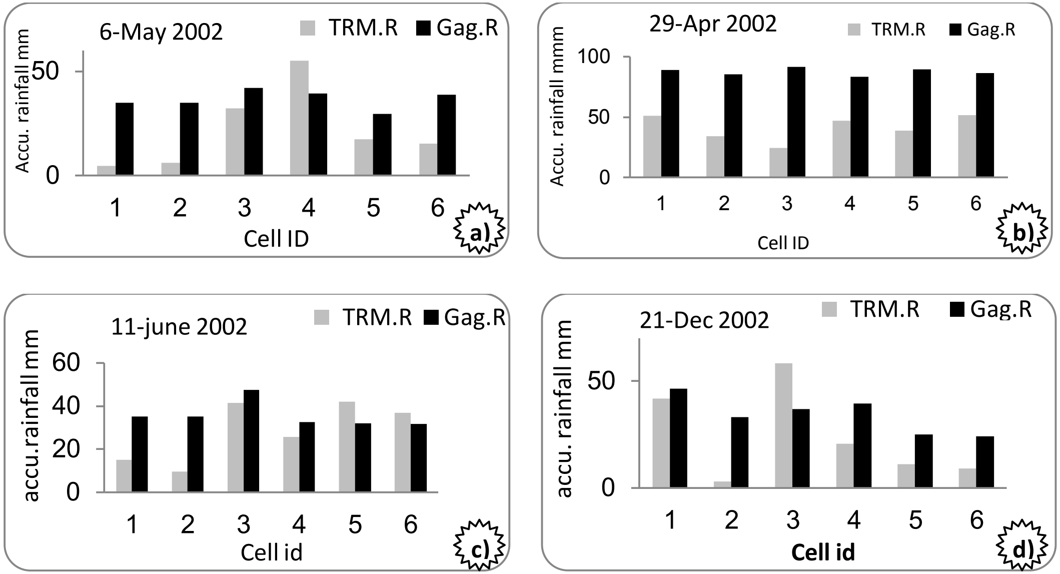

**Fig. 8.** Spatial distribution of total rain depth over the 6 TRMM cells. **(a)** Comparison of TRMM estimates with observed storm depth of 6 May 2002, **(b)** comparison of TRMM estimates with observed storm depth of 29 April 2002, **(c)** comparison of TRMM estimates with observed storm depth of 11 June 2002, **(d)** comparison of TRMM estimates with observed storm depth of 21 December 2002.

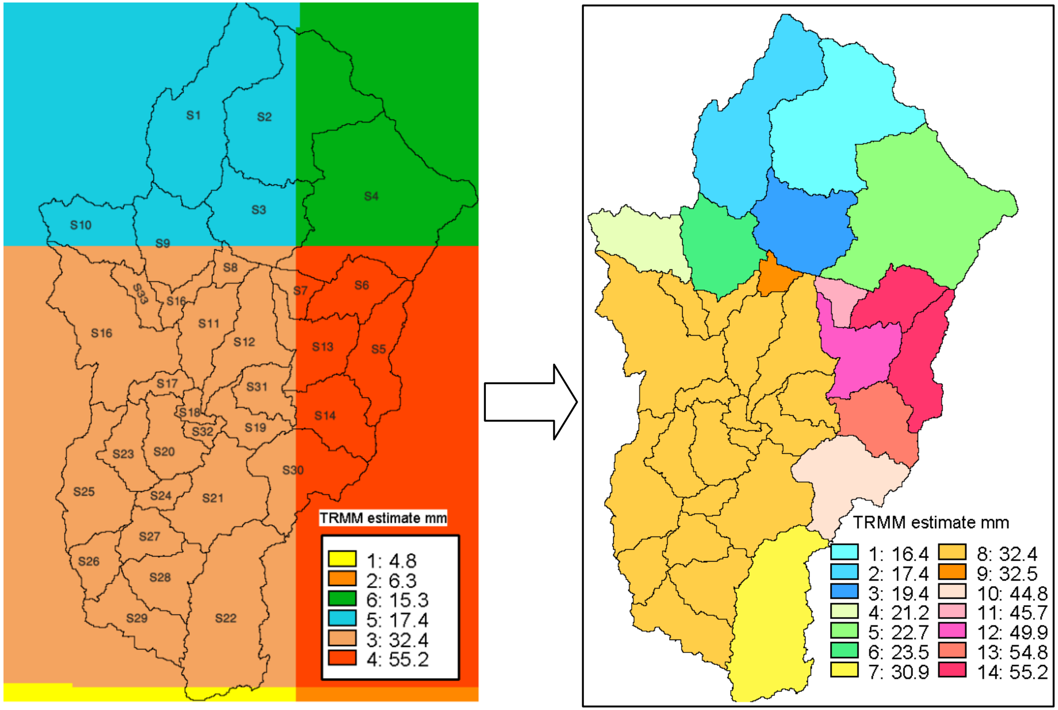

**Fig. 9.** Subbasins wais estimation of accumulated TRMM rainfall (event 6 May) over Klang watershed. Crossing sub-watersheds with TRMM estimates result from events 6 May 2002 (left panel). Groping the TRMM cell values based on sub-watersheds using ILWIS (right panel).

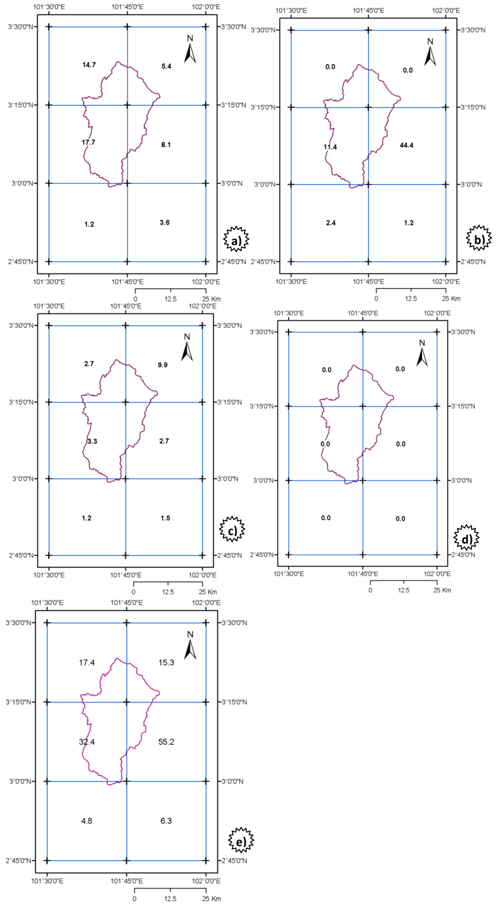

**Fig. A1.** Accumulated 3-hourly rainfall (mm) estimates of TRMM 3B42 (v6) for flood event 6 May 2002. **(a)** 06-06-05-02, **(b)** 09-06-05-02, **(c)** 12-06-05-02, **(d)** 15-06-05-02, **(e)** Total.

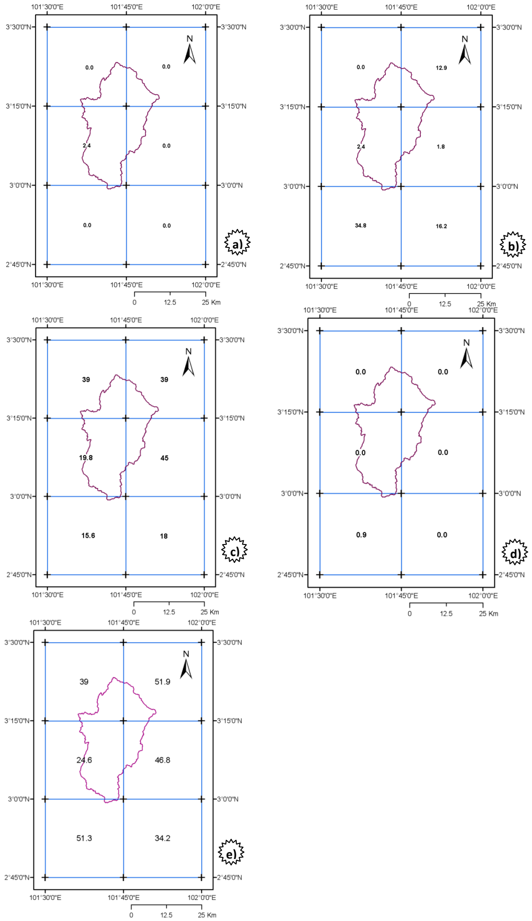

**Fig. A2.** Accumulated 3-hourly rainfall (mm) estimates of TRMM 3B42 (v6) for flood event 29 April 2002. **(a)** 06-29-04-02, **(b)** 09-29-04-02, **(c)** 12-29-04-02, **(d)** 15-29-04-02, **(e)** Total.

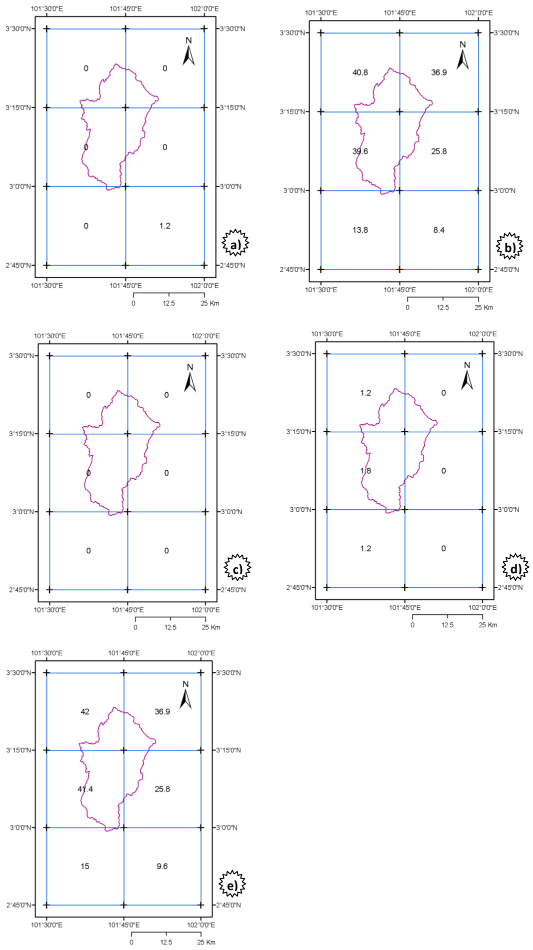

**Fig. A3.** Accumulated 3-hourly rainfall (mm) estimates of TRMM 3B42 (v6) for flood event 11 June 2002. **(a)** 09-11-04-02, **(b)** 12-11-04-02, **(c)** 15-11-04-02, **(d)** 18-11-04-02, **(e)** Total.

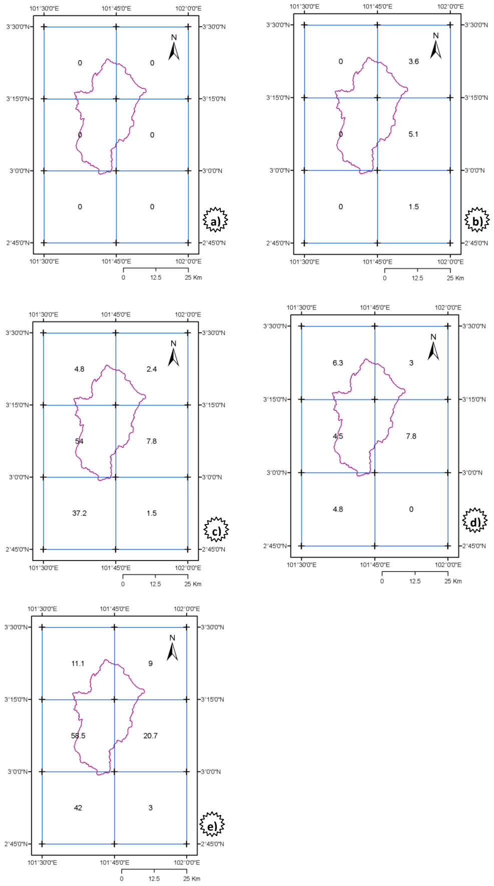

**Fig. A4.** Accumulated 3-hourly rainfall (mm) produced by TRMM 3B42 (v6) for rainfall event 21 December 2002. **(a)** 03-21-12-02, **(b)** 06-21-12-02, **(c)** 09-21-12-02, **(d)** 12-21-12-02, **(e)** Total.