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Evaluation of TRMM satellite-based precipitation indexes for flood forecasting over Riyadh City, Saudi Arabia

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SUMMARY

Floods are among the most common disasters harming humanity. In particular, flash floods cause hazards to life, property and any type of structures. Arid and semi-arid regions are equally prone to flash floods like regions with abundant rainfall. Despite rareness of intensive and frequent rainfall events over Kingdom of Saudi Arabia (KSA); an arid/semi-arid region, occasional flash floods occur and result in large amounts of damaging surface runoff. The flooding of 16 November, 2013 in Riyadh; the capital city of KSA, resulted in killing some people and led to much property damage. The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) Real Time (RT) data (3B42RT) are used herein for flash flood forecasting. 3B42RT detected high-intensity rainfall events matching with the distribution of observed floods over KSA. A flood early warning system based on exceedance of threshold limits on 3B42RT data is proposed for Riyadh. Three different indexes: Constant Threshold (CT), Cumulative Distribution Functions (CDF) and Riyadh Flood Precipitation Index (RFPI) are developed using 14-year 3B42RT data from 2000 to 2013. RFPI and CDF with 90% captured the three major flooding events that occurred in February 2005, May 2010 and November 2013 in Riyadh. CT with 3 mm/h intensity indicated the 2013 flooding, but missed those of 2005 and 2010. The methodology implemented herein is a first-step simple and accurate way for flash flood forecasting over Riyadh. The simplicity of the methodology enables its applicability for the TRMM follow-on missions like Global Precipitation Measurement (GPM) mission.

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1. Introduction

Among various natural disasters, floods have been the most common one (World Disasters Report, 2003). Moreover, flash floods are among the mostly faced and the most deadly (Hapuarachchi et al., 2011; Jonkman and Kelman, 2005) despite their limited affected area (Borga et al., 2014) and being one of the most challenging topics for the research community (Alfieri et al., 2011). Hapuarachchi et al. (2011) tied the driving mechanisms of flash floods either to excessive rainfall or to dam failure; they mentioned the rareness of dam failures and focused on excessive rainfall.

Regions with plentiful rainfall, as well as arid and semi-arid regions, are equally vulnerable to flash floods. Actually, the strongest convective storms are detected in semi-arid regions (Zipser et al., 2006). Recent flood events that occurred in Riyadh, Jeddah and Abha Regions among others in Kingdom of Saudi Arabia (KSA) reflect flash flood risks in arid/semi-arid regions (Fig. 1).

The high fatalities and damages of flash floods arise from the fact that they occur rapidly without enabling time to take mitigation effects. Severity of the damage increases in developing countries where generally warning systems are missing and infrastructures are inadequate (Pombo and de Oliveira, 2015). Developing flood warning systems have been reported in literature as the most effective way to reduce loss of life and property damage (Negri et al., 2005). The advances and criteria in flash flood occurrence methods were reviewed and summarized in Hapuarachchi et al. (2011) and Alfieri and Thielen (2012) in three main categories: Flood Susceptibility Assessment (FSA), Rainfall Comparison (RC) and Flow Comparison (FC). They mentioned that RC indicates a good tradeoff between simplicity and good estimates by requiring just Quantitative Precipitation Estimates (QPE).

As mentioned in Negri et al. (2005), during the flooding events rainfall measurements from ground-based gauging stations can be problematic, since they can be damaged or data transmission may not be possible. These can be minimized by optimal sensor

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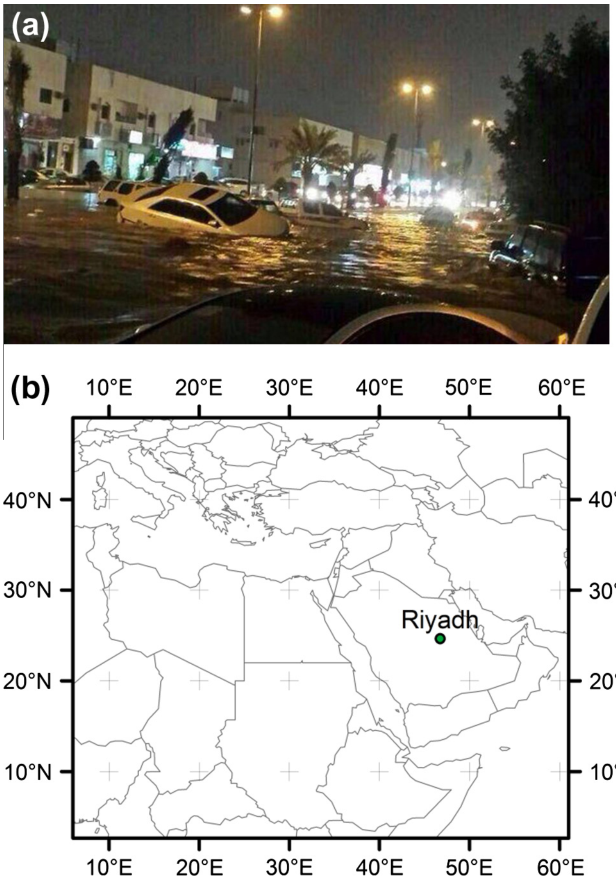

Fig. 1. Photos of flood on 16 November, 2013 in Riyadh (a) *Source:* http://english.alarabiya.net/en/News/middle-east/2013/11/17/Video-Saudi-capital-flooded-with-heavy-rains.html, location of Riyadh in KSA (b).

selection based on the physiographic condition of the region and provision of redundant telecommunication systems. However, Borga et al. (2014) mentioned the inadequacy of rain gauge networks in reproducing the high spatial variability. Thus, the use of remote sensing either from ground-based radar or satellite-based systems is gaining importance (Wardah et al., 2008) and is being widely used. However, both ground-based radar and satellite-based systems need to be validated. This validation can only be possible by ground observations, which are mainly recorded by gauges. An efficient way for flood monitoring can be achieved by combining all information from gauges, ground radars and satellite systems.

Especially, space-borne sensors gave researchers opportunities for developing new ways of flood warning systems to monitor and detect the extreme rain events during which the conventional systems may be obsolete. In this context, multi satellite imagery acquired and processed in real time can provide near real time rainfall fluxes at relatively fine spatiotemporal scales (kilometres to tens of kilometers and 30-min to 3-h) (Hong et al., 2010). Improvements in the hardware and the algorithm developments enabled the implementation of satellite-based flood warning systems supplementing ground-based observations and provide uninterrupted monitoring of extreme events (Asante et al., 2007; Hong et al., 2007). Extreme flooding events and sub-daily variations of rainfall can be tracked by multi-satellite images acquired and processed in real time. Fig. 2 shows the heavy rain areas on 12 March, 2014 in Middle East, North Africa and Southern Europe. It is believed that satellite-based precipitation products can decrease mortality by improving and enabling timely warning (Hong et al., 2007). Borga et al. (2014) expressed that detection of precipitation by remote sensing and numerical weather predictions became major component in flood warning systems. Early warning systems combining satellite observations, ground radars, in situ gauges and numerical weather prediction systems have been mentioned in the literature (Seyyedi, 2010; Zhang, 2012; Coning, 2013; Sene, 2013). However, no such system is operationally working over KSA at present.

In this study, different flood indexes based on TRMM satellite-derived precipitation rain rates are evaluated for forecasting of flooding events occurring in an arid/semiarid region in Middle East; i.e. KSA. Thus, the objective of the current article is to evaluate the capability of TRMM-based indexes in identifying the flooding events. Section 2 provides information about the study area and the data set used. Section 3 explains the methodology and the derivation of indexes. Section 4 summarizes the results and Section 5 concludes the study.

2. Study area and data sets

2.1. Study area

The capital city of KSA; Riyadh (Fig. 1b), is located in the centre of the Arabian Peninsula linking Asia to Africa (Subyani, 2010) and constitutes the study area. Riyadh's climate is classified as arid with summer months air temperatures reaching above 45 °C with no rainfall (PME, 2015). The number of rainy days in a year is on average 16, with an annual average total rain depth of 95 mm, which is mostly seen during November–April. Despite being scarce, high rainfall intensities can be observed (Almazroui, 2011a). Alamri (2011) mentioned that flood-based events hold 65% of the total fatalities in various disastrous over KSA. Impervious land use around the city reduces infiltration and increase runoff coefficients, leading to flash floods. Population growth with increasing constructions will further increase surface runoff amounts. Furthermore, in Almazroui (2011b) it is indicated that little precipitation in KSA can cause flash floods since the soil does not soak up water very easily.

Despite the high fatalities, it is extremely hard, if not impossible, to find information about flood events that occurred in KSA. Past flood events gathered from the International Disaster Database (TIDD, 2015) are presented in Table 1. Two more flooding events were obtained from the internet: one on 3 May, 2010 and another in February 2005 for which the exact date could not be found.

2.2. TRMM 3B42 RT

The Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TMPA) intended to provide a "best" estimate of quasi-global precipitation from the wide variety of modern satellite-borne precipitation sensors at relatively fine scales (0.25° × 0.25° and 3 h) in both real and post-real time to accommodate a wide range for researchers. 6–9 h after observation, Real Time (RT) data can be obtained and 15 days after the end of the month, research products are released (Huffman et al., 2007). The latter is known as 3B42, while the former is called 3B42RT.

Almazroui (2011b) concluded that TRMM results are good enough to be used in a variety of water-related applications over KSA where the rainfall climatology during 1998–2009 is determined based on 3B42. In addition, the high performance of TRMM 3B42 over KSA are mentioned in Kheimi and Gutub (2014). Although 3B42 data was tested over KSA before, to our present knowledge, this is the first time 3B42RT data are used. As the

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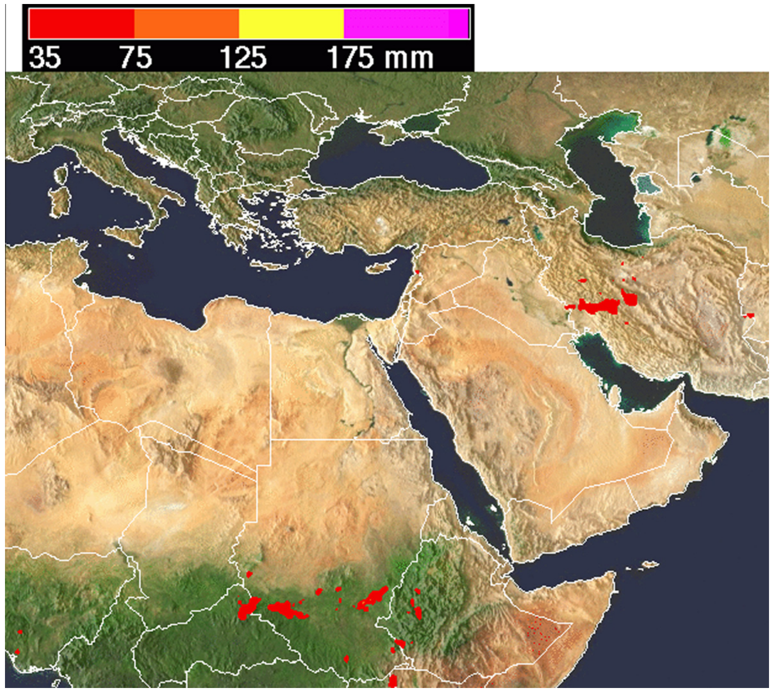

Fig. 2. Heavy rain areas on 12 March, 2014 in Middle East, North Africa and Southern Europe. *Source:* http://trmm.gsfc.nasa.gov/publications_dir/potential_flood.html

purpose is flood monitoring, there will not be enough time for calibration; thus RT data are used as is.

TRMM-RT, being available from 50°N to 50°S with a 3-h interval in a 0.25° spatial resolution, provides precipitation estimates using the multi-channel microwave and infrared observations obtained from satellites (Wanders et al., 2015). In this study, the latest version (V7), which includes several improvements and posted on public website in May 2012 (Duan and Bastiaanssen, 2013) are used. Further details about the data and production can be obtained from TRMM webpage (TRMM, 2015). The 3 hourly 3B42 RT images covering the 2000–2013 period are used herein. Despite the fast nature of flash floods, the event on 16 November, 2013 was detected in TRMM-RT images (see Fig. 3).

Fig. 4 shows the bounding areas of four TRMM 3B42RT pixels covering Riyadh.

3. Methodology

For short duration events like flash floods, warning systems mostly give priority to detection of the event (Borga et al., 2014) and rainfall threshold values have been utilized in flash flood forecasting (Zehe and Sivapalan, 2009). The regional differences and necessity of considering them in determining threshold values for rainfall extremes are mentioned in Hamada et al. (2014). Thus, three different methodologies to get the study area specific extremes and threshold values are mentioned below. Extreme events do not happen frequently; thus, large number of observations is needed to get regional characteristics. In this context, 3 hourly 3B42RT data from 2003 to 2013 is used to derive the related thresholds.

3.1. Intensity duration frequency curves

AlHassoun (2011) developed Eq. (1) to estimate the rainfall intensity in Riyadh Region.

$$I_T\ (\mathrm{mm/h}) = \frac{153 T_r^{0.35}}{t_d^{0.82}} \quad (1)$$

Table 1
Major flood events in KSA between 1964 and 2013 (compiled from TIDD 2015).

Date		Location
Start	End	In KSA
16 November 2013	*19 November 2013*	*Riyadh*
2 May 2013	2 May 2013	Bicha
14 April 2012	18 April 2012	Western Regions
25 January 2011	31 January 2011	Jeddah
23 July 2010	25 July 2010	Assir, Jizan
10 July 2010	12 July 2010	Najran
24 November 2009	26 November 2009	Jeddah, Makkah
22 January 2005	27 January 2005	Medinah
28 April 2005	28 April 2005	Assir, Jeddah
14 April 2004	16 April 2004	Jizan
8 Aug 2003	12 Aug 2003	Jizan
11 November 2003	11 November 2003	Makkah
8 April 2002	13 April 2002	Makkah
24 December 1985	24 December 1985	North West
4 April 1964	4 April 1964	Najran

Italics indicate the floods observed in Riyadh.

where T_r is the return period in years, t_d is the duration of storm in minutes, and I_T is the intensity of rainfall in mm/h. Table 2 presents the expected rainfall intensities that will lead to floods in the study region based on Eq. (1) for different return periods. Taking the 2.33 year as the return period for the average annual flood (Viessman and Lewis, 2002) and the duration of rainfall as 180 min (since TRMM data is 3 hourly), the threshold for rainfall rate causing floods is calculated as 2.91 mm/h and is taken as 3.00 mm/h.

3.2. Cumulative distribution functions

The implemented Cumulative Distribution Functions (CDF) approach is similar to the percent-based method used in Hamada et al. (2014), where regional characteristics of extreme rainfall events are derived from TRMM. The rainfall intensities obtained from 3 hourly 3B42RT data over the four pixels in Fig. 4, are grouped monthly. CDFs of monthly groups over the period

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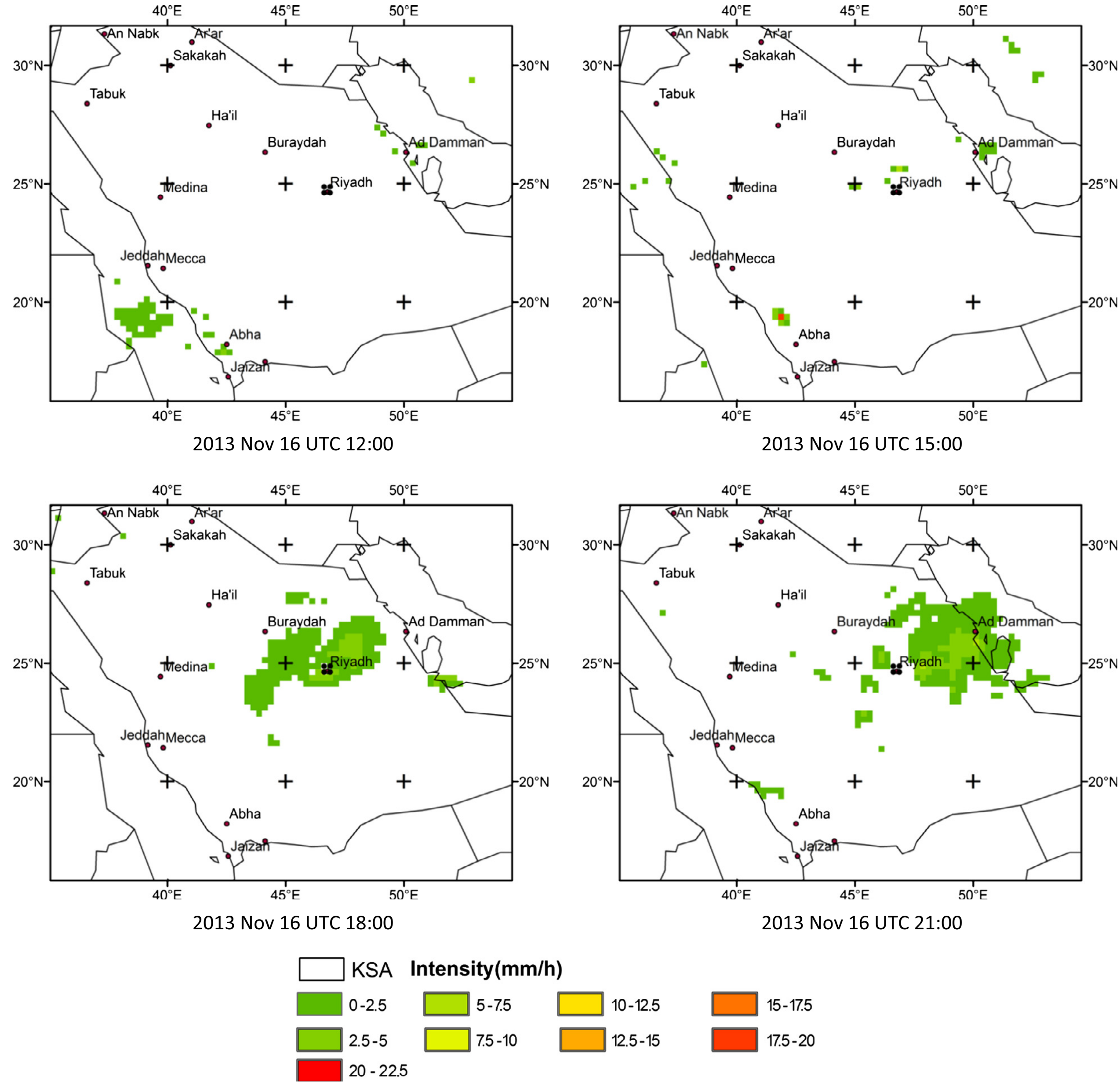

Fig. 3. TRMM-RT data on 16 November, 2013 over KSA.

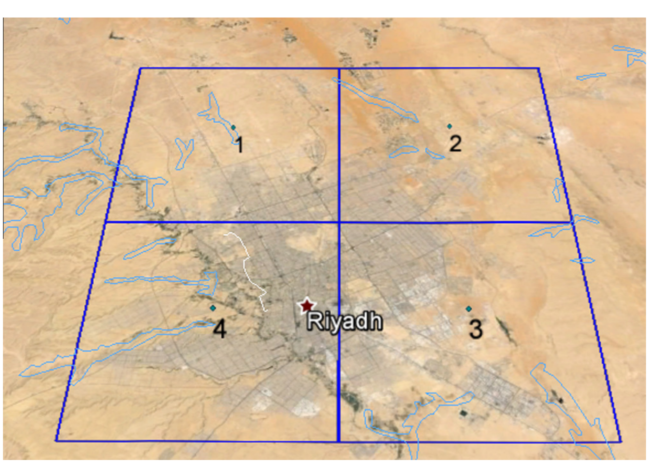

Fig. 4. Coverage of TRMM pixels over Riyadh, KSA.

Table 2
Expected rainfall intensities for different return periods.

T_r (years)	t_d (min)	I (mm/h)
2.33	180	2.91
5	180	3.80
25	180	6.68
50	180	8.51
100	180	10.85

2000–2013 are presented in Fig. 5. On the contrary to Pombo and de Oliveira (2015), the CDF plots do not show very similar characteristics.

3.3. Riyadh Flood Precipitation Index

Based on the long term TRMM 3B42RT data (March 2000–December 2013), Riyadh Flood Precipitation Index (RFPI) is calculated. RFPI is similar to European Precipitation Climatology Index (EPIC) mentioned in Alfieri et al. (2011). However, it is slightly changed herein. RFPI is calculated as given in the below Eq. (2).

$$\mathrm{RFPI} = \frac{P_i}{\frac{1}{N}\sum_{j=1}^{N}\mathrm{Max}(P_i)} \quad (2)$$

where P_i is the 3 hourly precipitation rates obtained from the TRMM 3B42 RT images. The denominator is the average of the maxima P_i's recorded in the study period and N is the number of data-available years, i.e. 14 years from 2000 to 2013.

RFPI is not only different from EPIC by formulation. Instead of the annual values of EPIC calculations, RFPI is calculated herein for each month. Thus, RFPIs are calculated monthly. The denominator of RFPI computed for each month over Riyadh is presented in Table 3.

Little underestimations and strong correlation of EPIC with simulated high flows are mentioned in Alfieri et al. (2011). Unfortunately, runoff data is not available for the current study.

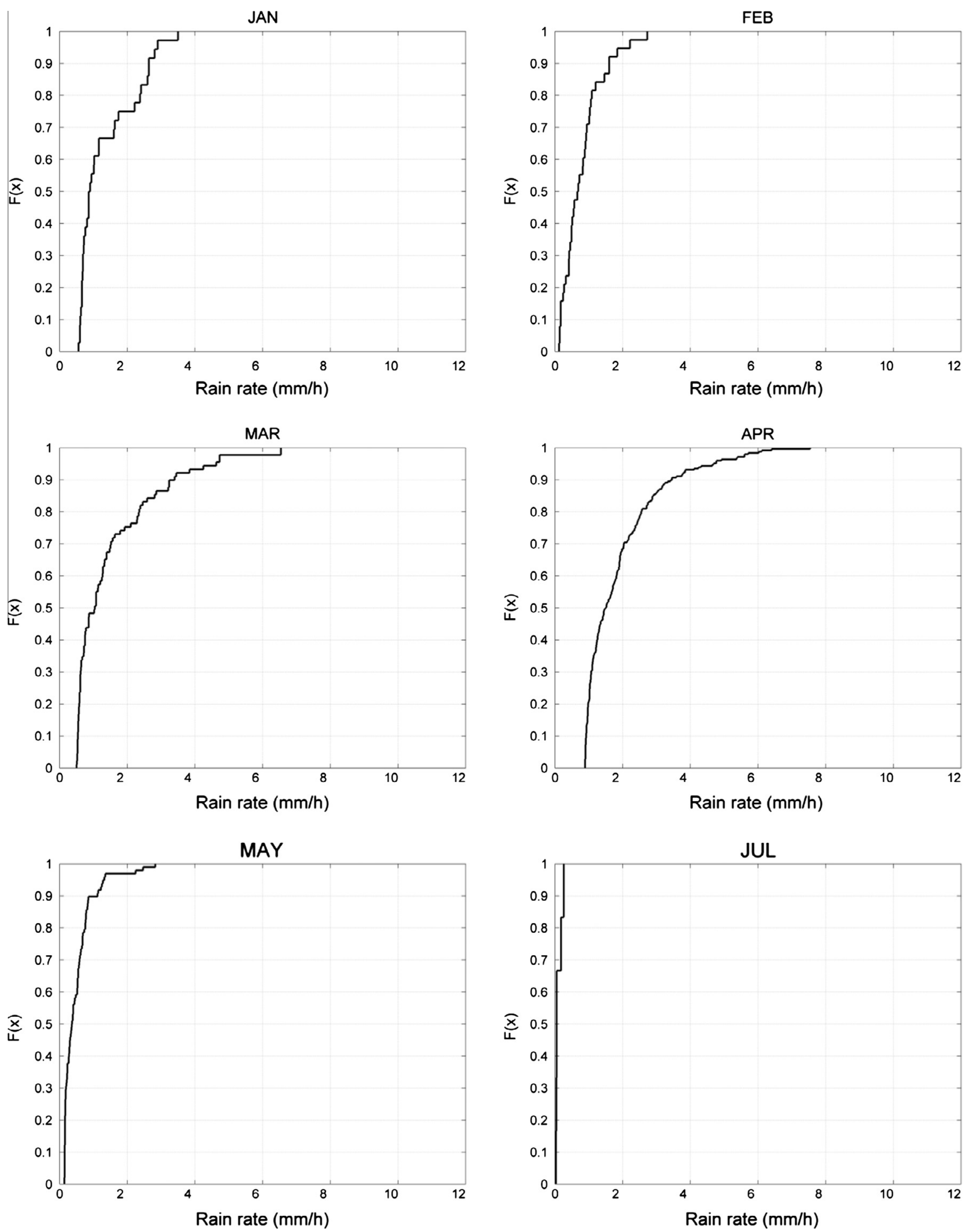

Fig. 5. Cumulative distribution functions of TRMM 3B42RT rain rates.

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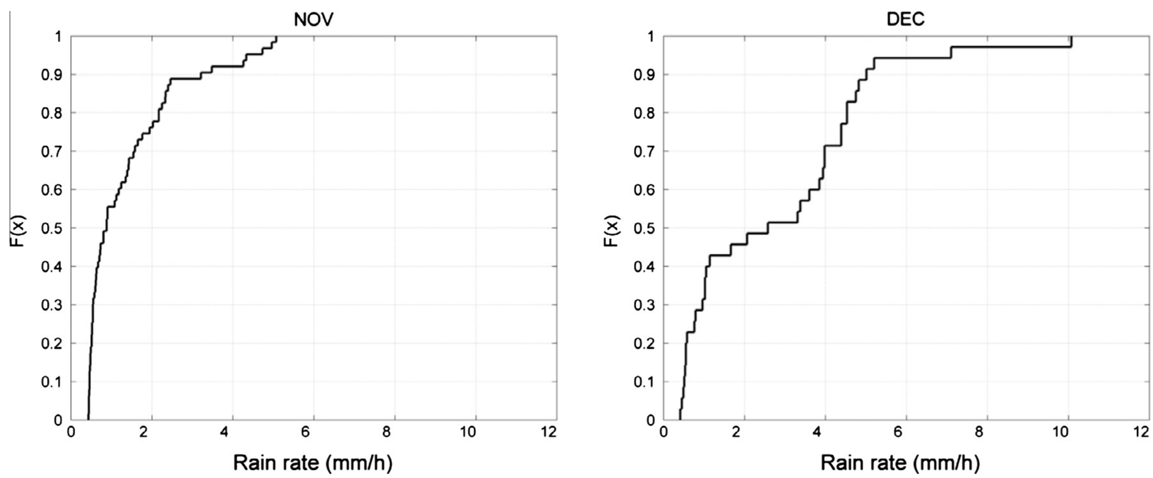

Fig. 5 (*continued*)

Table 3
Monthly denominator values for RFPI calculation.

Max 3 h rain rate (mm/h)	January	February	March	April	May	June	July	August	September	October	November	December
2000	No data	No data	0	3.85	0	0	0.26	0	0	0	4.33	3.85
2001	0	0	6.54	6.11	0.44	0	0	0	0	0	0.54	10.07
2002	0	0.17	3.40	2.41	0	0	0	0	0	0	0.80	0.105
2003	0.72	1.03	1.02	4.32	0.68	0	0	0	0	0	1.08	0.50
2004	0.81	0.12	0.55	7.54	0	0	0	0	0	0	1.76	4.39
2005	2.90	2.73	1.48	2.55	0.85	0	0	0	0	0	1.39	0
2006	0	0.83	1.57	3.33	0.53	0	0	0	0	0	1.58	0
2007	0	1.46	4.63	5.71	0.76	0	0.03	0	0	0	0	0
2008	1.60	1.20	1.28	1.92	0.17	0	0	0	0	0	0.90	3.98
2009	0	0	0.78	2.71	0.79	0	0	0	0	0	0	7.10
2010	0	0.17	0	2.80	2.83	0	0.04	0	0	0	0	0
2011	3.50	0	0.61	1.92	0	0	0	0.04	0	0	0.88	0
2012	1.16	0	0	5.39	0.58	0	0	0	0	0	1.54	3.60
2013	0.76	2.22	3.24	5.37	2.47	0	0.05	0	0	0	5.07	0
Average	1.64	1.10	2.28	4.00	1.01	N/A	0.1	0.04	N/A	N/A	1.81	4.88

Thus, two threshold values: medium and high EPIC (1 and 1.5, respectively) are taken in this study as proposed in Alfieri et al. (2011). Moreover, the threshold value of 2 is also considered.

4. Results and discussions

The maxima and minima rain rates obtained from 3 hourly 3B42RT over Riyadh are plotted monthly; with black diamonds and red squares, respectively, against the flood observations over KSA in Fig. 6. Despite the fact that the number of floods is not specific to Riyadh but to all KSA, 3B42RT data indicates higher rain rates over the frequent flood observed months. Seasonal variation of flood numbers and 3B42RT data in Fig. 6 are in agreement with the seasonal variation mentioned in Hamada et al. (2014), where the number of extreme events indicated higher percents during March, April and May. Moreover, Kheimi and Gutub (2014) mentioned that rainfall generally falls from October through April over the Kingdom. Furthermore, the existences of highest (lowest) rainfall amounts are mentioned to occur in spring (summer) being in parallel with the findings of Fig. 6.

The above mentioned three methodologies are applied over Riyadh for the 2000–2013 TRMM 3B42RT observations to test the flood detection efficiency of each method.

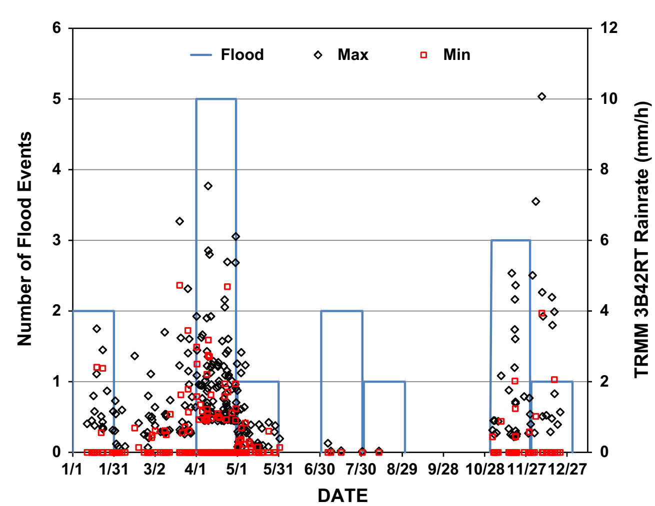

Fig. 6. Temporal distribution of major flood events over KSA throughout the year and maxima (black diamonds) and minima (red squares) rain rates observed by 3B42RT over Riyadh. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.1. Intensity duration frequency curves

TRMM 3B42RT are searched for values greater than or equal to 3.00 mm/h obtained by Eq. (1). This enabled detecting the event observed in November 2013 (Fig. 7c). However, the events of February 2005 and May 2010 could not be foreseen (Fig. 7a and b). P1, P2, P3 and P4 in Fig. 7 are the four TRMM pixels covering Riyadh (Fig. 4). Actually, the seasonal differences in

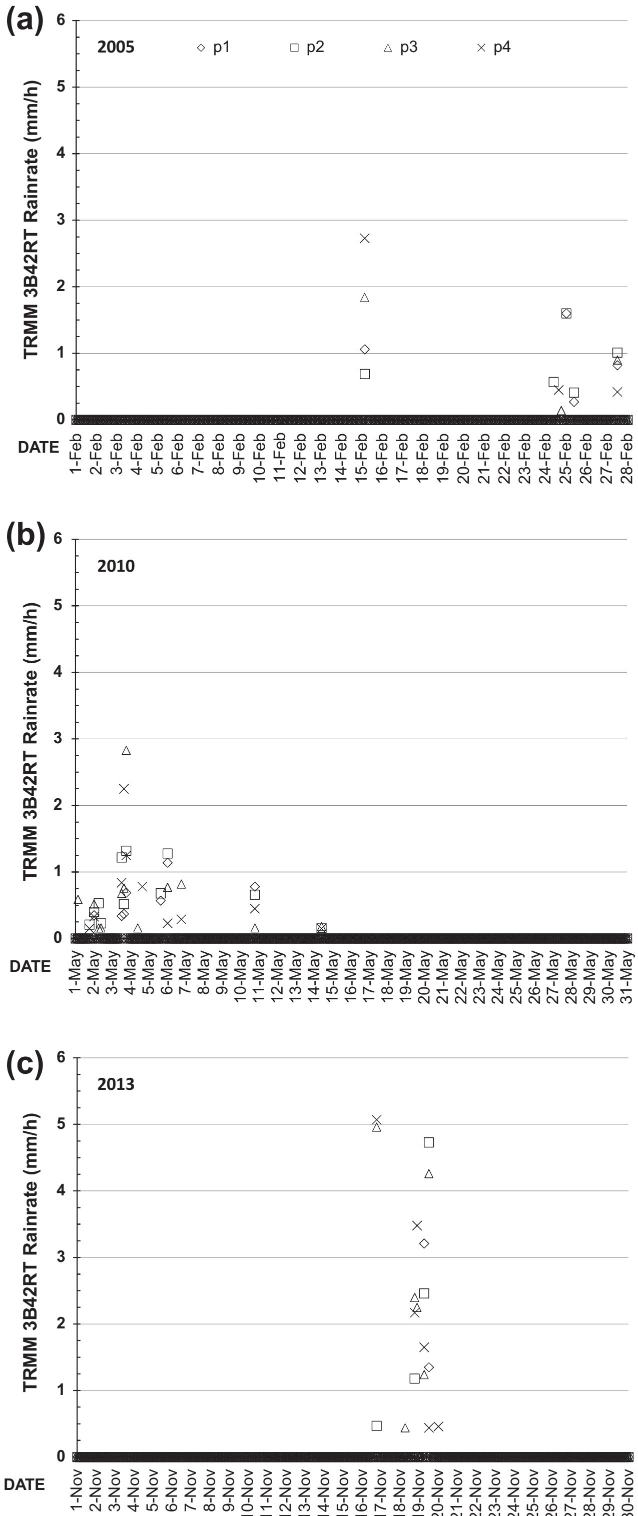

Fig. 7. 3-hourly rain rates obtained from TRMM 3B42RT pixels over Riyadh during February 2005 (a), May 2010 (b) and November 2013 (c).

rainfall extremes are mentioned in Hamada et al. (2014) and in Almazroui (2011b). Thus, instead of a constant threshold, a dynamic threshold schema is based on CDFs.

4.2. Cumulative distribution functions

As the 3.00 mm/h threshold found by Eq. (1) was approximately 90% of the CDF for November, the 90% of CDFs for each month were selected as the threshold values for the respective month. 90% is very near to 99.9% used by Hamada et al. (2014) in the definition of regional extreme rainfall definition. The obtained values are 1.60, 1.04 and 3.26 mm/h for February, May and November, respectively. From Fig. 7a–c it is seen that these thresholds enable the detection of the three observed flood events.

4.3. Riyadh Flood Precipitation Index

Three RFPI values (i.e. 1, 1.5 and 2) enabled the detection of all observed flood events. The flood assigned dates and times from each of the methodologies are presented in Fig. 8.

Fig. 8 indicates that the heaviest rain times are in agreement with the findings in Hamada et al. (2014) where distinct afternoon peaks are detected over land surfaces. Also, it is apparent that the constant threshold methodology (i.e. 3.00 mm/h) misses the floods in the observed low-precipitation months. This is the main reason for missing the 2005 February and 2010 May floods. And on the contrary, it gives too much false alarms during the observed relatively heavier precipitation months.

CDF with 90% threshold captured the three flood events. Despite CDFs yielded less false alarms compared to Constant Threshold (CT), it still provided high number of flood determinations.

The performance of RFPI with a value of 1 is comparable to CDF. However, it provided larger number of false alarms compared to CDF in January, February, March and November (months of higher precipitation as reported in Bashir and Fouli (2015)); the number of false alarms was smaller in April. It is also noticeable that as RFPI increased, the number of false alarms reduced.

The above mentioned three methodologies are tested for 2014, which was not used in threshold determination. Both CT and CDF 90% approaches indicated flooding on 2 April, 2014 at 12:00. However, none of the RFPI indices indicated that flooding. Other than the indicated flooding on 2 April, 2014, no flooding is determined with any of the approaches. Actually, 2014 was one of the driest periods in Riyadh, and no flooding was recoded at all.

While it may be argued that rainfalls with intensity of only 3.00 mm/h, as the threshold value in the CT method, cannot generate flash floods, especially in dry areas like Riyadh, Almazroui (2011b) reported that: “Even a small storm with little precipitation can produce flash flooding, because the Saudi Arabian desert soil does not soak up water very easily. Dry wadis (ravines) can quickly turn into raging rivers during and after heavy rains. Even rainfall intensities less than 3.00 mm/h (refer to Fig. 7a and b) caused flooding over Riyadh. These values are directly obtained from the TRMM data and the flood events, without any modification, i.e. they are the results of direct observations. Thus, even though one may think much more rainfall is needed to cause flooding, it seems that this is not the case. Fig. 3 shows that the flood that happened on Nov. 16, 2013 resulted from rainfall that had intensity of 2.5–5 mm/h; Fig. 1a shows a real snapshot of that flood.

5. Conclusions

High rain rates, daily and seasonal variation of these extreme events, observed over Riyadh City in KSA could be detected by 3B42RT data. These were mainly detected over March–May period, followed by December–February period and mostly seen as afternoon showers.

Three methodologies namely: Constant Threshold (CT), 90%-Cumulative Distribution Functions (CDF 90%) and Riyadh Flood Precipitation Indexes (RFPI), are developed to test the flood detection capabilities of 3B42RT data over Riyadh.

From 2000 to 2014, three major flood events on February 2005, May 2010 and November 2013, are determined over Riyadh. CT

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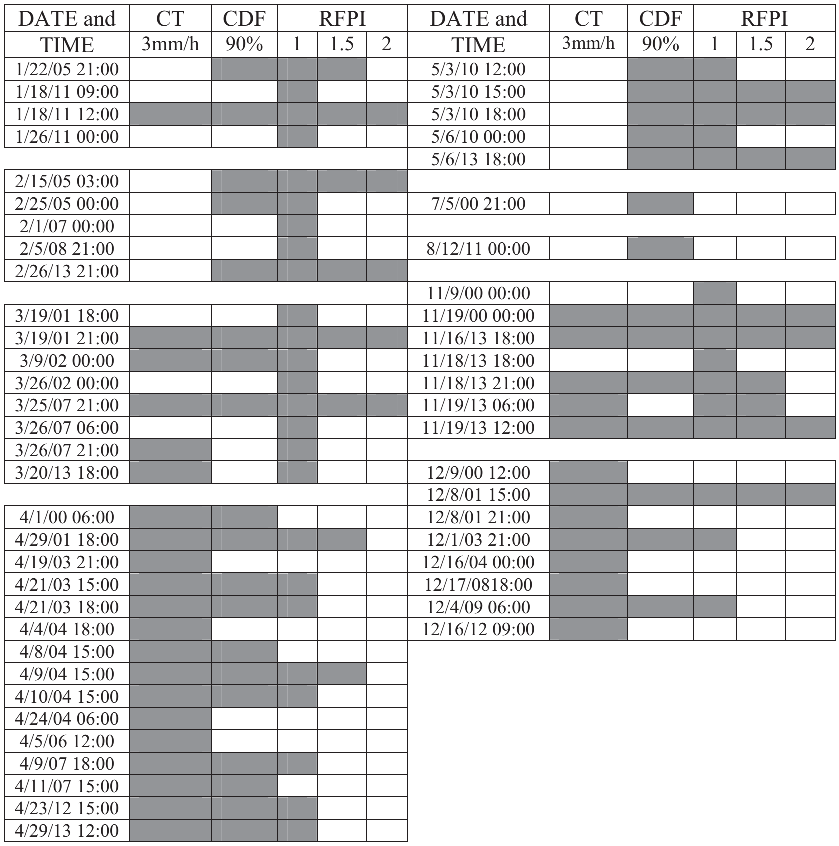

Fig. 8. Month wise distribution of the flood detection by each methodology. Gray boxes indicate the flood detection by the methodology and white boxes no flood threat (time is in UTC).

detected the 2013 event and missed the other two. CDF 90% indicated flooding of the three events. RFPI was tested for three different values of 1, 1.5 and 2. All RFPIs indicated flooding for the observed dates.

CT indicated false flood alarms during the relatively wetter periods (March, April, November and December), where else it missed flooding during the drier seasons (February and May). CDF 90%, RFPI 1, 1.5 and 2 followed CT in number of false alarms in a reducing manner.

All methodologies are tested for 2014 that was not used in development step. Only one flooding event for 2 April 2014 on 12:00 is determined by CT and CDF 90%. RFPI's, however, did not provide any flood warning for that event. Actually, no flooding events were reported in 2014.

The results in this article refer to flash floods based on precipitation data only. While the antecedent soil moisture may be thought of as another important factor for causing flash floods, Almazroui (2011b) and Kheimi and Gutub (2014) reported that as Saudi Arabian desert soil does not soak up water quickly, dry wadis can turn into raging rivers quickly. Due to that, even little precipitation may lead to flash floods; therefore, the results in this paper are quite useful and indicative.

It is believed that to get the best use of satellite data for flood forecasting, all three methodologies should be used in a combined sequential manner. The CT can be used to indicate a pre-warning and if CDF 90% also indicate flooding, then the warning severity can be increased. Concurrently if RFPI's also indicate flooding, then warning should be set at highest level. Indexes developed in here are suitable for flood forecasting using satellite data over Riyadh, KSA. The methodology is simple and can be applied easily to TRMM follow-on missions like Global Precipitation Measurement (GPM) Mission. However, to improve rainfall estimations from satellite based systems, ground observations are vital. The reduced functionality of ground based gauges arising from telecommunication and infrastructure problems during extreme events can be improved by selection of optimum sites and by providing redundant communication systems.

Furthermore, development of flash flood archives and initiation of post-flood surveys as mentioned in Borga et al. (2014) should be implemented as soon as possible over KSA, since studies such as herein necessitate the existence of such information.

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