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# Joint Use of Tropical Rainfall Measurement Mission (TRMM) and Ground Station Data to Develop Intensity Duration Frequency Relationships in Scarce data Arid Regions: Case Study in KSA

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## ملخص البحث

يحظى منحنى هطول الأمطار (أي العلاقة بين شدة ودوام وتكرار الأمطار) باهتمام الباحثين نظراً لأهميته فى تصميم المنشآت الهيدروليكية وشبكات تصريف مياه الأمطار. ويعتمد هذا المنحنى على تحليل بيانات الأمطارذات الديمومة القصيرة، والتي نادراً ما تكون متاحة في بلدان عديدة ويحتاج جمعها إلى تسجيلات مستمرةبمحطات الأمطار، وهو ما لايتوفر في كثير من البلدان النامية حتى الآن،فالمتاح عادة هي البيانات اليومية ومدة العاصفة، مما يجعل من تحديد منحنى هطول الأمطارعملية صعبة وغير دقيقة.

إن الهدف الرئيسي من هذا البحث هو دراسة استخدام تقديرات الأمطاربالأقمار الصناعية لملء الفجوات الناتجة من تناثر شبكات مقاييس الأمطار الأرضية أو عندما لا تكون هناك أية معلومات متاحة عن بيانات الأمطارذات الديمومة القصيرةفي المناطق الجافة.ولتحقيق هذا الهدف تم تجميع بيانات الأمطار ذات الديمومة القصيرة من 43 محطة رصد أرضية فى منطقة الدراسة (المملكة العربية السعودية) ومن بيانات الأقمار الصناعية لنفس إحداثيات المحطات الأرضية المستخدمة،وحُلِّلَت تلك البيانات باستخدام التحليل التواتري وذلك للعديد من التوزيعات وتم اختيار أكثرها ملائمة. كما تم اشتقاق نسب عمق الأمطارمن ثلاث ساعات إلى الأربع وعشرين ساعة عند أزمنة تكرارية مختلفة للمحطات الأرضيةوكذلك للأقمار الصناعية وتمت مقارنتهما.وللوصول إلى علاقة يمكن الاعتماد عليها والوثوق بها تم تقسيم منطقة الدراسة إلى أربع مناطق طبقاً للتوزيع المكاني لمحطات الرصد الأرضية.ثم استخدمت معادلة الانحدار لكل منطقة، ومن ثم تم التنبأ بنسبة أمطارالثلاث ساعات إلى الأربع وعشرين ساعة للمواقع غير المتاح بها بيانات الأمطار ذات الديمومة القصيرة والواقعة داخل أي من تلك المناطق طبقاً لإحداثياتها. وباستخدام النوع الثاني من توزيعات هيئة صيانة التربة الأمريكية والنسب المتنبأ بها تم اشتقاق نسب عمق الأمطارطوال مدة العاصفة (من 5 دقائق حتى 24 ساعة)، وبضرب هذه النسب فى عمق الأمطارعند 24 ساعة لأزمنة تكرارية مختلفة يمكن الحصول على عمق الدوام ومن ثمَّ منحنى الشدة مع الدوام.

## Abstract

In many countries, short duration (sub-daily) rainfall data are rarely available. Their proper collection requires continuously recording precipitation gauges, which have not been frequent, in developing countries, until recent years. Usually, only daily records – as well as occasionally, total storm durations – are available, making the task of developing Intensity-Duration-Frequency (IDF) relations with acceptable accuracy extremely difficult and uncertain. The main aim of this research is to investigate the use of rainfall estimates from the Tropical Rainfall Measurement Mission (TRMM) satellite to fill the gaps of sparse rainfall gauge networks.

To achieve this purpose, the following methodology was applied. Rainfall ground data were collected from forty three rainfall gauges with short duration records, in the study area which is the Kingdom of Saudi Arabia (KSA). TRMM data were also collected for the same ground stations locations, for comparison purposes, and also covering the entire KSA, for generalization purposes. Frequency analyseswere undertaken on the rainfall data from ground stations and TRMM sources, using several distributions and the best fitting is selected based on the Bayesian Criteria and ordinary-moments ratio diagram. Rainfall ratios

of3-hr to 24-hrdepths at different return periods were derived for ground stations and TRMM, then compared and spatially grouped into four zones. Regression equations were developed for each zone to predict the ground station 3-hr to 24-hrratios and predictions were extended to cover the entire study area for locations where short duration ratios are not available. These predicted ratios along with the SCS type II storm profiles were used to derive ratios of t-min durations to 24-hrrainfall depths. These ratios are to be multiplied by the 24-hr rainfall depths at different return periods to obtain the depth-duration-frequency and hence the IDF curves.
**Keywords:** Ground Stations; TRMM; Frequency Analysis; Intensity Duration Frequency; KSA

# Introduction

The rainfall intensity-duration-frequency curves (IDF) received considerable attention in engineering hydrology over the past decades as it has an important role in the design of hydraulic structures and storm water networks. The most common approach to develop an IDF is to undertake frequency analyses on the available sub-daily/daily rainfall depths data. However, sub-daily rainfall data are not always available in the location of interest. Only daily records – and sometimes total storm durations – are more frequently available. To determine rainfall at shorter duration, one has to make use of common storm profiles, developed for other locations and even climatic zones. It is also well-acknowledged by TP-40, the standard reference for short duration analysis in the Unites States) Hershfield 1962, Reich 1963, Miller et al. 1973Frederick et al.1973, Frederick et al.1977, and lately by NOAA 2007) that the ratios from t-minute rainfall to 1-hr rainfall are fairly stable across return periods in locations where convective storms prevail. These ratios were first extended by Bell (1969) to include 2-hr rainfall depth and have been confirmed for use in arid regions in general (FAO 1981, Awadallah and Younan 2012), and specifically in Saudi Arabia (Wan 1976 and Hamilton et al.1989) and in Sinai, Egypt (Fahmi et al.2005). The widely used Soil Conservative Service (SCS, now the Natural Resources Conservation Service) four storm distributions (USDA1986) tackled the extension of Bell ratios to the estimate of the ratio of the 1-hr to the 24-hr rainfall. Among the 4 storm distributions, the most conservative design storm with highest rainfall intensity is the SCS type II which is used in the relatively arid states of the USA. This later 1-hr to 24-hr rainfall depths are not constant neither in the USA nor across climatic regions.

Although Bell ratios validity were checked for use in arid regions, the ratios from 2-hr till 24-hr were not extensively studied. In fact, few researchers have questioned the adequacy and safety of using the SCS type II storm profile in arid regions. Ahmed (2011) stated that the SCS type II storm profile showed less conservative patterns than most rainfall gauges of short duration rainfall ratios in KSA and Sinai (Egypt). Awadallah and Younan (2012) analyzed available short duration rainfall data collected from 23 stations in Egypt, Saudi Arabia, Qatar, and Oman. They found that Bell ratios are suitable to express rainfall patterns in arid regions for durations less than 2-hr; however, the SCS type II ratios were not valid for use in some studied arid regions (e.g. Jeddah –Makkah, KSA).

In the absence of short duration data and in the light of the uncertainty of using predefined storm profiles, could we rely on satellite estimates to calculate the 2hr/24-hr or the 3-hr/24-hr ratio and hence, develop IDF curves? This builds on the significant developments in the field of satellite rainfall estimation in recent years. One of the main satellite products is the one by the Tropical Rainfall Measuring Mission (TRMM) satellite, which was launched late in 1997, as a joint project of the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), in a low earth orbit at a height of 350 km and an inclination of 35° (Huffman et al. 2007).

Recently, numerous researchers have checked the TRMM data with ground station data in different climate regions in the world as: (Adler et al .2009, Li and Shao 2010, Habib 2011,Almazroui 2011,Pombo and Oliveira2015).Many researchers concluded that TRMM data has limited capabilities to reproduce extreme storms. That's the reason why very few papers have investigated the use of TRMM data in IDF development. Among these, Endreny and Imbeah (2009) stated that it is essential to combine ground rainfall data and TRMM data for IDF generation in Ghana. Awadallah et al. (2011) developed an approach using regional analysis and satellite data to develop IDF curves for the North-West of Angola. Awadallah and Awadallah (2013) presented an approach based on the joint use of the available ground data (this time, both daily and monthly data) with TRMM satellite data to generate Intensity Duration Frequency (IDF).

On the other hand, there is no study that investigated the sub-daily rainfall depth ratios of the TRMM neither compared ground data sub-daily rainfall depth ratios to those of TRMM. In this study, we attempt to calibrate the ratio of 3-hr to 24-hrrainfall depths of the TRMM Multi- Satellite Precipitation Analysis (TMPA) (3B42) version 7, 0.25° x 0.25° resolution data (Huffman et al.2010, Bolvin and Huffman 2013,Buytaert et al. 2014) to their corresponding ground data sub-daily rainfall depth ratios in order use the TRMM ratios to develop IDF relationships in arid regions when no sub-daily rainfall information is available.

## Available Rainfall Data from Ground Stations and TRMM

### 1. Ground Stations Data

The database of extreme rainfall consists of the annual series of precipitation maxima with durations from 10, 20 and 30 min (sub-hourly durations); 1, 2, 3, 6, 12 and 24 hours (sub-daily durations).Data were obtained from the Ministry of Water and Electricity in the Kingdom of Saudi Arabia (KSA)and are available in the period from 1966 to 2005. Forty three rain gauge stations are available with at least 8 years of observations. Fig. 1 shows a map of the ground station locations while Table 1 summarizes the characteristics of the available rainfall stations including ID, coordinates, altitude and number of recorded years. The study focused on the maxima of (3-hr, 24-hr) since the 3-hr duration is the limit of TRMM temporal resolution.

### 2. TRMM Data

The research version of TRMM data (TRMM 3b42) (version 7) were obtained from 1998 till 2015 with a 0.25° x 0.25° resolution and a time step of 3-hr, covering the entire KSA as shown in Fig. 2. This dataset is the output from the TMPA (TRMM Multi-satellite Precipitation) Algorithm, and provides precipitation estimates in the TRMM regions that have the (nearly-zero) bias of the "TRMM Combined Instrument" precipitation estimate and the dense sampling of high-quality microwave data with fill-in using microwave-calibrated infrared estimates (Huffman et al. 2007). Ten ground validation sites, representing a reasonable variety of rain regimes, have been selected for calibration purposes of the TRMM estimates. They are located in Florida, Australia, Republic of the Marshall Islands, Texas, Israel, Brazil, Guam, Taiwan, Thailand, and Hawaii (Adler et al. 2007). Unfortunately, none of the stations is located in the Gulf Area, and hence the importance of this study as a mean to calibrate at least the ratio of the 3-hr to 24-hr rainfall depths. To calculate the 24-hr rainfall, eight consecutive 3-hr rainfall depths are added. For each year, the maximum 24-hr and 3-hr rainfall depths were determined.

Table 1:Characteristics of Available Rainfall Stations

| Station ID | Longitude | Latitude | Altitude | No. of Recorded years |
|---|---|---|---|---|
| A004 | 43º-06'-00" | 18º-10'-00" | 2400 | 18 |
| A005 | 42º-29'-00" | 18º-12'-00" | 2200 | 34 |
| A006 | 42º-36'-00" | 18º-15'-00" | 2100 | 23 |
| A007 | 42º-09'-00" | 19º-06'-00" | 2600 | 20 |
| B001 | 41º-16'-86" | 20º-10'-66" | 2400 | 18 |
| B004 | 42º-36'-00" | 20º-01'-00" | 1020 | 27 |
| B005 | 42º-32'-00" | 19º-52'-00" | 1090 | 26 |
| B006 | 43º-31'-00" | 19º-32'-00" | 975 | 13 |
| B007 | 41º-34'-15" | 19º-51'-74" | 2400 | 37 |
| B216 | 41º-59'-00" | 19º-28'-00" | 2000 | 17 |
| D001 | 44º-22'-00" | 24º-29'-00" | 940 | 8 |
| H215 | 41º-21'-00" | 26º-47'-00" | 980 | 9 |
| J001 | 41º-03'-00" | 19º-32'-00" | 53 | 14 |
| J204 | 40º-12'-00" | 21º-21'-00" | 720 | 29 |
| J205 | 40º-13'-00" | 21º-21'-00" | 910 | 29 |
| J214 | 39º-59'-00" | 21º-59'-00" | 710 | 24 |
| J216 | 40º-07'-00" | 21º-13'-00" | 540 | 21 |
| J219 | 39º-26'-00" | 22º-12'-00" | 125 | 22 |
| J220 | 39º-49'-00" | 22º-22'-00" | 470 | 22 |
| J221 | 39º-21'-00" | 21º-55'-00" | 90 | 19 |
| J239 | 39º-41'-00" | 21º-58'-00" | 350 | 18 |
| M001 | 39º-35'-00" | 24º-31'-00" | 590 | 25 |
| M205 | 40º-34'-00" | 23º-08'-00" | 860 | 20 |
| R001 | 46º-43'-00" | 24º-34'-00" | 564 | 24 |
| R002 | 47º-24'-00" | 24º-10'-00" | 430 | 14 |
| R003 | 46º-44'-00" | 22º-17'-00" | 539 | 9 |
| R004 | 44º-48'-00" | 26º-17'-00" | 670 | 30 |
| R005 | 45º-37'-00" | 25º-32'-00" | 665 | 18 |
| R006 | 45º-15'-00" | 25º-15'-00" | 730 | 10 |
| TA002 | 40º-30'-00" | 21º-18'-00" | 1500 | 26 |
| TA004 | 40º-27'-00" | 21º-24'-00" | 1530 | 15 |
| TA005 | 41º-40'-00" | 21º-11'-00" | 1126 | 12 |
| TA007 | 41º-28'-00" | 19º-59'-00" | 2200 | 8 |
| TA206 | 40º-24'-00" | 21º-17'-00" | 1680 | 23 |
| TA233 | 40º-39'-00" | 21º-08'-00" | 1650 | 32 |
| TA250 | 40º-27'-00" | 21º-40'-00" | 1465 | 8 |
| TA251 | 40º-22'-00" | 21º-22'-00" | 1900 | 8 |
| TB002 | 38º-29'-00" | 27º-38'-00" | 820 | 13 |
| U001 | 43º-59'-00" | 26º-04'-00" | 724 | 32 |
| U002 | 42º-11'-00" | 25º-50'-00" | 740 | 15 |
| U004 | 43º-48'-51" | 25º-52'-46" | 724 | 8 |
| U205 | 43º-37'-00" | 25º-21'-00" | 800 | 8 |
| U220 | 44º-17'-00" | 26º-30'-00" | 580 | 8 |

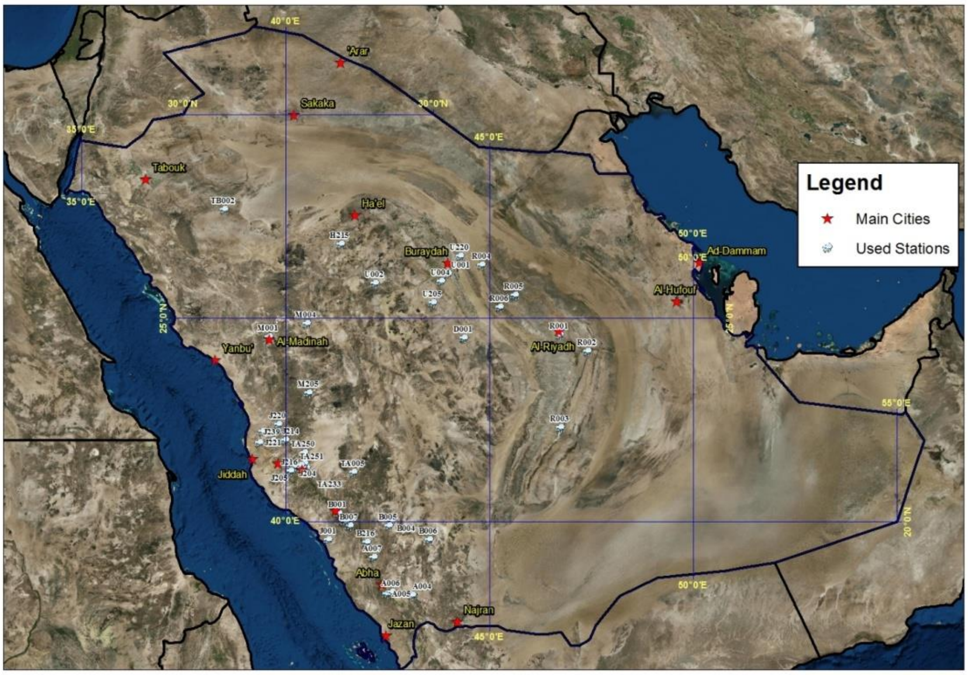



Fig. 1: Map of available ground station locations

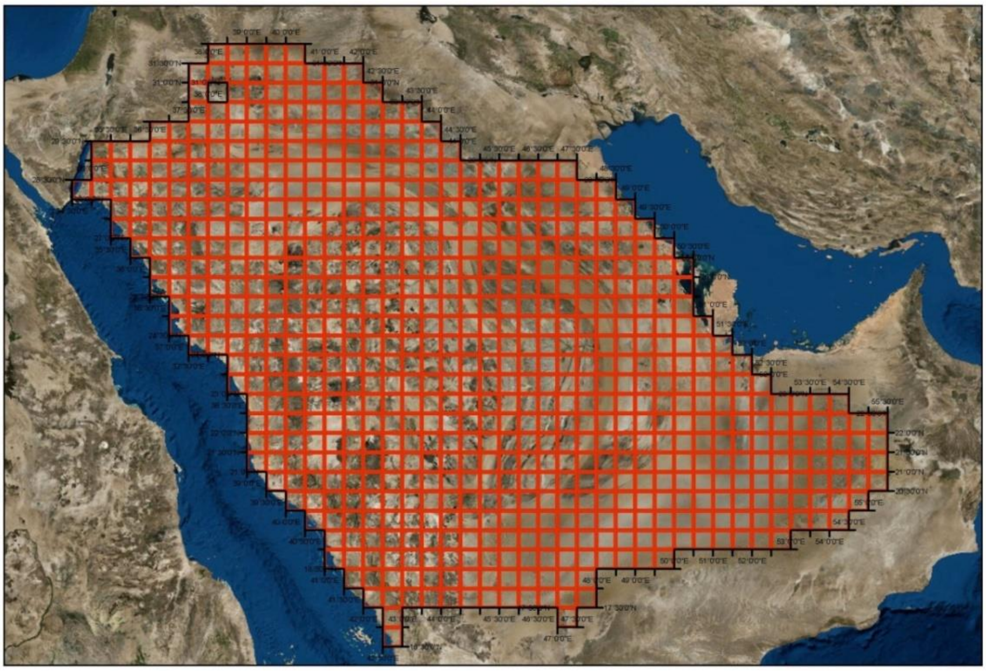
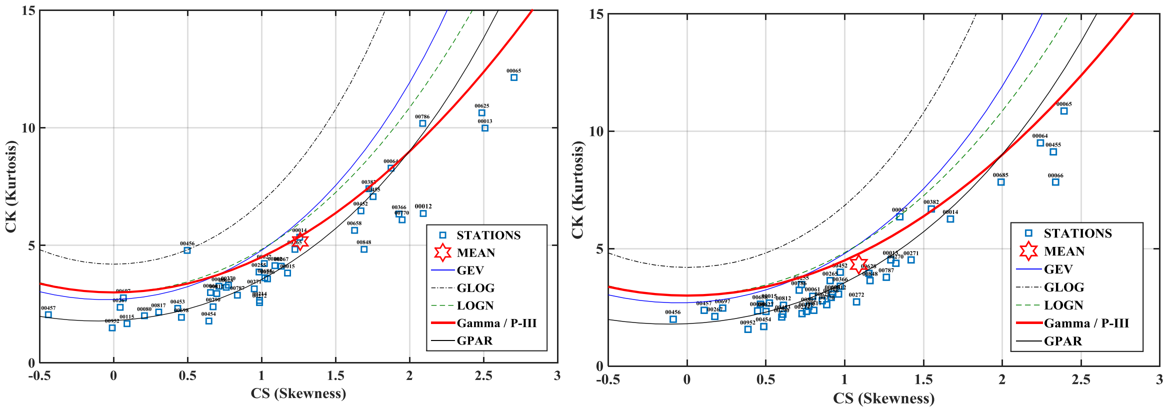


Fig. 2: TRMM data tiles with 0.25° x 0.25° resolution

## Methodology and Results

The methodology could be summarized in the following steps: The first step is to undertake frequency analyses on the ground stations annual maxima series for 3-hr and 24-hr durations. The primary issue in frequency analysis is to determine the most suitable distribution to fit the data. Gumbel, Pearson type III (PIII), 2-parameter Gamma, 3-parameter LogNormal (LOGN3), and Generalized Extreme Value (GEV) were all considered candidate distributions for fitting the studied data. The selection of the best distribution was based on the lowest Akaike Information Criterion (AIC)(Akaike 1973, 1974) and lowest Bayesian Information Criterion (BIC)(Schwarz 1978), as well as on the ordinary-moments ratio diagrams. As shown in Table 2, the Gamma distribution is the most suitable distribution for the majority of the stations in the study zone, as it takes the top rank in most of ground stations and produces the lowest sum of ranks. Furthermore, Fig. 3 (a and b) illustrates the ordinary-moment ratios (Coefficient of Kurtosis (CK) and Coefficient of Skewness (CS)) diagram for 3-hr and 24-hrrainfall depths, respectively. It shows that most of CK-CS couples, each representing an individual ground station, are aligned near the Gamma distribution curve and their mean is close to the same Gamma curve. From the above, the Gamma distribution was used to derive the rainfall values of 3-hr and 24-hr durations at various return periods especially that it is a 2-parameter distribution. As an example, Fig. 4 shows the Gamma fitting for station A004data for 3-hr and 24-hr rainfall depths.3-hr and 24-hr rainfall depths for 2-, 5-, 10-and 20-year return periods are calculated. We opted not to exceed 20-year return period in order to reduce uncertainties, associated with high return periods, due the short data record, and not to go below 2-year as this the lowest design return period for storm water network components design. The above-mentioned procedure was repeated for all 0.25° x 0.25° resolution annual maxima 3-hr and 24-hr rainfall depths extracted from TRMM data.

The second step is to calculate the *S*hort *D*uration *R*atios of 3-hr to 24-hr ground stations rainfall depths, *A*veraged across the 2-, 5-, 10-and 20-year return periods (ASDR). These ratios for ground stations are hereafter termed ASDR_GS. The same ratios for TRMM 0.25° x 0.25° resolution points are also calculated and termed ASDR_TRMM.




(a) 3-hr Rainfall CS-CK Moments Diagram

(b) 24-hr Rainfall CS-CK Moments Diagram

Fig. 3: Ordinary-moments (CS-CK) ratios diagram for 3-hr and 24-hr rainfall depths

Table 2: Ranking of candidate distributions based on AIC and BIC

| **Station code** | **Station code** | **Ranking of distributions for 3-hr** | | | | | **Ranking of distributions for 24-hr** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | GEV | Gumbel | LOGN3 | Gamma | PIII | GEV | Gumbel | LOGN3 | Gamma | PIII |
| 00012 | A004 | 4 | 2 | 5 | 1 | 3 | 5 | 4 | 3 | 1 | 2 |
| 00013 | A005 | 5 | 2 | 4 | 1 | 3 | 2 | 4 | 1 | 3 | 5 |
| 00014 | A006 | 5 | 2 | 3 | 4 | 1 | 5 | 2 | 4 | 1 | 3 |
| 00015 | A007 | 3 | 1 | 5 | 2 | 4 | 5 | 2 | 4 | 1 | 3 |
| 00061 | B001 | 4 | 2 | 5 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00064 | B004 | 3 | 4 | 2 | 1 | 5 | 4 | 2 | 3 | 1 | 5 |
| 00065 | B005 | 3 | 2 | 4 | 1 | 5 | 2 | 4 | 3 | 1 | 5 |
| 00066 | B006 | 3 | 4 | 2 | 1 | 5 | 3 | 4 | 2 | 1 | 5 |
| 00067 | B007 | 3 | 1 | 4 | 2 | 5 | 5 | 2 | 4 | 1 | 3 |
| 00080 | B216 | 3 | 1 | 5 | 2 | 4 | 5 | 2 | 4 | 1 | 3 |
| 00115 | D001 | 4 | 2 | 5 | 1 | 3 | 3 | 2 | 5 | 1 | 4 |
| 00214 | J001 | 4 | 2 | 5 | 1 | 3 | 4 | 2 | 5 | 1 | 3 |
| 00255 | J204 | 4 | 2 | 5 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00256 | J205 | 4 | 2 | 5 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00265 | J214 | 5 | 1 | 4 | 2 | 3 | 3 | 1 | 4 | 2 | 5 |
| 00267 | J216 | 3 | 2 | 5 | 1 | 4 | 3 | 2 | 5 | 1 | 4 |
| 00270 | J219 | 5 | 2 | 4 | 1 | 3 | 4 | 2 | 5 | 1 | 3 |
| 00271 | J220 | 5 | 2 | 4 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00272 | J221 | 5 | 2 | 4 | 1 | 3 | 4 | 2 | 5 | 1 | 3 |
| 00290 | J239 | 3 | 2 | 5 | 1 | 4 | 4 | 2 | 5 | 1 | 3 |
| 00366 | M001 | 5 | 2 | 4 | 1 | 3 | 3 | 4 | 2 | 1 | 5 |
| 00382 | M205 | 3 | 1 | 4 | 2 | 5 | 3 | 1 | 4 | 2 | 5 |
| 00452 | R001 | 5 | 2 | 4 | 1 | 3 | 4 | 3 | 2 | 1 | 5 |
| 00453 | R002 | 4 | 2 | 5 | 1 | 3 | 4 | 3 | 2 | 1 | 5 |
| 00454 | R003 | 3 | 2 | 5 | 1 | 4 | 3 | 2 | 5 | 1 | 4 |
| 00455 | R004 | 1 | 4 | 2 | 3 | 5 | 4 | 2 | 3 | 1 | 5 |
| 00456 | R005 | 2 | 3 | 4 | 1 | 5 | 5 | 1 | 4 | 3 | 2 |
| 00457 | R006 | 3 | 2 | 5 | 1 | 4 | 3 | 2 | 4 | 1 | 5 |
| 00625 | TA002 | 3 | 1 | 5 | 2 | 4 | 2 | 4 | 1 | 3 | 5 |
| 00627 | TA004 | 3 | 2 | 5 | 1 | 4 | 5 | 3 | 4 | 2 | 1 |
| 00628 | TA005 | 5 | 2 | 4 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00658 | TA206 | 3 | 2 | 5 | 1 | 4 | 3 | 4 | 2 | 1 | 5 |
| 00685 | TA233 | 2 | 3 | 1 | 4 | 5 | 5 | 2 | 4 | 1 | 3 |
| 00697 | TA250 | 3 | 2 | 5 | 1 | 4 | 3 | 1 | 4 | 2 | 5 |
| 00698 | TA251 | 5 | 2 | 4 | 1 | 3 | 4 | 2 | 5 | 1 | 3 |
| 00770 | TB002 | 4 | 2 | 5 | 1 | 3 | 4 | 5 | 3 | 2 | 1 |
| 00786 | U001 | 4 | 2 | 5 | 1 | 3 | 3 | 1 | 4 | 2 | 5 |
| 00787 | U002 | 5 | 2 | 4 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00802 | U205 | 4 | 1 | 5 | 2 | 3 | 3 | 1 | 5 | 2 | 4 |
| 00812 | H215 | 4 | 2 | 5 | 1 | 3 | 5 | 2 | 4 | 1 | 3 |
| 00817 | U220 | 4 | 2 | 5 | 1 | 3 | 4 | 2 | 5 | 1 | 3 |
| 00848 | U004 | 5 | 1 | 4 | 2 | 3 | 4 | 3 | 2 | 1 | 5 |
| 00952 | TA007 | 3 | 2 | 5 | 1 | 4 | 3 | 2 | 5 | 1 | 4 |
| | Sum of rank | 161 | 86 | 185 | 59 | 154 | 168 | 101 | 160 | 56 | 160 |

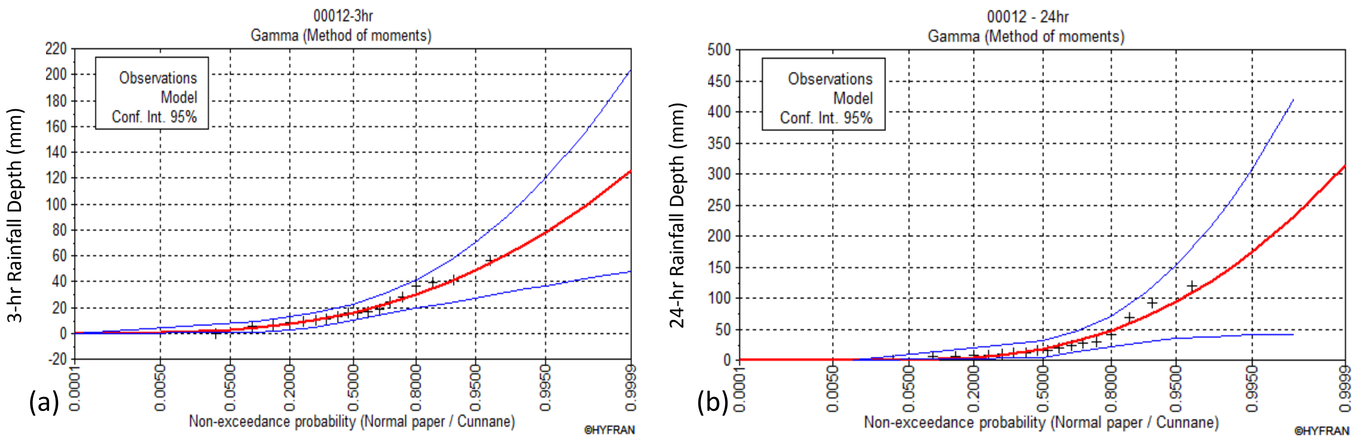



Fig4: 3-hr, 24-hr Gamma Fittings (Method of moments) for A004 station (a) 3-hr data and (b) 24-hr data

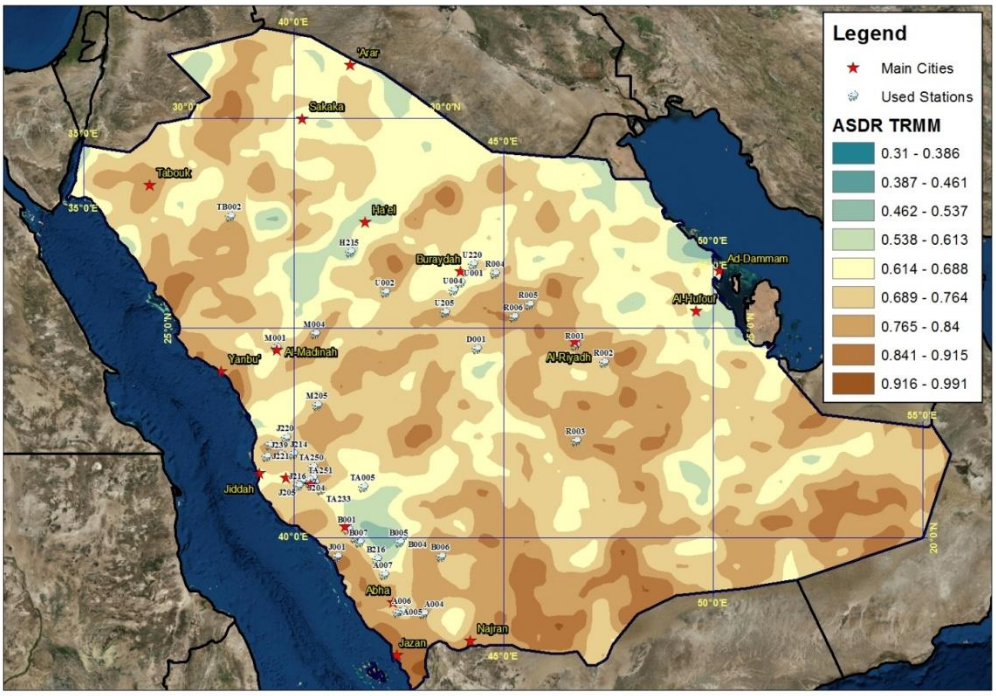



Fig. 5: ASDR_TRMM ratios at 0.25° x 0.25° resolution points

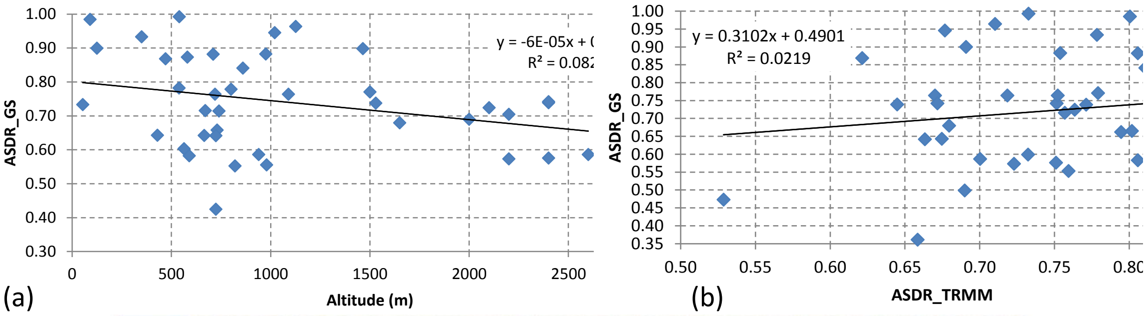
The third step is to compare ASDR_TRMM to ASDR_GS and develop regression relationships to predict the ASDR in ungauged sites. To investigate the predictors that could affect ASDR_GS, ASDR_GS values are plotted against stations altitudes as shown in Fig. 6 a, and against stations coordinates (Latitude and Longitude) shown in Table 3.The linear relationships were very poor and none of them produced statistically significant slopes. The next step is to investigate the relationships between ASDR_GS and ASDR_TRMM. A scatter plot between ASDR_GS and ASDR_TRMM is drawn with all available ground stations derived ratios against their corresponding TRMM ratios (Fig. 6b). Fig. 6b shows also a statistically insignificant relationship with a coefficient of determination ($R^2$) of 0.02.

Table 3: ASDR for TRMM and ground stations for the subdivided zones

| Station code | Station code | Altitude | Latitude | Longitude | Available Years | ASDR_TRMM | ASDR_GS | ASDR_GS (corrected) |
|---|---|---|---|---|---|---|---|---|
| | **Zone (A )** | | | | | | | |
| 00453 | R002 | 430 | 24.167 | 47.400 | 14 | 0.67465 | 0.64287 | 0.64287 |
| 00452 | R001 | 564 | 24.567 | 46.717 | 24 | 0.83388 | 0.60308 | 0.60308 |
| 00457 | R006 | 730 | 25.250 | 45.250 | 10 | 0.83558 | 0.65827 | 0.65827 |
| 00456 | R005 | 665 | 25.533 | 45.617 | 18 | 0.84580 | 0.64253 | 0.64253 |
| 00455 | R004 | 670 | 26.283 | 44.800 | 30 | 0.75690 | 0.71576 | 0.71576 |
| 00787 | U002 | 740 | 25.833 | 42.183 | 15 | 0.82400 | 0.71432 | 0.71432 |
| 00786 | U001 | 724 | 26.067 | 43.983 | 32 | 0.66328 | 0.64160 | 0.64160 |
| 00366 | M001 | 590 | 24.517 | 39.583 | 25 | 0.80572 | 0.58270 | 0.58270 |
| 00770 | TB002 | 820 | 27.633 | 38.483 | 13 | 0.75941 | 0.55261 | 0.55261 |
| 00115 | D001 | 940 | 24.483 | 44.367 | 8 | 0.68998 | 0.58643 | 0.43982 |
| 00802 | U205 | 800 | 25.350 | 43.617 | 8 | 0.79462 | 0.77845 | 0.58384 |
| 00848 | U004 | 724 | 25.867 | 43.800 | 8 | 0.65842 | 0.42468 | 0.31851 |
| 00817 | U220 | 580 | 26.500 | 44.283 | 8 | 0.75155 | 0.87306 | 0.65480 |
| 00812 | H215 | 980 | 26.783 | 41.350 | 9 | 0.52873 | 0.55589 | 0.41692 |
| 00454 | R003 | 539 | 22.283 | 46.733 | 9 | 0.80180 | 0.78227 | 0.58670 |
| | **Zone (B )** | | | | | | | |
| | Group (B1) | | | | | | | |
| 00265 | J214 | 710 | 21.983 | 39.983 | 24 | 0.8058113 | 0.8819554 | 0.8819554 |
| 00255 | J204 | 720 | 21.350 | 40.200 | 29 | 0.71849 | 0.76382 | 0.76382 |
| 00256 | J205 | 910 | 21.350 | 40.217 | 29 | | | |
| 00627 | TA004 | 1530 | 21.400 | 40.450 | 15 | 0.77115 | 0.73794 | 0.73794 |
| 00698 | TA251 | 1900 | 21.367 | 40.367 | 8 | | | |
| 00658 | TA206 | 1680 | 21.283 | 40.400 | 23 | | | |
| 00625 | TA002 | 1500 | 21.300 | 40.500 | 26 | 0.77915 | 0.77054 | 0.77054 |
| 00685 | TA233 | 1650 | 21.133 | 40.650 | 32 | 0.67957 | 0.67946 | 0.67946 |
| 00697 | TA250 | 1465 | 21.667 | 40.450 | 8 | 0.75219 | 0.89840 | 0.76364 |
| 00382 | M205 | 860 | 23.133 | 40.567 | 20 | 0.81077 | 0.84072 | 0.84072 |
| | Group (B2) | | | | | | | |
| 00272 | J221 | 90 | 21.917 | 39.350 | 19 | 0.80055 | 0.98447 | 0.98447 |
| 00290 | J239 | 350 | 21.967 | 39.683 | 18 | 0.77836 | 0.93326 | 0.93326 |
| 00270 | J219 | 125 | 22.200 | 39.433 | 22 | 0.69088 | 0.89953 | 0.89953 |
| 00271 | J220 | 470 | 22.367 | 39.817 | 22 | 0.62135 | 0.86843 | 0.86843 |
| 00267 | J216 | 540 | 21.217 | 40.117 | 21 | 0.73258 | 0.99257 | 0.99257 |
| | **Zone (C )** | | | | | | | |
| 00066 | B006 | 975 | 19.533 | 43.517 | 13 | 0.75380 | 0.88236 | 0.88236 |
| 00067 | B007 | 2400 | 19.850 | 41.567 | 37 | 0.64485 | 0.73883 | 0.73883 |
| 00065 | B005 | 1090 | 19.867 | 42.533 | 26 | 0.67012 | 0.76414 | 0.76414 |
| 00061 | B001 | 2400 | 20.167 | 41.267 | 18 | 0.67175 | 0.74208 | 0.74208 |
| 00064 | B004 | 1020 | 20.017 | 42.600 | 27 | 0.67673 | 0.94559 | 0.94559 |
| 00628 | TA005 | 1126 | 21.183 | 41.667 | 12 | 0.71034 | 0.96377 | 0.96377 |
| | **Zone (D )** | | | | | | | |
| 00012 | A004 | 2400 | 18.167 | 43.100 | 18 | 0.75103 | 0.57579 | 0.57579 |
| 00013 | A005 | 2200 | 18.200 | 42.483 | 34 | 0.72297 | 0.57330 | 0.57330 |
| 00014 | A006 | 2100 | 18.250 | 42.600 | 23 | 0.76359 | 0.72412 | 0.72412 |
| 00015 | A007 | 2600 | 19.100 | 42.150 | 20 | 0.70028 | 0.58643 | 0.58643 |
| 00080 | B216 | 2000 | 19.467 | 41.983 | 17 | 0.82605 | 0.69006 | 0.69006 |
| 00214 | J001 | 53 | 19.533 | 41.050 | 14 | 0.82499 | 0.73363 | 0.73363 |

In search of a relationship that would be acceptable from an operational / design perspective, the study zone was divided into 4 geographical regions. Most of the study area lies in zone A, englobing the very arid Rub' El Khaly eastern region and the northern part of the study, while zones B, C and D subdivide the south western zone including the Asseer and Hejaz mountains and the narrow fringe between the mountains and the Red Sea coast. Fig. 7 presents a map for these zones and Table 3 lists the coordinates and latitude of each of the stations belonging to each of the 4 zones, as well as the ASDR_GS value of each station and its corresponding ASDR_TRMM value. A thorough investigation of the

ASDR_GS values reveals that the ratio of ASDR_GS to. ASDR_TRMM is not consistent. In fact, depending on the number of years in the ground stations records– which should not be a key governing parameter –, this ratio differs as shown in the boxplot of Fig. 8, drawn for the ratio values of the geographically consistent zone A. The medians of the ASDR_GS to ASDR_TRMM ratios of stations with more than 10 years of record are significantly higher, to a level of significance of 0.1, using the Mann-Whitney non-parametric test, than those of stations with less than 10 years of records. This calls for a correction of the ASDR_GS ratios for stations where the record length is less than 10 years. We estimated this correction by a 25% reduction of the ASDR_GS values, based on the median ratios reported in Fig. 8. Corrected values are also reported in Table 3. The ASDR_GS vs. ASDR_TRMM developed relationships are hereafter described for each zone.



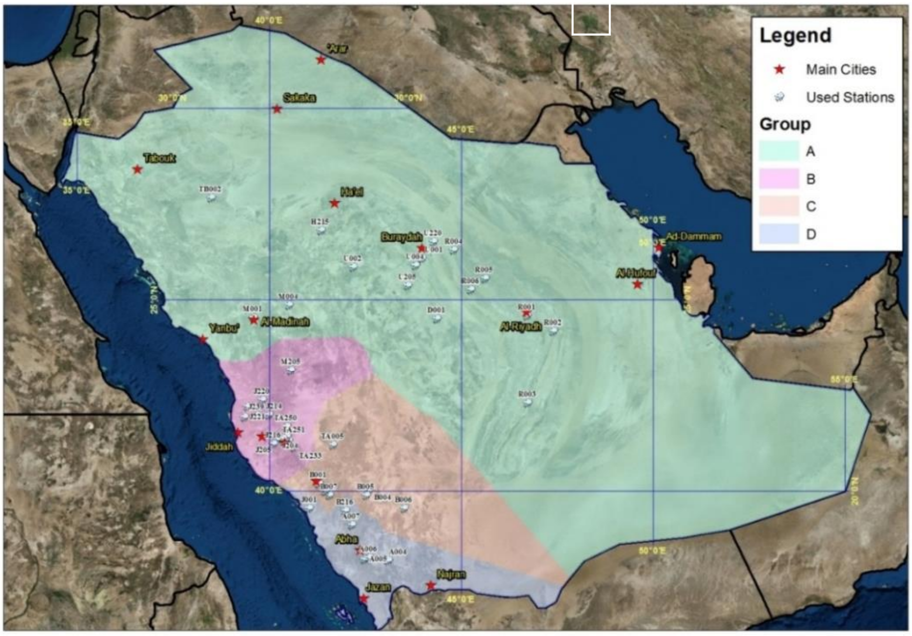




Fig 7: Map for the zones subdivisions

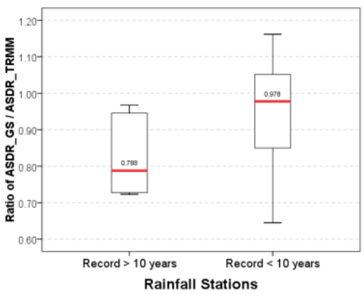



Fig. 8: Boxplots of the ratio of ASDR_GS /ASDR_TRMM
grouped by the number of years available in the record of the ground stations

Zone (A) consists of 15 stations. Its ASDR_GS vs. ASDR_TRMM relationship had a relatively weak $R^2$ = 0.164 before the correction (not shown). After the previously mentioned 25% reduction for ASDR_GS values for stations with limited record, the coefficient of determination$R^2$ increased to 0.366, which is acceptable (Fig. 9a).

Zone (B) consists also of 15 stations. In a first attempt, all stations of the zone were grouped. However, the obtained relationship was not acceptable with an $R^2$ of 0.03 (Fig. 9a). To reach a higher coefficient of determination, the zone was subdivided into two groups according to station altitudes. Group B1 was formed by high altitude stations (> 700 m) and group B2 was formed by low altitude stations (< 700 m). The obtained relationships were significantly improved with $R^2$ = 0.71 (Fug. 9c), and $R^2$ = 0.63 (Fig. 9d), for groups B1 and B2, respectively.

Zones(C) and (D) are formed by 6 stations each. Their ASDR_GS vs. ASDR_TRMM relationships have reasonable $R^2$ of0.34and 0.62, for Zones C (Fig. 9e) and D (Fig. 9f), respectively.

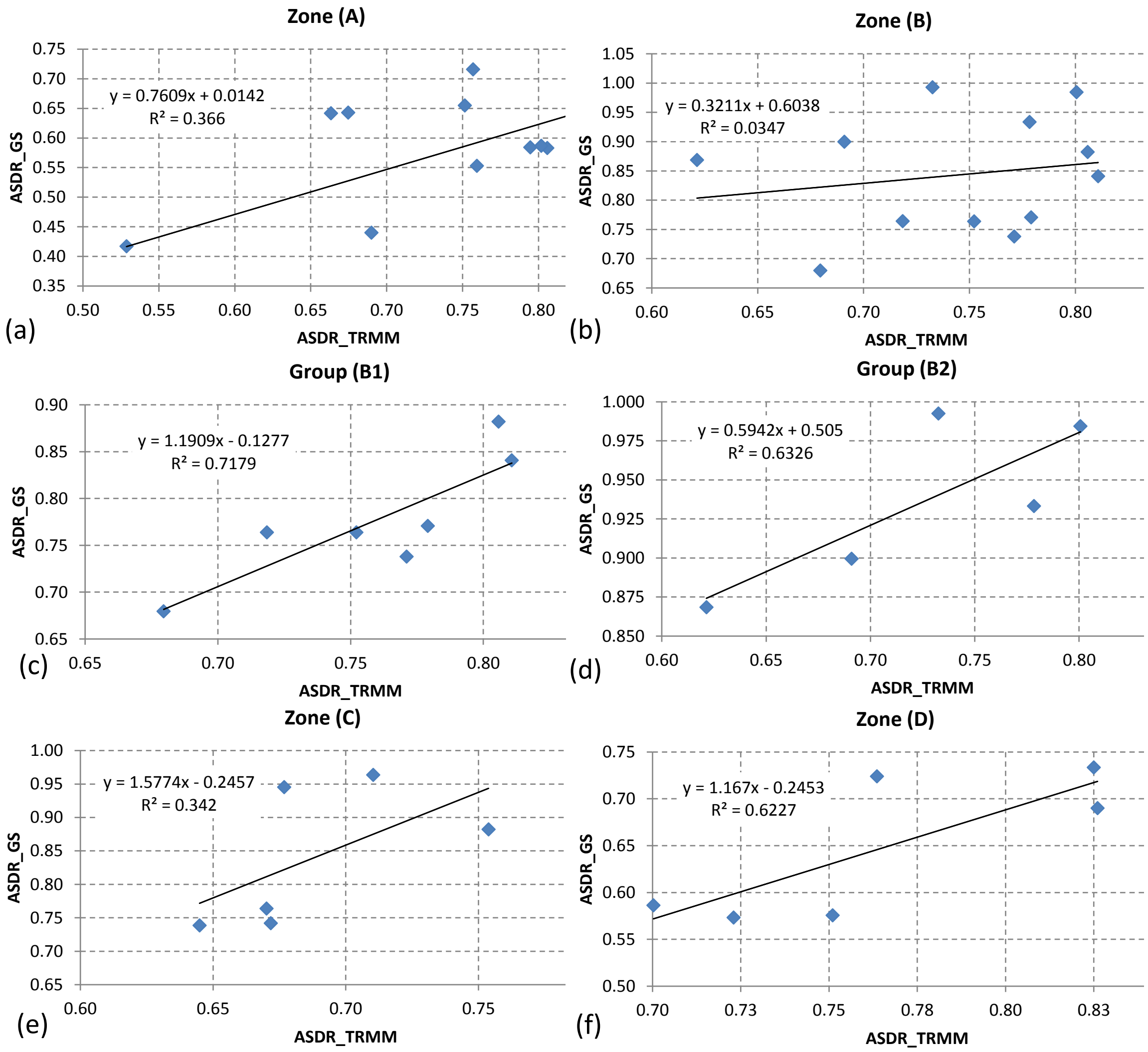



Fig 9: Plot of ASDR_GS against ASDR_TRMM for all zones

To proceed with IDF development in a site where only daily records are available, the following steps are suggested to make use of the findings of this research:

1- Identify the location of the site of interest and its altitude.
2- Undertake frequency analysis on the annual maxima of daily rainfall series of the ground station data and determine the daily rainfall depths at the required return periods. To calculate the 24-hr estimates, the daily estimates are to be multiplied by 1.13 (Hershfield 1961).
3- Download the 3-hr TRMM data for the location of interest and calculate the 24-hr TRMM values as the sum of eight consecutive 3-hr values. For each year of data, determine the maximum annual 3-hr and 24-hr rainfall depths. For these 2 annual maxima series, undertake frequency analyses using Gamma distribution and determine the 3-hr and 24-hr rainfall depths at 2-, 5-, 10- and 20-yr return periods. Calculate the short duration ratios of 3-hr to 24-hr depths at the above-mentioned return periods. Calculate the average of these return period ratios to get the ASDR_TRMM value at this site.
4- Based on the location, determine the zone of applicability (A, B, C or D) from Fig. 7.If the site is located in Zone (B), determine if it belongs to Group (B1) or (B2), based on its altitude.
5- Based on the above step 3, use the relevant equation from the ones shown on Fig. 8 (a, c to f) and predict the outcome of the equation, based on the previously calculated ASDR_TRMM as in input to the chosen equation. We hereafter term the predicted value as ASDR_Pr.
6- Using the ASDR_Pr obtained from step 5, modify the Bell ratios to conform to the TRMM derived ratios as shown in Table 4 and Eq. 1. It is well known that ratios for durations from 2 hours to 5 minutes are fairly constant in different climates because of the similarity of convective storms patterns, as previously discussed in the Introduction section.

$$Modified\_Ratio_{atDurationt} = Original\_SCS\_Bell\_Ratio_{atDurationt} * \frac{ASDR\_Pr}{0.600} \quad (1)$$

Table 4: Ratios between 24-hr duration intensity and other storm duration intensities.

| Storm Duration ($t$) (min) | 5 | 15 | 30 | 60 | 120 | 180 | 360 | 720 | 1440 |
|---|---|---|---|---|---|---|---|---|---|
| $Original\_SCS\_Bell\_Ratio_{at\ Duration\ t}$ | 0.139 | 0.276 | 0.38 | 0.453 | 0.545 | 0.600 | 0.710 | 0.843 | 1 |
| $Modified\_Ratio_{at\ Duration\ t}$ | $0.139 * \frac{ASDR\_Pr}{0.600}$ | *Similar to 5 min duration equation* | | | | ASDR_Pr | *Similar to 5 min duration equation* | | 1 |

7- Based on multiplying the 24-hrrainfall depths (step 2) by the modified ratios of Table 4 (step 6), the rainfall depths at different storm durations are calculated and hence the intensity-duration rainfall values. This could be repeated for all return periods to obtain the full IDF curves.

## Conclusions

In order to develop Intensity-Duration-Frequency curves in locations where only daily rainfall data is available, this research presents an approach based on the joint use of 3-hrto 24-hr ratios of the available ground data and the same ratios obtained from TRMM satellite data, to develop relationships allowing to predict sub-daily ground stations ratios to be used. To achieve this purpose, rainfall ground data were collected from forty three rainfall gauges with short duration records. TRMM data were also collected for the same ground stations locations. Frequency analyses were undertaken on the ground and TRMM data using several distributions and the best fitting was selected. The study area was subdivided into zones to obtain robust and reliable relationships. Regression equations were developed for each zone to predict 3-hr to 24-hrratios and predictions are extended to cover the entire study area for locations where short duration ratios are not available. These predicted ratios along with the SCS type II storm profiles were used to derive rainfall depth ratios for all storm durations. These ratios are to be multiplied by the 24-hr rainfall depths at different return periods to obtain the depth-duration-frequency and hence the IDF curves.

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