Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (39) No. (2) April, 2017

Development of Design Storm Hyetographs in hyper arid and arid regions: Case study of Sultanate of Oman

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ملخص البحث

يهدف هذا البحث الى تطوير ملامح العاصفة التصميمية الممثلة للمناطق الجافة والمناطق شديدة الجفاف معتمدا على بيانات فعلية لهطول الامطار فى منطقة الدراسة . تم تجميع ٢٣٦ عاصفة من ١٧ محطة لرصد الامطار التى تغطى المنطقة الساحلية لسلطنة عمان فى الفترة من سنة ١٩٩٣م حتى سنة ٢٠٠٧ م. تم تصنيف العواصف الى اربع فئات طبقا لمدة حدوث العواصف. وقد استمدت العاصفة التصميمية من خلال سجلات الامطار باستخدام طريقة الكتل المتناوبة واستمدت ايضا بتطبيق طريقة الكتل المتناوبة على منحيات (الشده – المدة – التردد). تمت مقارنة كلا من ملامح العاصفة التصميمية ووجد انهم متساويين. العاصفة التصميمية المطوره فى هذا البحث تمت مقارنتها بالنوع الثانى من توزيعات خدمة صيانة التربة و ملامح العاصفة التصميمية للمملكة المتحدة وهما الاكثر استخداما فى المناطق الجافة. وأظهرت النتائج ان العاصفة التصميمية المستمدة من النوع الثانى من توزيعات خدمة صيانة التربة والمستمده من ملامح العاصفه للمملكة المتحدة غير امنه للاستخدام فى المناطق الجافة والمناطق شديدة الجفاف. توصى هذه الدراسة باستخدام العاصفه التصميمية المستخدمه فى هذا البحث من بيانات هطول الامطار الفعلية.

Abstract

The temporal distribution of the design storm is an important input in hydrological models. This research aims to develop design storm profiles representative of arid and hyper-arid areas based on actual storm recordings. Two hundred thirty six rainfall storms were collected from seventeen rainfall gauges that cover the coastal zone of Oman for the period from 1993 to 2007. Storms were classified into four categories according to their total durations. Design storm hyetographs were derived from raw rainfall records for all four categories using the Alternating Block Method (ABM) and were also computed by ABM applied on the Intensity-Duration-Frequency (IDF) curves. Both design storm profiles were compared and it was found that the ABM_IDF storm profiles are equivalent to the four ABM_Storms profiles. The storm profiles developed in the current research were also compared to the commonly used Soil Conservation Service (SCS) dimensionless distributions and the UK50 storm profiles. The results showed that the most conservative commonly used storm profiles of the SCS type II and the UK50 summer profiles are not safe to be used in design purposes in such arid and hyper arid regions, despite their wide utilization in many codes of practice. The study recommends using the newly developed dimensionless storm profiles derived from the actual records.

Key words: Design storm profile; Alternating Block Method; SCS storm profiles, UK50 storm profiles; arid and hyper arid regions; Oman.

Introduction

Design storm hyetographs are important inputs in hydrological models. Even with the availability of Intensity-Duration-Frequency (IDF) curves, the assumed temporal distribution of the design storm remains crucial in hydrological models, especially those relying on Unit Hydrograph methods. According to Veneziano and Villani (Veneziano & Villani, 1999), most methods used in developping design storms can be classified into four classes: (1) Geometrical shapes anchored to a single point of the IDF curve; (2) Using the entire IDF information via the Alternating Block Method (ABM) (Chow, et al., 1988); (3) Obtaining standardized profiles directly from rainfall records; and (4) Simulation from stochastic models (Cunderlik & Simonovic, 2004).

Among the methods classified under the third above-mentioned class are the well-acknowledged procedures of Huff (Huff, 1967), the Soil Conservation Service (SCS, now the Natural Resources Conservation Service (NRCS)) derivations of their 4 types of storm profiles (Kent, 1973) and the procedure initiated in the Flood Studies Report (NERC, 1975) to derive the UK 50% (UK50) storm profiles. Huff (Huff, 1967) analyzed two hundred sixty one rainfall storms collected from 49 rainfall gauges that covered the state of Illinois, USA, dividing the storms to four quartiles – based on the time of occurrence of the peak rainfall intensity – and provided the 25th, 50th, 75th and 90th percentiles dimensionless hyetograph curves.

The Soil Conservation Service (SCS) (Kent, 1973) developed four types (termed I, II, III, and IA) of dimensionless hyetograph curves covering many regions of the United States. Kent (1973) stated that the cumulative curve, which is the basis for type II distribution for example, was "established by (1) plotting a ratio of rainfall amount for any duration to the 24- hour amount against duration for a number of locations and (2) selecting a curve of best fit." Average intensity-duration values were used to develop the above-mentioned curves and were arranged so that the greatest 30-minute depth occurs near the middle of the 24-hour period, the second largest in the next 30 minutes, and the third largest in the preceding 30 minutes. The procedure used to derive these symmetrical nested storm profiles is generally termed the Alternating Block Method (ABM) (Chow, et al., 1988). Using these nested profiles, in stormwater networks design for example, avoids multiple runs to determine critical storm duration (as all durations are nested within one single profile) but tends to overestimate intensities, particularly for frequent events (Frederick, et al., 1977). Yet, methods based on alternating rainfall blocks are common in codes of practice and are included, for example, in most drainage manuals of USA (such as TxDOT (TxDOT, 2016) to give an example of an arid state), in the HEC-HMS Technical Reference Manual of the Hydrologic Engineering Center (HEC) (Feldman, 2000), in relatively recent handbooks and textbooks such as Chin et al. (Chin, et al., 2013), Wurbs and James (Wurbs & James, 2002) and McCuen (McCuen, 2005).

As for the UK50 storm profiles, a family of standard, symmetrical profiles was produced by Wallingford Institute of Hydrology – in the framework of the Flood Studies Report (NERC, 1975), with maximum rainfall intensity at the center of the storm and variable in amplitude. The FSR procedure was later updated by the Flood Estimation Handbook (CEH, 1999); however, the UK50 storm profiles were maintained. The UK50 storm profiles were derived for different storm durations using the same number of time increments within the storm duration instead of fixing the same time step across durations. A "peakedness" factor of the profiles is defined as the ratio of maximum to mean intensity and the percentile peakedness is the percentage of storms that are equally or less peaked. The profile shape was not found to vary significantly with storm duration, return period or geographical region. However, on average, summer storms were found to be more peaked than winter ones, with the peakedness factor of the UK50 summer storm profile of 3.92 (Butler & Davies, 2004).

Design storm profile research is still on vogue, despite the number of decades that passed since the above-mentioned pioneering studies ((Al-Saadi, 2002); (Asquith, 2003); (Thompson, et al., 2002); (Reilly & Piechota, 2005), (Guo & Hargadin, 2009), (Ogunlela, et al., 2012), to name a few). Fewer studies focused on the Arab Gulf regions ((Subyani & Al-Dakheel, 2009); (Subyani, 2011); (Al-Rawas & Valeo, 2009); (Awadallah & Younan, 2012); and (Elfeki, et al., 2014)). All studies derived the design storms from IDF curves except for (Al-Rawas & Valeo, 2009) and (Elfeki, et al., 2014) who used the actual storm recordings. However, these later two studies confused the processed form of data with that of the original storms and thus obtained unrealistic and also unsafe design storm profiles.

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The objective of this research is thus to develop dimensionless design storm hyetographs from actual storms, for hyper arid and arid regions, based on measured data from seventeen rainfall stations distributed over Oman. The obtained results are compared with the SCS type II and the UK50 summer profile. The SCS type II storm profile is in fact stipulated to be used in Egypt (MWRI, 2011) and Saudi Arabia ((Riyadh Municipality, 2012) and (MOC, 1989)) codes of practice, while the UK50 summer storm profile is used in Qatar (PWA, 2005), Kuwait (Hyder Consulting, 2002) and Dubai (MWH, 2014) codes of practice, with their same American or British derived values without comparing them to parameters derided from the actual rainfall records in the above mentioned countries. The only code of practice proposing a different storm profile is the Omani Highway design manual (Ministry of Transport and Communications of

Oman, 2010) which stipulates the use of Wheater and Bell (Wheater & Bell, 1983) storm profile.

Available rainfall data

Two hundred thirty six rainfall storms were collected from seventeen rainfall gauges in Sultanate of Oman. The rainfall records begin in different years (i.e. from 1952 to 2007) and end in 2007. The available data of storm profiles only begin in 1993. The number of storms for each rainfall station ranged from one storm in Amrat, Wadi Al Khawd1 stations to sixty four storms in Tahwah 3 station. Figure (1) shows a map of the locations of the rainfall gauges over the study area, while Table (1) shows the metadata collected for each station including the station name, station ID, years of records, coordinates and number of storms available for the study.

Methodology and results

As described in the literature review, possible ways to derive design storm profiles are based either on the individual storms or on the resulting Intensity-Duration-Frequency values. To derive the design storm profiles based on individual storms, one has to identify prevailing storm patterns. This could be achieved by classifying the storms based on their storm durations and checking if each group shows specific characteristics (i.e. randomness or, on the contrary, peak of storms are occurring in a certain quartile, specific ratios of peak intensities to average intensities, …). If no such patterns are depicted, design storm profiles could be developed based on design considerations rather than meteorological ones; i.e. storm profiles could be developed in such a way to produce the highest peak discharges, taking into consideration the method used for rainfall-runoff transformation.

The two hundreds thirty six storms were thus classified into four categories according to their durations. Categories 1, 2, 3 and 4 include storms that have total durations ranging from 5 minutes to 1 hour, 1 to 6 hours, 6 to 12 hours, and 12 to 24 hours, respectively. The dimensionless cumulative hyetograph is a plot between the dimensionless cumulative duration (i.e. percentage of the cumulative duration to the total storm duration), on the x-axis, and the dimensionless cumulative rainfall depth (i.e. percentage of the cumulative rainfall depth to the total rainfall depth), on the y-axis. Figure 2 (a, b, c, and d) shows the cumulative dimensionless hyetographs for the four categories. From Figure 2, it is clear that storms, in all 4 groups, have no definitive pattern with peak intensities in the beginning, middle or end of the storm. This variation is the main reason behind searching for a design (critical) storm that could produce higher runoff discharges, such as symmetrical, nested, peak centered profiles, derived using ABM.

The ABM consists of calculating the rainfall depth for different storm durations, with a user-defined analysis time step (usually in the range of 5 to 10 minutes) and arranging the incremental rainfall depth blocks alternatively at each side of the center of the storm hyetograph. This type of ABM is hereafter termed ABM_storms. Rainfall depths for different time increments are obtained from the individual storms. To allow averaging storms with different durations and depths, dimensionless hyetographs are first derived by dividing each depth by the total storm depth and each duration by the total storm duration. The averages of the dimensionless profiles are computed at each time increment to obtain the design storm hyetographs. Figure 3 presents the obtained average hyetograph for each storm duration category. It is clear from Figure 3 that the ratio of the peak rainfall depth at 5-min duration to the rainfall depth corresponding to the total storm duration decreases with the storm duration (e.g. from a ratio of 0.368 for storms with durations ranging from 5 min to 1 hour to a ratio of 0.077 for storms with durations ranging from 12 to 24 hours).

Another method to derive design storm profiles is to apply the ABM on the Intensity-Duration-Frequency (IDF) values. The method is hereafter termed ABM_IDF. First, to derive the ID, the maximum values of the five minutes incremental rainfall depth are obtained from each storm. For all rainfall gauges, the maximum value of the five minutes depths for each year is calculated. The previous procedure is repeated for the 10, 15, 30, 60, 120, 180, 360, 720 and 1440 minutes rainfall durations. Frequency analyses are undertaken on these series of annual maxima. Four common statistical distributions are tested to fit the rainfall data: Lognormal, Gumbel, Pearson Type III and Gamma statistical distributions. The distribution that best fits the data is selected based on the ordinary moments diagram, the log-log plots and the mean excess function (Adlouni, et al., 2008) and the Akaike Information Criterion (Akaike, 1974) and Bayesian Information Criterion (Schwarz, 1978) using HYFRAN (Hydrological Frequency Analyses) (INRS-ETE, 2008) software. Gamma distribution was found to give the best fit on all durations based on the previously mentioned selection criteria. The 5, 10, 25, 50 and 100-year rainfall depths are calculated using Gamma for each duration. To derive the design storm profiles, the same ABM is used but on the IDF results this time, using time increments of multiples of 5 minutes. The storm profile derived using ABM_IDF procedure for the 100-year return period is also shown in Figure 3.

Except for the 5min-1 hour storm profile, Table (2) shows that the ratios of peak rainfall depth to total depth of the storm profiles based on ABM_IDF are equivalent to those obtained based on ABM_Storms. Figure 4d shows a comparison of the entire ABM_IDF and ABM_Storms profiles. It shows that the central peak of the ABM_IDF is larger (steeper rise in the cumulative profile) but the profile tends to have a milder transition through time increments towards the central time. On the contrary, the ABM_Storms profile shows a smaller central peak but the transition is less smooth. However, both storm profiles are quasi-equivalent from a practical design point of view and the ABM_IDF storm profile is thus safe to use in stormwater networks design without the need to undertake individual storm analyses.

Comparison with standard storm profiles used in Gulf countries codes of practice

The developed dimensionless rainfall profiles using ABM_Storms or ABM_IDF are compared to the standard SCS type II and the UK50 summer storm profiles (Figure 4 a to d). For all storm durations, the developed profiles are more critical (steeper rises) than the SCS type II and the UK50 summer storm profiles, indicating the inadequacy of the use of these storm profiles in arid regions. On the contrary, when compared to the

Wheater and Bell (1983) storm profile, the developed storm profiles were found less critical.

Moreover, to further compare with the UK50 summer storm profile, the ratios between the peak intensity and the average intensity for all storms were obtained and averaged for each of the previously mentioned four storm duration categories. The average ratios are not constant across storm durations and the four obtained ratios are more than double the 3.92 value of the UK50 storm profile, indicating the large discrepancy between the characteristics of the UK50 storm profile and those of the studied Oman storms.

Conclusion and Recommendations

Analysis of the temporal profile of rainfall for Oman region has been carried out. Two hundred thirty six rainfall storms were collected from seventeen rainfall gauges that covered Oman area for the period 1993 to 2007. Storms were classified into four categories according to their total durations. Design storm hyetographs were derived from raw rainfall records for all four categories using the Alternating Block Method (ABM) and were also computed by ABM applied on the Intensity-Duration-Frequency (IDF) values. Both design storm profiles were compared and it was found that the ABM_IDF storm profiles are equivalent to the four ABM_Storms profiles. The developed storm profiles were also found more conservative than the SCS type II and the UK50 summer profiles, despite the wide utilization of these later two profiles in many codes of practice. Therefore, the study recommends using the newly developed dimensionless storm profiles derived from the actual records for arid and hyper arid regions.

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Figure 1: Rainfall gauges locations over the study area

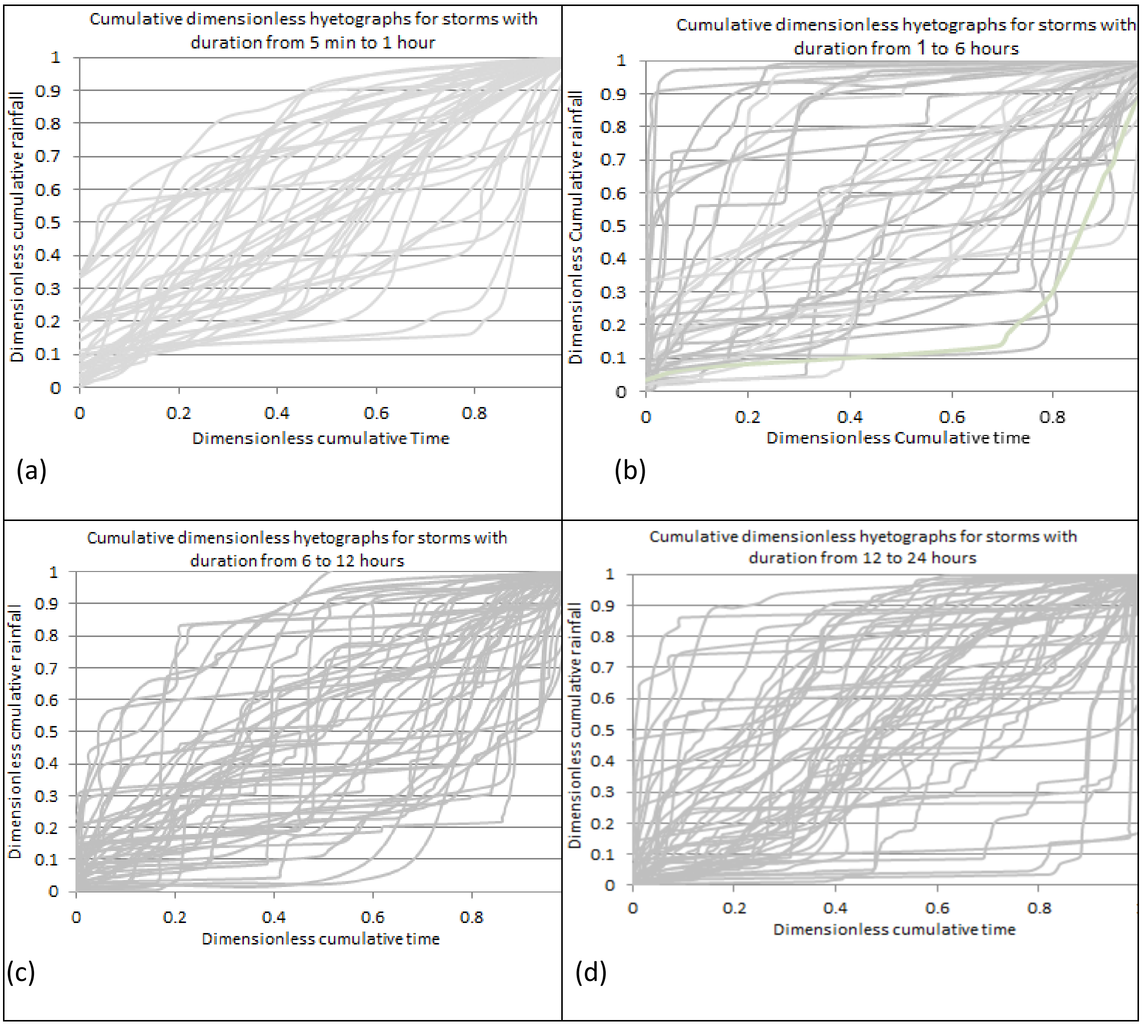

Figure 2: Cumulative dimensionless hyetographs for each storm category

(a) Storm durations from 5 min to 1 hour
(b) Storm durations from 1 to 6 hours
(c) Storm durations from 6 to 12 hours
(d) Storm durations from 12 to 24 hours

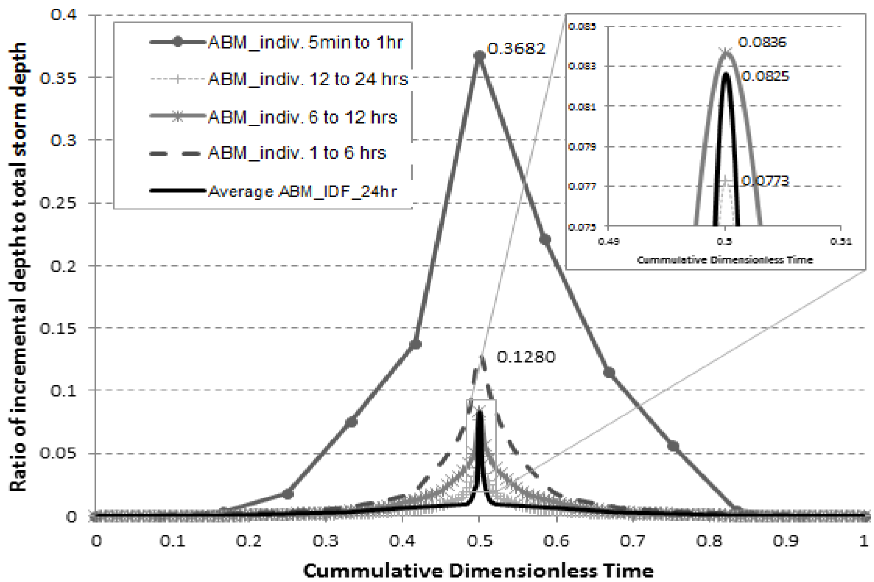

Figure 3: Dimensionless design hyetographs developed by ABM from the individual storms and ABM from the IDF

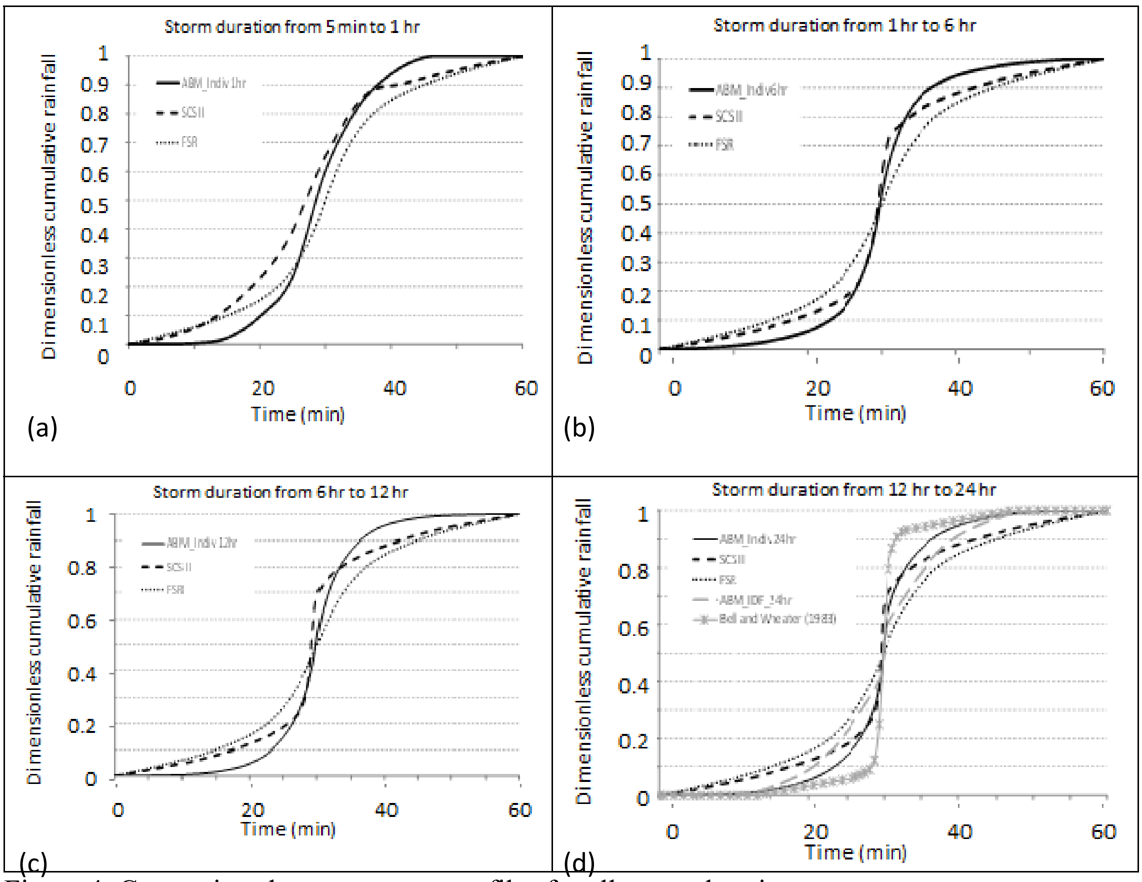

Figure 4: Comparison between storm profiles for all storm durations

Table 1: Metadata of the used rainfall gauges

Name	Staion ID	Long.	Lat.	Start record	End Record	No. of Storms
ZAYMI	DN206495AF	56°16'44.40"E	24°27'10.81"N	1995	2007	21
AR RAJMI	DN226358AF	56°16'28.79"E	24°37'39.00"N	2003	2007	30
WADI FIZH	DN417300AF	56°28'54.84"E	24°32'5.38"N	1986	2007	61
YITI	FL609065AF	58°39'40.70"E	23°30'21.97"N	1998	2007	3
BUEI	FL672275AF	58°35'25.62"E	23°15'13.44"N	1994	2007	2
FUWAD	FL681271AF	58°34'54.13"E	23°20'25.86"N	1973	2007	2
TABA	FL771702AF	58°40'19.52"E	23°17'43.18"N	1994	2007	2
HAYFADH	FL788017AF	58°44'30.85"E	23°19'34.22"N	1994	2007	2
MAZARA	FL950429AF	58°51'25.12"E	23° 5'30.77"N	2000	2007	2
QURAYAT	FL974085AF	58°54'13.89"E	23°13'55.87"N	1987	2007	2
WADI AL KHAWD1	FM104840AF	58° 7'15.90"E	23°34'42.29"N	1986	2007	1
RUWI	FM517016AF	58°32'22.93"E	23°35'53.91"N	1982	2007	2
AMRAT	FM593824AF	58°43'30"E	23°23'16"N	2007	2007	1
MUSCAT	FM612285AF	58°35'44.73"E	23°36'53.64"N	1952	2007	2
SABT	GK186672AF	59° 6'21.71"E	22°28'6.36"N	1979	2007	24
SNAF	GK308083AF	59°19'21.81"E	22°35'33.85"N	1996	2007	63
TAHWAH 3	GK371911CF	59°14'41.53"E	22°24'8.83"N	1982	2007	64

Table 2: Ratios of peak central depth to total storm depth of the dimensionless design hyetographs developed by ABM from the individual storms and ABM from the IDF

Storm Duration	Design storm derived using ABM on individual storms	Design storm derived using ABM from IDF curves for different return periods			
		100-year	50-year	25-year	10-year
5 min - 1 hour	0.3682	0.3102	0.3083	0.3049	0.3018
1 - 6 hours	0.1280	0.1137	0.1178	0.1228	0.1356
6 - 12 hours	0.0836	0.0859	0.0892	0.0928	0.1023
12 - 24 hours	0.0772	0.0767	0.0795	0.0828	0.0909