International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V70I1P240
Volume 70 Issue 1, 362-372, January, 2022

Original Article

Development of Rainfall Design Storm Hyetographs for Al-Quassim Region – Kingdom of Saudi Arabia

Ahmed H. Soliman[1]

[1]*Irrigation and Hydraulics Department, Faculty of Engineering, Cairo University, Egypt*

[1]a.soliman@cu.edu.eg

Abstract – *The design storm hyetograph is a very important input to the hydrologic modelling either for flood hazards assessment purposes or urban stormwater drainage studies as it has a significant effect on the judgment concluded from the hydrological study results. So, it is very crucial to well identify the design of storm hyetograph before all hydrological and hydraulic modelling studies. Several pieces of research and studies were conducted in the literature regarding the development of the design of storm photographs for several countries all over the world. Unfortunately, very limited studies are focusing on the Arabian regions. Al-Quassim region – Kingdom of Saudi Arabia has been suffering from flood hazards during the last decades. So, it is in dire need of accurate design storm hyetographs. 557 storms are collected from eight rainfall gauges distributed over the Al-Quassim region area. Six approaches are used to develop the design of storm hyetographs. The developed hyetographs are compared together in addition to the currently available hyetograph for the Al-Quassim region to exclude low-performance hyetographs. Additionally, hydrological modelling is used to compare the screened developed hyetographs together. The study reveals that the design storm hyetographs developed using the alternating block method is the best hyetographs among the developed and currently existing hyetographs.*

Keywords — *Alternating Block, Design Storm, Euler II, Huff, Rainfall Hyetograph.*

I. INTRODUCTION

The rainfall design pattern is one of the crucial elements which affect the hydrological modelling of either rural or urban watersheds. So, it is vital to define the rainfall design pattern accurately. The rainfall design pattern may also be called the rainfall design storm hyetograph or sometimes called the design storm profile. Also, the design storm could be defined as the synthetic hyetograph, which is used in several engineering applications (e.g. design of stormwater drainage system, flood hazards assessment, design of flood protection schemes, …etc.) [1]. Regardless of its name or definition, the rainfall design storm hyetograph plays an important role in the prediction process of the generated surface runoff flow due to rainfall events. So, to assure that the estimated surface runoff flow characteristics are accurate enough, the rainfall design storm hyetographs should be identified carefully and in a proper way.

Several techniques were applied in the literature to develop the required rainfall design storm profile. The available techniques could be categorized into four main categories. The first category is based on the usage of the intensity duration curve (IDC) to anchor a specific simple geometrical shape on a specific point on the IDC. The second category uses the entire intensity curve to initiate the design storm profile (hyetograph) instead of using a single point on it (like what happened in the first category). The third category is devoted to all methods in which the hyetograph is defined using standardized design storm profiles calculated using the actual rainfall measurements. Finally, the fourth category is devoted to all techniques in which stochastic models are used to predict the rainfall hyetograph [2].

The techniques of the first category are usually used a rectangular shape to present the design storm profile in which the duration is taken to be equal to the time of concentration calculated for the watershed under consideration while rainfall intensity is extracted from the rainfall intensity duration curve [3]. Sometimes in order to maximize the flow rate, the design storm profile duration may be taken equal to the time extracted from the intensity duration curve corresponding to the predefined rainfall intensity [4]. Unfortunately, the rectangular shape of the design storm profile is usually underestimated in the actual rainfall volume [5]. So several trials were conducted to use other shapes like triangular shape instead of rectangular shape [6]–[7].

The techniques of the second category are usually used the entire intensity duration curve to generate the design storm profile at all durations instead of the usage of a single point value of the intensity duration curve at a specific duration. One of the well-known design storm profiles which were developed using the techniques of this category is the Chicago hyetograph [8]. Chicago hyetograph is characterized by that the rainfall value extracted from the intensity duration frequency curve at any duration is greater than the maximum rainfall value extracted from the Chicago hyetograph at the same duration [2].

The techniques of the third category rely on the standardization process of the rainfall durations and depths, which may not be solely adequate due to rainfall variability and randomness [2]. So, in these techniques, the standardized rainfall durations and depths should be classified and categorized based on intensity, season, and/or type, in addition to applying temporal smoothing and averaging [9]. Central Illinois design storm profiles are the earliest defined dimensionless design storm profiles that were developed using rainfall observations of heavy storms [10]. Several dimensionless design storm profiles were defined worldwide in which real rainfall records were used (e.g. Wallingford Procedure) [11]–[12]. The dimensionless design storm profile was found to be independent of season, depth, and duration [13].

The techniques of the fourth category are using stochastic approaches to model the natural rainfall event to capture rainfall patterns complexity [14]–[18]. The stochastic models in this category have several variables which may differ from one cell to another (e.g. cell shape, temporal variability, intensity distribution, …etc.) [19]–[22]. Stochastic modelling needs a lot of parameters to be defined to be able to reach acceptable and accurate results. So, this technique is very difficult to be applied in practice, especially in the case of standard and typical design [2].

As can be depicted from the four categories of techniques, the first and second categories predict the design storm profile based on rainfall intensity duration curve in addition to the watershed characteristics. So, both categories can not be used for general design storms as both of them should be applied to a specific watershed. Meanwhile, the third and fourth categories of methods use the actual rainfall storm pattern solely to generate the design storm profile regardless of the watershed characteristics. So, the third and fourth categories of methods can be used to develop general design storm profiles which could be applied for all watersheds regardless of their characteristics.

Several studies have been used the techniques of the third category to develop the rainfall design storm hyetographs. One of the earliest applications of these techniques is the design of storm hyetographs of the state of Illinois – the USA was generated using rainfall data collected from 49 rainfall stations distributed all over the state [10]. Reference [10] used 261 rainfall storms covered 11 years of records (i.e. 1955 to 1966) to develop the required design storm hyetographs. The collected rainfall storms were classified into four groups based on the occurrence time of the maximum rainfall intensity. The four groups presented the first, second, third, and fourth quartiles (e.g. Q1, Q2, Q3, and Q4). The first, second, third, and fourth quartiles included all storms in which the maximum rainfall intensity occurred during the first, second, third, and fourth quarters of the entire storm duration, respectively. The design storm hyetographs were presented in dimensionless form and based on four percentiles (e.g. 25^{th}, 50^{th}, 75^{th}, and 90^{th}).

One of the well-known and usually common in international codes of practice (e.g.[23]-[27]) is the Alternating Block Method which is classified to be one of the techniques included in the third category [28]. The Alternating Block Method was originally designed and used to develop the four types of design storm hyetographs developed by the Soil Conservation Service (SCS) [29]. The main concept of the Alternating Block Method is to re-arrange the rainfall depths over the entire storm duration so that the maximum rainfall depth occurred at the middle of the entire storm duration while the second greatest value occurred at the one-time step after the occurrence of the maximum one and the third greatest value occurred at the one-time step before the occurrence of the maximum one and so on. The usage of the developed design storm hyetographs using the Alternating Block Method is preferable in the design of stormwater networks because the designer will not need to conduct several runs to identify the critical storm duration. On the other hand, the main drawback of this method is that it tends to overestimate the rainfall intensities, especially in the case of repeated rainfall events [30].

DWA (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V.) method is another method which is commonly used in several European countries. The DWA method is also called the Euler Type II pattern [31]-[32]. The main philosophy of the Euler Type II pattern is to sort the rainfall depths or intensities from the largest value to the smallest value, then flip the first one-third of the sorted data [33].

Although several studies were conducted in the literature to develop design storm hyetographs based on actual rainfall events measurements (e.g. [34]-[38]), there are very limited studies conducted for the Arabian countries. Among the very limited studies conducted to study rainfall characteristics and design storm hyetographs in the Arabian region, several studies focused only on the study of rainfall characteristics without studying the design of storm hyetographs for the same regions (e.g. [39]). Reference [40] used 236 measured storms collected from 17 rainfall gauges to develop design storm hyetographs for the Sultanate of Oman. Meanwhile, rainfall data collected from 18 rainfall gauges distributed over four Arabian countries (i.e. Egypt, Kingdom of Saudi Arabia, Qatar, and Sultante of Oman) were used to derive the rainfall design storm from intensity duration frequency curves [41]. Also, 599 measured rainfall storms covering 20 to 28 years distributed over the entire area of the Kingdom of Saudi Arabia were used to develop storm hyetographs for the Kingdom of Saudi Arabia [42].

Based on the complexity of the techniques of the fourth category and the difficulty of applying these techniques in real practice, especially for standard design, in addition to the lack of studies in the design storm hyetographs in the Arabian region, this paper is devoted to developing the design storm hyetographs of Al-Quassim region, Kingdom of Saudi Arabia using the techniques of the third category. The selected methods which will be tested in this study are Alternating Block Method, Huff's Four Curves, and Euler Type II pattern. The results of these six methods will be compared with the currently used design storm hyetographs in the Al-Quassim region.

II. STUDY AREA, DATA COLLECTION AND DATA ANALYSIS

A. Study Area

The Kingdom of Saudi Arabia has 13 administrative regions, as presented in Fig. 1. Al-Quassim region is one of these administrative regions, which is nearly located in the middle of the Kingdom of Saudi Arabia. The area of the Al-Quassim region represents about 3% of the Kingdom of Saudi Arabia's entire area. Al-Quassim region is surrounded by other three regions (i.e. Ar Riyad, Al Madinah, and Ha'il regions).

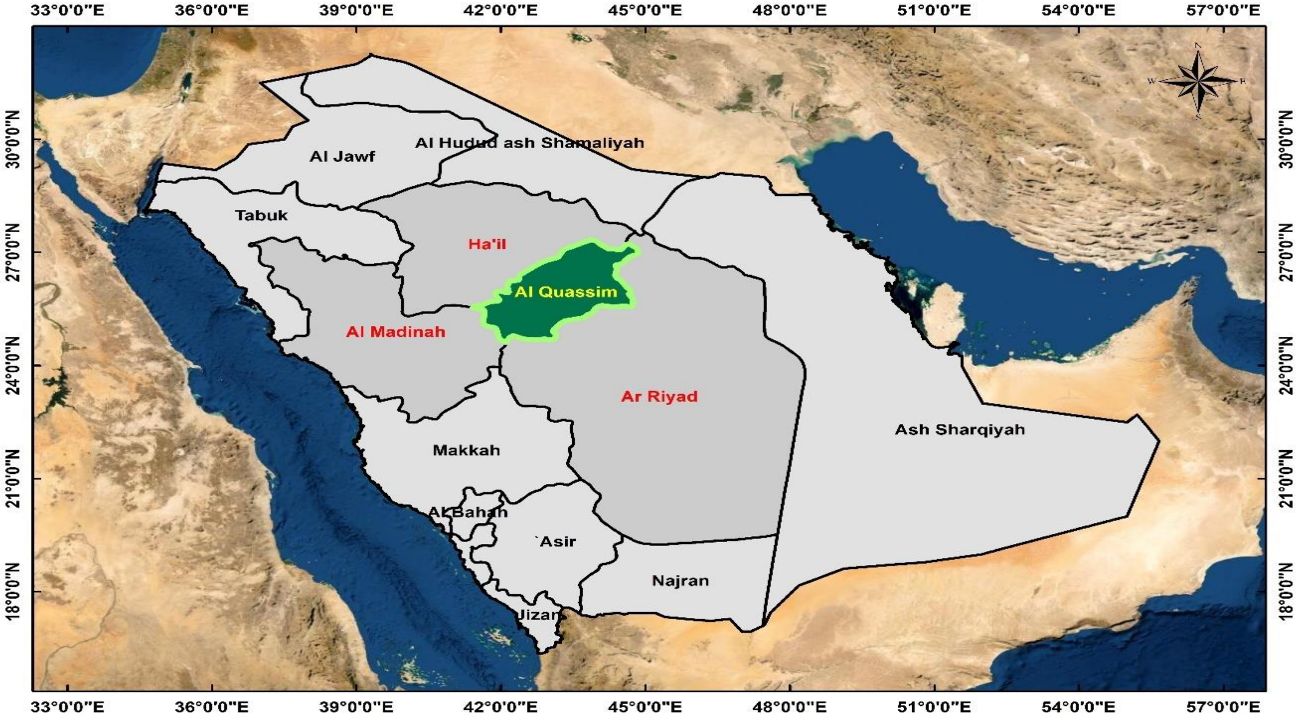

Fig. 1: Administrative Regions of Kingdom of Saudi Arabia

Al-Quassim region is characterized by a flat topography in which the natural ground levels are varied between 600 and 900 meters above mean sea level except at the very limited hilly areas at which the elevation may reach 1200 meters above mean sea level. Al-Quassim region is subjected to flood hazards due to its flat topography and the special relation between its topography and the surrounding region's topography. In fact, the Al-Quassim region faced several severe floods (e.g. floods occurred in the years 1956, 2009, and 2017). These severe floods affected a lot of buildings, roads, and personal properties, in addition to the very high number of fatalities. So, it is very crucial for the Al-Quassim government to construct adequate stormwater drainage systems and flood protection schemes to protect this region against flood hazards. As aforementioned, the design storm hyetograph plays a pivotal role in the flood risk assessment and stormwater drainage networks designs. Based on that, the Al-Quassim region is in dire need of updated design storm hyetographs developed specifically for its rainfall characteristics and using the actual measured rainfall data.

B. Data Collection

In order to conduct the development process of the design storm hyetographs for the Al-Quassim region, all available rainfall gauges data are collected. It is found that the Al-Qassim region has 16 rainfall gauges spatially distributed over its entire area, as presented in Fig. 2. The details of the collected rainfall gauges in the study area are presented in Table 1.

Table 1: Details of the Collected Rainfall Gauges

Code	Name	Recording Period	
		Start	End
U001	Unizah	1964	2018
U002	Uqla Al Soqure	1969	2018
U004	Keraa El Maro	1986	2018
U102	Dhariah	1968	2018
U103	Al Fawarah	1963	2018
U104	Al Rass	1967	2018
U107	Buraidah	1963	2018
U113	Dhulea Rashid	1966	2004
U114	Al Asyah	1999	2018
U120	Al Bekirayah	2009	2018
U205	Dakhnah	1969	2017
U211	Al Nabhanyah	1971	2018
U213	Dhariah 2	1971	1999
U217	Al Muzanab	1981	2018
U218	Al Quarin	1981	2010
U220	Al Nabkyah	1981	2001

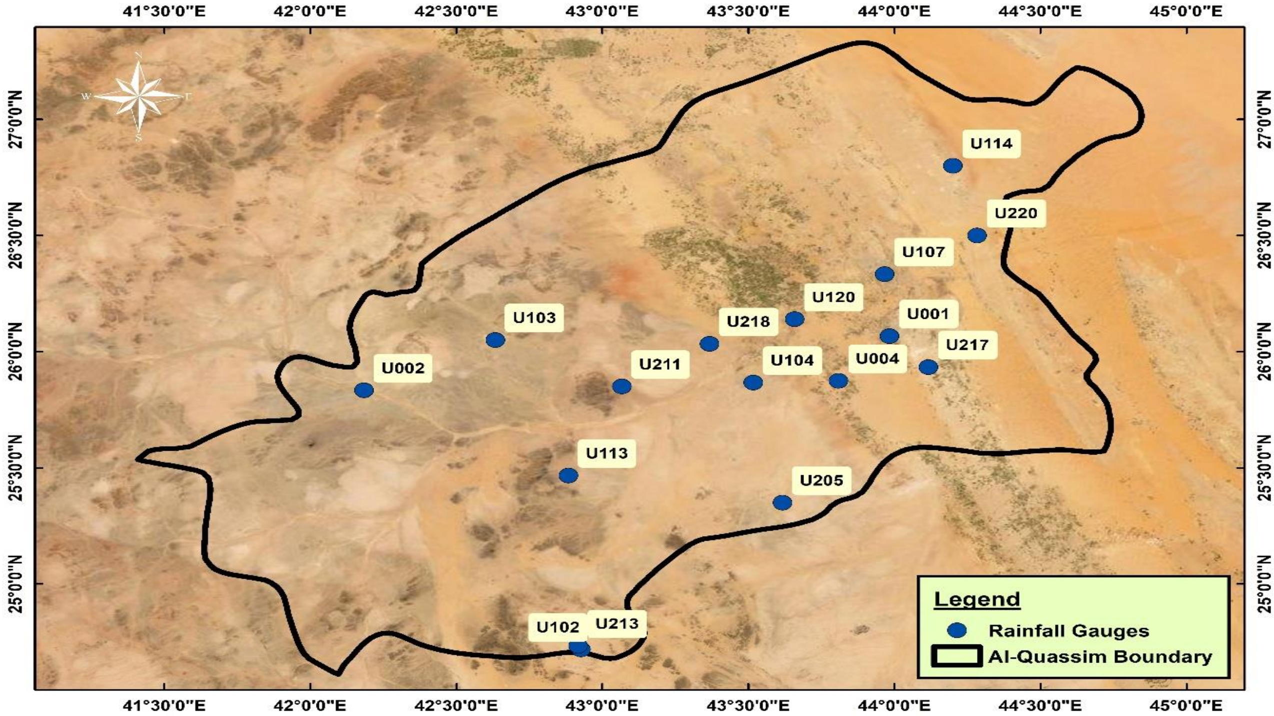

Fig. 2: Al-Quassim Collected Rainfall Gauges

As depicted from Table 1, the minimum recording period is 10 years, while the maximum is 56 years. Also, the majority of the collected rainfall gauges cover at least two historical severe floods that occurred in the study area. So, the collected data will be adequate to develop the design storm hyetographs of the study area.

C. Data Analysis

Several checks and analyses are conducted on the collected rainfall data to screen the collected data and exclude any embedded discrepancies. The first check conducted on the collected data is to find how many rainfall gauges which have short-duration rainfall records among the collected 16 rainfall gauges. As a result of this check, it is found that eight rainfall gauges (out of 16 rainfall gauges) have short-duration rainfall records. A detailed list of the available rainfall gauges which have short-duration rainfall records is presented in Table 2.

Table 2: Rainfall Gauges with Short-Duration Records

Code	Name	Number of Storms
U001	Unizah	321
U002	Uqla Al Soqure	59
U004	Keraa El Maro	48
U205	Dakhnah	27
U211	Al Nabhanyah	26
U213	Dhariah 2	19
U217	Al Muzanab	20
U220	Al Nabkyah	37
Total Number of Storms		**557**

As depicted from Table 2, the total number of storms recorded in the collected eight stations is 557, while the maximum and the minimum number of storms are 321 and 19 storms, respectively. The collected number of storms is adequate for the required study as it is more than double the number of storms used for developing the design of storm hyetographs for the Sultanate of Oman. The Sultanate of Oman study used only 236 storms collected from 17 rainfall gauges [40]. Although the Al-Quassim region area represents about 3% of the Kingdom of Saudi Arabia's entire area, the collected number of storms represents about 93% of the used number of storms to develop the design storm hyetographs of the Kingdom of Saudi Arabia. The Kingdom of Saudi Arabia study was based on 599 storms (58 storms out of them are collected from Al-Qassim rainfall gauges) collected from 28 rainfall gauges distributed on the entire area of the Kingdom of Saudi Arabia [42].

III. METHODOLOGY AND APPROACHES

As aforementioned, six approaches will be used to develop the design storm hyetographs of the Al-Quassim region – Kingdom of Saudi Arabia. The first approach is the Alternating Block Method (ABM), the second approach is Euler Type II Pattern (Euler-II), and the third to sixth approaches are Huff's curves (i.e.Huff-Q1, Huff-Q2, Huff-Q3, and Huff-Q4). The details of each method are presented in the introduction section.

The applied methodology in this paper is shown in Fig. 3 and described in detail in the following points:

1. Split the collected storms into specific groups based on storm duration,
2. Transform all storms to dimensionless form in time and depth by dividing the incremental depth

by the total storm depth and dividing the incremental time by the total storm duration,
3. Draw the dimensionless cumulative rainfall storms for each group of storms,
4. Check if there is any specific and clear trend or storm distribution pattern or not.
5. In case there are clear storm distribution patterns, calculate the design storm hyetographs directly.
6. If there is no clear pattern, then apply the six approaches to develop the design storm hyetographs.
7. Compare the developed design storm hyetographs with the currently available design storm hyetographs.

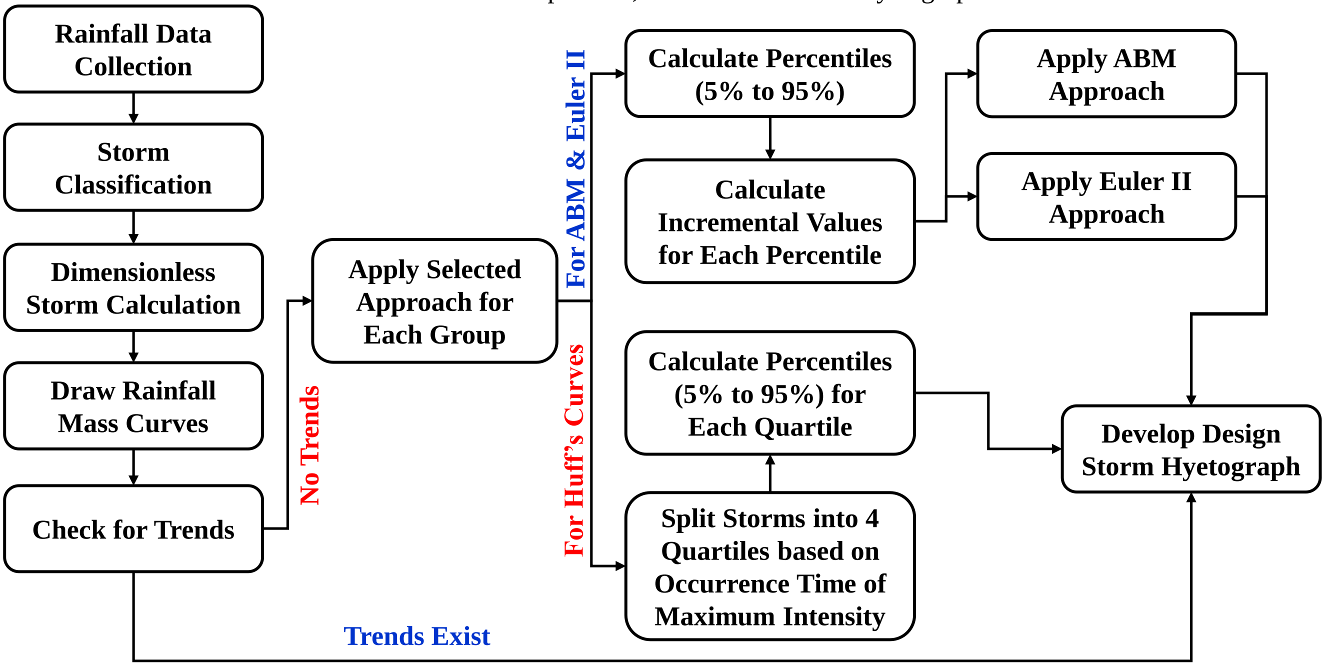

Fig. 3: The Applied Methodology Flow Chart

IV. RESULTS AND DISCUSSIONS

The initial step conducted to start the development of the design storm hyetographs is the analysis of the collected storms durations. The storm durations of the collected rainfall storms are varied between 10 minutes and 24 hours. So, in order to facilitate the analysis of the collected storm duration, the storm duration frequency histogram is calculated based on three hours time step as presented in Fig. 4.

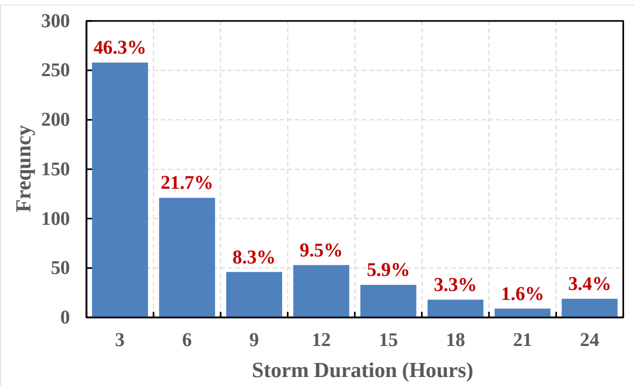

Fig.4: Storm Duration Frequency Histogram

As depicted from Fig. 4, the maximum number of storms occurred with a duration less than or equal to three hours (46.3% of the collected storms), while the second-largest number of storms has a duration from three to six hours (21.7% of the collected storms). At the same time, the remaining durations have a total percentage of occurrence of about 32%. So the first two frequency groups have adequate data to conduct the required analyses, while the other six frequency groups have very limited data for each. Based on that, it is preferable to redistribute the last six frequency groups on two groups only. Consequently, the new groups of storm durations will be as presented in Table 3.

Table 3: Selected Storm Duration Groups

Group	Storm Duration (Hours)		Number of Storms	
	<	>=	Count	%
1	0	3	258	46.3
2	3	6	121	21.7
3	6	12	99	17.8
4	12	24	79	14.2
Total Number of Storms			557	

As depicted from Table 3, the first and second groups cover three hours for each one, the third group covers six hours, and the fourth group covers 12 hours.

The dimensionless storms are calculated for all storms included in one group then the dimensionless storms are plotted for each group as presented in Fig. 5 to Fig. 8.

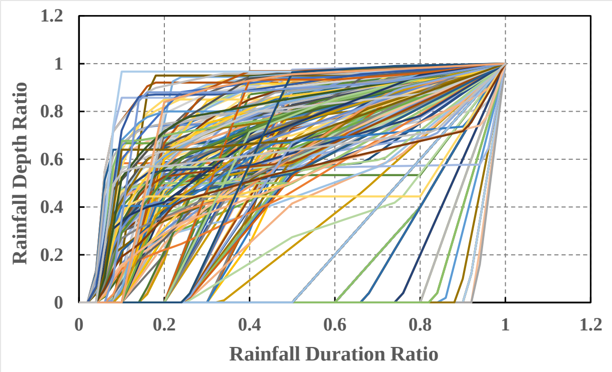

Fig.5: Cumulative Dimensionless Storms for the First Group (Storm Duration up to 3 hours)

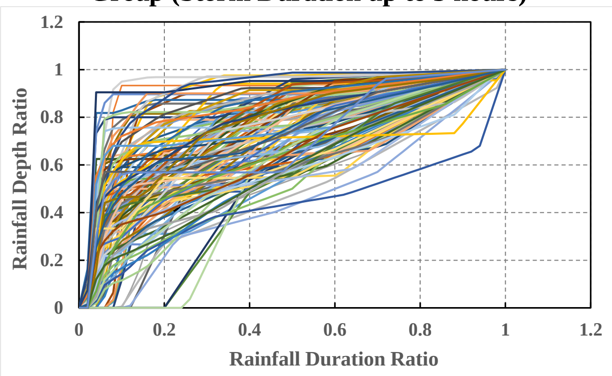

Fig.6: Cumulative Dimensionless Storms for the Second Group (Storm Duration from 3 to 6 hours)

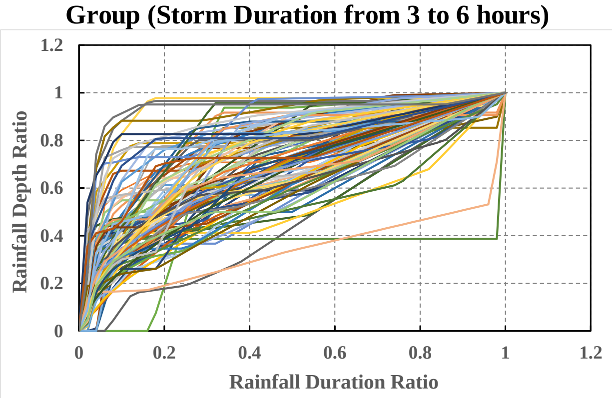

Fig.7: Cumulative Dimensionless Storms for the Third Group (Storm Duration from 6 to 12 hours)

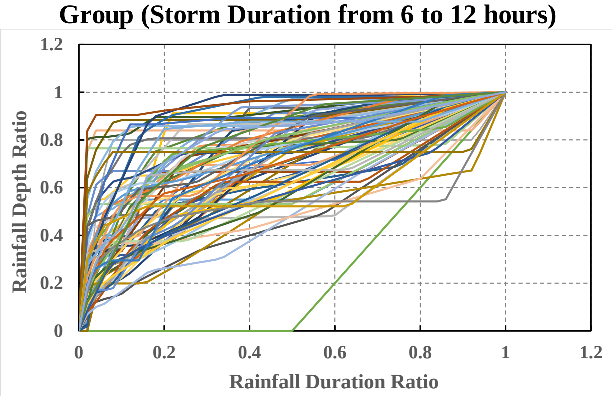

Fig.8: Cumulative Dimensionless Storms for the Fourth Group (Storm Duration from 12 to 24 hours)

As shown in Fig. 5 to Fig. 8, there is no clear trend or pattern that could be extracted directly from the plotted actual storm hyetographs for all storm duration groups. So, it is very important to apply the selected six approaches to develop the design of storm hyetographs for each storm duration group.

The percentiles 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 95 are calculated for each storm duration group in order to apply Alternating Block Method and Euler Type II pattern. Then the incremental rainfall ratios are calculated and rearranged for each percentile based on the applied rules for each one of the two approaches. As examples for the conducted analysis, Fig. 9 and Fig. 10 present the developed design storm mass curves corresponding to each percentile using Alternating Block Method and Euler Type II pattern, respectively.

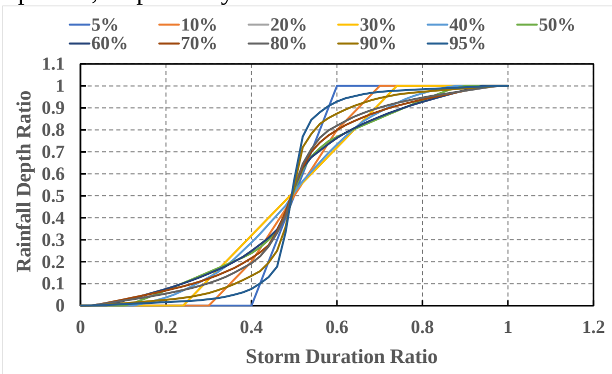

Fig.9: Design Storm Mass Curves Using ABM for the First Group (Storm Duration up to 3 hours)

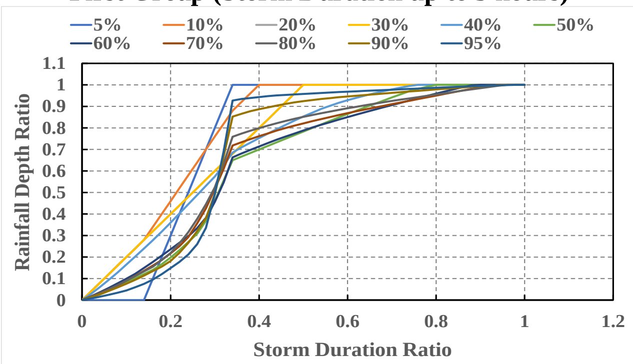

Fig.10: Design Storm Mass Curves Using Euler-II for the First Group (Storm Duration up to 3 hours)

In order to apply Huff's Curves approach, the storms included in each storm duration group are divided again into four quartiles based on the storm duration ratio at which the maximum incremental rainfall depth ratio occurred. The first quartile (Q1) includes all storms in which the maximum incremental depth ratio occurred at a duration ratio less than or equal to 25%, the second quartile (Q2) includes all storms in which the maximum incremental depth ratio occurred at a duration ratio more than 25% and less than or equal to 50%, the third quartile (Q3) includes all storms in which the maximum incremental depth ratio occurred at a duration ratio more than 50% and less than or equal to 75%, and the fourth quartile (Q4) includes all storms in which the maximum incremental depth ratio occurred at a duration ratio more than 75% and less than or equal to 100%. The number of storms included in each quartile for each group of storm duration is presented in Table 4.

Table 4: Number of Storms for Each Quartile

Group	Quartile			
	Q1	Q2	Q3	Q4
1	124	36	54	44
2	116	3	0	2
3	96	0	0	3
4	78	0	1	0
Total Number of Storms	**414**	**39**	**55**	**49**

As shown in Table 4, the first quartile (Q1) is the only one of the four quartiles which have a sufficient number of storms among the four storm duration groups. Meanwhile, the other three quartiles either do not have data for some storm duration groups or have very limited data in other storm duration groups. So, it may be concluded that the first storm duration group is the only group that contains storms with maximum incremental depth ratio occurring at different duration ratios during the storm. Additionally, the maximum incremental depth ratio for the other three storm duration groups occurs only during the first quartile. Based on that, a major conclusion may be extracted about the maximum time measured from the beginning of the storm during which the maximum incremental rainfall depth ratio will occur. This maximum time will be 6 hours. Also, based on Table 4, the four quartiles of Huff's Curves approach will be applied only on the first storm duration group, while for the other three groups, two to three quartiles only will be applied. As examples for the conducted analysis, Fig. 11 and Fig. 12 present the developed design storm mass curves corresponding to each percentile of the first quartile of Huff's Curves approach (Huff-Q1) for the first and second storm duration groups, respectively.

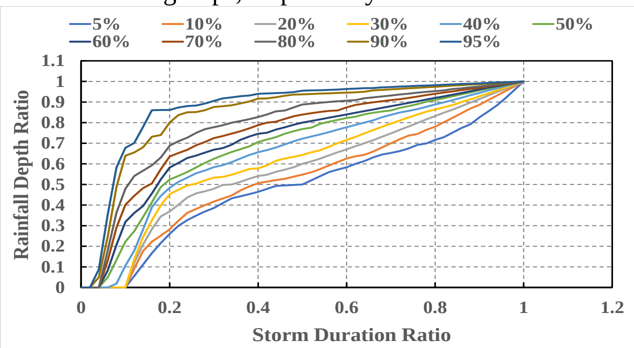

Fig.11: Design Storm Mass Curves of Huff-Q1 for the First Group (Storm Duration up to 3 hours)

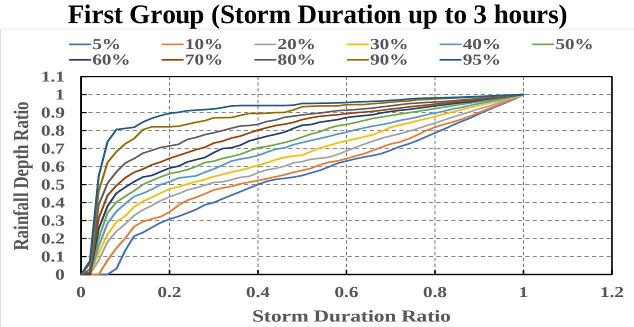

Fig.12: Design Storm Mass Curves of Huff-Q1 for the Second Group (Storm Duration from 3 to 6 hours)

Based on the conducted analysis, several design storm profiles are developed presenting 11 percentiles (5% to 95%) for each group of storm durations using the applied six methods (results samples are presented in Fig. 9 to Fig. 12). From a practical point of view, only one storm profile should be selected to present the applied approach. Then the selected storm profiles for all approaches should be compared together to select the best storm profile which well represents the study area. Usually, the average or median (50% percentile) is preferable for feasible design objectives, while 10% percentile (or less) and 90% percentile (or more) are considered as extreme percentiles which may be used to model unusual and rarely occurred storm conditions [42]. So, 50% percentile is selected to present each applied method for each storm duration group and compared together as presented in Fig. 13 to Fig. 16.

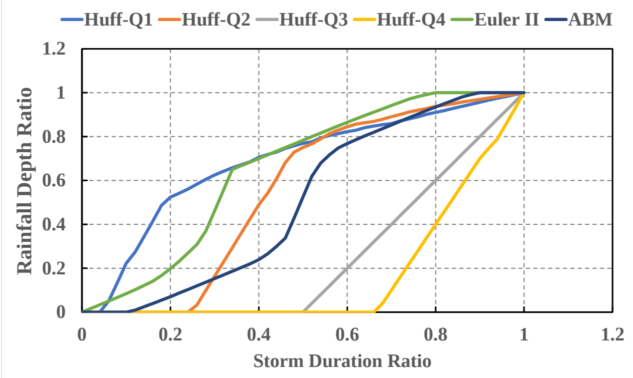

Fig.13: Selected Storm Profiles for the First Group (Storm Duration up to 3 hours)

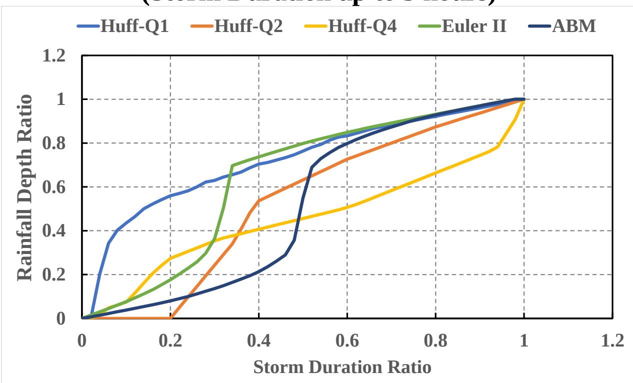

Fig.14: Selected Storm Profiles for the Second Group (Storm Duration from 3 to 6 hours)

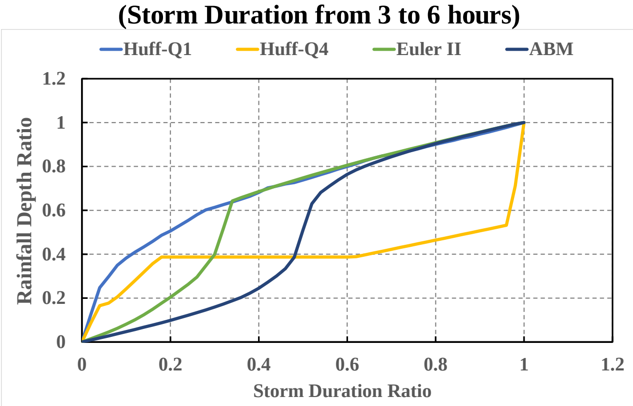

Fig.15: Selected Storm Profiles for the Third Group (Storm Duration from 6 to 12 hours)

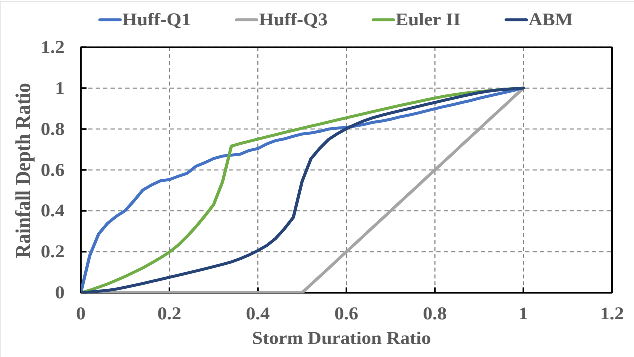

Fig.16: Selected Storm Profiles for the Fourth Group (Storm Duration from 12 to 24 hours)

As depicted from Fig. 13 to Fig. 16, there is no clear conclusion that could be directly extracted to select the best design storm profile. So, the incremental depth ratio is calculated to compare the developed design storm hyetographs together. The calculated maximum incremental depth is presented in Table 5.

Table 5: MaximumIncremental Rainfall Depth Ratio

Group	ABM	Euler	Huff			
			Q1	Q2	Q3	Q4
1	0.09	0.09	0.09	0.07	0.04	0.07
2	0.19	0.19	0.20	0.07	NA	0.09
3	0.12	0.12	0.13	NA	NA	0.29
4	0.18	0.18	0.18	NA	0.04	NA

As depicted in Table 5, the maximum incremental rainfall depth ratios calculated from the developed design storm profiles using ABM, Euler-II, and Huff-Q1 are nearly equal for each one of the storm duration groups. Meanwhile, the maximum incremental rainfall depth ratios calculated for the other three approaches are either not applicable (NA), outlier (as Huff-Q4 in the third group), or lower than that calculated using ABM, Euler-II, and Huff-Q1. So, the developed design storm profiles using ABM, Euler-II, and Huff-Q1 will be compared with the previously developed design storm profiles in addition to the currently applied design storm profiles in the Kingdom of Saudi Arabia in general and Al-Quassim region specifically.

The second type of the design storm hyetographs developed by the Soil Conservation Service, which is called SCS-II, is usually recommended to be applied in several Gulf and Arabian countries code of practice and design standards (e.g. [43]-[44]). The design standards and codes of practice of the Kingdom of Saudi Arabia in general and the Al-Quassim region specifically also recommend the usage of SCS-II design storm with a storm duration of 24 hours [40]-[43]. Also, four design storm hyetographs were recommended to be used in the design-related subjects. The first design storm hyetograph presented storms with duration less than or equal to six hours, the second one presented storm duration ranging between six and 12 hours, the third design storm hyetograph presented storm duration ranging between 12 and 18 hours, and the fourth one presented storm duration between 18 and 24 hours [42].

Based on that, the developed design storm profiles sing ABM, Euler-II, and Huff-Q1 will be compared with SCS-II and previously developed design storm profiles (which will be called here El-Feki). The comparison results are presented in Fig. 17 to Fig. 20.

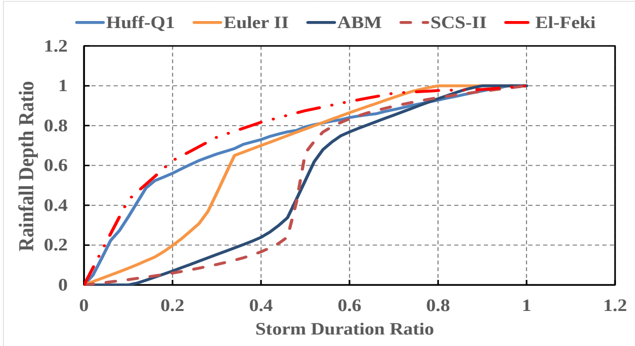

Fig.17: Design Storm Profiles Comparison for the First Group (Storm Duration up to 3 hours)

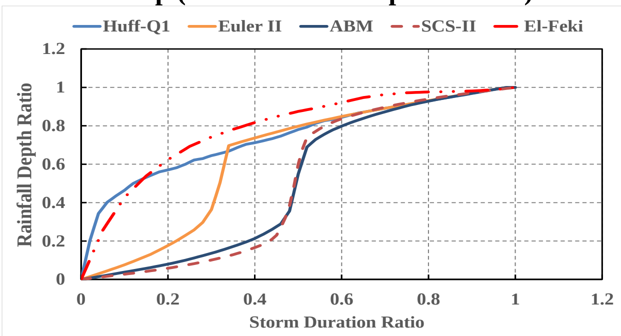

Fig.18: Design Storm Profiles Comparison for the Second Group (Storm Duration from 3 to 6 hours)

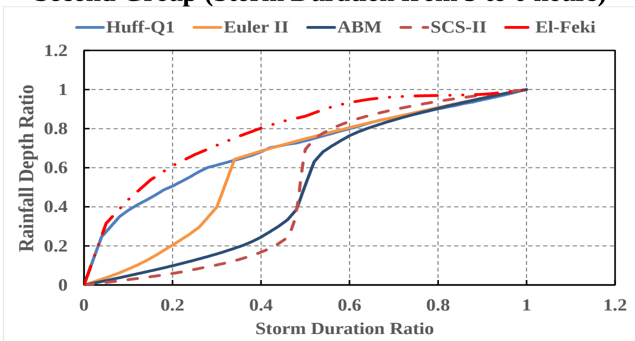

Fig.19: Design Storm Profiles Comparison for the Third Group (Storm Duration from 6 to 12 hours)

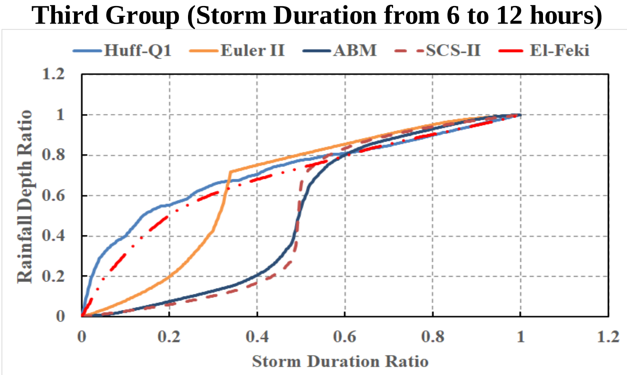

Fig.20: Design Storm Profiles Comparison for the Fourth Group (Storm Duration from 12 to 24 hours)

As shown in Fig. 17 to Fig. 20, the trend of the SCS-II design storm profile matches with the trend of the ABM design storm profile, and the trend of the El-Feki design storm profile matches with the trend of the Huff-Q1 design storm profile. Meanwhile, the trend of the Euler-II design storm profile tends to be like an average profile between SCS-II and El-Feki profile. Additionally, the maximum incremental rainfall depth ratio of SCS-II is much higher than other design storm profiles, while the maximum incremental rainfall depth ratio of El-Feki is lower than other profiles. So, SCS-II design storm hyetographs tend to overestimate the incremental rainfall depth ratios while El-Feki design storm hyetographs tend to underestimate the incremental rainfall depth ratios. Based on that, SCS-II and El-Feki design storm hyetographs are not matching with the available rainfall records at the Al-Quassim region. Consequently, the developed design storm hyetographs using ABM, Euler-II, and Huff-Q1 approaches present the actually measured rainfall storm pattern better than the currently applied design storm hyetographs (i.e. SCS-II and El-Feki design storm hyetographs).

On the other hand, five hypothetical watersheds with different areas (varied between 1.3 to 100 squared kilometres) are used to check the performance of the developed design storm hyetographs and select the most critical design storm hyetograph pattern for each group of storm durations. The Hydrologic Modeling System (HMS) model, which was developed by the Hydrologic Engineering Center – Corps of Engineers – the USA [27], is used to calculate the generated runoff from the selected five watersheds in each case of design storm hyetograph. The HMS results are presented in Table 6, assuming a fixed total rainfall depth of 50 mm.

Table 6: Summary of HMS Results

Group	Catchment Area (Km^2)	Peak Flow (m^3/sec)			Time to Peak (Hours)		
		ABM	Euler	Huff-Q1	ABM	Euler	Huff-Q1
1	1.3	3.5	2.6	2.5	2.75	2.25	1.75
	6.8	20.5	14.6	14.1	2.50	1.75	1.50
	18.5	44.5	34.7	32.2	3.00	2.75	2.25
	63.3	119.7	104.7	95.1	3.75	3.50	3.00
	100	160.1	146.7	136.4	4.25	4.00	3.75
2	1.3	3.1	2.6	1.3	4.00	2.75	1.75
	6.8	18.9	16.4	7.8	3.75	2.5	1.25
	18.5	38.0	32.1	17.7	4.50	3.25	2.25
	63.3	100.2	84.0	57.7	5.25	4.00	4.50
	100	137.1	115.2	87.0	5.75	4.50	4.45
3	1.3	2.1	1.9	0.8	7.00	4.75	3.75
	6.8	12.8	11.7	4.4	6.75	4.50	3.50
	18.5	27.2	23.1	11.2	7.50	5.00	3.75
	63.3	73.9	59.9	34.7	8.25	5.75	4.50
	100	102.4	81.7	51.4	8.75	6.25	5.25
4	1.3	1.8	1.9	0.6	13.25	8.50	4.00
	6.8	10.4	11.1	3.5	12.75	8.25	3.75
	18.5	23.0	23.6	8.4	13.50	8.75	4.25
	63.3	63.9	61.5	24.7	14.25	9.25	4.75
	100	89.2	83.3	35.5	14.75	9.75	5.25

As shown in Table 6, the design storm hyetograph developed using the ABM approach gives peak flow values greater than that calculated using Euler-II and Huff-Q1 design storm hyetographs for the first, second, and third groups of storm durations. Meanwhile, for the fourth group of storm durations, Euler-II and ABM design storm hyetographs are alternatingly giving the maximum peak flow for the investigated five hypothetical watersheds. On the contrary, Huff-Q1 design storm profiles are always giving the minimum peak flow compared with the other two approaches. Additionally, Huff-Q1 design storm hyetographs are always giving the minimum time to peak for all investigated cases compared with the other two approaches. So, it is recommended to use Huff-Q1 design storm hyetographs in case of flood hazards early warning alarm system application while the ABM design storm hyetographs are recommended to be used for flood hazards assessment and stormwater drainage systems applications. Also, it is recommended for storm duration greater than 12 hours to compare the results of ABM and Euler-II design storm profiles together in all relative applications.

The final form of the developed design storm hyetographs for each storm duration group are presented in Table 7 and Table 8.

Table 7: Developed Design Storm Profiles in Cumulative Form (1st and 2nd Groups)

Time (Ratio)	First Group		Second Group	
	ABM	Huff-Q1	ABM	Huff-Q1
0	0.000	0.000	0.000	0.000
0.05	0.027	0.164	0.018	0.364
0.10	0.055	0.323	0.038	0.464
0.15	0.087	0.474	0.057	0.528
0.20	0.120	0.556	0.079	0.567
0.25	0.153	0.605	0.105	0.606
0.30	0.186	0.644	0.136	0.639
0.35	0.224	0.683	0.171	0.673
0.40	0.272	0.718	0.214	0.707
0.45	0.383	0.748	0.277	0.735
0.50	0.524	0.776	0.547	0.772
0.55	0.647	0.804	0.736	0.809
0.60	0.742	0.829	0.792	0.839
0.65	0.784	0.848	0.833	0.864
0.70	0.820	0.869	0.867	0.886

Time (Ratio)	First Group		Second Group	
	ABM	Huff-Q1	ABM	Huff-Q1
0.75	0.853	0.890	0.897	0.905
0.80	0.886	0.913	0.922	0.923
0.85	0.919	0.936	0.943	0.943
0.90	0.950	0.959	0.963	0.962
0.95	0.976	0.980	0.982	0.981
1.00	1.000	1.000	1.000	1.000

Table 8: Developed Design Storm Profiles in Cumulative Form (3rd and 4th Groups)

Time (Ratio)	Third Group		Fourth Group		
	ABM	Huff-Q1	ABM	Euler	Huff-Q1
0	0.000	0.000	0.000	0.000	0.000
0.05	0.023	0.273	0.009	0.036	0.313
0.10	0.047	0.381	0.025	0.082	0.404
0.15	0.072	0.446	0.048	0.137	0.514
0.20	0.099	0.507	0.073	0.206	0.553
0.25	0.127	0.567	0.099	0.311	0.601
0.30	0.159	0.614	0.125	0.466	0.655
0.35	0.195	0.644	0.156	0.723	0.674
0.40	0.246	0.682	0.204	0.751	0.706
0.45	0.318	0.715	0.284	0.778	0.747
0.50	0.510	0.738	0.509	0.804	0.776
0.55	0.696	0.769	0.724	0.829	0.794
0.60	0.763	0.800	0.799	0.855	0.808
0.65	0.808	0.832	0.846	0.880	0.827
0.70	0.844	0.854	0.876	0.905	0.848
0.75	0.875	0.875	0.903	0.928	0.872
0.80	0.904	0.901	0.928	0.951	0.899
0.85	0.930	0.924	0.953	0.970	0.924
0.90	0.955	0.947	0.976	0.983	0.950
0.95	0.979	0.972	0.991	0.992	0.975
1.00	1.000	1.000	1.000	1.000	1.000

V. CONCLUSION

In conclusion, detailed analyses are conducted on the collected 557 rainfall storms from eight rainfall gauges distributed over the entire area of the Al-Quassim region. The main target of the conducted analyses is to develop the design of storm hyetographs of the Al-Quassim region, Kingdom of Saudi Arabia. The following points summarize the main conclusions of the conducted analyses:

- The collected storms are divided into four groups depending on storm duration. The first group includes all storms which have a duration less than or equal to three hours. The second group covers the range between three and six hours, the third group covers the range between six and 12 hours, and the last group includes all storms which have storm durations greater than 12 hours up to 24 hours.
- 68% of the collected storms have durations less than or equal to six hours, while other storm durations represent only 32% of the collected storms.
- The pattern of the collected storms is totally random.
- Six design storm hyetograph development approaches are tested (i.e. ABM, Euler-II, Huff-Q1, Huff-Q2, Huff-Q3, and Huff-Q4).
- The developed design storm hyetographs using ABM, Euler-II, and Huff-Q1 approaches are the best among the tested approaches.
- The developed design storm hyetographs are compared with SCS-II and El-Feki design storm hyetographs.
- The developed design storm hyetographs are better than SCS-II and El-Feki hyetographs because the SCS-II hyetographs are overestimating the incremental rainfall depth ratios, and El-Feki ones are underestimating them.
- It is recommended to use a shorter design storm duration because about 74% of the collected storms have the maximum incremental rainfall depth ratio occurred during the first quarter of their durations.
- The developed design storm profiles are compared together using the HMS model to select the best one of them.
- It is recommended to use the developed design storm hyetograph using the ABM approach in all flood hazards and urban stormwater drainage studies. Meanwhile, the developed Huff-Q1 design storm hyetograph is recommended to be used for flood hazards early warning system related-applications.
- Euler-II design storm hyetograph should be checked in case of storm duration of more than 12 hours.

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