The impact of Rainfall Distribution Patterns on Hydrological and Hydraulic Response in Arid Regions: Case Study Medina, Saudi Arabia

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ABSTRACT

Rainfall Distribution Patterns (RDPs) are the basic source for hydrologic and hydraulic design projects. Typically, hydrologic and subsequently hydraulic modelling approaches based on the *Soil Conservation Services* (SCS) type RDPs (SCS type I, IA, II, III) are widely used by many practitioners in arid regions, especially SCS type II method. These RDPs were primarily designed for the United States (US) and other similar temperate regions; however, they have no direct scientific justification. The consequences of using such approaches have a great impact on the hydrologic and hydraulic modelling studies. An investigation must be carried out in order to justify the validity of the SCS type II and its application in arid regions. New temporal RDPs were applied and the validity of SCS type II RDPs was analysed by comparing the produced peak discharges, volumes, maximum flood inundation depths, maximum top flood inundation widths, and velocities from both approaches in arid regions, specifically, for a small catchment at Medina, Saudi Arabia. Rainfall data was obtained for a period up to 48 years. The extensive methodology was used for covering all technical aspects of designing temporal RDPs, which included frequency analysis, catchment (watershed) modelling, hydrological modelling, and hydraulic modelling. The methodology for the designed RDPs involved grouping of rainfall data into four quartiles. Then construction of mass curves for rainfall depths and durations and finally transformation of these mass curves into dimensionless mass curves. The watershed modelling, hydrological modelling, and hydraulic

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modelling were performed on the Taibah University and the Islamic University (TU and IU) catchment in Medina, Saudi Arabia. The study presented a comparison between the application of designed temporal RDPs in Medina region and the SCS type II RDPs. Results from the comparisons of runoff volumes, peak discharges, inundations depths, inundation widths, and flow velocities indicated that there are considerable consequences if inappropriate RDPs are used. The investigation confirmed that the SCS type RDPs do not reflect the actual temporal rainfall patterns in arid regions. A great care must be taken for using RDPs in arid regions; the use of inappropriate RDPs could lead to erroneous results and unreliable constructions of infrastructure and engineering works.

Keywords:

Rainfall Distribution Patterns, SCS type distribution; hydrologic modelling; hydraulic modelling; flood management; arid regions

1. Introduction:

Hydrologic and hydraulic calculations are essential for the practical applications of the hydraulic design of flood protection structures. The estimated design rainfall is a required input for the hydrologic and hydraulic design calculations. The design rainfall, was estimated by various rainfall distribution patterns (RDPs) to generate the runoff hydrographs. The runoff hydrographs are further routed in the watershed from the upstream to the downstream through the hydraulic modelling for producing flood hydrographs at various locations along the main stream. The resulting flood hydrographs are used for investigating the response of channels, streams and other infrastructure in the watershed for different storm events. This establishes the fact that the correct design rainfall plays an important role in the hydrologic and hydraulic analysis.

Different distributions have been tested for different climate of the world. Widely used empirical RDPs were developed by Natural Resources Conservation Service (NRCS). Such RDPs are called the U.S. Soil Conservation Service (SCS) RDPs. The SCS developed charts for estimating instantaneous peak discharges resulting from the small watershed. The peak discharge rates were used for analysis of water control measures. SCS method presents four different types of 24 hours (24-hr) RDPs; namely, SCS Types I, IA, II, and III (SCS, 1986). Typically, SCS types I and IA are recommended for Alaska, Hawaii, and the coastal side of the Sierra Nevada and Cascade mountainous region. While for the rest of the U.S., Puerto Rico, and the Virgin Islands, the SCS type II RDPs are recommended. The use of SCS type III is recommended for the hurricane-affected areas (Guo and Hargadin, 2009).

The justification for the use of SCS type RDPs to other parts of the world is questionable. Yet, most practitioners use SCS type RDPs in their studies even though it may not be applicable in their study area. The alternative way is to use the design RDPs. The derivation of such distributions is generally based on the precipitation depth-distribution-frequency (DDF) or intensity-distribution-frequency (IDF) relationships that describe the burst with the most intensity during different rainfall durations (Pilgrim and Cordery, 1975; Ewea *et al.*, 2017). The SCS types RDPs are used to simulate DDF or IDF curves for the 24-hr duration. Huff (1967) used the time-distribution-characteristics of heavy storms to develop the families of curves for designing the RDPs for approximately 400 square mile areas in Illinois and the Midwest. The design RDPs were recommended for evaluating the design and operation of runoff control structures and assessing the storm events in weather modification operations. Different procedures are available for constructing the design RDPs. The most notably used procedures are; constructing the RDPs based on the DDF relationship, suggested by the Hershfield (1961); constructing the design distributions

based on the time quartile technique using the observed storm events, presented by Huff (1967); and constructing the distributions based on the hyetograph method, explained by Kerr (1974). Apart from these procedures, Guo and Hargadin (2009) suggested another technique for designing the rainfall distributions by using the concept of enveloping curves which is based on the similar approach as was used for constructing SCS curves; Humphreys et al. (2013) used rainfall intensity formulas and a log-log distribution for combining 6-hr and 24-hr rainfall into a single storm distribution hydrograph in order to utilize a hypothetical nested rainfall distribution for the hydrologic computations; Dullo et al. (2017) proposed a framework for constructing the site-specific temporal RDPs using a clustering technique.

Rainfall processes in arid regions, especially in most parts of Saudi Arabia, are characterized by large random special and temporal distributions, and further influenced by a climate change> Recently Climate has been cited as i one of the significant challenges for flood risk analysis and water supply works (Ishak et al., 2013). The analyses of different rainfall events present dramatic changes with respect to the rainfall events that occur in humid regions. Most of the existing methodologies for humid regions usually require modifications, in order to be applicable to the arid regions (Ewea et al., 2016). The use of the SCS types RDPs is further complicated by the data coverage and length limitations in arid regions. Runoff in such regions is generated from random localized rainfall events, exhibiting high intensities with short durations. The most common of them is the convective type rainfall events, resulting from unstable synoptic conditions (Yair and Lavee, 1985; El- Hames and Richards, 1998). The generated hydrograph from the convective type rainfall is characterized by a steep rising limb with a short time to peak, and a rapid recession to zero base flow. The major hydrological factors that influence the runoff occurrences are high-intensity rainfall, geological and geomorphological features, initial abstraction losses, and transmission losses in the dry channel (Gheith and Sultan, 2002).

The correct use of the RDPs plays an important role in the analysis and design of hydrology, hydraulics and water resources projects. Especially, it is important for the flood risk analysis. The flooding phenomenon cannot be ignored because it is established that different parts of the world have been experiencing increased flooding risks from extreme rainfall events, which usually resulted in the loss of human lives, and in extensive destructions of infrastructures, especially in urban areas. At the global level, more than one-third of the urban areas where 82% of the population resides in the flood-prone areas (Dilley et al., 2005). It is known that occurrences of extreme rainfall-flooding events have been associated with an extreme weather phenomenon that is common in arid regions. Flooding in the form of flash floods is influenced by the random rainfall events in arid

regime characteristics, exhibiting large variations in time and space, with high intensities, short durations. The generating flood flows have high velocities and high peak discharge, with small time to peak. The characteristic of small time to peak contributes to the severe destructions of infrastructures from flooding events, which commonly happens in the arid regions.

This research paper investigates the importance of temporal RDPs in arid regions, where the case study is Medina region. The construction of the design temporal RDPs is very important in the arid regions because the post rainfall-runoff processes, such as the flood analysis depends upon the correct use of the rainfall distribution patterns in the study area. The conventional method in the rainfall-runoff analysis is the use of SCS type II method, which is compared with the design temporal RDPs in this study. The results advocate that the use of SCS type II has no justification in the arid regions and is associated with significant overestimation of peak discharges. The paper addresses all the implications arising from the use of RDPs by further investigating the flood inundation depths. Comparison of flood inundation depths resulting from the simulations of two different types of RDPs: (1) the inundation depths based on the SCS type II RDPs, and (2) the inundation depths based on the designed RDPs, further establishes the importance and significance of the correct method for estimating the RDPs.

2. Study Area and Rainfall Characteristics:

The study area is a small catchment covering Taibah and Islamic universities campuses in Medina region, Saudi Arabia as shown in Figure 1. The catchment is located at N $24°$ $28.788'$ and E $39°$ $32.767'$ and its topography is characterized by the gentle elevation surrounded by relatively high mountains in the upstream area, and flat area with some hills covering both universities (Figure 1 and 2). The ground elevation varies from $533\ m$ to $966\ m$. The topographic characteristics indicate that the catchment has an average slope of 1%, orienting from West to East direction towards the downstream of the main channel (wadi Al Aqiq). The geological characteristics of the catchment revealed that the geology mainly consists of a barren surface with hard igneous and metamorphic rocks, limited exposure of the surface rocks in some upstream area and the barren vegetation. The catchment bounds the channel that is flowing along the Taibah University and the Islamic University. The channel is a composite channel; comprising of a natural earthen channel, where the Taibah University is located to the North of the channel; and the artificial man-made concrete channel, where the Islamic University is located to the South of the channel. The same TU and IU channel was analysed and modelled for flood inundation mapping. Both universities are surrounded by the urban infrastructure; like buildings and roads, as shown in Figure 2.
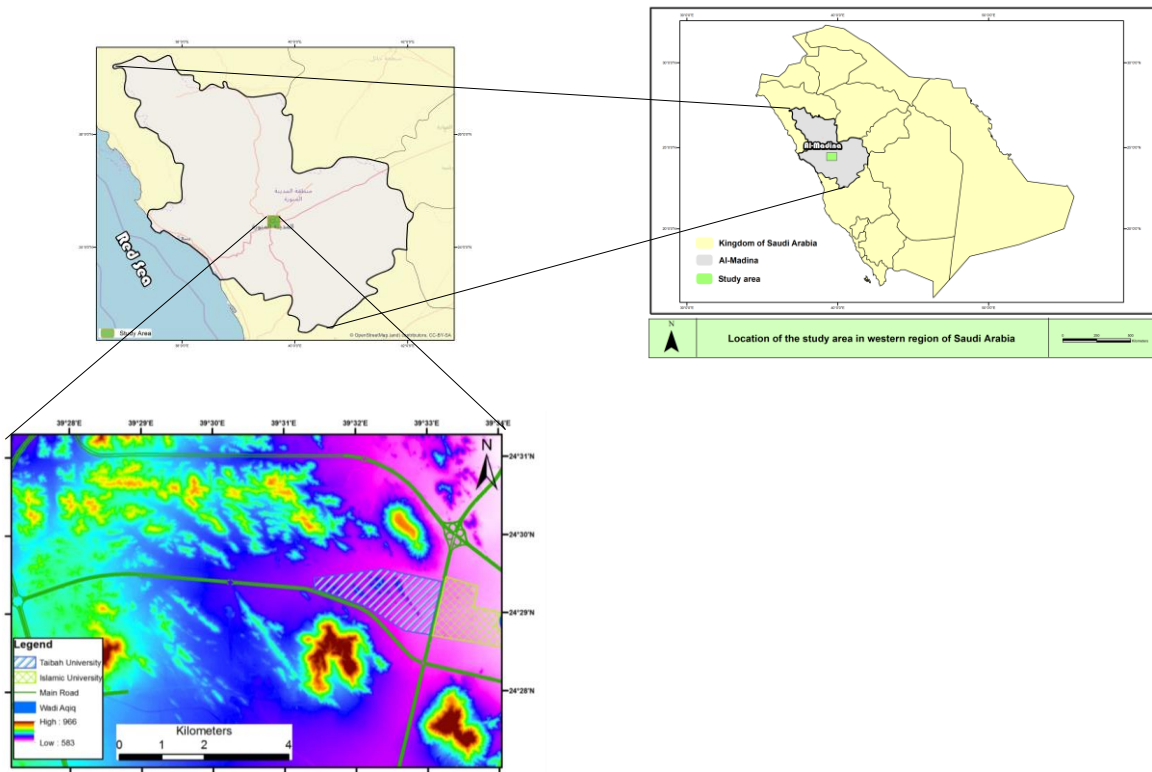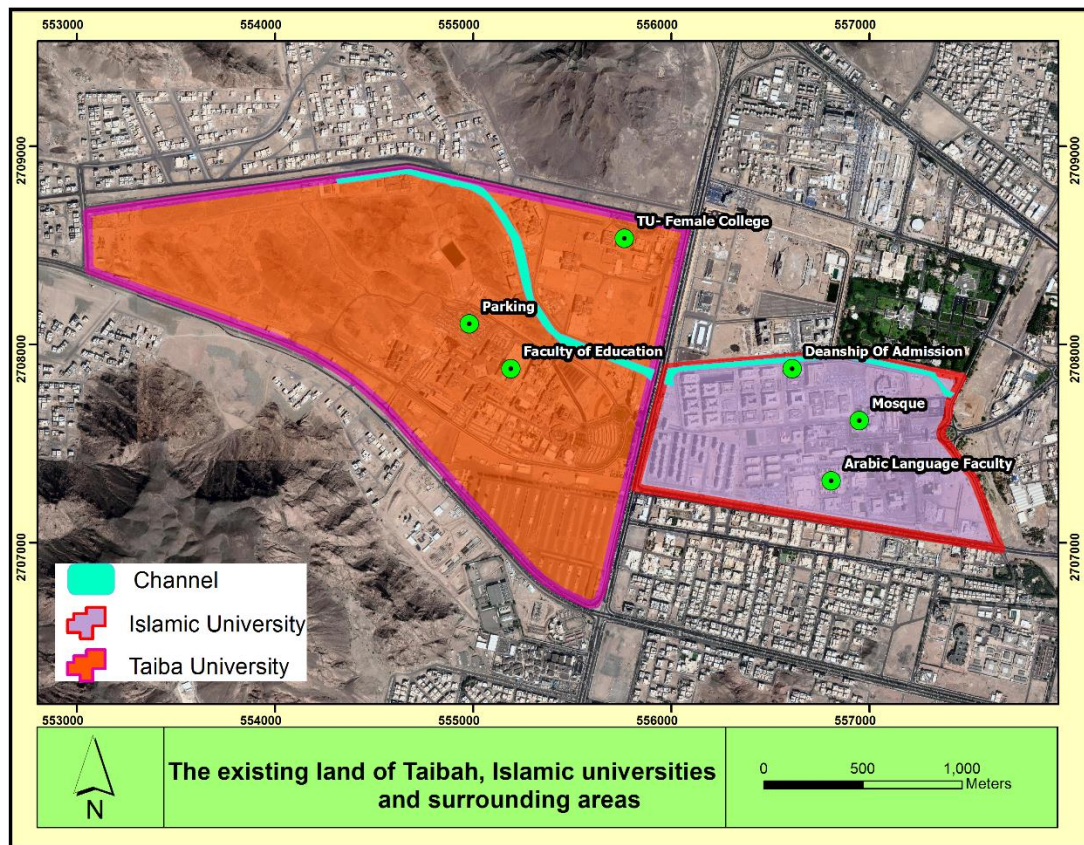
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Figure 1 Location of the study area

Figure 2 Infrastructures in and around the TU and IU and the flood channel form Satellite imagery

Rainfall characteristics, were estimated using the records of two main stations M001 and M103, shown in Table 1. The station M001 is located in Sultanah district, which is 4.3 km Northeast from the TU and IU catchment, while the station M103 is located in Bir-Almashi. M001 station was established in 1968, with its elevation at 590 m above the mean sea level and average annual rainfall at 60 mm. The rainfall events mainly occur in spring season (March, April, and May), as shown in Figure 4, with average seasonal depth of 35 mm. Further evaluation of rainfall characteristics revealed the random nature of rainfall events, with their occurrences mainly in the months of January, April, March, and November. The high values were recorded in months of March and April. Average rainfall depths ranged from 18 mm to 29 mm.

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Table 1 Rainfall characteristics of stations M001 and M103

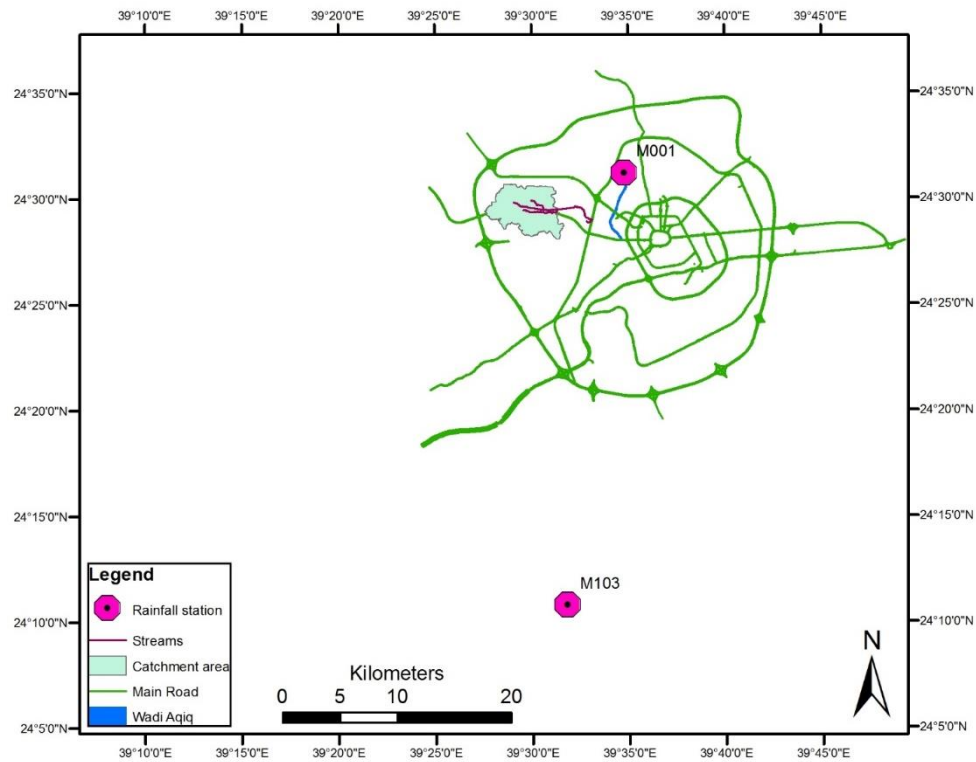| Station Name	Station ID	Coordinates		Type of data	Record length (year)
		Latitude (N)	Longitude (E)		
Medina Farm	M001	24°30'58"	39°35'5"	Rainfall (Daily)	43
BirMashi	M103	24°10'58"	39°32'5"	Rainfall (Daily)	48

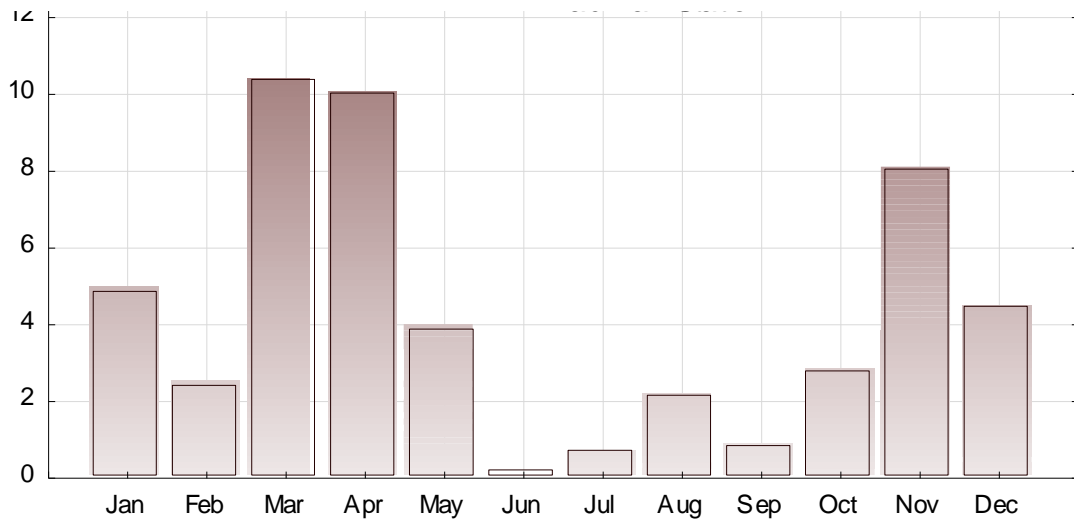**Figure 3 Location of rainfall stations M001 and M103**

Figure 4 Average monthly rainfall depth for station M001

3. Methodology:

The schematic of the methodology is illustrated in Figure 5. First, the data were collected for the study region. The data consisted of the rainfall records from the two rainfall gauges (M001 and M103). Different types of statistical distributions were used for performing the frequency analysis for different return periods and various distributions were compared in order to select the best distribution method where the curve could relatively best fit the data for estimating the possible maximum rainfall depths based on the available rainfall data from the two rainfall stations. The Inverse Distance Weighing (IDW) interpolation technique was used to distribute the maximum rainfall depths from the two rainfall stations over the whole catchment for different return periods. The next important task was to develop the design RDPs for the study region. The designed RDPs provide curves for estimating the hyetographs for various return periods. Other characteristics of the catchment were found from the watershed modelling of the TU and IU catchment using WMS software. In succeeding steps, hydrological and subsequent hydraulic modellings were performed. The impacts of different RDPs on hydrologic modelling and hydraulic modelling were analyzed in the last step. From the hydrologic modelling, the time to peak, peak discharge and volume, and from the hydraulic modelling, top width, inundation depth, maximum depth and velocity of the flow from the SCS type II RDPs were compared with the same parameters from the designed RDPs.

Figure 5 Schematic working flow of the used methodology

3.1. Frequency Analysis

Frequency analysis was made for the two rainfall records (i.e. M001 and M103) having more than 30 years of data. Different statistical distributions were applied: Normal Distribution, Gumbel Distribution Type 1, Generalized Extreme Value (GEV) Distribution, 2-Parameter and 3-Parameter Log-Normal Distributions, Pearson Type III Distribution, and Log-Pearson Type III Distributions. The most suitable distributions to fits the rainfall record relatively better among others was chosen for the study area using SMADA program. The comparison is based on the Root Mean Square Error (RMSE) statistical technique, in which the distribution method that resulted in the least RMSE value, was chosen as the relatively best distribution method.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[\bar{R}_i - R_i]^2} \tag{1}$$

where, R_i is the observed rainfall depth at the station, $\bar{R}_i$ is the expected rainfall depth from the frequency distribution method (i.e. Probability Distribution Function, PDF) at the station, and n is the number of storm records

The frequency analysis estimated the probable maximum depths for the six chosen return periods at the rainfall stations. These maximum depths are spatially distributed over the catchment using the IDW technique. It is a well-known interpolation technique, which resulted into spatially distributed probable maximum rainfall depths for the six different return periods.

$$P(x_0, y_0) = \sum_{i=1}^{m} w_i P_i \tag{2}$$

where, $w_i = \dfrac{\frac{1}{x_i^2}}{\sum_{i=1}^{m}\frac{1}{x_i^2}}$, $x_i^2 = (x_i - x_0)^2 + (y_i - y_0)^2$, $P(x_0, y_0)$ is the estimated rainfall at coordinates (x_0, y_0),

P_i is the rainfall at the given station i, w_i is the station weight, and $\mathbf{x}_i = (x_i, y_i)$ is the coordinates of the station

3.2. Designing RDPs

A large dataset of rainfall records is required for designing the RDPs were grouped according to the location of the maximum intensity. Four groups of storms were formed according to the quartile number (1st quartile, 2nd quartile, 3rd quartile, and 4th quartile). Mass curves were developed to relate the rainfall depths with their

corresponding durations. In order to make the curves flexible, the dimensions were removed by dividing the individual rainfall depths of each storm by their total by depths (y-axis) and dividing the elapsed time of the corresponding by the total duration of the storm. Elfeki *et al.* (2014) followed this procedure and developed mass curves for Medina region. These temporal RDPs are instrumental in developing appropriate hyetographs for the location under study using the maximum rainfall depths for different return periods. Such temporal distributions are essential inputs for the hydrological modelling.

3.3. Watershed Modelling

Watershed modelling was performed in WMS software in order to delineate the catchment boundary ad characteristics and schematic for the hydrological modelling in HEC-HMS software and subsequent hydraulic modelling in HEC-RAS Software. All pertinent data were obtained for different modelling procedures and applications. The *Digital Elevation Model* (DEM) with a resolution of 30 m for Medina was used in *Watershed Modelling Software* (WMS) software for the purpose of a catchment modelling, as shown in Figure 6. WMS generated flow directions and stream networks using the DEM which was used in the catchment delineation. GIS and remote sensing approaches were used for preparation of the land use data and soil type data for the TU and IU catchment. Land use and land cover maps were prepared from Image Sentinel-2 with 10 m by 10 m resolution, which was acquired from the European Space Agency (ESA) on 3rd December 2016. The morphometric and hydrologic parameters were obtained using the integration of the delineated catchment, soil type classifications in the catchment and land use data. These parameters along with the catchment delineation and schematic are needed for running the hydrological model in HEC-HMS.
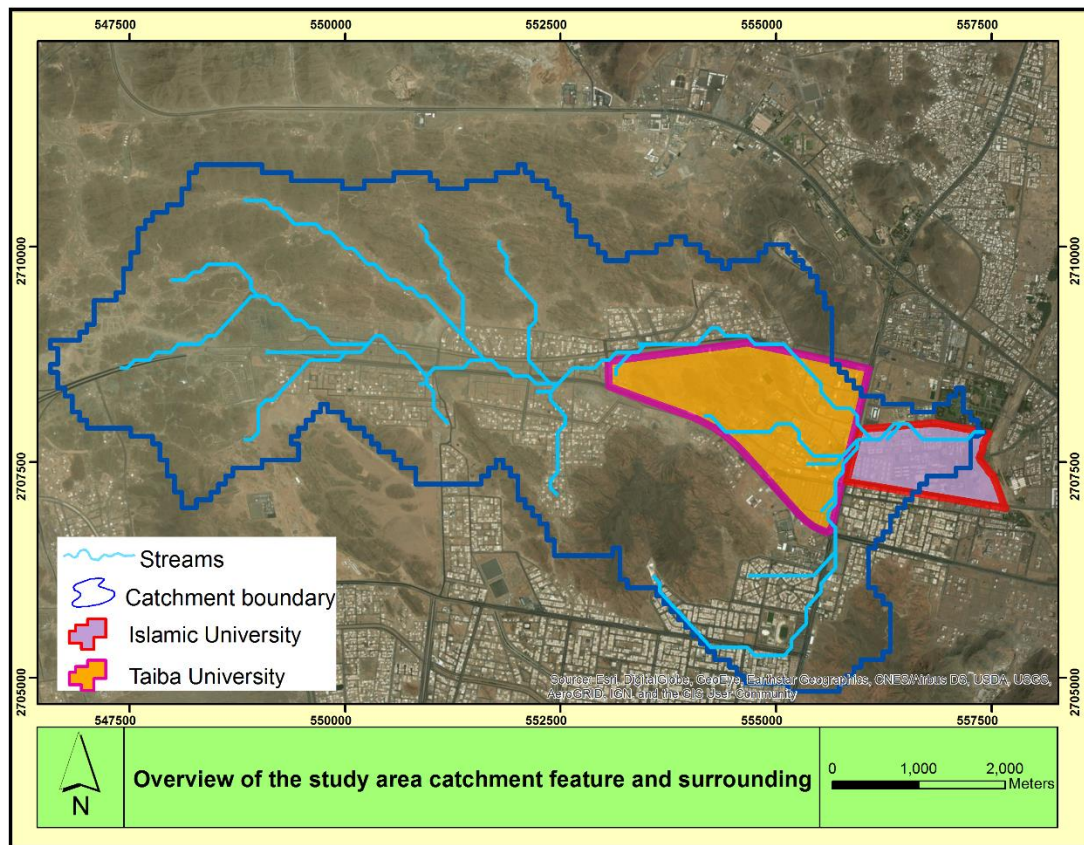
Figure 6 TU and IU campuses and catchment superimposed over satellite image.

3.4. Hydrological Modelling

All data obtained from WMS were used in HEC-HMS software for performing hydrological modelling. The rainfall-runoff modelling in HEC-HMS requires three essential inputs: (1) the meteorological data, which consisted of rainfall (obtained from the designed RDPs), (2) the basin parameters (obtained from the watershed modelling in WMS), and (3) the control inputs (a user-defined inputs for the start and end time of the simulations). Based on these three inputs, the simulations in HEC-HMS were performed for different frequencies of floods using the designed RDPs. For evaluating the importance of the designed RDPs and assessing the validity of the SCS type RDPs, it was necessary to make a comparison between the designed RDPs and the SCS type RDPs. Therefore, the hydrologic modelling was also performed for the different frequencies of floods using the SCS type II RDPs and then simulated results were compared.

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3.5. Hydraulic Modelling

The application of HEC-RAS flow model requires a large number of iterative steps for numerical solutions of wave models contained within the subroutines of different modelling approaches and their different options. The different options have GUI popup windows used for entering different types of data that are required for hydraulic modelling, like channel geometric features, hydraulic parameters, flow data from the hydrographs in order to evaluate water elevations and flood inundations for different frequencies. Peak discharges for different frequencies of floods based on the designed RDPs and the SCS type II RDPs were obtained from the runoff hydrographs. These peak discharges, along with the geometric data which consisted of the TU-IU channel and their cross-sections, were used in HEC-RAS software for hydraulic modelling. The simulations were performed for different return periods based on the designed RDPs and the SCS type II RDPs. The hydraulic model in the HEC-RAS generated flood inundation depths and flood inundation widths showing the inundation area. For visualizing the flood maps, the data from the HEC-RAS were exported to GIS software. Processing of HEC-RAS data was performed in GIS software for preparing the flood inundation maps.

Lastly, statistical analyses were performed in order to compare the designed RDPs and the SCS type II RDPs using different outputs from both hydrological and hydraulic models for different flood frequencies.

4. Results and Discussion:

4.1. Frequency Analysis:

Different statistical distribution techniques were applied based on the rainfall records of over 40 years. SMADA program was used for employing these techniques. RMSE values, as represented in Table 2, were analyzed for choosing the relatively best statistical distribution technique for estimating the maximum depths at station M001 and station M103. From Table 2, it is evident that 2-Parameter Log-Normal and 3-Parameter Log-Normal distribution techniques resulted in relatively small RMSE values of 7.92 and 4.56 for station M001 and station M103, respectively. Thus, these two distribution techniques were used for estimating the maximum depths for six different return periods.

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Table 2 Comparison of different statistical distribution techniques based on RMSE values

Distribution type	RMSE (M001)	RMSE (M103)
Gumbel Type 1	15.17	5.72
Generalized Extreme Value (GEV)	12.17	4.64
2-Parameter Log-Normal	**7.92**	5.02
3-Parameter Log-Normal	12.19	**4.56**
Pearson Type III	11.6	4.57
Log-Pearson Type III	13.56	7.59

Apart from the RMSE values, probability plots of different statistical techniques (shown in Figure 7) for the rainfall records of over 30 years validate the fact that the 2-Parameter Log-Normal and 3-Parameter Log-Normal distribution curves relatively best fitted the given records of data among the other distribution techniques.
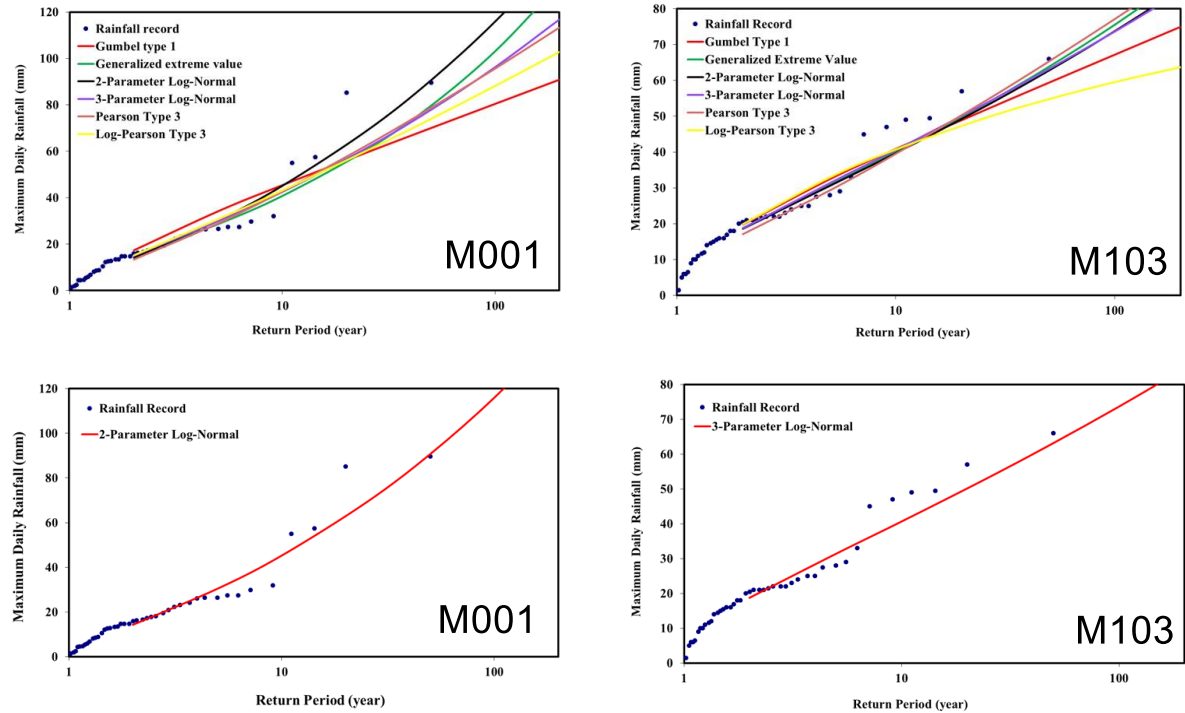

Figure 7 Probability plots of different statistical distribution techniques for fitting the given rainfall records at stations in the study area: M001 and M103.

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Six return periods of 5, 10, 25, 50, 100 and 200 years are used in this study for the rigorous comparison of the designed RDPs and the SCS type II RDPs. The maximum estimated depths for six return periods based on the 2-Parameter Log-Normal and 3-Parameter Log-Normal distribution techniques at station M001 and station M103 are given in Table 3.

Table 3 Estimated maximum depths for different return periods based on the best distributions for M001 and M103

Station	5 Years	10 Years	25 Years	50 Years	100 Years	200 Years
M001	30.44	45.24	69.04	90.71	115.96	145.19
M103	31.36	40.61	53.18	63.15	73.60	84.59

These maximum depths of the rainfall events were distributed over the TU and IU catchment using the IDW interpolation technique. The expected rainfall depths distributed over the whole catchment are presented in Table 4.

Table 4 Expected rainfall depths for different return periods distributed over the TU and IU catchment

Rainfall depth (mm)					
5 Years	10 Years	25 Years	50 Years	100 Years	200 Years
30.5	45	68.2	89.2	113.7	142

4.2. Designing RDPs:

The dimensionless cumulative rainfall SCS type II and designed rainfall curve for the study area, modified from Elfeki *et al.* (2014), are represented in Figure 8. The cumulative rainfall depths based on the designed RDPs were obtained by multiplying maximum rainfall depths for different return periods, as shown in Figure 10. Applications of hyetographs of the designed RDPs and SCS type II RDPs are presented in the hydrological modelling subsection under the results and discussion section.
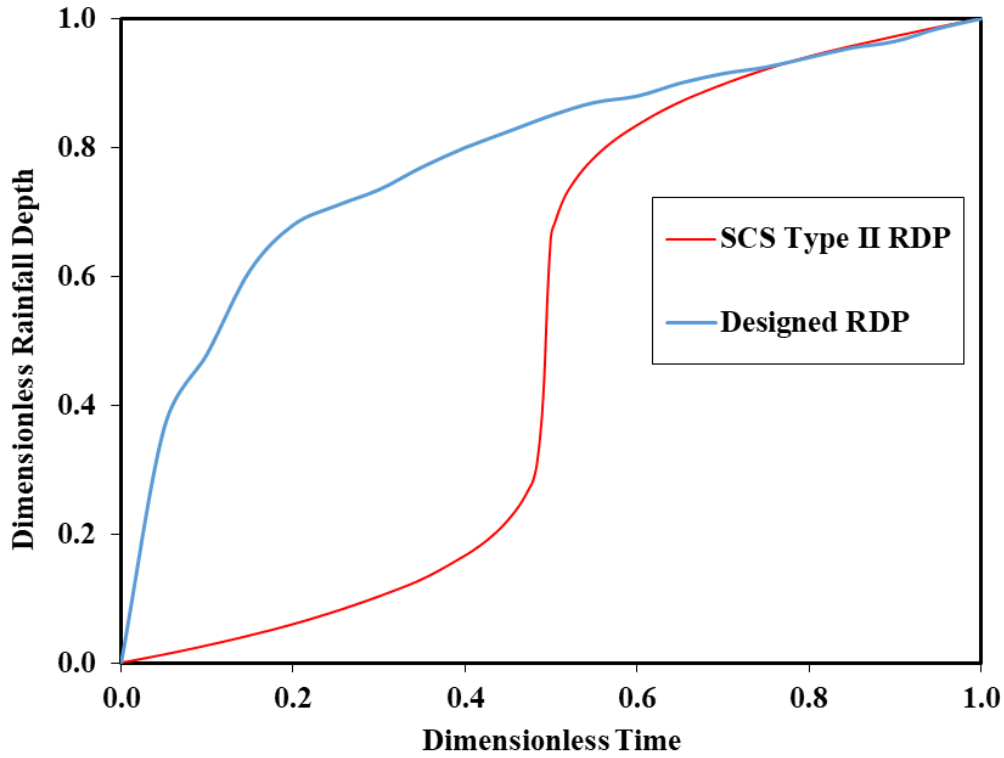
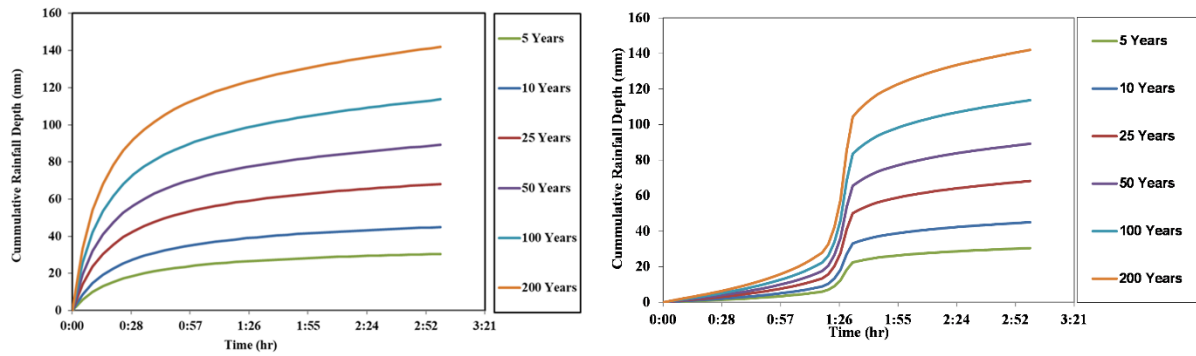**Figure 8 Dimensionless cumulative rainfall distribution curves for Medina region**

Figure 9 Cumulative rainfall depths based on the designed RDPs (left) and SCS type II (right) for TU and IU catchment

4.3. Watershed Modelling:

The catchment characteristics were obtained using the WMS software. The morphological parameters of the catchment are summarized in Table 5. GIS software and remote sensing were used to obtain the land cover characteristics and the soil type classification. Maximum likelihood criterion was used in Envi software to obtain the land cover characteristics. This approach is a common supervised learning technique in which the known land

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use categories like an urban area, rocks etc. were used as training classes and Envi software allocated cover types to each pixel in the image to which the spectral response is most similar, as shown in Figure 6. Land cover characteristics indicated that the land consists of some vegetation, urban area, infrastructure (like roads), soil and rocks, as shown in Figure 10. The soil type is usually identified by the hydrological soil group (HSG). The CN for HSG and the corresponding land use features of the TU and IU catchment was found to be 86.1, using weighted composite CN, as shown in Table 6.

Table 5 Morphological parameters of TU and IU catchment

| Parameter	Simple Abbr.	Unit	Value
Basin Area	A	Km^2	34.22
Basin Slope	BS	Km/Km	0.101
Maximum Flow Distance	MFD	Km	13.197
Maximum Flow Slope	MFS	Km/Km	0.011
Centroid Stream Distance	CSD	Km	6.41
Centroid Stream Slope	CSS	Km/Km	0.007
South Aspect ratio	%SF	%	0.49
North Aspect ratio	%NF	%	0.51
Maximum stream Length	MSL	Km	12.26
Maximum Stream Slope	MSS	Km/Km	0.01
Basin Length	L	Km	10.8
Shape Factor	Shape	m^2/m^2	3.42
Sinuosity Factor	Sin	m/m	1.13
Perimeter	P	Km	40.81
Mean Basin Elevation	AVEL	Km	694.1
Basin Centroid X		m	552158
Basin Centroid Y		m	2708342
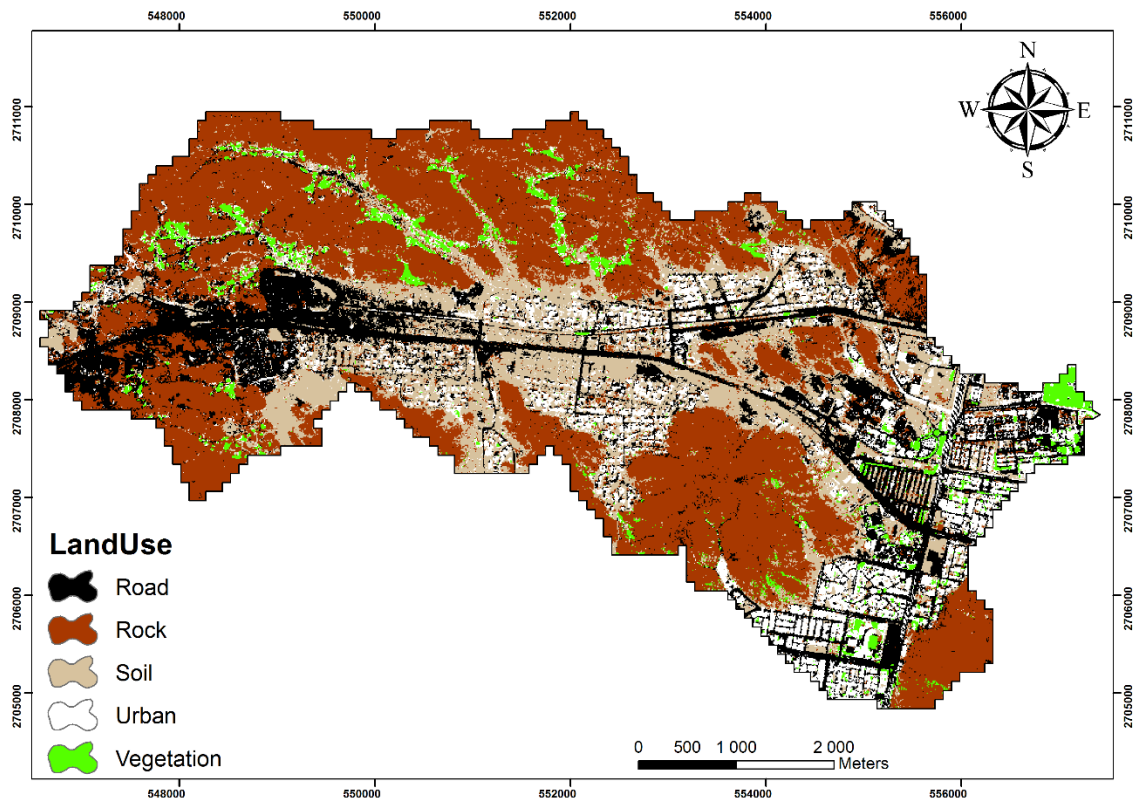
Figure 10 Land use map of the TU and IU catchment

Table 6 Land cover characteristics and the composite CN value

Land cover and land use feature	SCS-CN	Area (Km^2)	Composite CN
Urban Roads	98	8.61	
Vegetation	60	0.83	86.1
Rocks	95	14.76	
Soil Alluvium	65	10.02	

4.4. Hydrologic Modelling:

Hydrological modelling was performed using HEC-HMS software, which gave the peak discharges for six different return periods. The objective of the hydrological modelling was to perform rainfall-runoff modelling. The rainfall-runoff models produced runoff hydrographs which were essential inputs for the flood modelling. The input data for HEC-HMS were obtained from watershed modelling, the most important of them were the catchment schematic, drainage network and the morphological parameters of the TU and IU catchment. Different simulations were performed in HEC-HMS, which were based on the different hyetographs for six different return periods. The RDPs for different hyetographs for six return periods were grouped into two types. One of them was based on the designed RDPs and the other was based on the SCS type II RDPs. The simulated results from the designed RDPs and the SCS type II RDPs are presented in Figure 11.
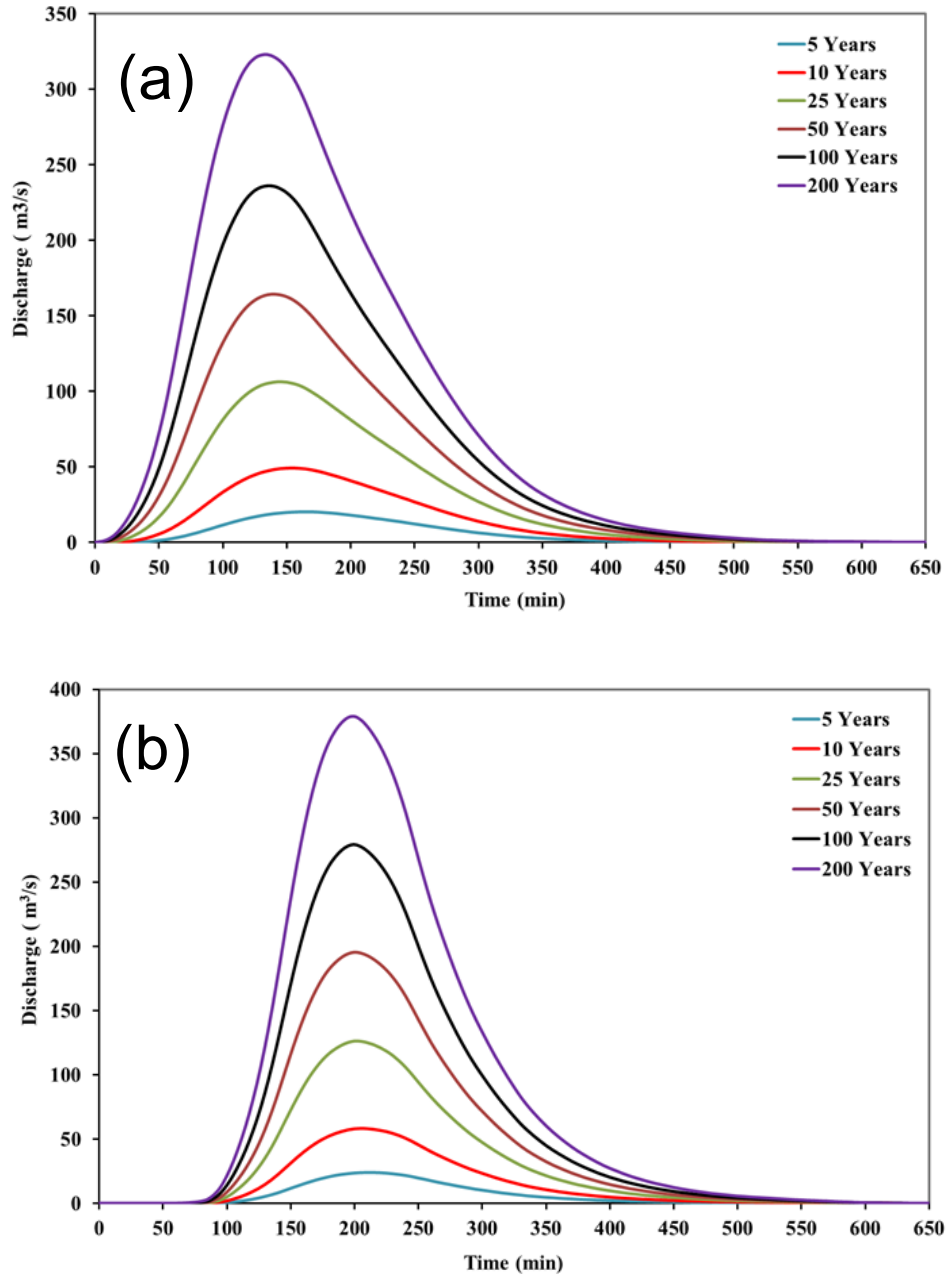
Figure 11 Runoff hydrographs based on the designed RDPs (a) and SCS type II RDPs (b) for different return periods

The peak discharges from the hydrological modelling for both types of the RDPs are plotted in Figure 12. Peak discharges, volumes and time at peak discharges are summarised in Table 7, which were used as inputs to the hydraulic modelling of the TU and IU catchment. By comparing the designed RDPs and the SCS type II RDPs, it is evident that the peak discharges are overestimated for the SCS type II RDPs. The difference in peak discharges increases with respect to the recurrence interval. This leads to the inaccurate and expensive design of the

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infrastructure in the TU and IU catchment. Another important difference is the starting time of the runoff hydrographs. The runoff hydrographs are delayed for the SCS type II RDPs as compared to the designed RDPs. The approximate starting time for the hydrographs based on the SCS type II RDPs is after one hour from the rainfall event, while the designed RDPs indicate that runoff hydrographs are immediately started as soon as the storm events occur. The Time at peak discharges in Table 7 indicates that the peak discharge for the SCS type II RDPs relatively occurred at around one hour later as compared to the designed RDPs. The negative volume difference means that the volumes for the SCS type II RDPs are lesser than that of the designed RDPs (The designed RDPs values are always subtracted from the SCS type II RDPs values). The runoff hydrographs based on the designed RDPs are the true representatives of the excess rainfall which are proven from the flash flood events that happened in the arid regions immediately after the torrential storm event. Thus, the hydrological modelling establishes the fact the use of SCS type II RDPs in the arid regions, like Medina, is unjustified, while the designed RDPs are the true representatives of the actual events.
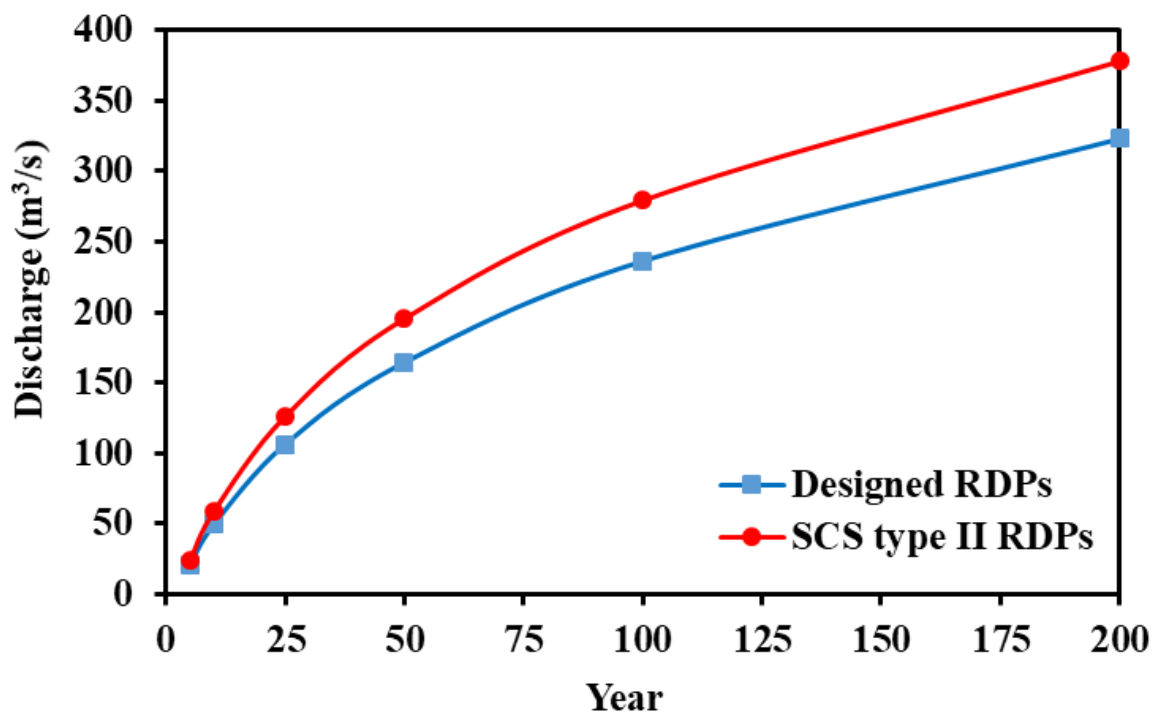

Figure 12 Comparison of peak discharges for two different types of RDPs

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Table 7 Comparisons of time at peak discharges, volumes (runoff hydrographs), and peak discharges between the designed RDPs and the SCS type II RDPs

Return period (year)	Designed RDPs			SCS type II RDPs			Difference		
	Time at peak discharge (hr)	Volume (1000 m³)	Peak discharge (m³/s)	Time at peak discharge (hr)	Volume (1000 m³)	Peak discharge (m³/s)	Time at peak discharge (hr)	Volume (1000 m³)	Peak discharge (m³/s)
5	2:45	228.6	20.5	3:30	221.6	23.9	0:45	-7.0	3.4
10	2:35	546.6	49.4	3:25	538.2	58.5	0:50	-8.4	9.1
25	2:25	1161.0	106.4	3:20	1150.0	126.1	0:55	-11.0	19.7
50	2:20	1779.0	164.5	3:20	1778.1	195.5	1:00	-0.9	31.0
100	2:15	2534.2	236.4	3:20	2532.1	279.4	1:05	-2.1	43.0
200	2:15	3437.7	323.0	3:20	3438.4	378.0	1:05	0.7	55.0

4.5. Hydraulic Modelling:

Hydraulic modelling was performed using HEC-RAS software. The peak discharges from runoff hydrographs were used as the input data. Numerous simulations were performed based on the peak discharges for two different RDPs. Hydraulic modelling plays a great role in designing new hydrological or hydraulic structures. From hydraulic modelling application, flood inundation widths, flood inundation maximum depths, minimum depths, average depths, and flow velocities were obtained for the two different types of RDPs.

Longitudinal profiles of flood flow for both types of RDPs from the hydraulic modelling are compared in Figure 13. For more detailed analysis, the different parameters like flood inundation depths, widths, areas, and flow velocities are compared in Figure 14 and for their quantitative analysis, values are summarised in Table 8-11. The values in these tables indicate the increasing trend of values for the flood inundation depths, widths, areas, and velocities. Thus, representing the overestimation of these variables when SCS type II RDPs were used. From Tables 8-11, it is evident that the differences of inundation widths, areas and velocities are more significant as compared to the inundation depths. However, the pattern of velocity profiles along the channel do not show variations, as shown in Figure 15. The velocities in the channel fluctuate as expected where the fluctuations approximately range from 1.9 to 10 m/s, for both types of RDPs (velocities of the SCS type II RDPs are comparatively higher, however, their fluctuation patterns do not show variations). The flood inundation mappings of the TU and IU channel are compared in Figures 16 and 17 for the two different types of RDPs. The mappings

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are plotted to cover the whole catchment, therefore, the differences may not be significantly evident from the figures and in addition to this, the inundation patterns are same for all mappings. The difference in the inundation depths are illustrated in their respective legends, which are also displayed in Table 8
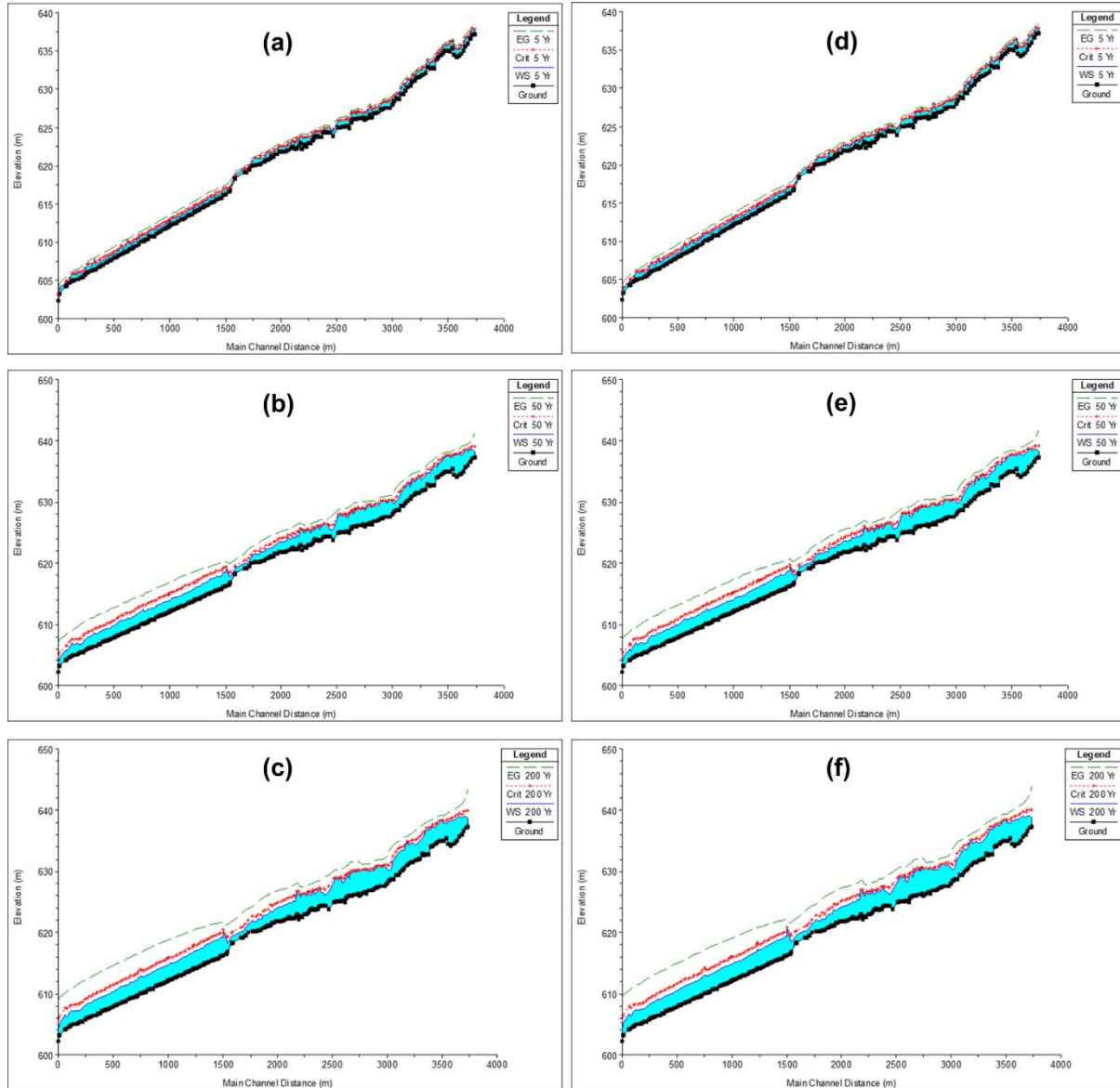

Figure 13 Comparison of the longitudinal flow profiles along the channel of the designed RDPs (sub-figures a, b, and c) and the SCS type II RDPs (sub-figures d, e, and f) for the return periods of 5, 50 and 200 years
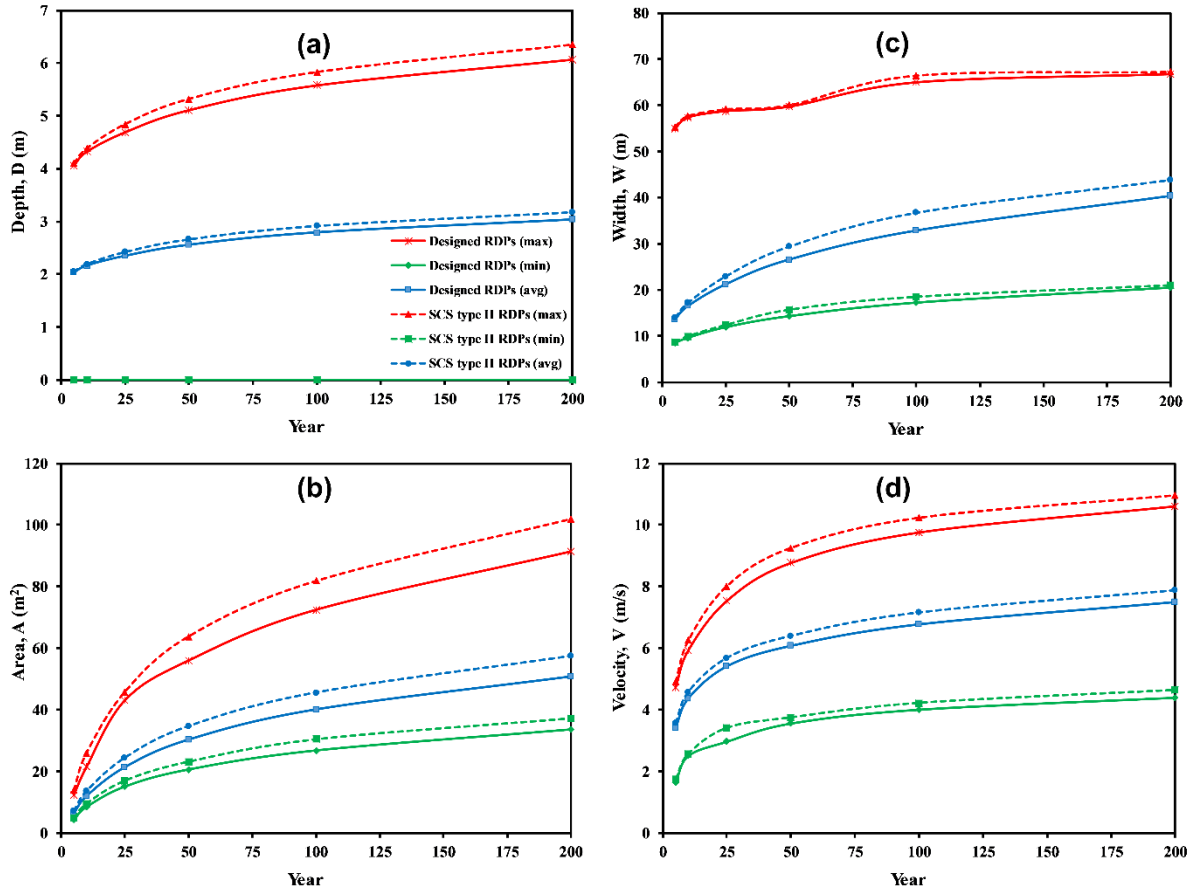
Figure 14 Comparisons of (a) flood inundation depths, (b) widths, (c) flow areas, and (d) velocities between the two different types of RDPs

Table 8 Comparison of maximum, minimum, and average flood inundation depths between the two different types of RDPs for different return periods

	Designed RDPs			SCS Type II RDPs			Difference		
Return period (Year)	Maximum depth, D_{max} (m)	Minimum depth, D_{min} (m)	Average depth, D_{avg} (m)	Maximum depth, D_{max} (m)	Minimum depth, D_{min} (m)	Average depth, D_{avg} (m)	Maximum depth, D_{max} (m)	Minimum depth, D_{min} (m)	Average depth, D_{avg} (m)
5	4.06	0.00006	2.03	4.10	0.00006	2.05	0.04	0	0.02
10	4.32	0.00006	2.16	4.38	0.00012	2.19	0.06	0.00006	0.03
25	4.69	0.00006	2.35	4.84	0.00006	2.42	0.15	0	0.07
50	5.11	0.00006	2.56	5.32	0.00006	2.66	0.21	0	0.11
100	5.58	0.00006	2.79	5.83	0.00006	2.92	0.25	0	0.13
200	6.07	0.00006	3.04	6.35	0.00006	3.18	0.28	0	0.14

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Table 9 Comparison of maximum, minimum, and average flood inundation widths between the two different types of RDPs for different return periods

Return period (Year)	Designed RDPs			SCS Type II RDPs			Difference		
	Maximum width, W_{max} (m)	Minimum width, W_{min} (m)	Average width, W_{avg} (m)	Maximum width, W_{max} (m)	Minimum width, W_{min} (m)	Average width, W_{avg} (m)	Maximum width, W_{max} (m)	Minimum width, W_{min} (m)	Average width, W_{avg} (m)
5	54.92	8.48	13.68	55.29	8.70	14.07	0.37	0.22	0.39
10	57.37	9.60	16.51	57.63	9.97	17.20	0.26	0.37	0.69
25	58.75	11.93	21.24	59.13	12.43	22.98	0.38	0.50	1.74
50	59.74	14.34	26.58	60.03	15.73	29.42	0.29	1.39	2.84
100	65.02	17.30	32.84	66.46	18.55	36.72	1.44	1.25	3.88
200	66.82	20.60	40.33	67.25	21.07	43.82	0.43	0.47	3.49

Table 10 Comparison of maximum, minimum, and average flood inundation areas between the two different types of RDPs for different return periods

Return period (Year)	Designed RDPs			SCS Type II RDPs			Difference		
	Maximum area, A_{max} (m^2)	Minimum area, A_{min} (m^2)	Average area, A_{avg} (m^2)	Maximum area, A_{max} (m^2)	Minimum area, A_{min} (m^2)	Average area, A_{avg} (m^2)	Maximum area, A_{max} (m^2)	Minimum area, A_{min} (m^2)	Average area, A_{avg} (m^2)
5	12.40	4.34	6.36	13.72	4.91	7.09	1.32	0.57	0.73
10	21.53	8.44	11.96	25.89	9.58	13.53	4.36	1.14	1.57
25	43.09	15.03	21.32	45.72	17.02	24.35	2.63	1.99	3.03
50	56.04	20.57	30.27	63.78	23.20	34.62	7.74	2.63	4.34
100	72.49	26.74	40.07	81.84	30.46	45.52	9.35	3.72	5.45
200	91.40	33.55	50.77	101.99	37.27	57.38	10.59	3.72	6.60

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Table 11 Comparison of maximum, minimum, and average velocities between the two different types of RDPs for different return periods

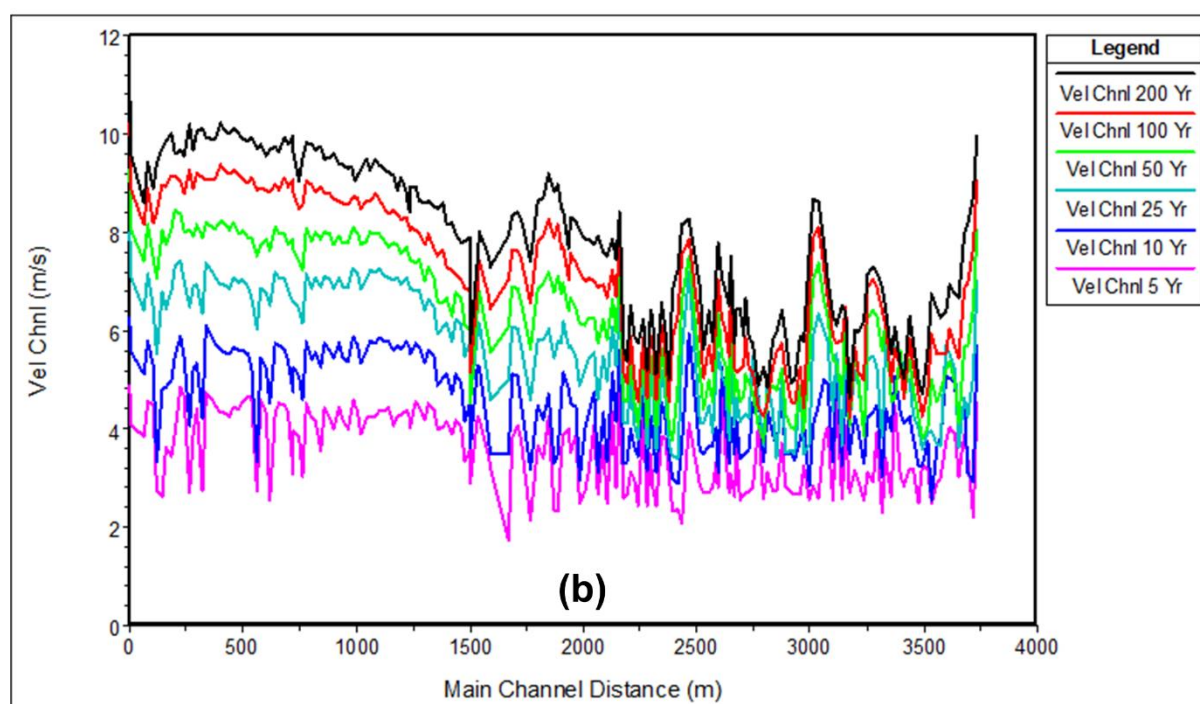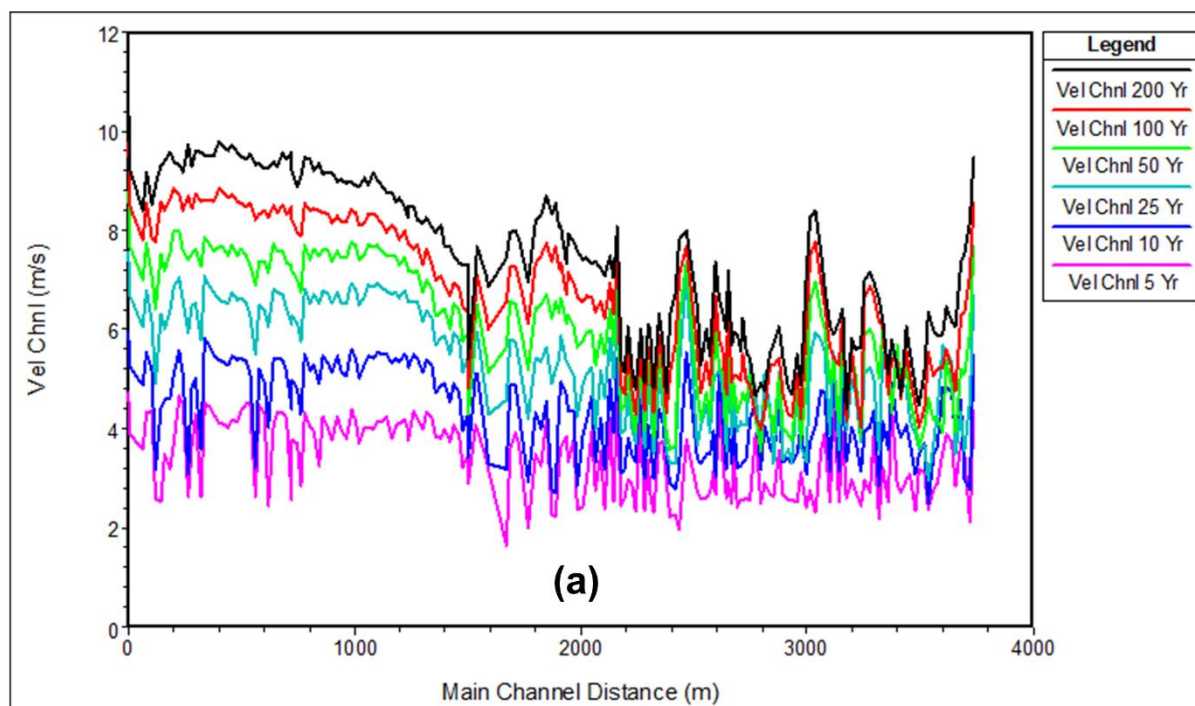| Return period (Year)	Designed RDPs			SCS Type II RDPs			Difference		
	Maximum velocity, V_{max} (m/s)	Minimum velocity, V_{min} (m/s)	Average velocity, V_{avg} (m/s)	Maximum velocity, V_{max} (m/s)	Minimum velocity, V_{min} (m/s)	Average velocity, V_{avg} (m/s)	Maximum velocity, V_{max} (m/s)	Minimum velocity, V_{min} (m/s)	Average velocity, V_{avg} (m/s)
5	4.73	1.65	3.41	4.90	1.74	3.56	0.17	0.09	0.00
10	5.94	2.51	4.37	6.25	2.57	4.58	0.31	0.06	0.21
25	7.54	2.97	5.41	8.01	3.41	5.67	0.47	0.44	0.27
50	8.77	3.56	6.08	9.25	3.75	6.39	0.48	0.19	0.32
100	9.76	4.01	6.77	10.23	4.22	7.15	0.47	0.21	0.38
200	10.61	4.4	7.50	10.96	4.64	7.87	0.35	0.24	0.37

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Figure 15 Comparison of velocity profiles along the channels between (a) the designed RDPs, and (b) the SCS type II RDPs for different return periods
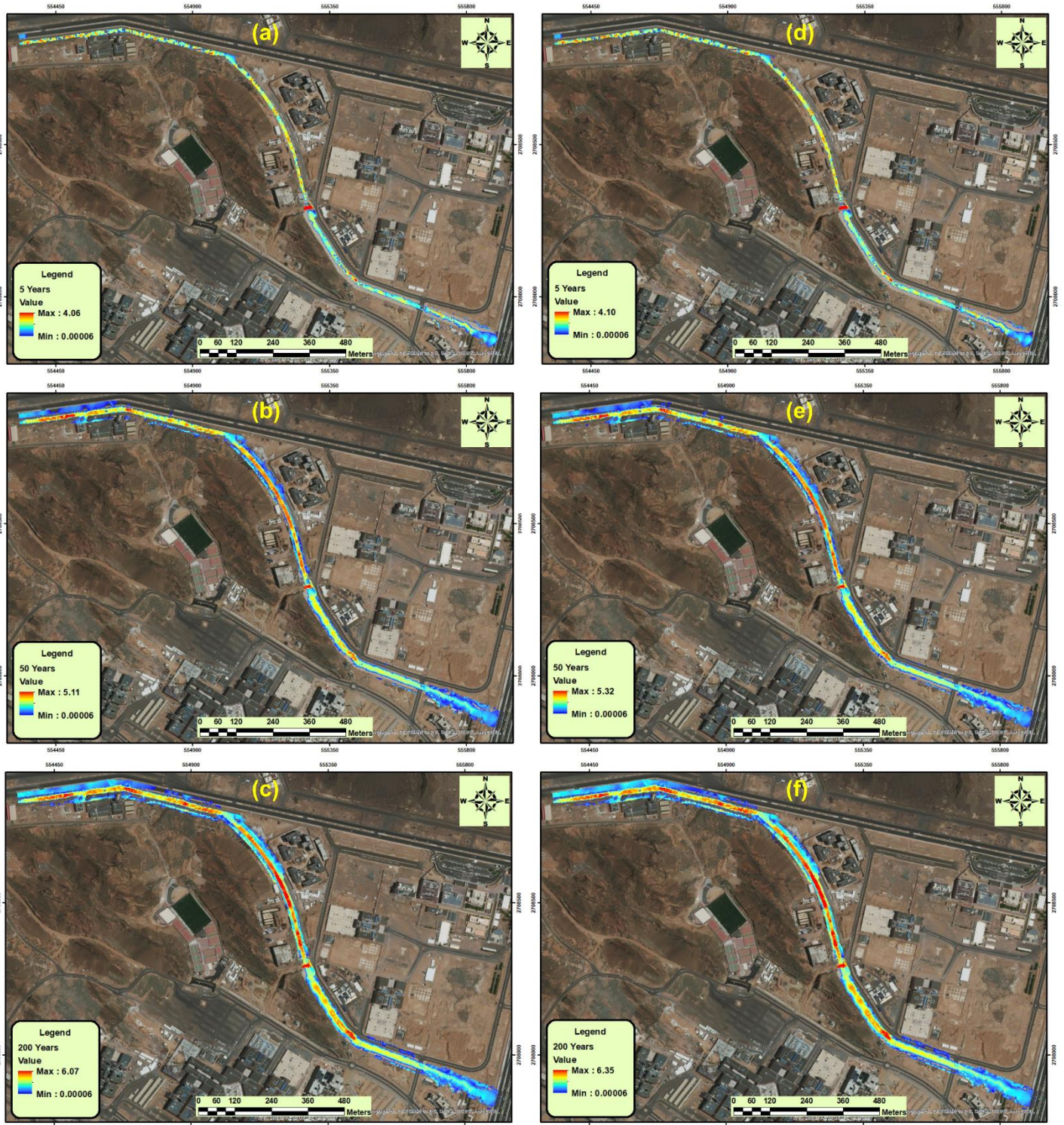
Figure 16 Flood inundation mapping of the Taibah University channel, where a, b, and c represent the return periods of 5, 50, and 200 years for the designed RDPs, and d, e, and f represent the return periods of 5, 50, and 200 years for the SCS type II RDPS, respectively

Figure 17 Flood inundation mapping of the Islamic University channel, where a, b, and c represent the return periods of 5, 50, and 200 years for the designed RDPs, and d, e, and f represent the return periods of 5, 50, and 200 years for the SCS type II RDPS, respectively

5. Conclusions:

Common practices in arid regions indicate that the SCS type II RDPs are used by the hydrologists. However, there is no scientific justification available for such practices. In this study, the two different types of RDPs were analyzed for the TU and IU catchment in Medina, which is an arid region. One of them is the designed RDPs and the other is the SCS type II RDPs. Firstly, the rigorous methodology was used for accurately comparing the two patterns. The methodology involved the collection, organizing, and evaluation of the rainfall records at the two stations (station M001 and station M103). Different types of frequency analyses were performed for statistically distributing the maximum rainfall depths for the six chosen return periods (they are 5, 10, 25, 50, 100, and 200 years return periods) at the two stations. SMADA program evaluated the different distributing techniques using the RMSE value statistical comparison. The program indicated that the 2-Parameter and 3-Parameter Log-Normal techniques generate small RMSE values as compared to the other distribution techniques at station M001 and station M103, respectively. These two techniques were used for estimating the probable maximum rainfall depths which were later distributed over the whole TU and IU catchment using the IDW interpolation technique. The maximum values of rainfall depths were used for estimating the designed RDPs from the dimensionless RDPs presented by Elfeki *et al.* (2014). These RDPs for different return periods were used for the hydrological modelling in HEC-HMS which were then compared with the SCS type II RDPs. For hydrological modelling, the watershed modelling was performed in WMS, in which the morphological characteristics were obtained together with the catchment schematic. GIS and remote sensing were used for obtaining the CN by integrating the land use and soil type characteristics of the catchment. The peak discharges for both types of RDPS were used in HEC-RAS for the hydraulic modelling for different return periods. The results of flood inundation depths, widths, areas, and velocities were compared for both types of RDPs, which indicated that the SCS type II RDPs overestimated these variables. Hence, using the SCS type II RDPs for designing the hydraulic structures will be inaccurate, unjustified and uneconomical. Therefore, the designed RDPs are the best estimated RDPs for the arid regions and should be employed in designing new water resources projects in the arid regions.

6. References:

Dilley M, Chen RS, Deichmann U, Lerner-Lam AL, Arnold M, Agwe J, Buys P, Kjevstad O, Lyon B, Yetman G. 2005. Natural Disaster Hotspots: A Global Risk Analysis. The World Bank Group.

Dullo TT, Kalyanapu AJ, Teegavarapu RS. 2017. Evaluation of Changing Characteristics of Temporal Rainfall Distribution within 24-Hour Duration Storms and Their Influences on Peak Discharges: Case Study of Asheville, North Carolina. Journal of Hydrologic Engineering, **22**: 05017022.

El- Hames A, Richards K. 1998. An integrated, physically based model for arid region flash flood prediction capable of simulating dynamic transmission loss. Hydrological Processes, **12**: 1219-1232.

Elfeki AM, Ewea HA, Al-Amri NS. 2014. Development of storm hyetographs for flood forecasting in the Kingdom of Saudi Arabia. Arabian Journal of Geosciences, **7**: 4387-4398.

Ewea HA, Elfeki AM, Al-Amri NS. 2017. Development of intensity–duration–frequency curves for the Kingdom of Saudi Arabia. Geomatics, Natural Hazards and Risk, **8**: 570-584.

Ewea HA, Elfeki AM, Bahrawi JA, Al-Amri NS. 2016. Sensitivity analysis of runoff hydrographs due to temporal rainfall patterns in Makkah Al-Mukkramah region, Saudi Arabia. Arabian Journal of Geosciences, **9**: 424.

Gheith H, Sultan M. 2002. Construction of a hydrologic model for estimating Wadi runoff and groundwater recharge in the Eastern Desert, Egypt. Journal of Hydrology, **263**: 36-55.

Guo JC, Hargadin K. 2009. Conservative design rainfall distribution. Journal of Hydrologic Engineering, **14**: 528-530.

Hershfield DM. 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. US Department Commerce Technical Paper, **40**: 1-61.

Hjelmfelt Jr AT. 1991. Investigation of curve number procedure. Journal of Hydraulic Engineering, **117**: 725-737.

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Huff FA. 1967. Time distribution of rainfall in heavy storms. Water resources research, **3**: 1007-1019.

Humphreys S, Mohrlock C, Cooper D, Paquette J, Beighley RE. 2013. Analysis of results for the county of San Diego rainfall distribution study project. Bureau Veritas North America, Inc.

Ishak EH, Rahman A, Westra S, Sharma A, Kuczera G. 2013. Evaluating the non-stationarity of Australian annual maximum flood. Journal of Hydrology, **494**: 134-145.

Kerr RL. 1974. Time-distribution of storm rainfall in Pennsylvania.

Pilgrim DH, Cordery I. 1975. Rainfall temporal patterns for design floods. Journal of the Hydraulics Division, **101**: 81-95.

Ponce VM, Hawkins RH. 1996. Runoff curve number: Has it reached maturity? Journal of hydrologic engineering, **1**: 11-19.

SCS U. 1986. Urban Hydrology for Small Watersheds, Technical Release No. 55 (TR-55). US Department of Agriculture, US Government Printing Office, Washington, DC.

Yair A, Lavee H. 1985. Runoff generation in arid and semi-arid zones. Hydrological forecasting/edited by MG Anderson and TP Burt.