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IDF curves and daily rainfall generation for Al-Madinah city, western Saudi Arabia

Ali M. Subyani[1] · Nassir S. Al-Amri[2]

Abstract Due to the increase in global warming and climate change impact, especially in urban arid regions, the intensity-duration-frequency (IDF) curves and rainfall generation procedures become essential for storm design and hydraulic structures dimensioning for future planning and management. Al-Madinah, the second holiest city for all Muslims, is located in the western part of Saudi Arabia. This city needs special attention for hydrologic and hydraulic structure projects due to highly developed and rapid expansion in land use. The purpose of this study is to develop an empirical formula from IDF curves, which have been generated from 43-year records for Al-Madinah rainfall station. The absence of some daily rainfall records led to the application of the reduction method to disaggregate daily rainfall to hourly time series for developing suitable IDF curves. The formula is derived using the analysis of the best fit of Gumbel and log-Pearson Type III frequency methods. An average empirical formula can be used for predicting any return period with a given storm duration for Al-Madinah area. Generating wet, dry, and rainfall intensities are also investigated using autorun analysis on a daily time step. The results show that the dry spell continues for 71 days while the wet spell is about 1.58 days on the average based on the rainfall intensity threshold of 5.9 mm/day. Based on the goodness of fit for the dry and wet spells and the rainfall intensities, the daily rainfall sequences can be generated for any duration, which is adopted here as for the next 43 years.

Introduction

In arid regions, knowledge of rainfall variability, intensities, shifts, and trends are important for variety of applications in water resources management under the global warming effects. This variability pattern may cause different impacts on human life and engineering structure designs (Maragatham 2011; Goyal 2014). According to the IPCC et al. (2007) report, until the end of the twenty-first century, the global temperature increase is expected to cause increase in the frequency and amount of different weather events leading to extraordinary hydrological phenomena as floods, droughts, water shortages, or stresses as well as on the agricultural productivity (Wentz et al. 2007; IPCC et al. 2012; Artlert et al. 2013).

Several studies are carried out on the analysis of rainfall variability and distribution in arid regions. For instance, Zaman et al. (2012) analyzed the regional flood frequency in an arid region (Australia) to develop growth curve to estimate design floods for the ungauged catchments with reasonable accuracy. They concluded that this may be adapted to other similar regions of the world along with the locally developed prediction equation for the scaling to derive preliminary design flood estimates. Gong et al. (2004) analyzed daily precipitation of 30 gauge stations in the semiarid area of northern China from 1956 to 2000. Their study showed that the number of rainy days is decreasing significantly at a rate of −1.56 day per 10 years, implying an increase in drought stress. They conclude that global warming and human-induced land cover

✉ Ali M. Subyani
asubyani@hotmail.com

Nassir S. Al-Amri
nalemari@kau.edu.sa

[1]   Water Research Center, King Abdulaziz University, P.O. Box 80200, Jeddah 21589, Saudi Arabia

[2]   Department of Hydrology and Water Resources Management, King Abdulaziz University, P.O. Box 80208, Jeddah 21589, Saudi Arabia

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Fig. 1 Location map of the study area
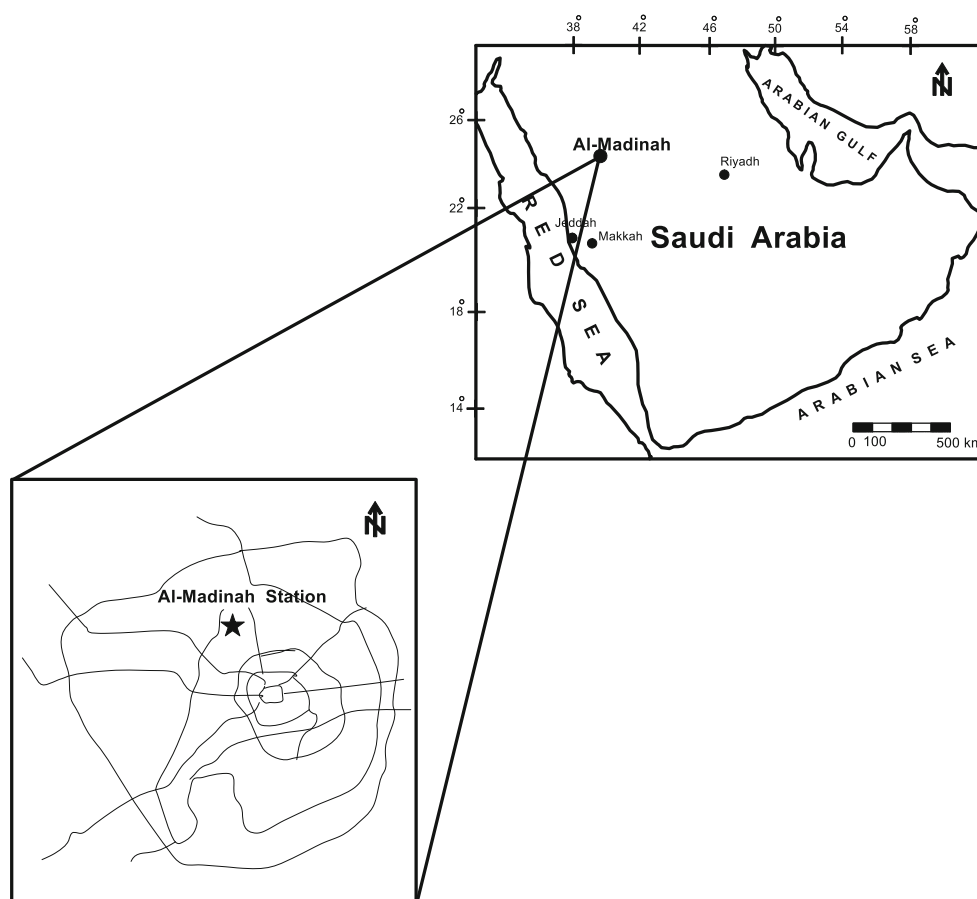
changes are supposed to be frequently related, at least partly, to the changes in precipitation.

In the Kingdom of Saudi Arabia (KSA), rainfall can be described as being little, unpredictable, and irregular but very extensive during the local storms. Almazroui et al. (2012) studied the recent climate change in the Arabian Peninsula and the seasonal rainfall and temperature climatology of KSA for 1978–2009. Surface observations indicated that, irrespective of season, rainfall insignificantly increase in the first period (1978–1993) and then significantly decrease in the second period (1994–2009). Elfeki and Al-Amri (2010) used Markov chains for modeling monthly rainfall records in KSA; they developed two spreadsheet models to check the probability distribution function (PDF) of the rainfall data at some stations and the other model is for calculating the Markov chain parameters from the data series. Alhassoun (2011) developed empirical formulae to estimate rainfall intensity in the Riyadh region, where the formula was derived using three different frequency methods (Gumbel, log-Pearson Type III, and log normal). These intensity-duration-frequency (IDF) curves are obtained for different durations and frequency periods. He stated that the derived equation could predict rainfall intensity in the Riyadh region for any return period with a given storm duration and calibrated parameters obtained from IDF curves according to a given storm duration.

Elsebaie (2012) developed a rainfall-duration-frequency relationship for two regions at Najran and Hafr Albatin regions in the KSA. Gumbel and the log-Pearson Type III of PDF frequency analyses techniques are used to develop the IDF relationship from rainfall data of these regions. Rainfall intensities obtained from these two methods showed good agreement with results from previous studies on some parts of the study area.

The western part of KSA receives a moderate amount of rainfall with long memory of dry periods due to its geographic nature and location within the subtropical zone. Subyani and Al-Ahmadi (2011) adapted runoff model from the US Soil Conservation Service and applied for the catchments of five selected ungauged dry wadis in the Al-Madinah area. Data from 16 rain gauges that have been recording the annual maximum daily rainfall for over 30 years are analyzed for derivation of the Gumbel extreme value PDF for 25, 50, and 100-year return periods. Hydrographs for different return periods are drawn using the results from this analysis along with the morphometric parameters of the wadi catchments. Regional maps of maximum probable precipitation and probable maximum flood are also produced for the study area.

Table 1 Annual maximum daily rainfall depth (mm) with number of rainy days

Year	Max. rainfall mm	No. of rainy days	Year	Max. rainfall mm	No. of rainy days
1972	16	11	1994	29.8	15
1973	1.4	4	1995	27.4	5
1974	30.1	10	1996	17	6
1975	10.5	8	1997	14.8	20
1976	12.2	15	1998	21	4
1977	3.6	4	1999	35.8	2
1978	7.7	1	2000	55	4
1979	28.2	14	2001	23.2	9
1980	8.8	4	2002	32	1
1981	26.4	6	2003	14.8	2
1982	85.2	14	2004	4.5	3
1983	24.2	5	2005	57.5	4
1984	18.2	6	2006	10.5	13
1985	27.4	6	2007	6	2
1986	26.8	9	2008	26	9
1987	4.4	8	2009	16.3	15
1988	8.5	9	2010	14.8	10
1989	30.8	16	2011	4.7	3
1990	17.3	4	2012	26.5	5
1991	6.8	14	2013	13.5	7
1992	12.8	9	2014	19.5	5
1993	89.6	21			

Subyani (2012) studied the flood vulnerability in the western part of the KSA which has extremely high spatial and temporal variability in rainfall occurrence. His study showed that the prediction of annual maximum 24-h duration rainfall along with prediction of 25-, 50-, 100-, and 200-year return periods for the best fit of Gumbel PDFs. In addition, the probable maximum precipitation is also estimated on the basis of the same PDF. He concluded that the study will aid decision-making for future project designs and flood protection studies.

Knowledge and prediction of wet and dry spell probability occurrence, rainfall variability, shifts, and trends are critical when considering the impact of the climate change and can be estimated with reliability from reasonably available records (Şen 1983; Alyamani and Şen 1992; Subyani 2004). Wet and dry sequences are treated by different authors (Lioubimtseva 2004; Şen 2009; Almazroui 2011).

Subyani and Hajjar (2014) present detailed features of dry and wet spell durations and rainfall intensity series available (1971–2012) on daily basis for the Jeddah area, in the western Saudi Arabia. Their study showed trend changes in dry and wet spell durations and rainfall amount on daily, monthly, and annual time series. Three rain seasons are proposed in this investigation as "high" rain, "low" rain, and "dry" seasons. It shows that the overall average dry spell durations is about 80 consecutive days while the average wet spell durations is 1.39 days on the basis of average rainfall intensity threshold of 8.2 mm/day. Annual and seasonal autorun analyses confirm that the rainy seasons are tending to have more intense rainfall; in general, the seasons are becoming drier.

Because of the tremendous development in Al-Madinah city and modern projects in the Prophet's Masjed and the increasing number of residents and visitors (MRSC 2013), these development projects need administrative decisions based on not only classical approaches but also additionally on consideration of the climate change and rainfall variability conditions.

The main objectives of the present study are to identify the statistical characteristic of the rainfall on daily bases and using the reduction method to disaggregate some missing daily rainfall records to hourly time series. The average empirical formula will be developed from IDF curves for Al-Madinah city using and testing different suitable methods of 10, 20, 30, 60, 120, 180, 360, 720, and 1440-min rainfall depth for different return periods (5, 10, 25, 50, 100, and 200-year). Another objective is to generate of wet and dry spells and daily rainfall amounts for the next 43 years based on the most suitable PDF fit for these sequences with best goodness of fit. The proposed methodology will be applied to the observed daily rainfall
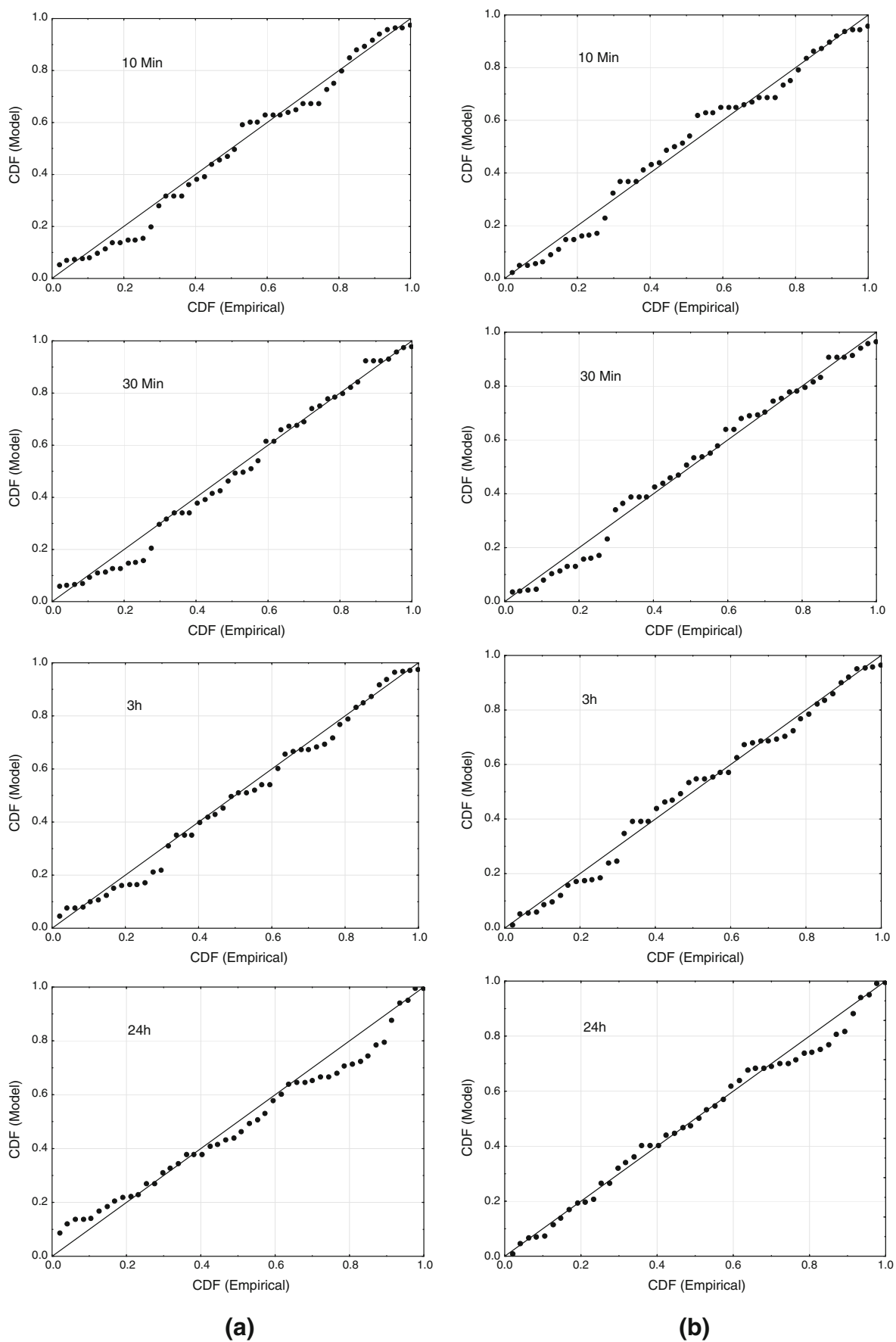
Table 2 Parameter estimation of the best fitted distributions

Duration	Gumbel					Log-Pearson Type III					
	σ	μ	K-S	Darling	χ^2	α	β	γ	K-S	Darling	χ^2
M10	2.48	3.31	0.1	0.48	2.36	16	−0.19	4.51	0.11	0.43	5.9
M20	3.3	4.5	0.08	0.31	1.42	11.5	−0.23	4.26	0.075	0.21	1.9
M30	3.75	5.32	0.1	0.41	1.84	27.6	−0.13	5.61	0.08	0.36	3.0
H1	4.78	6.86	0.08	0.36	2.08	19.5	−0.16	5.26	0.07	0.24	2.67
H2	6.57	8.87	0.07	0.31	1.3	15.74	−0.19	5.31	0.08	0.24	2.3
H3	7.28	9.7	0.08	0.36	1.8	14.6	−0.2	5.32	0.08	0.26	0.7
H6	9.6	11.3	0.1	0.41	1.18	17.2	−0.2	5.9	0.07	0.18	1.1
H12	12.1	13	0.09	0.56	2.17	15.5	−0.21	5.95	0.08	0.2	2.4
H24	14.5	14.5	0.11	0.86	1.7	13.3	−0.23	5.9	0.08	0.3	6.7

Fig. 2 P-P plot for empirical CDF values against theoretical CDF values with different durations. **a** Gumbel and **b** LPT III CDF

Fig. 3 IDF for Al-Madinah (Gumbel method)
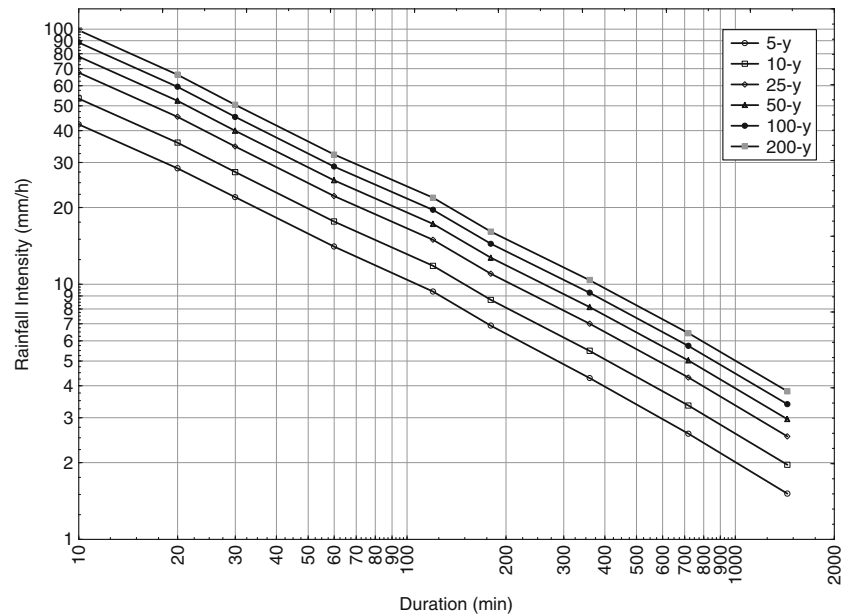
records for 1972–2014 from Al-Madinah rainfall stations located in western region of the KSA.

Study location and rainfall data

The Al-Madinah area, located in the western part of KSA, is bounded between latitude 24° 30′ and 24° 45′ N and longitude 39° 30′ and 39° 45′ E (Fig. 1). Geologically, the Al-Madinah area is a part of the mid-western Precambrian Arabian Shield, which is bounded on the west by the Red Sea rift and on the east by the Paleozoic and younger sedimentary rocks. The area is classified under predominately arid but hot summer and cooler winter seasons on the average. The mean temperature ranges from 24 to 40 °C in the summer and from 15 to 25 °C in the winter. Rainfall is sporadic, characterized by moderate to high variations in space and time. Each year, the rainy season is from October to April. The average annual rainfall is about 50 mm with some variations outside the metropolitan areas. In addition, the extraordinary increases of rainfall in frequency, occurrence, and amount are critical when considering the impact of the climate change. Al-Madinah climate station is located in Al-Madinah city with longitude 39.58° E and latitude 24.52° N, and the elevation is about 600 m above sea level (Fig. 1).

For the purpose of IDF curves and rainfall generation, 10-, 20-, 30-, 60-, 120-, 180-, 360-, 720-, and 1440-min duration rainfall data for the period 1972 to 2014 (43 years) are obtained from the Ministry of Water and Electricity, Hydrology Division (Ministry of Water and Electricity 2014) for Al-Madinah weather station (M001). Rainfall intensity ranges from 3.6 to 74 mm/h and for durations of 10 to 1440 min.

Table 1 shows the annual maximum daily rainfall for Al-Madinah station.

Unfortunately, 50 % of the rainfall intensity records are for 24 h only. However, to fill this gap and complement the data, methods suggested by Bell (1969) and Rathnam et al. (2000) are used to disaggregate daily rainfall to hourly time series. The maximum values of 24 h are converted into shorter duration (1, 2, 3, 6, and 12-h) values using the reduction formula suggested by the Indian Meteorological Department (Rathnam et al. 2000), as

$$p_t = p_{24} (t/24)^{1/3} \tag{1}$$

where, P_t is the required rainfall depth in millimeters for t-hour duration, P_{24} is the daily rainfall in millimeters, and t is the duration of rainfall for which the rainfall depth is required in hours. This formula gives the best estimation of short duration rainfall (Chowdhury et al. 2007; Awadallah et al. 2011).

Rainfall intensity-duration-frequency curves

In arid areas, rainfall does not occur uniformly; variations in its intensity occur not only from the center to the peripheries of the storm rainfall but also temporally at a given point. In many design problems related to watershed management, it is necessary to know the rainfall intensities of different durations and return periods. One of the first steps in many hydrologic design projects is the determination of the rainfall event or event to be used for design purposes. Rainfall IDF curves are derived from the statistical analysis of single storm rainfall records over a period of time and they are used to capture important characteristics of point rainfall for any desired

Fig. 4 IDF for Al-Madinah (LPT III method)
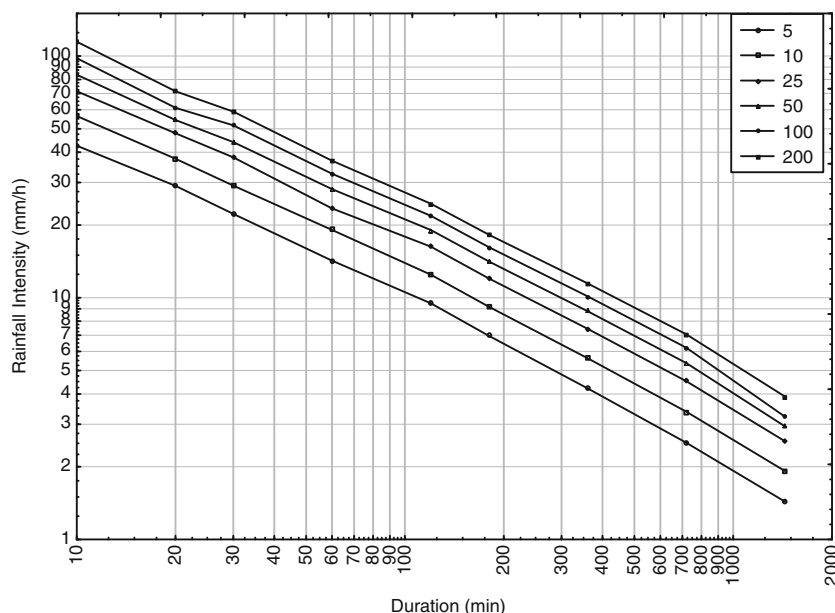
shorter durations. In other word, it is defined as the calculation of average design rainfall intensity for a given exceedance probability over a range of duration.

The IDF formula is in the form of empirical equation representing the relationship among maximum rainfall intensity, as dependent variable, and other parameters such as rainfall duration and frequency (as independent variables). The general form of IDF curves can be written as follows (Chow et al. 1988)

$$I_T = \frac{P_T}{t_d} \qquad (2)$$

where I_T is the design rainfall intensity (mm/h), t_d is the duration (hours), and P_T is return periods (years).

The typical technique for establishment of the IDF curves can be achieved after the execution of the following steps.

(a) Processing and selection of reliable of maximum annual single storm rainfall.
(b) Finding the best fit as the reliable PDF to each group of the data values for a set of specific durations.
(c) From the fitted relationships the rainfall intensity for any duration and return period can be derived.

(d) Finally, the IDF curves can be obtained in two different ways, either by plotting the intensity versus duration for different return periods or the rainfall intensity is related in functional relationship to the rainfall duration and the return period using regression analysis (Chow et al. 1988; Alhassoun 2011).

There are commonly used theoretical distribution functions that are applied in many hydrological studies. Two common distributions are used in this study, namely, (Gumbel and log-Pearson Type III PDFs).
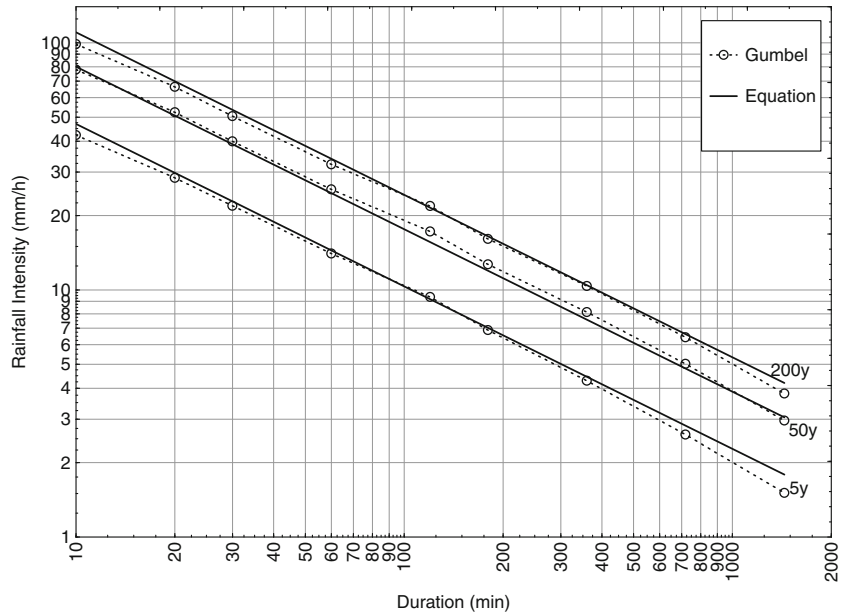
Methodology

Gumbel's method

This is one of the most widely used PDF for calculating extreme values in hydrological and meteorological studies for the prediction of extreme meteorological events such as flood peaks, maximum rainfalls, and maximum wind speed. According to this PDF, a flood is the largest of the 365 daily flows, and the annual series of flood amounts constitutes a series of flow values. Its PDF is given by,

$$p = 1 - e^{-e^{-y}} \qquad (3)$$

where p is the probability of a given flow being equal or exceeded and y is the reduced variate as a function of the convenient PDF from statistical tables. In order to obtain the frequency rainfall depth P_T (in mm) for any rainfall duration t_d (in hour) with specific return

Table 3 rainfall intensity parameters for Al-Madinah area

Method	a	m	b
Gumbel	147.1	0.231	0.657
LPT III	151.1	0.258	0.669
Average	149.1	0.244	0.66

Fig. 5 Comparison of IDF
Gumbel model and equation

period T_r (in years), it is necessary to employ the following relationship.

$$P_T = \overline{P} + K_T \sigma_P \qquad (4)$$

where $\overline{P}$ and σ_P are the mean and standard deviation of rainfall in specific duration (mm), respectively. K_T is the Gumbel frequency factor of the t given by (Chow et al. 1988) as

$$K_T = -\frac{\sqrt{6}}{\pi} \left\{ 0.5772 + \ln \left[\ln \frac{T_r}{T-1_r} \right] \right\} \qquad (5)$$

The use of Eq. 5 yields the values of $K_5 = 0.72$, $K_{10} = 1.3$, $K_{25} = 2.04$, $K_{50} = 2.59$, $K_{100} = 3.14$, and $K_{200} = 3.68$.

Log-Pearson Type III

The log-Pearson Type III PDF is particularly useful for hydrological analysis because the skew parameter enables sample fitting where other PDFs fail. The log-Pearson Type III frequency curve is characterized by three parameters. The mean represents the average ordinate, the standard deviation is for the slope of the straight line on the probability paper, and the

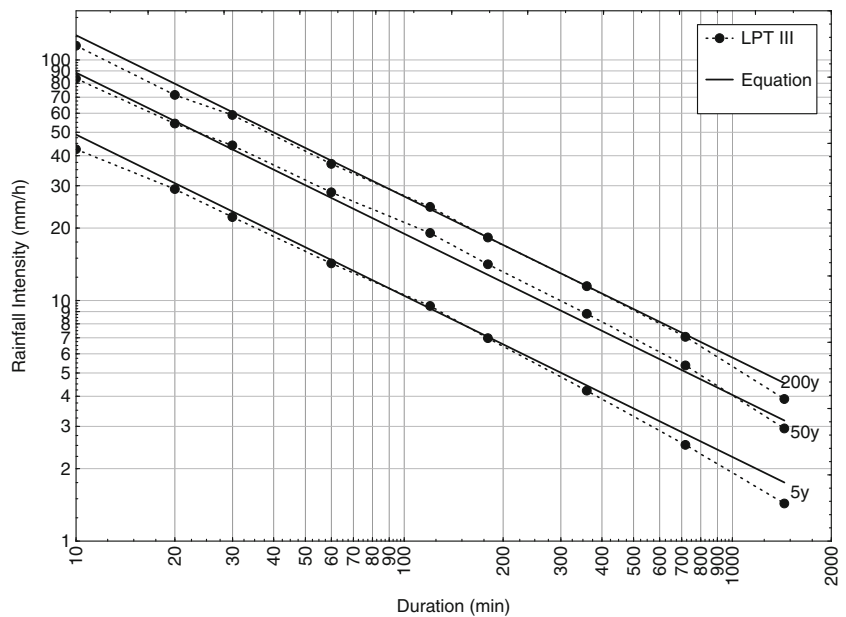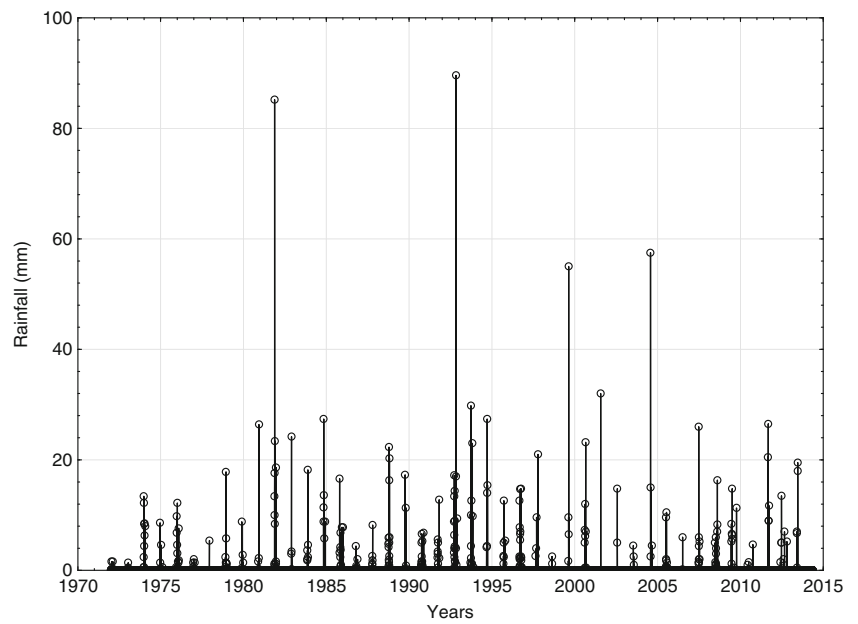**Fig. 6** Comparison of IDF LPT
III model and equation

Fig. 7 Daily rainfall series of Al-Madinah station (1972–2014)

skew coefficient corresponds to represents the degree of curvature. However, this technique is mainly based on the use of log-transformed data. The following equations have been used extensively in the literature (Zaman et al. 2012; Elsebaie 2012).

$$\overline{\log x} = \frac{\sum \log x}{n} \tag{6}$$

$$\sigma_{\log x} = \sqrt{\sum \left(\log x - \overline{\log x}\right)^2 / (n-1)} \tag{7}$$

$$G = n \sum \left(\log x - \overline{\log x}\right)^3 / (n-1)(n-2)(\sigma \log x)^3 \tag{8}$$

The value of **x** for any recurrence interval is calculated by the following expression:

$$\log x = \overline{\log x} + k\sigma_{\log x} \tag{9}$$

After obtaining rainfall values by one or two of the above methods for different return periods, chi-square, Anderson-Darling, and Kolmogorov-Smirnov (K-S) tests are carried

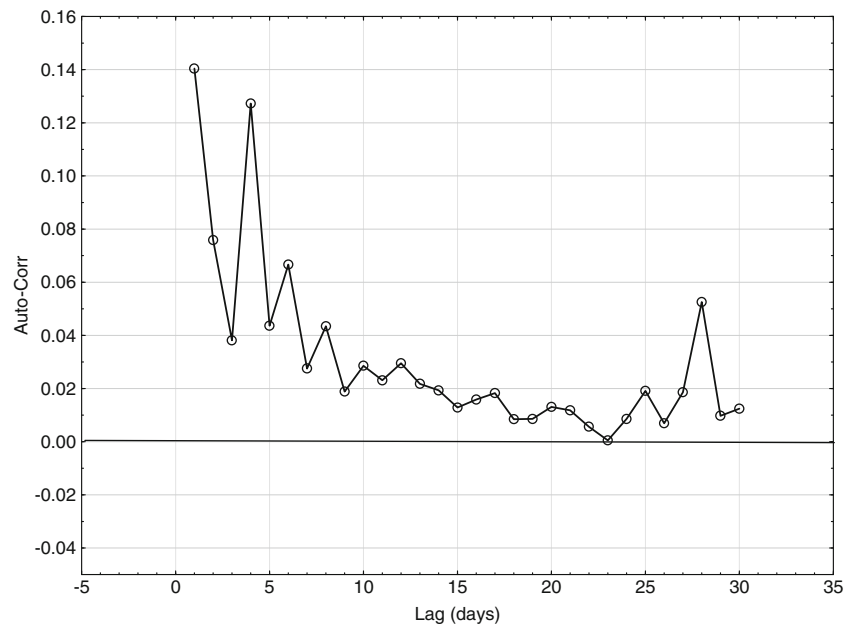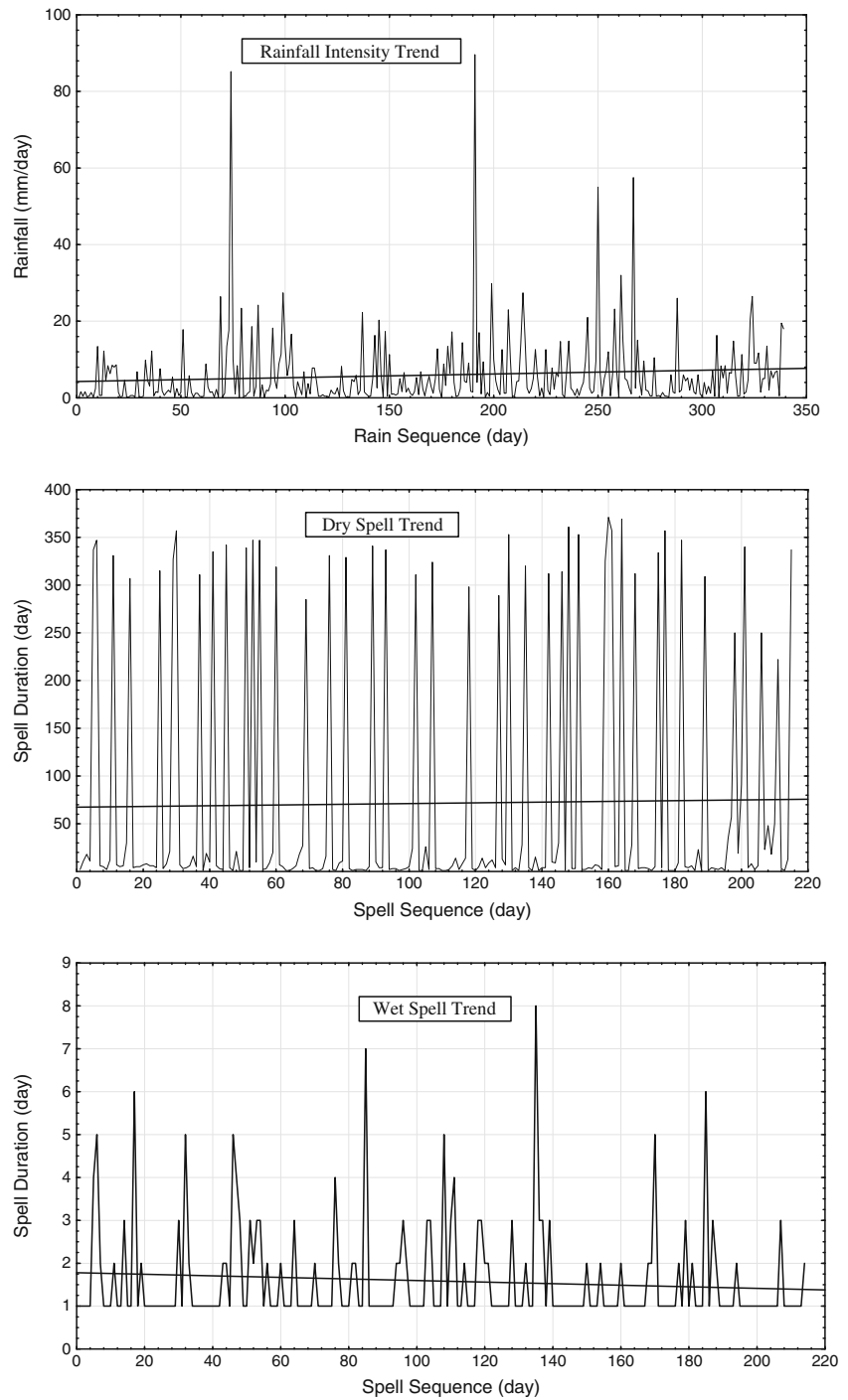**Fig. 8** Autocorrelation functions of daily rainfall

Fig. 9 Trends for rainfall
intensities and dry and wet spells

out to assess the "goodness of fit" in addition to visual inspections for graphical comparisons.

IDF curve results

EasyFit software (EasyFit Professional 2009) is used in this work. Table 2 shows the model parameters and goodness of fit for both Gumbel and log-Pearson Type III PDFs. According

to goodness of fit (K-S, Darling, and chi-square tests), it is observed that there is no big difference between them. P-P plot is also used to determine how well a specific distribution fits to the observed data. An example of P-P plot for empirical CDF values against theoretical cumulative distribution function (CDF) values for 10-min, 30-min, 3-h, and 24-h durations is shown in Fig. 2. Within all rainfall durations and high rainfall values, the matching curves for both Gumbel and LPT III

Table 4 Statistics for dry and wet spell durations and rainfall intensities

	Mean	Median	Max	Std
Dry spell (days)	71.4	6	371	128.5
Wet spell (days)	1.58	1	8	1.16
Rainfall (mm/day)	5.9	2.4	89.6	9.7

Table 5 Trends for dry and wet spells and rainfall intensities with MK test

	Trend	p value
Dry spell	0.04	0.653
Wet spell	−0.001	0.26
Rainfall	0.01	0.0001

are acceptable, where the high rainfall durations (e.g., 3 and 24 h) and low rainfall values, LPT III is a more reliable CDF. However, due to the climate change report (IPCC et al. 2007, 2012) it is better to take the most risky case and its corresponding numerical value in any design business. From this point of view, the best fit appears with log-Pearson Type III PDF.

Figures 3 and 4 show the IDF curves on logarithmic scale for Gumbel and log-Pearson Type III methods, respectively. For any storm design, it is recommended to use LPT III method.

Empirical IDF formula

From the previous results, empirical IDF formula for IDF for Al-Madinah area can be related using a derived equation in power law (Koutsoyiannis et al. 1998; Alhassoun 2011) as,

$$I_T(\text{mm/h}) = \frac{aT_t^m}{t_d^b} \tag{10}$$

Table 3 shows the results of the empirical parameters from Gumbel and LPT III methods and the average. Finally, the general average IDF formula in Al-Madinah city for any design storm can be derived in the following form,

$$I_T(\text{mm/h}) = \frac{149T_t^{0.24}}{t_d^{0.66}} \tag{11}$$

To compare between the results from IDF-derived equation (Eq. 11) and the models, Figs. 5 and 6 show an example of these results (T_r = 5, 50, 200-year) for Gumbel and LPT III methods, respectively. In conclusion, the average formula (Eq. 11) could be accepted for storm design in Al-Madinah city.

Daily rainfall generation

Daily rainfall data time series of Al-Madinah stations is presented in Fig. 7, which shows the high variations in rainfall amounts throughout the 43 years (1972–2014) as the normal situation in arid regions. Statistically, the daily rainfall mean of rainy days is 0.13 mm/day with a standard deviation of 1.66 mm/day. This general statistics may not be informative; a better statistics would be to separate the rainy days data from the dry ones. The expected mean of rainy days is 5.9 mm/day and standard deviation is 8.32 mm/day.

Autocorrelation function (ACF) may give a better statistics of rainfall variability in this study. It is calculated for 10 years
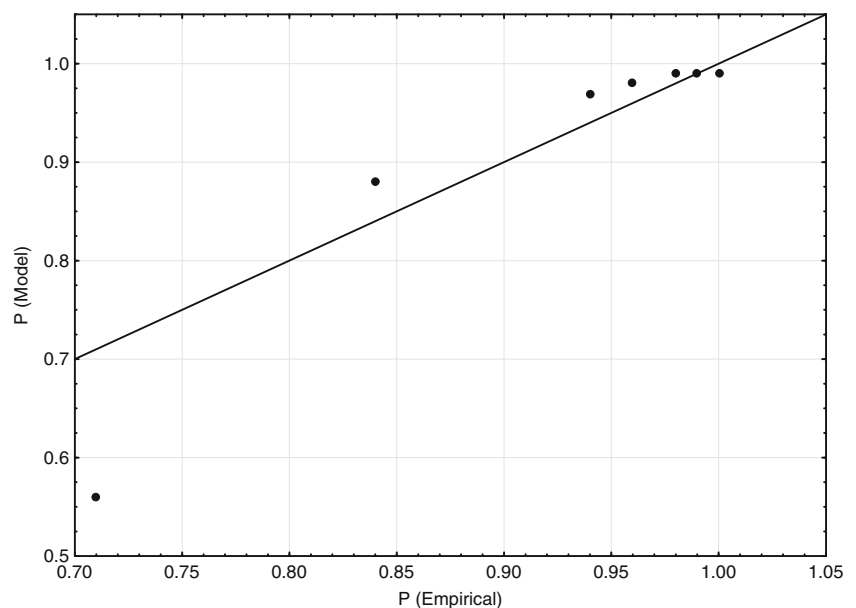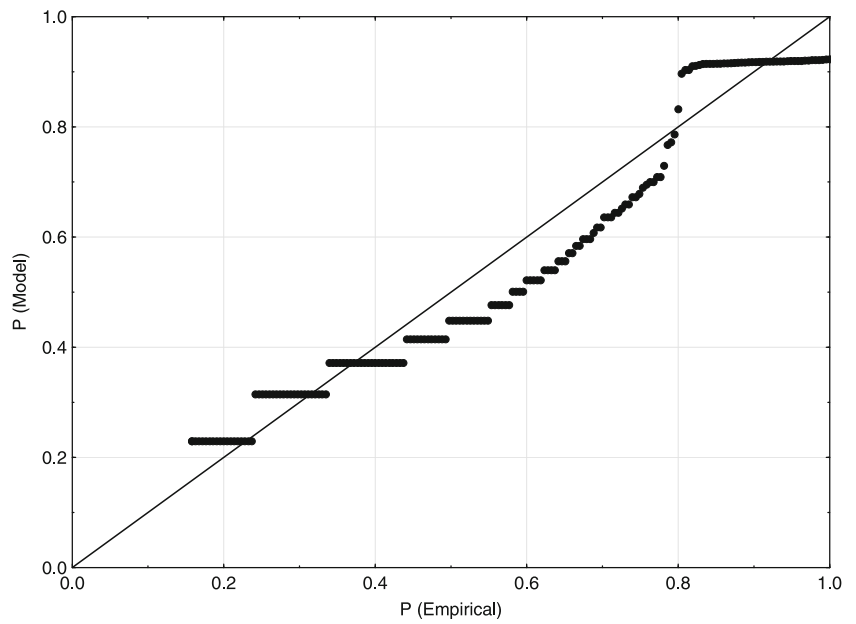
Fig. 10 P-P plot for empirical CDF values against Poisson CDF values for wet spell

Fig. 11 P-P plot for empirical
CDF values against log-logistic
CDF values for dry spell

as shown in Fig. 8. This figure shows weak annual repeatability and no significant correlation values (<0.2).

Autorun daily rainfall

To analyze daily rainfall, a mechanism for synthetic daily rainfall generation for Al-Madinah rainfall station needs to preserve the historical wet and dry spell properties. Such a generating model of synthetic sequences requires identification of a suitable PDF model (Şen 1985; Subyani and Hajjar 2014). In addition to the classical statistical parameters and serial correlation coefficients, the wet and dry period statistics are also considered as they are estimated from the available historical sequences.

Spell durations statistics

From the daily rainfall data, the dry and wet spell durations are extracted as well as the rainfall intensity of the rainy days. Data are truncated at zero rainfall level in this study. The general statistics are shown in Table 4. As can be seen, the overall average dry spell duration is 71 consecutive days,

Fig. 12 P-P plot for empirical
CDF values against LPT III CDF
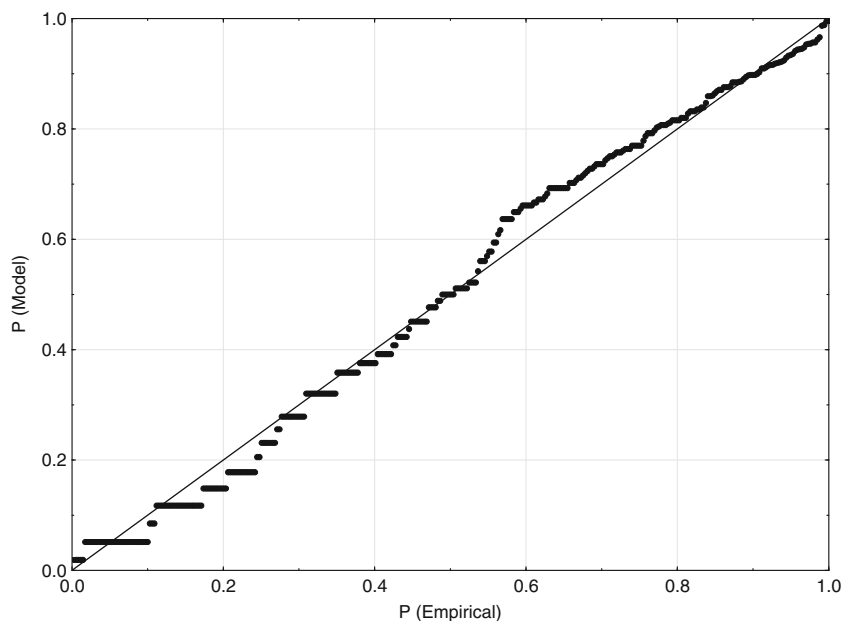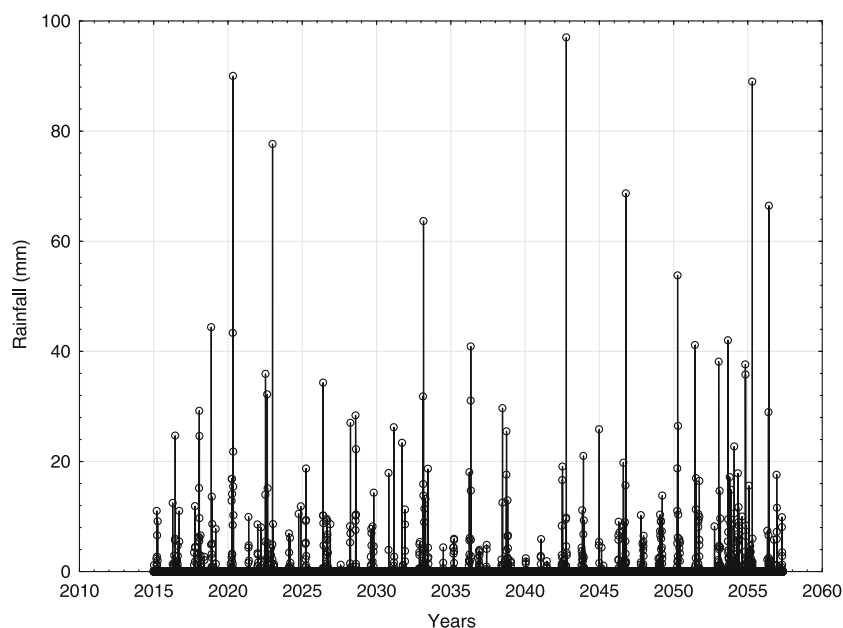values for rainfall intensities

Fig. 13 Daily rainfall generation (2015–2058)

while the wet spell durations average is 1.58 days with rainfall intensity of 5.9 mm/day. From the maximum values for both wet and dry spells, one can find that it did not rain at all for 371 days (almost 1 year) at Al-Madinah station, while at most it rained consecutively for 8 days. The median values give better statistics when extreme values occur in the data. It can be seen that the dry and wet spell durations have medians of 6 days and 1 day, respectively.

When analyzing the dry and wet spell durations and the rainfall intensity over the years, the trend is observed at Al-Madinah station (Fig. 9). Table 5 lists the trends along with its Mann-Kendall p values for testing them. On average, the dry spells have positive trends towards longer days (0.04). For the wet spells, there is a negative trend, which means that the rainfall days with more rainfalls are expected in the future due to global warming and human activities. For the rainfall intensities, there are positive trends but they are not significant. In addition, these figures may support the effect of climate change.

Spell duration distributions

For rainfall generation, the essential step is to find the best probability mass function (or density function) for the dry and wet spell durations as well as the rainfall intensities of the rainy days. Besides, the search for fitting suitable distributionsis an essential step in the any rainfall generation. Utilizing the professional statistical software package (EasyFit software EasyFit Professional 2009), which includes numerous distribution functions, exhaustive fittings are performed on the data. One can notice that the dry and wet spell durations

are integer numbers with a minimum of 1 day, while the rainfall intensity is a continuous positive non-zero number.

Results of the best fittings adopting Kolmogorov-Smirnov (K-S) goodness of fit for the dry spells, wet spells, and the rainfall intensities are as follows.

- Dry spell duration is best distributed as log-logistic with parameters $\alpha = 0.625$, $\beta = 6.96$, and $\gamma = 1$.
- Wet spell duration is best distributed as according to Poisson with $\lambda = 1.584$.
- Rainfall intensities are best distributed as log-Pearson Type III with $\alpha = 265.5$, $\beta = -0.09$, and $\gamma = 24.8$.

P-P plot is also used to determine how well a specific distribution fits to the observed data. Figures 10, 11, and 12 show the P-P plot for empirical CDF values against theoretical CDF values for dry spell duration, wet spell, and rainfall intensities, respectively. By combining these three distributions, the random number of daily rainfall is generated for the next 43 years (2015–2058) as shown in Fig. 13.

Conclusion

Detailed characteristics of the observed daily rainfall series available in Al-Madinah area are investigated over the period of 1972–2014 (43 years). The main objective of the present study area is to develop a suitable formula for storm design in different rainfall intensities and different return periods; in addition, generating 43 years of wet and dry spells and daily rainfall amounts are adapted using the most suitable probability distribution function (PDF) model fit for these sequences

with best goodness of fit. This study shows generated intensity-duration-frequency (IDF) curves using different rainfall intensity analyses to find an equation for describing storm design. Disaggregation of daily rainfall to hourly time series using reduction method is helpful to find suitable PDF for analysis. The results show no remarkable difference between Gumbel and LPT III methods. An empirical formula for storm design is developed for various durations and different return periods for Al-Madinah area. This formula is recommended for design duration for planning storm water structure in Al-Madinah area.

On the other hand, autorun analysis is implemented in this study to investigate the properties of the dry and wet durations and rainfall intensities. However, the study shows that the overall average dry spell durations is about 71 consecutive days while the average wet spell durations is 1.58 days with an average rainfall threshold intensity of 5.9 mm/day. From trend analysis, the dry spells have positive trends towards longer days. For the wet spells, there is a negative trend, which means that the rainfall days are bound to have more intense rainfalls in the future due to global warming and human activities.

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