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Research paper

Development of precipitation intensity-duration-frequency curves for litani river basin - Lebanon

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Abstract

Most countries in the Middle East region lack the availability of rainfall data and relationships for the rainfall durations and frequencies. In this study, the daily rainfall data collected from Lebanese Agricultural Research Institute and Beirut Airport Weather Forecast for five stations in Litani River Basin-Lebanon over a period of twenty-three years are analyzed. SCS Type II rainfall distribution was adopted for short duration intervals. Gumbel, Normal, and the Log Pearson Type III distributions are used to develop the relationship between the rainfall intensity, storm duration, and return periods. Chi-Square test is used to confirm the suitability of the fitted distributions. Results obtained using Log Pearson and Gumbel distributions are very close and are more applicable compared to that of the Normal Distribution. Also, results show that IDF equations of Kimijima and Sherman may fit well at all stations.

Keywords: *Rainfall; Litani River; IDF Curves; Rainfall Intensity; Distribution; Rainfall Probability Distribution Semicolon.*

1. Introduction

Rainfall Intensity–Duration–Frequency “IDF” relationship is a scientific relationship that estimates the rainfall intensities, i (mm/hr) of different storm durations, d (min), and return periods, T (the annual frequency of exceedance). The first step in any hydrologic and hydraulic design is the determination of the design rainfall depth or intensity. Intensity-Duration-Frequency relationships predict the intensity of rainfall of given duration of storm having desired return period [4].
The establishment of such relationship, based on statistical frequency analysis, was done as early as in 1931 (e.g., Sherman, 1931; Bernard, 1932) [5]. Since then, many sets of IDF mathematical equations have been developed for several regions of the world (e.g., Dickinson, 1977; Al-Sobayel, 1983; Al-Dokhayel, 1988; Kothyari and Garde, 1992; Froehlich, 1995; Ferro and Bagarello, 1996, Nhat, L.M, 2006). Methods other than frequency analysis were also used to develop the IDF relationships like generalized formula and scaling theory of rainfall. Since 1969, a generalized IDF formula was proposed by Bell using an index of one hour and 10 years rainfall depths (P_1^{10}) then chen (1983) further developed a new generalized IDF formula based on three rainfall indexs (P_1^{10}, P_{24}^{10}, and P_1^{100}) for any location in united states with the subscript indicating the rainfall duration and the superscript as the return period [1], [2]. Gupta and Waymire (1990) characterized the probabilistic structure of the precipitation process by utilizing the concepts of simple and multiple scaling. Also Koutsoyiannis and Foulfoula-Georgiu (1993) constructed storm hyetographs by using the concept of scaling theory. A multifractal point of view in developing rainfall Intensity-Duration-Frequency curves was used by Bendjoudi et al. (1997) [8]. Rosso and Burlando (1990), and later Burlando and Rosso (1996) studied traditional forms of Depth-Duration-Frequency relationships by using scaling theory concept [7].
However, such Intensity-Duration-Frequency relationships have not been built in many developing countries. There is a high necessity for IDF curves in the developing regions, but unfortunately, the availability of long historical records, at different time intervals, are frequently not exist. For this reason, forecasting, prediction and simulation of the rainfall events at all scales both in time and space is a great challenge for the hydrologists and meteorologists in these developing countries.
The main objectives of this study are to construct IDF relationships, for the different metrological regions in Litani Rivr Basin, by finding the best probability distribution function for the available daily rainfall data by chi-square test [6] (Chi-Square test is a statistical tool used to test the agreement of fit and whether the frequencies of occurrence in a sample and the expected frequencies obtained from the hypothesized distributions have significant statistical difference or not) as well as to develop short duration rainfall IDF curves based on SCS Type II- 24 hour’s storm distribution for various return periods. (SCS Types are the expected percentage breakdown of different storm events as per USA Geological Survey Department -USDA SCS, 1955) [11].

2. Study area

Because of its location on the eastern edge of the Mediterranean, weather in Lebanon is characterized by having a Mediterranean climate of a wet cold winter and a long hot dry summer. The variation of the topography within the basin creates different metrological patterns with average rainfall ranging between 900 mm in mountainous region especially in the north and 200 mm in Bekaa valley (the southern and eastern regions). The catchment of interest in this study is the Litani River watershed (33°20'12.00" N 35°14'25.80" E – Fig. 1). This River is considered as being the main water resource in Lebanon from one hand and a good representative of the Mediterranean Basin's response to climate change from the other hand. [14]

The Litani is the biggest river in Lebanon long and width, with approximately 170 Km length and annual water capacity of 750 Mm^3. Numerous activities and studies were led to profit by this waterway by generating hydroelectric energy and supplying irrigation and drinking water to the Bekaa district, the south and the seaside zones with vision to improve both the electrical and the agricultural sectors [14].

The Litani's Basin area is about 2,175 km^2, it represents 20% of Lebanon's area; the area of the basin is distributed between Bekaa valley (about 80% with semi-arid climate) and South Lebanon (about 20% with coastal climate). The average annual rainfall in the basin is 700 mm/year, or about 764 $M.m^3$. 71% of the annual precipitations (543 M.m3) feeding the Qaraoun dam and the remaining 29% (221 $M.m^3$) feeding the rest of the dams [9].

The Litani River derives most of its discharge from Al-Oleik sources, at approximately 1000m attitude to the west of of Baalbek. The Litani River passes from North to South through the Bekaa Valley conserving an altitude ranging between 800 to 1000 meters. At an attitude of 800m, the upper and the lower Litani basins are separated by an artificial lake (Qaraoun Lake) of 11 km^2. Downstream the Qaroun dam, the river run about 40 km with steep slope then, at Al-Khardali bridge, it starts to turn towards west at an altitude of 235 m near Deir Mimas village where it is called "Qasimiya River" which pours into the Mediterranean Sea about 8 km to the North of Tyre city [14].

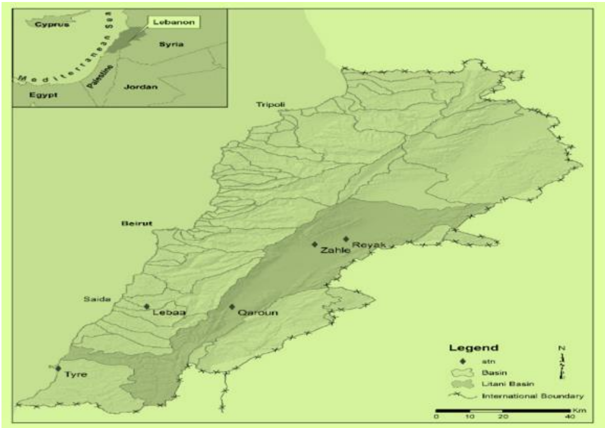


Fig. 1: Litani River Basin and Weather Stations.

3. Data collection

Daily rainfall data, from the period of 1998 to 2020, are collected from Lebanese Agricultural Research Institute (LARI) and Beirut Airport Weather Forecast, with five different stations scattered along the southern part of Lebanon as shown in Figure 1, to represent the different basin metrological conditions. The Location and the length of the records of rain gauges, at each station, are shown in Table 1. The annual peak daily rainfall records are extracted from the available daily data.

Like most developing countries, Lebanon lacks the historical rainfall data of short durations and consequently the IDF curves. With the aim of deriving short rainfall data from the available maximum daily records; a comparison was made between short records derived using SCS-Type I, SCS-Type II, Indian Metrological Formula [12] and the extreme rainfall storms observed during the period between Sept 2017 to April 2020 using four tipping bucket rain gauges.

The comparison (as described in the methodology, part a) shows that SCS-Type II Distribution is more suitable for deriving sub-hourly rainfall data from the available daily records. Therefore, the available daily rainfall data, at each station, are used later to develop the sub-hourly and hourly rainfall records using SCS-Type II method.

Table 1: List of Weather Stations Used in This Research

Station	Latitude	Longitude	Elevation	Records Period
Tyre	33 °15’ 46’’	35 °12’ 55.7’’	5.80 m	1997-2020
Lebaa	33 °32’ 55.38’’	35 °27’ 10.54’’	359.6 m	1999-2020
Qaroun	33 °32’ 50.58’’	35 °40’ 55.07’’	870.2 m	1998-2019
Zahle	33 °50’ 7.22’’	35 °54’ 15.24’’	941.8 m	1999-2020
Reyak	33 °51’ 36’’	35 °59’ 17.34’’	914.4 m	1998-2020

4. Methodology

Three commonly frequency analysis techniques (typically used in Hydrological studies) are used to develop Intensity-Duration-Frequency curves from rainfall data for Litani River Basin in Lebanon. These techniques are Log Pearson Type III, Gumbel and the Normal, distributions. These distributions are used to develop the IDF curves for nine different time intervals (15, 30, 45, 60, 180, 360, 540, 720, 1440 mins.) and six return periods (2, 5, 10, 25, 50, 100 years). The best statistical distribution among them is chosen based on the chi-squared goodness-of-fit test. The IDF curves for each station are constructed by using Talbot, Bernard, Kimijima, and Sherman equations. The parameters of the four empirical equations are selected based on the minimum of the Root Mean Square Error (RMSE) between the rainfall intensity, $I_{d,}^{T}$ produced by the statistical frequency analysis method and that calculated by the IDF equations.

4.1. Estimation of short duration rainfall

In order to breakdown daily rainfall to shorter durations of 0.25, 0.5, 0.75, 1.0, 3.0, 6.0, 9.0, 12.0, and 18.0 hours, a model is generated such as the maximum daily rainfall records are used to derive the sub-hourly and hourly data based on three methods : SCS Type I, SCS Type II (Fig. 2 - USDA SCS, 1955) and the well-known Indian Metrological Formula, $P_t = P_{24}\left(\frac{t}{24}\right)^{\frac{1}{3}}$ (where, P_t is the max. rainfall depth in mm at time, t, and P_{24} is the max. 24 hours rainfall depth in mm) [12].

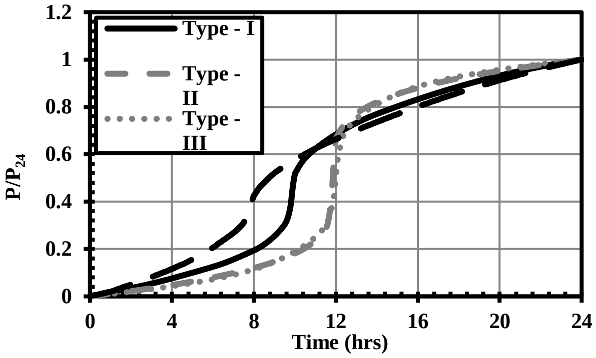


Fig. 2: Types of SCS Storms Distribution (After USDA SCS, 1955) [11].

Breaking down data shows the analogy between the SCS-Type II (which is recommended for use in relatively arid regions of the USA and considered the most conservative design storm) and IMF (Indian Metrological Formula). To check the validity of this approach, maximum sub-hourly and hourly records, measured by four rain gauges (installed at the same stations from Sept. 2017 to April. 2020) are compared to the hourly rainfall data derived using IMF, SCS-Type I, SCS-Type II for equal daily depths at all stations (25 comparisons are made at each duration).

Fig. 3 shows an example of comparing derived sub-hourly and hourly rainfall data using SCS-Type I, SCS Type II and IMF with the rain gauges measurements at Tyre station in 2019 for the same extreme daily record.

Comparisons of 25 extreme storms, measured from Sept 2017 to April 2020, show that SCS Type I is the storm distribution of lowest average error 4.37%, however it underestimates the rainfall observations for 36% of the storms, while the IMF formula underestimates the observations for 24% of the compared storms and finally the SCS Type II although its average error is 8.3% which is a little high but it has the best overall estimation for the rainfall observations. In this study SCS Type II distribution is adopted because it gives the highest rainfall intensity and more conservative than the other rainfall distribution methods. Besides, it is commonly used in the Middle East region codes of practice [13].

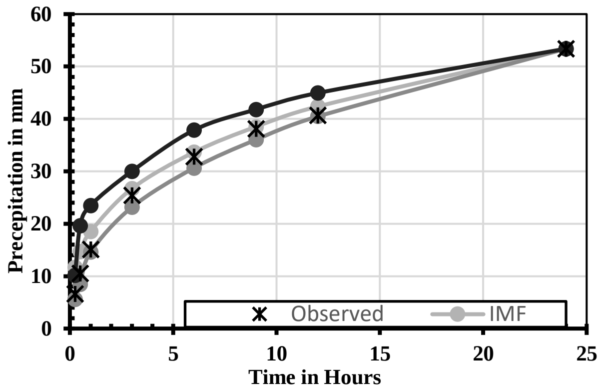


Fig. 3: Comparison between Derived Sub-Hourly and Hourly Rainfall Data Using SCS Type I, SCS Type II, IMF and Recorded Rain Gauge Data Collected at Tyre Station in 2019.

4.2. Fitting probability distribution to data series

The typical method for developing the IDF curves of precipitation is usually done by three steps as shown in Fig. 4. The first step is to find an appropriate probability distribution to the available rainfall data series. Three common frequency functions are used here: Normal distribution, Gumbel distribution and Log Pearson III distribution. These frequency functions are used to find the relationship between maximum rainfall intensity (i, mm/hr), storm duration (d, minutes) and recurrence interval (T, years). For example, Fig. 5 shows the probability distribution functions for 24 hrs rainfall series at Reyak station. The chart shows the best fitting of Log Pearson III Distribution at this station. Once a best representative cumulative frequency is selected for each data series, the maximum rainfall intensity is determined using the chosen theoretical distribution function (e.g. Gumbel, Log Pearson type III, Normal distributions). In the second step, the probability distribution functions, derived in the first step, are used to calculate the rainfall intensities for each duration and a set of selected return periods (e.g. 5, 10, 25, 50,100 years, etc.). Finally, in the third step, the rainfall IDF curves are constructed by applying the least-square method to calculate the parameters of the four empirical IDF equation (as described later in section 5.4).

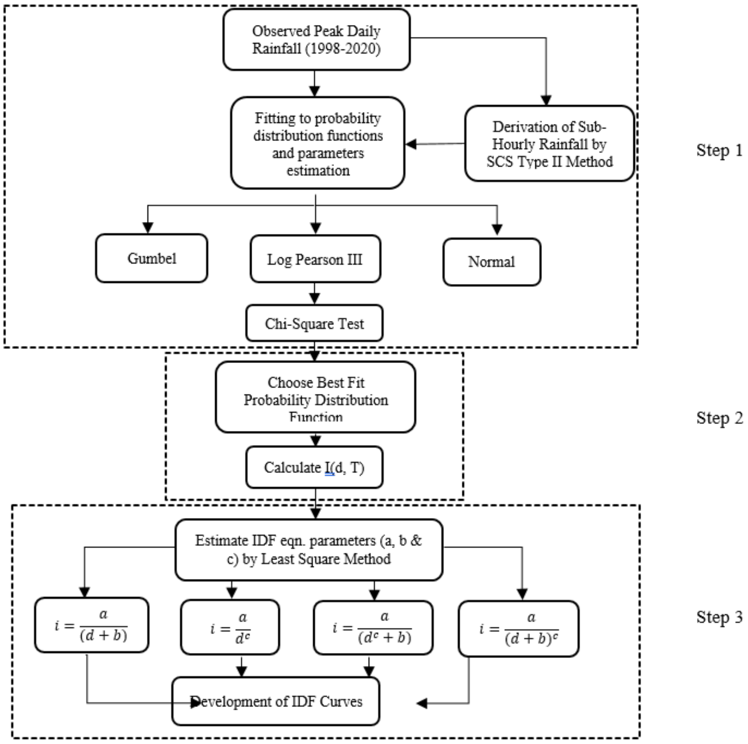


Fig. 4: Flow Chart for the Development of IDF Relationships.

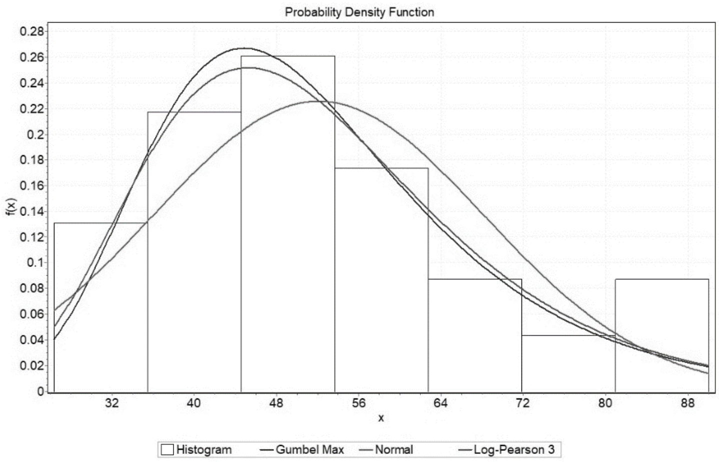


Fig. 5: 24 Hours' Rainfall Histogram and Probability Density Functions (Gumbel, Normal & Log Pearson II) at Reyak Station.

4.3. Chi-squared method

A goodness-of-fit test between observed and expected frequencies is based on the chi-square quantity, which is expressed as,

$$X_c^2 = \sum_i^k \frac{(O_i - E_i)^2}{E_i} \quad (1)$$

Where, E_i and O_i represent the expected and observed frequencies, respectively and k represents the number of categories. If the raw data (annual peak rainfalls) frequencies are close to the corresponding frequencies obtained from the probability distribution function, the X_c^2 value will be less than the chi-square critical value, indicating a good agreement of fit; the smaller the X_c^2 value the more representing of the probability distribution. If X_c^2 value is greater than critical value, then the probability distribution function considered as poor or not representative.

4.4. IDF empirical equations

The following equations are the empirical form of the IDF relationship used in this study [13]:

Talbot equation: $i = \frac{a}{(d+b)}$ (2)

Bernard equation: $i = \frac{a}{d^c}$ (3)

Kimijima equation: $i = \frac{a}{(d^c+b)}$ (4)

Sherman equation: $i = \frac{a}{(d+b)^c}$ (5)

All these equations are commonly used in the design of hydraulic & hydrological structures. the parameters of the four empirical IDF equations are determined by using the least-square method.
where, i is the rainfall intensity in mm/hour, d is the rainfall duration in minutes. a, b and c are the fitting parameters.

5. Results and analysis

From the available rainfall data, the maximum rainfall, P, and the statistical variables (average and standard deviation) for each duration (15, 30, 45, 60, 180, 360, 540, 720, 1440 mins.) are calculated. Using SCS Type II method, peak rainfalls at various duration like 10, 20, 30, 60, 120, 180, 360, 720 and 1440 mins. are estimated from the available annual maximum daily rainfall data, P_{24} (Annual peak daily rainfall),. These estimated various duration data are used in Gumbel‟s Extreme Probability Method, Normal Method and Log Pearson Type III to determine the rainfall, P_T values (Peak Rainfall depth in mm at Return Period T-Years), and the intensities, I_T (Peak Rainfall Intensity in mm/hour at Return Period T-Years), for the five stations in Litani River Basin - Lebanon.
The results show that the annual maximum rainfall data (at each duration "d") for the regions under study follow fairly well the Log Pearson III distribution at Qaroun stations, Normal distribution at Tyre, and Gumbel distribution at Zahle, Reyak and Lebaa stationS. Table 2 is the Chi-Square Test for the three probability distributions at all stations. All values are below critical chi-square values which indicate the applicability of all distributions, however, at Reyak station for example, Log Pearson III distribution has the lowest X^2_C value indicating the best fitting at confident level 95%.

Table 2: Chi Square Test Results for Peak Daily Rainfall at All Stations, Value in Bracket Is the Critical Chi-Square Value

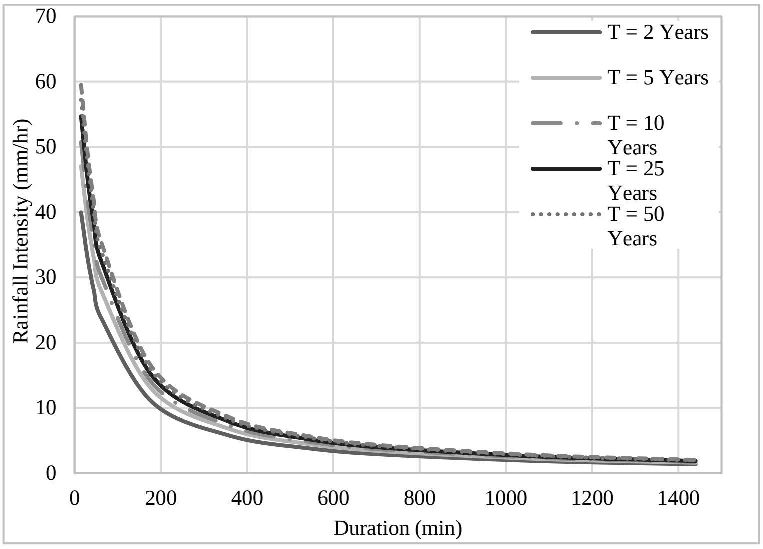
Station	Chi-Square X^2_C		
	Gumbel	Log Pearson III	Normal
Tyre	7.66 (15.51)	7.11 (14.1)	5.47 (15.51)
Lebaa	2.01 (14.07)	1.99 (12.59)	3.95 (14.07)
Qaroun	7.28 (12.59)	5.25 (11.07)	9.28 (12.59)
Zahle	3.39 (12.59)	2.19 (11.07)	4.90 (12.59)
Reyak	3.57 (11.07)	2.90 (9.49)	6.40 (11.07)

After finding out the values of P_T, and intensities, I_T, the IDF relationships at each station are constructed by using Bernard, Talbot, Kimijima, and Sherman equations. Table 3 shows the values of the different parameters at Tyre Station. Fig. 6 shows the IDF curves using Kimijima equation.
Comparison between the four empirical equations at the five stations, shows that the results of Kimijima and Sherman equations can be applied at the five stations that has RMSE (Root mean square error) between 1.48 to 4.38 mm/hour and with R^2 equal to 0.99. Kimijima and Sherman empirical IDF equations can be implemented in Litani River Basin. Fig. 7 shows the root mean square error of the four IDF equations for return period T = 25 years.
After determining the parameters of the IDF formula, Arc view/GIS is used to prepare contour maps for different return periods. These maps can be used for ungauged areas in the Basin. The parameters contour map for Kimijima equation is shown in Fig. 8 for T=10, 25 & 100 Years.

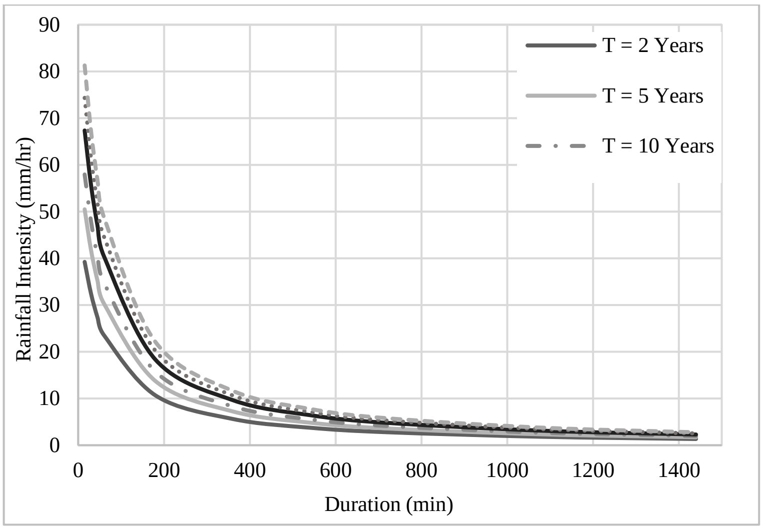
Table 3: The Parameters of the Four Empirical Equations at Tyre Station

Return Period	Talbot $i = \frac{a}{(d+b)}$		Bernard $i = \frac{a}{d^c}$		Kimijima $i = \frac{a}{(d^c+b)}$			Sherman $i = \frac{a}{(d+b)^c}$		
	a	b	a	c	a	b	c	a	b	c
2	2575.36	48.78	183.64	0.531	4381.29	89.6	1.106	4407.68	58.70	1.092
5	3029.53	48.73	216.26	0.531	5148.51	89.41	1.106	5383.32	59.17	1.10
10	3267.08	48.73	235.2	0.531	5550.18	89.38	1.106	5666.76	59.01	1.095
25	3521.75	48.74	251.35	0.531	5982.63	89.38	1.106	6095.68	58.69	1.095
50	3685.73	48.74	263.08	0.531	6258.82	89.34	1.106	6734.38	59.76	1.104
100	3832.86	48.74	273.58	0.531	6507.85	89.33	1.106	6596.48	58.76	1.093

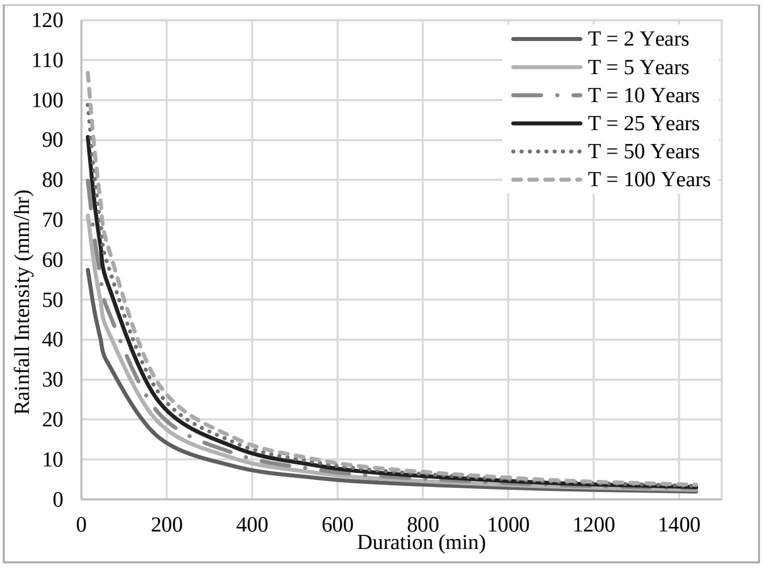
a) Tyre



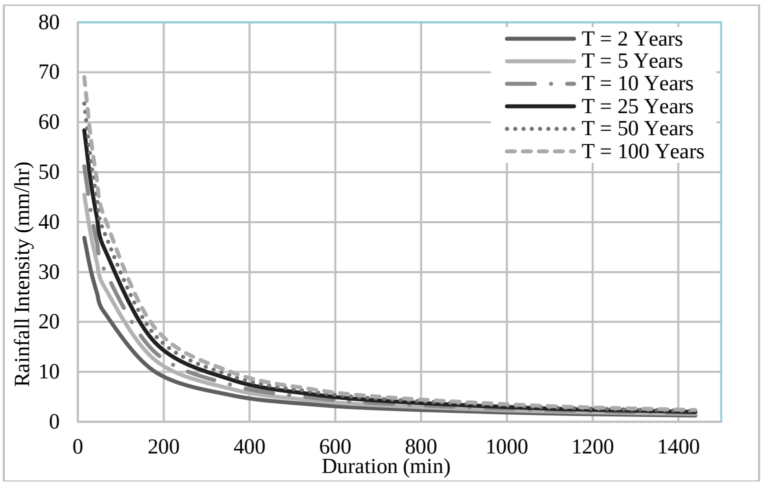
a) Reyak



b) Qaroun



c) Zahle



d) Lebaa

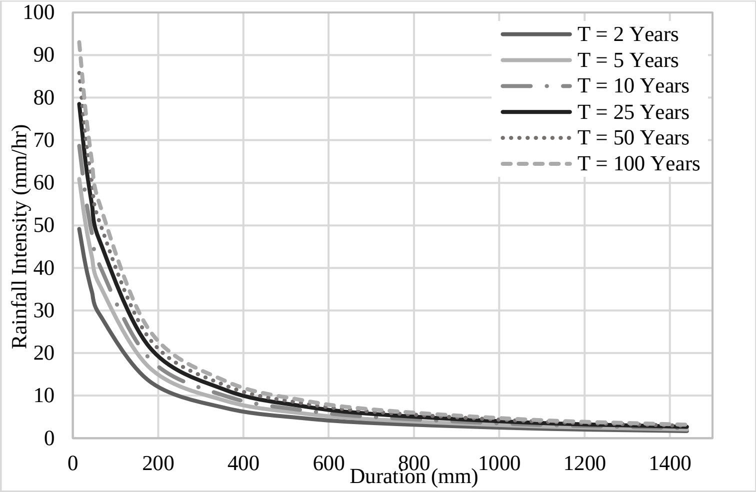


Fig. 6: Rainfall IDF Curves at Litani Weather Stations Using Kimijima Equation.

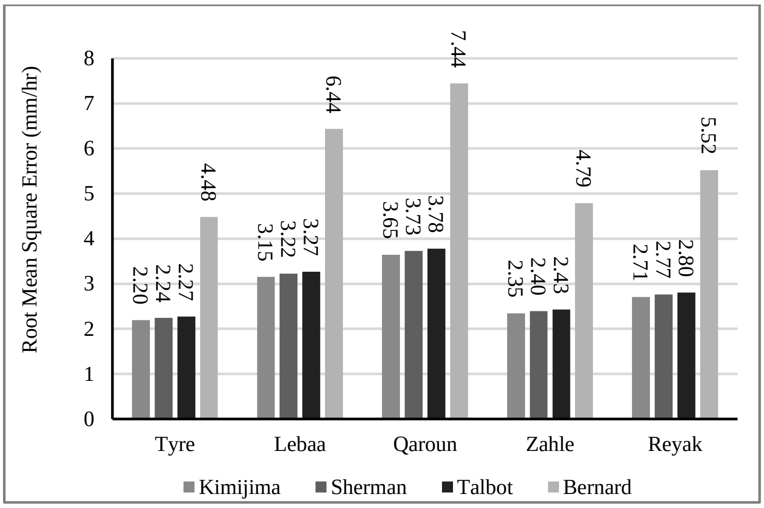
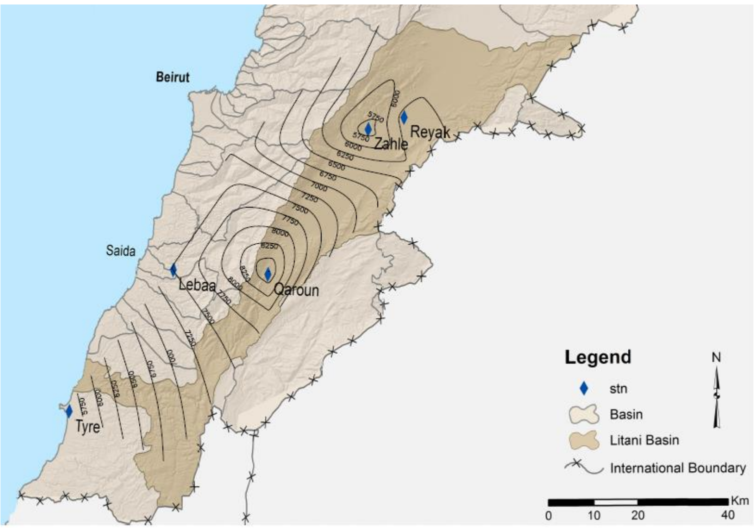
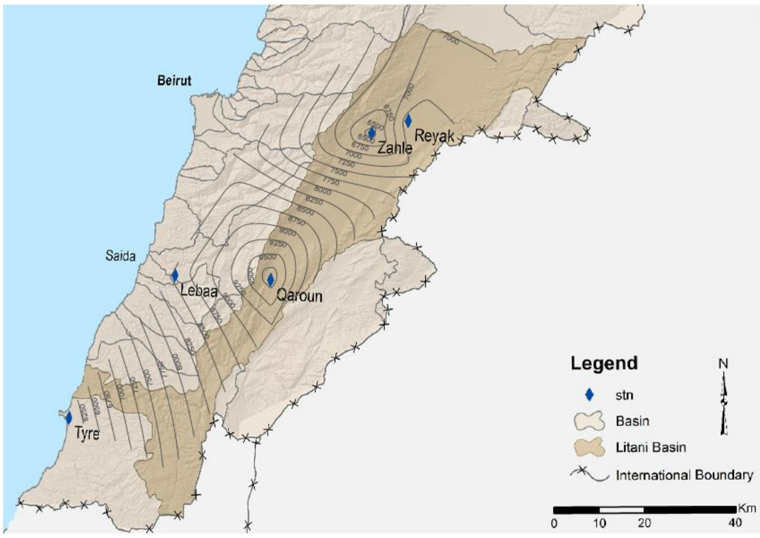


Fig. 7: Root Mean Square Error (RMSE) for Return Period, T = 25 Years.

a) T = 10 yrs.



b) T = 25 yrs.



c) T = 100 yrs.

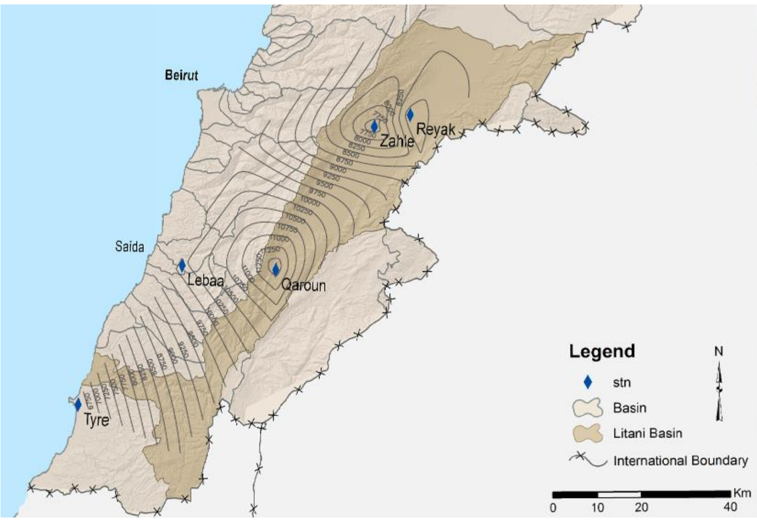


Fig. 8: Calculated Contour Values of Parameter “A” with Return Periods of 10, 25, and 100 Years (Kimijima Equation, $I = \frac{A}{(D^C+B)}$, B = 89.35 and C = 1.106).

6. Conclusions

The goal of this study was the development and construction of IDF relationships, for the first time in Lebanon, by using three distribution functions: Log Pearson III, Gumbel and Normal distributions. Gumbel distribution gave some larger rainfall intensity estimates compared to Log Pearson Type III and Normal distribution. Chi-Square test is used as a goodness-of-fit test between observed and expected frequencies. Results of the test showed the null hypothesis that the maximum rainfall, for each time interval, from all distributions is acceptable at the 95% level of confidence. However, EVI & Log Pearson III distributions is the superior distribution in developing IDF curves. Analysis of different equations to construct, the IDF curve relationship shows that Kimijima equation is the more suitable for Litani River Basin. Using the fitting parameters of the Kimijima equation, a contour map is developed which can then be used for ungauged locations within the basin.

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