Development of intensity–duration–frequency curves for the Kingdom of Saudi Arabia

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ABSTRACT
This paper presents the derivation of the intensity–duration–frequency (IDF) curves for the Kingdom of Saudi Arabia. Such curves were obtained based on rainfall events measured in 28 meteorological stations distributed throughout the Kingdom. For 20–28 years period, 2027 rainfall storms of durations ranging from 10 min to 24 hours were collected and analyzed. Both Institute of Hydrology model (IH-Flood) and Excel-sheet program are used for developing IDF equations for every station. The method of least squares was used to get relationships for the parameters of the IDF formulas. The calculated goodness of fit shows strong correlations range between 0.99 and 0.98 for one of the parameters, and between 0.92 and 0.74 for the other parameters and thence indicating robust IDF formulas for practical use. Regionalization of the IDF parameters for the 13 distinct regions of the Kingdom has been developed. In addition, an average of IDF parameters is made over the Kingdom as a whole to be used in regions of no rainfall records. The resulting IDF curves are usually used for flood estimation in urban/rural watersheds. Using the resulting IDF curves is highly recommended for rigorous, efficient and safe design of hydraulic structures and flood protection works.

1. Introduction
The intensity–duration–frequency (IDF) relationship is a mathematical relationship between the rainfall intensity $i$, the duration $D$ and the return period $T_r$ (or, equivalently, the annual frequency of exceedance, typically referred to as ‘frequency’ only). IDF curves are discussed in numerous hydrologic engineering books, e.g. Chow et al. (1988) and Koutsoyiannis et al. (1998). IDF relationships are crucial for any flood mitigation measures, water engineering project and water resources engineering designs. Such relationships are used to develop design storms (DS) to obtain peak discharge and hydrograph shape in any hydraulic design. The DS are used extensively by civil engineers to design and size safely and economically storm water network of a city or flood control structures.

Establishing IDF relationships requires historical data of good quality and continues for long term, which is normally not available in most arid countries. Although, many studies have been done to develop the IDF relationships in various regions, e.g. Samawi and Sabbagh (2004); Hadadin (2005) and Bara et al. (2009), few studies have been conducted in Saudi Arabia.

Al-Anazil and El-Sebaie (2013) developed IDF relationships for Abha city in the Kingdom of Saudi Arabia (KSA). For eight different durations (10, 20, 30, 60, 120, 180, 360 and 720 min) and six
frequency periods (2, 5, 10, 25, 50 and 100 years), IDF curves are obtained relying on 34 years of data. Three frequency distributions, namely: Gumbel, Log normal and Log Pearson Type III (LPT III) distributions have been used. It has been shown that there were small differences between the results obtained from the three methods.

Al-Shaikh (1985) divided Saudi Arabia into four regions and derived a rainfall depth–duration–frequency relationship for each region. The author used extreme value type-1 (EV1) (Gumbel extreme value type I) distribution with the application of the maximum likelihood method for parameter estimation procedure using rainfall intensity data from individual stations available at that time (in the 1980s).

Al-Saleh (1994) studied frequency analysis of rainfall in Al-Quwayiyah area, Saudi Arabia. The highest daily amount of rainfall per year follow the probability distribution of the maximum values (EV1) at the significance level 0.10.

Al-Hassoun (2011) performed a study regarding rainfall analysis of IDF curves in Riyadh area using Gumbel and LPT III methods. The author did not find high difference in results between the two methods and referred to the flat topography and the semi-arid climate of Riyadh region.

Elsebaie (2012) derived IDF equations for two regions (Najran and Hafr Albatin regions) using two distribution methods, Gumbel and LPT III distributions, for duration varying from 10 to 1440 min and return periods from 2 to 100 years. The results obtained using Gumbel distribution are slightly higher than the results obtained using the LPT III distribution. Rainfall intensities obtained from these two methods showed good agreement with results from previous studies on some parts of the study area.

Thus, a few rainfall IDF relationships have been constructed for some parts of KSA. In most other parts of the KSA, such relationships either have not been constructed until now or developed based on a small number of rainfall storms, since 30 years ago such as the unpublished MSc thesis made by Al-Shaikh (1985).

Consequently, the objective of the present study is to develop IDF curves for each individual station based on all available rainfall events measured in the meteorological stations distributed throughout the KSA. Representative formulas have been developed also to construct the IDF relationships over various regions in Saudi Arabia. For an immediate use in engineering design, a regional IDF formula and curves are developed for the 13 administrative regions in the KSA, and an overall IDF curve for the whole country as well. To the best of the authors’ knowledge, this is the first attempt to derive such curves for all regions in the KSA.

2. Climate and rainfall

With the exception of the south-west region of Saudi Arabia (Asir area), the climate of KSA is classified as arid. It is characterized by extreme heat during the day, an abrupt drop in the temperature at night and slightly erratic precipitation. According to Elfeki et al. (2014), the region of Asir (Figure 1) is subject to Indian Ocean monsoons, usually occurring between October and March. An average of 300 mm of rainfall occurs during this period (about 60% of the annual total). Condensation caused by the high mountains contributes to the total rainfall.

For the rest of the country, the rainfall is low and erratic. Rainfall generally is unevenly distributed and is the only form of precipitation. The entire year’s rainfall may consist of one or two torrential outbursts that flood the wadis. The average rainfall is 100 mm per year.

3. Data collection

Data used in the current study were extracted from records of autographic rain gauges set up and maintained by the Ministry of Water and Electricity, which is responsible for all hydrological activities in the KSA. Table 1 summarizes the available data from the rainfall stations (28 stations). These stations contain rainstorm events in details, i.e. sub-daily measurements.
Following Elfeki et al. (2014), KSA is divided into 13 districts. Each district has some recording rainfall gauges (Figure 1). Trustworthy data are available from only 28 stations of rainfall in all districts. The stations are spread over the KSA, with intensity of 1 per 70 square kilometres. It should give a fair representation of the varied rainfall over the country according to Linsley et al. (1988). Each district has at least 1–4 stations.

Historic records of annual maximum rainfall depths in millimetres from 1975 to 2003 with time interval (10, 20, 30, 60, 120 min, etc.) for the stations were available. 2027 rainfall storms from the 13 regions covering the KSA are collected for 20–28 years period. Not all of these stations had a reliable data. Large number of stations have a very few records which are not worthy to be considered in the study. Only reliable data that have detailed rainfall temporal distribution were considered. So, only 28 rainfall gauges of 599 rainfall storms are analyzed (see Table 1). The number of storms varied between 15 and 28 storms/station.

Criteria to identify rain events often rely on threshold values for selected properties of rain events. Storms’ depths more than a threshold value of 10 mm are only considered. It should give acceptable representation of the storms that could produce run-off according to Dams and Moore (1985), Dunkerley (2008a, 2008b) and Elfeki et al. (2014). Accordingly, 269 rainfall storms out of 599 rainfall storms were selected for further analysis. Relying on such storms, IDF studies were carried out as follows.

4. Derivations of IDF curves

Derivations of IDF relationships for each of the 28 stations for the different time intervals (10, 20, 30, 60, 120 min, etc.) are developed by fitting EV1 distributions that is referred to as Gumbel distribution to the corresponding maximum daily rainfall per year at the various stations.
The actual IDF curves for a given site are usually given by a power expression (Chow et al. 1988), such as

\[ i = c T^k \frac{D^e}{x} \]  \hspace{1cm} (1)

where \( i \) is the average intensity (i.e., \( i = x/D \), where \( x \) is the depth over any time period \( D \)), \( T \) is the return period, and \( c, e \) and \( k \) are constants.

Since the procedure for constructing IDF curves is not given elaborately in textbooks, a description is given herein. Details of construction of IDF relationships and IDF curves in the current study are conducted via the following steps:

1. Data collection, processing and selection of reliable storms: efforts have been made to collect the measured rainfall data from the Ministry of Water and Electricity. Not all rainfall data are used, only continuous rainfall storms are considered.
2. Ranking the list of rainfall depth in ascending order and computing the plotting position (Ang & Tang 1975) for each rainfall depth, \( x \), as

\[ P(X \geq x) = \frac{m}{n+1} \]  \hspace{1cm} (2)

### Table 1. Stations used in the current study.

| Z. No. | Station       | Station number | Station name     | Station symbol | Recorded storms From | To       | Longitude | Latitude | Total number of storms Total |
|--------|---------------|----------------|------------------|----------------|----------------------|----------|-----------|----------|------------------------------|
| 1      | Abha          | 12             | Serat Abida      | A 004          | 1975                 | 2002     | 43°06'00" | 18°10'00" | 19                            | 68                            |
|        | Abha          | 13             |                   | A 005          | 1975                 | 2003     | 42°29'00" | 18°12'00" | 28                            |                               |
|        | Sir Lasan     | 14             |                   | A 006          | 1975                 | 2000     | 43°36'00" | 18°15'00" | 21                            |                               |
| 2      | Bishah        | 61             | Al Mundak        | B 001          | 1975                 | 2003     | 41°17'00" | 20°06'00" | 21                            | 66                            |
|        | Tathilth      | 66             |                   | B 006          | 1975                 | 2003     | 43°31'00" | 19°32'00" | 18                            |                               |
|        | Billjorshi    | 67             |                   | B 007          | 1975                 | 2002     | 41°33'00" | 19°52'00" | 27                            |                               |
| 3      | Eastern province | 138       | Qatif            | EP 002         | 1975                 | 2002     | 50°00'00" | 26°30'00" | 27                            | 46                            |
|        | As Sarrar     | 139           |                   | EP 003         | 1975                 | 2003     | 48°23'00" | 26°59'00" | 19                            |                               |
| 4      | Hail          | 186           | Hail             | H 001          | 1975                 | 2001     | 41°38'00" | 27°28'00" | 26                            | 26                            |
| 5      | Jeddah        | 214           | Mudiaylif        | J 001          | 1975                 | 2001     | 41°03'00" | 19°32'00" | 19                            | 19                            |
| 6      | Al Medinah    | 366           | Al Medinah Farm  | M 001          | 1975                 | 2002     | 39°35'00" | 24°31'00" | 28                            | 28                            |
| 7      | Najran        | 405           | Najran           | N 001          | 1975                 | 1999     | 44°15'39" | 17°34'00" | 23                            | 23                            |
| 8      | Riyadh        | 452           | Riyadh           | R 001          | 1975                 | 2003     | 46°43'00" | 24°34'00" | 29                            | 68                            |
|        | Zifi          | 455           |                   | R 004          | 1980                 | 2003     | 44°48'00" | 26°17'00" | 24                            |                               |
|        | Hutah Sudair  | 456           |                   | R 005          | 1975                 | 2003     | 45°37'00" | 25°32'00" | 15                            |                               |
| 9      | Sabya         | 496           | Malaki           | SA 001         | 1975                 | 2003     | 42°57'00" | 17°03'00" | 23                            | 60                            |
|        | Kwash         | 498           |                   | SA 003         | 1975                 | 2003     | 41°53'00" | 19°00'00" | 22                            |                               |
|        | Kiyat         | 499           |                   | SA 004         | 1975                 | 2002     | 41°24'00" | 18°44'00" | 15                            |                               |
| 10     | Sakakah       | 592           | Sakakah          | SK001          | 1975                 | 2002     | 40°12'00" | 29°58'00" | 26                            | 59                            |
|        | Qurayyat      | 593           |                   | SK002          | 1975                 | 2002     | 37°21'00" | 31°20'00" | 17                            |                               |
|        | Tabarjal      | 594           |                   | SK003          | 1975                 | 2002     | 38°17'00" | 30°31'00" | 16                            |                               |
| 11     | Taif          | 625           | Hema Saysid      | TA 002         | 1975                 | 2000     | 40°30'00" | 21°18'00" | 27                            | 61                            |
|        | Taif          | 627           |                   | TA 004         | 1980                 | 2003     | 40°27'00" | 21°24'00" | 19                            |                               |
|        | Turabah       | 628           |                   | TA 005         | 1975                 | 1997     | 41°40'00" | 21°11'00" | 15                            |                               |
| 12     | Tabuk         | 770           | Tayma            | TB 002         | 1975                 | 1995     | 38°29'00" | 27°38'00" | 17                            | 17                            |
| 13     | Unayzah       | 786           | Unayzah          | U 001          | 1980                 | 2003     | 43°59'00" | 26°04'00" | 24                            | 58                            |
|        | Uclat As Suqur | 787        |                   | U 002          | 1982                 | 2003     | 42°11'00" | 25°50'00" | 16                            |                               |
|        | Kuraa Almarw  | 848           |                   | U 004          | 1975                 | 2003     | 43°48'51" | 25°52'46" | 18                            |                               |

**Total** 599
where \( P(X \geq x) \) is the plotting position which corresponds to the exceedance probability of rainfall depth \( x \), \( m \) is the ordered sequence of rainfall depth values and \( n \) is the number of observations.

3) Compute the recurrence interval \( T_r \) for each predicted rainfall depth as the reciprocal of the plotting position (Shultz 1976) with the equation:

\[
T_r = 1/P(X \geq x) = \frac{n + 1}{m}
\]

(3)

4) Plot the rainfall depth in relation to recurrence interval. A Gumbel extreme value distribution (Type I) is fitted to all data points of the rainfall depth. The Gumbel extreme value cumulative distribution is written as

\[
P(X \leq x) = e^{-e^{\alpha(x - \beta)}}
\]

(4)

where \( P(X \leq x) \) is the probability of non-exceedance, \( e \) is the Napier’s constant, \( \alpha \) and \( \beta \) are the distribution parameters which are given by Kite (1978):

\[
\alpha = \frac{1.2825}{\sigma}
\]

(5)

\[
\beta = \mu - 0.45\sigma
\]

(6)

where \( \mu \) is the mean of the rainfall data, and \( \sigma \) is the standard deviation of the rainfall data. The reciprocal of the recurrence interval (return period) is also equal to the exceedance probability (Shultz 1976) in the equation:

\[
\frac{1}{T_r} = P(X \geq x) = 1 - P(X \leq x)
\]

(7)

Equations (4) and (7) are equated, rearranged, and the logarithm taken twice to yield a formulation for rainfall depth as

\[
x = \beta - \frac{1}{\alpha} \ln \{ \ln T_r - \ln(T_r - 1) \}
\]

(8)

5) Compute the rainfall depth for each return period using equation (8).

6) Plot the rainfall depths in relation to return periods in a semi-log graph. A best-fit line can be drawn through the data based on equation (8), and extrapolation can be made for return periods of 5, 10, 25, 50, 100 and 200 years.

7) Consequently, rainfall intensities for each duration (10, 20, 30, 60, 120 min, etc.) are calculated based on the aforementioned steps. Figure 2 shows the results of the fitting procedure mentioned above for some stations as an example; however, the procedure is made for all stations. Figure 3 shows spatial distribution of the 24 hours rainfall depth data over the Kingdom for 5, 10, 25, 50, 100 and 200 years return periods.

8) Develop the IDF equations: some empirical formulas are used to construct the rainfall IDF curves in the form of,

\[
i = aD^b
\]

(9)

where \( D \) is the rainfall duration, \( a \) and \( b \) are fitting constants for the durations.

The least-square method is applied to determine the parameters of the empirical IDF equation that is used to represent intensity–duration relationships. The parameters \( a \) and \( b \)
are also related to the return period and obtained by the least-square fitting method in a form of,

\[ a = \delta \ln T_r + \varepsilon \]  \hspace{1cm} (10)

\[ b = \varphi \ln T_r + \omega \]  \hspace{1cm} (11)

where \( \delta, \varepsilon, \varphi, \omega \) are fitting constants for the return periods.

The parameters in equations (9)–(11) are estimated and tabulated for the 29 stations and for the regional model. Table 2 shows the parameters given in equations (10) and (11) for the 29 stations.

(9) Regionalization of the parameters of the IDF equations: the IDF curves presented in Table 2 are derived from the point rainfall gauges; only sets of IDF curves at gauging location are established. However, the designer always needs the IDF curves for ungauged specific region, therefore a regional IDF formula and there specific parameters are established. This is done by averaging the parameters \( a \) and \( b \) over each region (regionalization). Also, an average IDF parameters is made over the Kingdom as a whole. These averaging equations may be used in regions that have no rainfall records.
For one to implement the flood study in certain area using the current IDF curves, he should first determine the design return period ($T_r$) to be able to obtain the values $a$ and $b$ for any specific station from Table 2. Then, the rainfall intensity can be calculated using equation (9), for any required DS duration ($D$).

5. Analysis of individual stations

Institute of Hydrology (1999) developed IH-Flood model for statistical analysis of hydrological data. Both IH-Flood model and Excel-sheet program are used for the analysis of the 28 individual stations. A summary of the relationships of the fitting parameters of the IDF equations for the individual stations and the accompanied coefficient of determination is given in Table 2 and Figure 4.
while Table 3 and Figure 5 summarize the derived relations for the 13 regions of the KSA. Table 4 and Figure 6 show the overall relationships for the KSA as a whole.

The resulted IDF curves show that the rainfall intensity increases as the return period increases. As the duration increases, the intensity decreases for the same return period and in all return periods. These common trends in all stations are consistent with the common IDF behaviour in the literature.

The method of least squares was used to get relationships for $a$ and $b$ parameters of the IDF formulas. The goodness of fit is shown by the calculation of the coefficient of determination, $R^2$, as shown in Tables 2, 3 and 4. In all cases, the $R^2$ for the parameter $a$ is very high and ranges between 0.9999 and 0.9861, while for parameter $b$, the $R^2$ ranges between 0.9238 and 0.7479 which still show strong correlations. Such coefficients indicate robust IDF formulas for practical use.

### 6. Regional analysis

Regional IDF relationships are highly needed for hydrologic design applications in the KSA. These curves were not available long time ago. Therefore, the current study developed the regional rainfall IDF relationships for the 13 regions comprising KSA and for the country as a whole. However, caution has to be considered while using the derived IDF relationships for high return periods (e.g. greater than 50 years) because most records of individual stations are relatively short (less than 28 years) (Bell 1969). Moreover, the available number of stations is not enough to adequate coverage.
Figure 4. Fitted IDF formulas for some KSA stations and the accompanied relationships for $a$ and $b$ parameters.

Table 3. Fitted relationships for parameters $a$ and $b$ of the IDF formulas for the various regions (13 districts) in KSA and the accompanied coefficient of determination.

| Zone            | $a$                              | $R^2$ | $b$                              | $R^2$ |
|-----------------|----------------------------------|-------|----------------------------------|-------|
| Abha            | $a = 119.97\ln(T_R) + 133.94$    | 0.9995| $b = 0.0043\ln(T_R) - 0.6568$   | 0.7431|
| Bishah          | $a = 154.48\ln(T_R) + 238.11$   | 0.9987| $b = 0.0054\ln(T_R) - 0.6951$   | 0.8269|
| Eastern province| $a = 224.88\ln(T_R) + 33.776$   | 0.9991| $b = -0.016\ln(T_R) - 0.7092$   | 0.784 |
| Hail            | $a = 23.077\ln(T_R) + 24.511$   | 0.9861| $b = -0.011\ln(T_R) - 0.4945$   | 0.8256|
| Jeddah          | $a = 236.63\ln(T_R) + 388.48$   | 0.999 | $b = 0.0107\ln(T_R) - 0.7869$   | 0.8237|
| Al Medinah      | $a = 69.014\ln(T_R) + 156.69$   | 0.9997| $b = 0.0156\ln(T_R) - 0.7287$   | 0.8168|
| Najran          | $a = 100.6\ln(T_R) + 147.79$    | 0.9987| $b = 0.0036\ln(T_R) - 0.7662$   | 0.8324|
| Riyadh          | $a = 93.899\ln(T_R) + 54.35$    | 0.9995| $b = -0.019\ln(T_R) - 0.6455$   | 0.8251|
| Sabya           | $a = 117.93\ln(T_R) + 486.14$   | 0.9995| $b = 0.0137\ln(T_R) - 0.768$    | 0.9126|
| Sakakah         | $a = 97.563\ln(T_R) + 23.488$   | 0.9996| $b = -0.012\ln(T_R) - 0.6774$   | 0.8127|
| At Taif         | $a = 240.78\ln(T_R) + 185.4$    | 0.9991| $b = -0.006\ln(T_R) - 0.7679$   | 0.8189|
| Tabuk           | $a = 151.02\ln(T_R) + 263.5$    | 0.9991| $b = 0.0071\ln(T_R) - 0.743$    | 0.7999|
| Unayzah         | $a = 92.051\ln(T_R) + 80.495$   | 0.9992| $b = 0.0003\ln(T_R) - 0.6975$   | 0.6524|
Figure 5. Fitted IDF formulas for the various KSA regions and the accompanied relationships for parameters $a$ and $b$. 
Figure 5. (Continued)
Figure 5. (Continued)
for the regions since the density of these stations is low. The above mentioned issues have inspired to develop a regional rainfall IDF. IDF parameters of individual stations were averaged to produce representative regional IDF curves and formulas. This approach has been successfully applied in rainfall studies by many researchers such as Natural Resources Conservation Service (NRCS) (1975) and Baghirathan and Shaw (1978).

A summary of the regional IDF relationships is given in Table 3, while Figure 5 summarizes the derived curves and parameters.

Once the regional relations and the figures were developed for each region in the KSA, data of individual regions were averaged to produce representative regional IDF curve for the KSA as presented in Figure 6 and Table 4.

The parameters of the IDF curves indicate a nonlinear increasing relationship between values of the $a$ parameter and the corresponding return period in all cases and on the contrary for the $b$ parameter for most cases. Usually, the $a$ parameter is greater than the $b$ parameter for all values of return periods. The $a$ parameter shows relatively high sensitivity with respect to return periods, while the $b$ parameter exhibits very low sensitivity for return periods.

Since some regions are represented with only one station such as Jeddah, Al Medinah, Najran and Tabuk, and effects of the monsoons and the topography often distinguish variable rainfall
pattern over the KSA, cautious application may be considered in the use of the IDF equations in those regions.

Caution has to be considered when using the IDF curves for durations less than 20 min, since the fitting is not good locally in this part of the curve in some stations.

7. Conclusions

Analysis of rainfall data from recording stations in KSA has been conducted to formulate and construct IDF curves and formulas. IDF formulas are used to estimate rainfall intensities for different durations and different return periods.

Since the area of the Kingdom is large and has different climatic conditions, an IDF relationship for each available and reliable recording station has been obtained with their specific parameters.

The current study has been conducted by using Gumbel distribution method which is suited for extreme value events such as erratic rainfall in arid regions. Some published literature has shown closed values of IDF obtained from Gumbel and LPT III in some regions in KSA (Al-Shaikh 1985) and in Riyadh region (Al-Hassoun 2011). However, Elsebaie (2012) noticed some larger rainfall intensity estimates of Gumbel compared to LPT III distribution. Some other researches like Subyani and Al-Amri (2015) found no remarkable difference between Gumbel and LPT III in Al-Madinah city, western Saudi Arabia.

Referring to the persistent need for IDF relationships for hydrologic design applications in the KSA, the study developed regional rainfall IDF relationships for the 13 regions comprising the whole country. The use of these curves rather than those for individual stations should logically provide somewhat more confidence, particularly for the higher return periods. The curves and formulas resulted are intended to enhance watershed design practice in KSA.

Future studies should consider more recent sub-daily measurements of rainfall depths, the establishment of new stations and maintenance of the rainfall gauges to get longer rainfall records. The analyses described above should be repeated perhaps every five years to accommodate the effects of climate change on these IDF curves as well as introducing the uncertainty on these curves.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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