Development of Empirical Formula to Estimate Short Duration Rainfall

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Abstract

Daily rainfall data is more available than short duration (10, 20, 30, 60 and 120 minutes). Short duration rainfall is highly required for hydrological analysis, proper design of drainage system in urban and to propose and design different hydraulic structures. The objective of this research is to develop an empirical formula for generating short duration rainfalls depth using 24 hr rainfall depth. Rainfall data from 12 stations in Sinai were collected and analyzed to estimate the maximum rainfall depth at different durations. Depth ratios at each duration are calculated based on 24 hr depth for each gauge. Also, frequency analyses are carried out. Average ratios of storm depth at durations of 10, 20, 30, 60 and 120 minutes with respect to 24 hours depth were calculated for each return period. Weighted average of the ratios is calculated according to the number of records at each gauge. These ratios were used to develop an empirical formula to estimate short duration rainfall up to two hours. Also, similar ratios were obtained from WRRI-24hr storm distribution developed by the author. These developed ratios were compared with other common ratios such as Bell's ratios and Indian Meteorological Department (IMD) empirical reduction formula. These ratios were used to estimate the rainfall depth for the hydrological model to compute the runoff. The result shows that there is a distinct difference between the developed ratios and the other ratios. To quantify the impact of calculation of rainfall storm depth based on these ratios, Rainfall-runoff model is used to compute runoff volume and discharge. The results of the model showed that the computed runoff using the developed ratios is significantly higher. As the developed ratios are mainly based on field records, therefore they can be considered more accurate for Sinai region. It is recommended to use the developed formula to reduce the available 24 hours rainfall values and obtain the required short duration rainfall for the hydrological model applications.

***Key words**:* Rainfall frequency analysis, Short duration rainfall, Daily rainfall, Runoff estimation.

INTRODUCTION

The distribution of the rainfall is variable in space and time. Rainfall characteristic is highly needed for hydrological analysis. The rainfall Intensity-Duration-Frequency (IDF) relationship is one of the most important tools in water resource engineering to assess the risk and vulnerability of water resource structure as well as for planning, design and operation(Rashid et al., 2012). Daily rainfall records are usually more available than short duration ones. For estimation of runoff especially for urban areas short duration rainfalls are necessary(Ahmed et al., 2012). The construction of IDF relationship started for several parts of the world in early time (Bell, 1969; Chen, 1983)however, many researchers have established Intensity-Duration-Frequency relationships for their areas(Awadallah and Younan, 2012; F. Y. Logah, 2013; Jaleel and Maha Atta Farawn, 2013; Rasel and Hossain, 2015). To create these relationships, short duration rainfall records are needed. Indian Meteorological Department (Jaleel and Maha Atta Farawn, 2013; Rashid et al., 2012) has developed an empirical reduction formula for IDF relation. Several researches depend on this formula to generate shorter duration series for different countries such as India, Saudi Arabia and Iraq(Aysar, 2016; Jahnvi et al., 2014; Subyani and Al-Amri, 2015). A theoretical ratio of 1.13 to 1.14 is adopted between daily and 24-hr rainfall values(U.S. Department of Commerce, 1961). Then, they used this short duration series to develop their regions IDF curves without studying the suitability of this formula before the application. Very few papers have discussed short duration ratio in arid regions specifically to the 1-h and the 24-h depth. (Awadallah and Younan, 2012)found that Bell ratios are adequate to represent rainfall patterns in arid regions for rainfall durations less than two hours. However especially in developing countries, availability of short duration rainfalls is scarce and data available is mostly for daily rainfall data. In such cases determination of design rainfall is becoming an approximation and thus leading to frequent failure of drainage network and subsequent floods(Ahmed et al., 2012). In case of the absence of short duration rainfall data, there is a need for developing a specific procedure to convert 24 hr rainfall data into short duration. The objective of this research is to develop an empirical formula for generating short duration rainfalls depth using 24 hr rainfall depth. Rainfall data from 12 stations in Sinai were collected and analyzed to estimate the maximum rainfall depth at different durations. Depth ratios at each duration are calculated based on 24 hr depth using three methods. These ratios were used to develop an empirical formula to estimate short duration rainfall up to two hours. The developed ratios were compared with other common ratios such as Bell's ratios and Indian Meteorological Department (IMD) empirical reduction formula.

1. MATERIAL AND METHOD

Recoded rainfall storms are collected from 12 rainfall gauges distributed over the entire area of Sinai as shown in **Figure (1)**. Three methods are applied to obtain the ratios of storm depth at durations; 10, 20, 30, 60 and 120 minutes with respect to 24 hours depth. The first method is based on the recoded rainfall depth. The second method is based on the frequency analysis. The third method is based on WRRI-24hr rainfall time distribution which developed by the author.

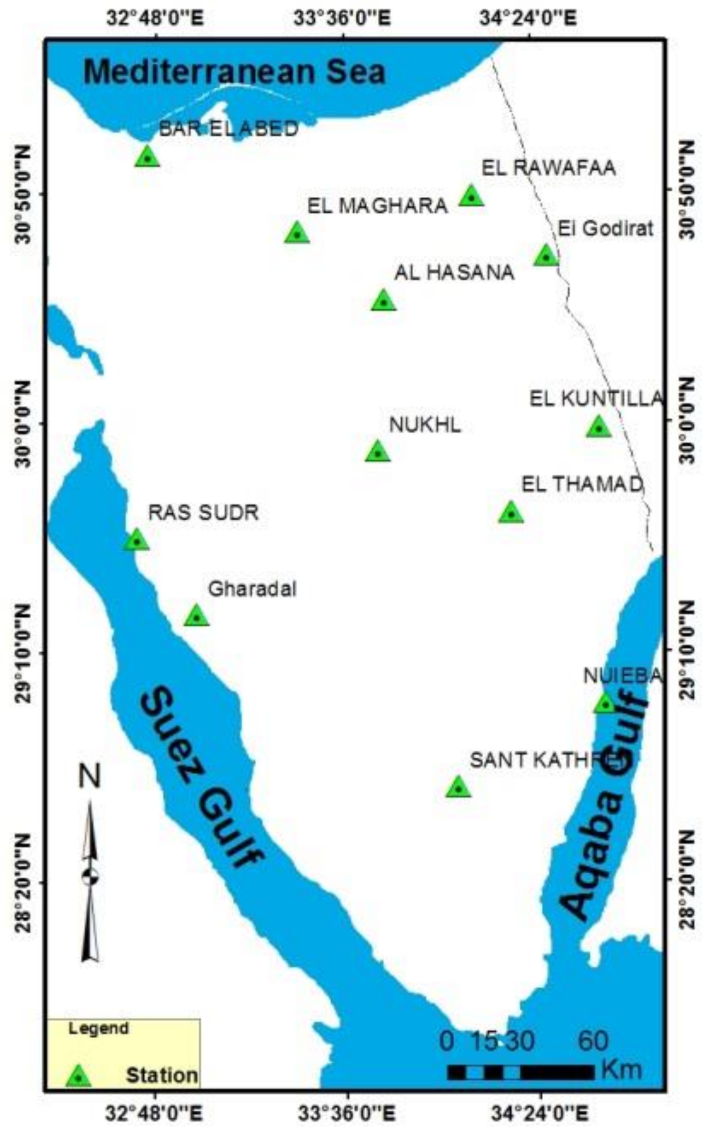

Figure (1): Rainfall Gauges Distributed Over the Entire Area of Sinai

1.1. First Method: Using Recorded Rainfall Storms

For each storm, maximum rainfall depths are calculated at durations 10, 20, 30, 60 and 120 minutes. Then, maximum yearly rainfall depth series are calculated at different duration for each gauge. Finally, depth ratios at each duration are calculated based on 24 hr depth for each gauge as presented in **Table 1** and **Figure 2**.

Table (1): Depth Ratios with Respect to 24 hr Using Recorded Rainfall Storms

		Duration (min)				
No.	**Gauge**	**10**	**15**	**30**	**60**	**120**
1	**Rawafaa**	0.29	0.35	0.43	0.51	0.63
2	**Godirat**	0.29	0.40	0.58	0.72	0.86
3	**Kontila**	0.31	0.36	0.42	0.50	0.65
4	**EL Maghara**	0.47	0.54	0.64	0.75	0.88
5	**El Timed**	0.32	0.38	0.55	0.71	0.82
6	**Ghrandal**	0.22	0.27	0.38	0.49	0.65
7	**Bir Abd**	0.26	0.32	0.41	0.57	0.70
8	**El Hassana**	0.21	0.26	0.37	0.49	0.61
9	**Nekhel**	0.40	0.45	0.53	0.67	0.81
10	**Kathrine**	0.21	0.26	0.35	0.45	0.65
11	**Ras Sudr**	0.28	0.32	0.42	0.52	0.66
12	**Nuwiebaa**	0.31	0.36	0.50	0.63	0.77

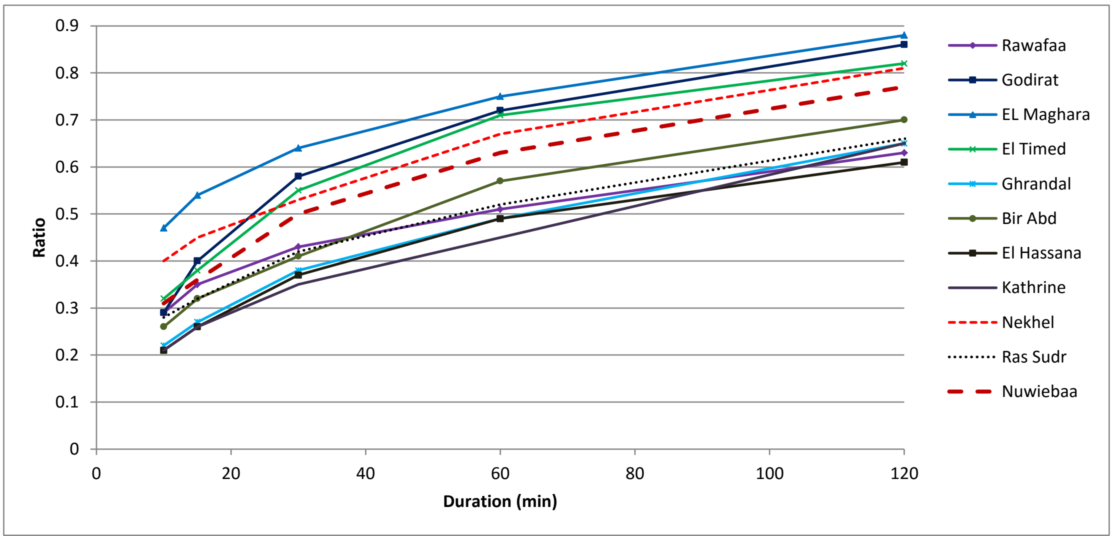

Figure (2): Depth Ratios with Respect to 24 hr Depth at Different Durations for All Gauges

1.2. Second Method: Using Frequency Analyses

Frequency analyses are used to develop the relationship between the rainfall depth, storm duration, and return periods from measured rainfall data. These analyses give the rainfall depths at different return periods (2, 5, 10, 20, 25, 50, 100, 200 and 500 years) for every durations (10, 20, 30, 60, 120 and 1440 minutes). Then, ratios of storm depth are calculated at each duration based on 24 hours depth for each return period. Average values at each gauge are calculated for different time durations. The results of these analyses are presented in **Table (2)** and **Figure (3)**.

Table (2): Depth Ratios with Respect to 24 hr Depth Using Frequency Analyses

		Duration (min)				
No.	**Gauge**	**10**	**15**	**30**	**60**	**120**
1	**Rawafaa**	0.16	0.22	0.29	0.36	0.49
2	**Godirat**	0.24	0.27	0.32	0.37	0.49
3	**Kontila**	0.55	0.61	0.67	0.77	0.82
4	**EL Maghara**	0.29	0.31	0.35	0.37	0.45
5	**El Timed**	0.18	0.25	0.35	0.60	0.74
6	**Ghrandal**	0.23	0.34	0.50	0.62	0.76
7	**Bir Abd**	0.24	0.29	0.40	0.51	0.60
8	**El Hassana**	0.32	0.36	0.42	0.60	0.61
9	**Nekhel**	0.35	0.37	0.43	0.53	0.74
10	**Kathrine**	0.23	0.27	0.33	0.39	0.52
11	**Ras Sudr**	0.21	0.25	0.29	0.39	0.55
12	**Nuwiebaa**	0.26	0.31	0.43	0.55	0.60

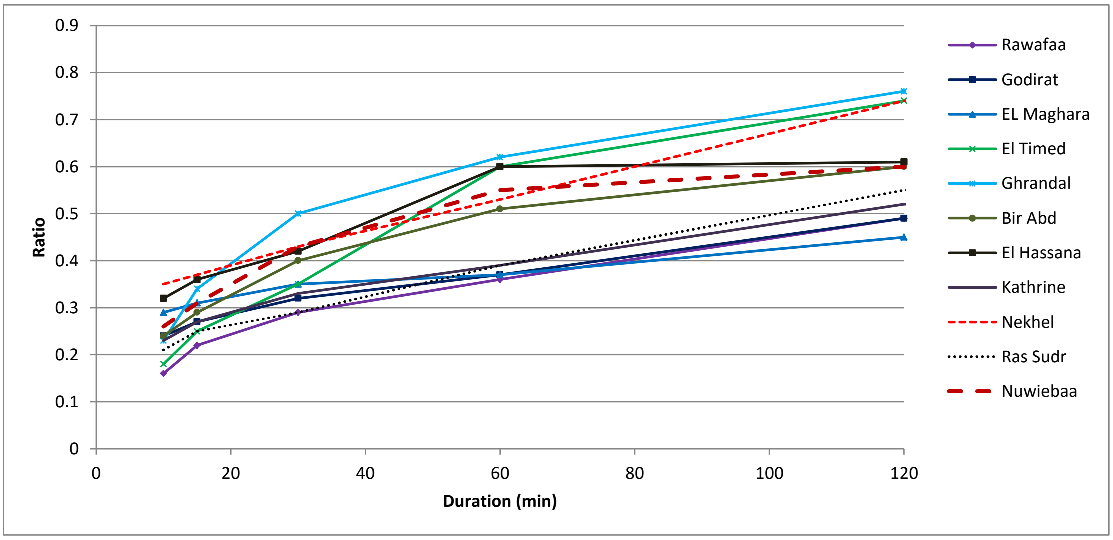

Figure (3) Depth Ratios with Respect to 24 hr Depth at Different Durations for All Gauges

1.3. Third Method: Using WRRI-24hr Rainfall Distribution

Also, similar ratios are calculated using the rainfall storm distribution curve. This distribution curve is developed for Sinai area using the same gauges and records for 24 hr (El- Sayed, 2017)as shown in **Table (3)**.

Table (3): Depth Ratios to 24 hr Depth Using WRRI-24hr Rainfall Distribution

Duration(min)	**10**	**15**	**30**	**60**	**120**	**1440**
Ratio	0.14	0.23	0.29	0.43	0.61	1.00

2. DEVELOPED FORMULA

Weighted average of the ratios of first and second methods is calculated according to the number of records at each gauge. **Table (4)** presents the developed ratios using the three methods. **Figure (4)** shows the values of the average ratios at different durations up to two hours. A trend exponential line is added and the fitting equation is calculated.

Table (4): Average Depth Ratios with Respect to 24 hr Depth at Different Duration

Ratio	Duration (min)					
	10	15	30	60	120	1440
First method	0.29	0.34	0.45	0.56	0.70	1.00
Second method	0.27	0.32	0.40	0.50	0.61	1.00
Third method	0.14	0.23	0.29	0.43	0.61	1.00

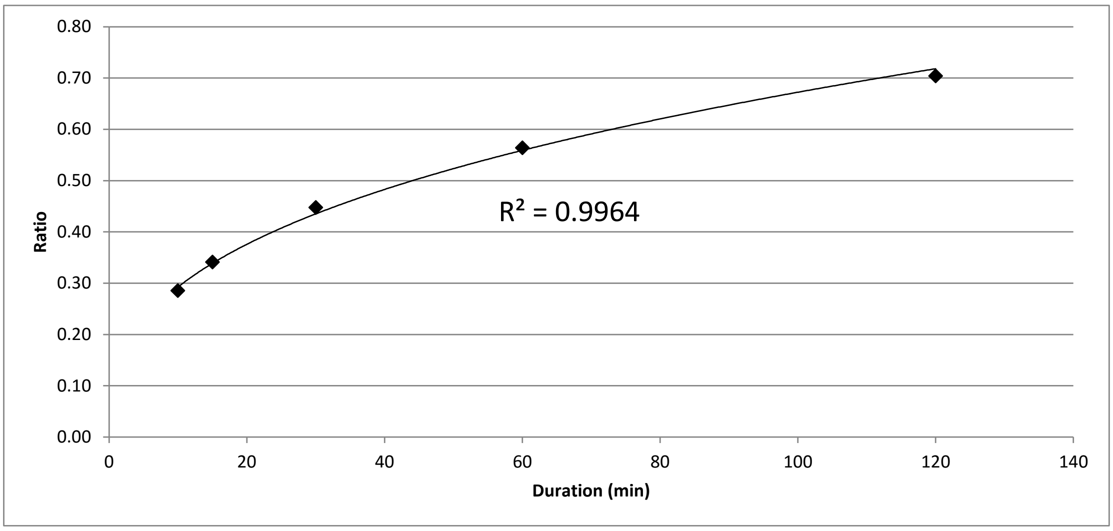

Figure (4): Average Depth Ratios with Respect to 24 hr Depth at Different Durations

The developed formula (WRRI Formula) for estimation short duration up to two hours rainfall is:

$R_t = R_{24} (0.00335t)^{(0.3614)}$ Eq. (1)

Where:

R_t is the required rainfall depth in mm at t-hr duration.

R24 is the 24 hr rainfall depth in mm.

t is the storm duration for which the rainfall depth is required in hr.

3. RESULTS AND DISSCUSIONS

(Bell, 1969)has calculated t-minute rainfall ratio to the 1-h rainfall of the same return period and extended these ratios to include 2-h rainfall and stated that these ratios are independent of the return period. He also reported that these ratios are applicable to other regions of the world(Awadallah and Younan, 2012).
Indian Meteorological Department (IMD) uses an empirical reduction formula (Eq. 2) for estimation of various duration rainfall values from annual maximum values.

$P_t = P_{24} (t/24)^{(1/3)}$ Eq. (2)

Where, P_t = the required rainfall depth in mm at t-hr duration, P_{24} = the daily rainfall in mm,
t = the duration of the rainfall for which the rainfall depth is required in hr.

Developed WRRI ratios are compared with other common ratios such as Bell's ratios (Awadallah et al., 2011) and Indian Meteorological Department (IMD) empirical reduction formula as presented in table (5). Also, these ratios are compared to the work of (Awadallah and Younan, 2012)for two gauges; Rawafaa and Godirate in Sinai, Egypt.

Table (5): Comparison Between the Calculated Ratios and Other Ratios at Different Duration with Respect to 24 hr Depth

Ratio	Storm Duration (min)									
	5	10	20	30	60	120	360	720	1080	1440
Bell's Ratios	0.13	0.2	0.28	0.34	0.44	0.57	0.63	0.75	0.88	1.00
IMD	0.15	0.19	0.24	0.28	0.35	0.44	0.63	0.79	0.91	1.00
Awadallah and Younan				0.50	0.57	0.68	0.70	0.72	0.82	1.00
WRRI ratios	**0.18**	**0.30**	**0.36**	**0.46**	**0.58**	**0.72**	**0.77**	**0.85**	**0.92**	**1.00**

From **Table (5)**, it can be noticed that WRRI ratios are significantly higher than both Bell's ratios and IMD ratios. On the other hand, the developed ratios are close and indicate fairly good agreement with the ratio developed by (Awadallah and Younan, 2012) using two gauges in Sinai for the duration up to three hours. This agreement and disagreement refers to the rainfall storm characteristics in each region.

Rainfall-runoff model is used in order to quantify the impact of calculation of rainfall storm depth based on the previously mentioned ratios. Recorded rainfall depth of 24 hr storm is selected to estimate different rainfall depths (120, 360, 720, 1080 min) using Bell's ratios, IMD equation and the developed WRRI ratios. The other input data for the model is kept constant except the rainfall to avoid their interference to the resulted runoff. These inputs are; the catchment area, the rainfall losses and the rainfall-runoff transformation method. For rainfall losses estimation Soil Conservation Services (SCS) Curve Number (CN) method is used. The value of (CN) is estimated based on soil type and land use of the catchment(Chow et al., 1988). For rainfall-runoff transformation method, SCS unit hydrograph method is applied. For rainfall storm distribution, 120, 360, 720 and 1080 min WRRI distributions are used. The result of the rainfall runoff model is shown in **Figures (5), (6), (7) and (8)**.

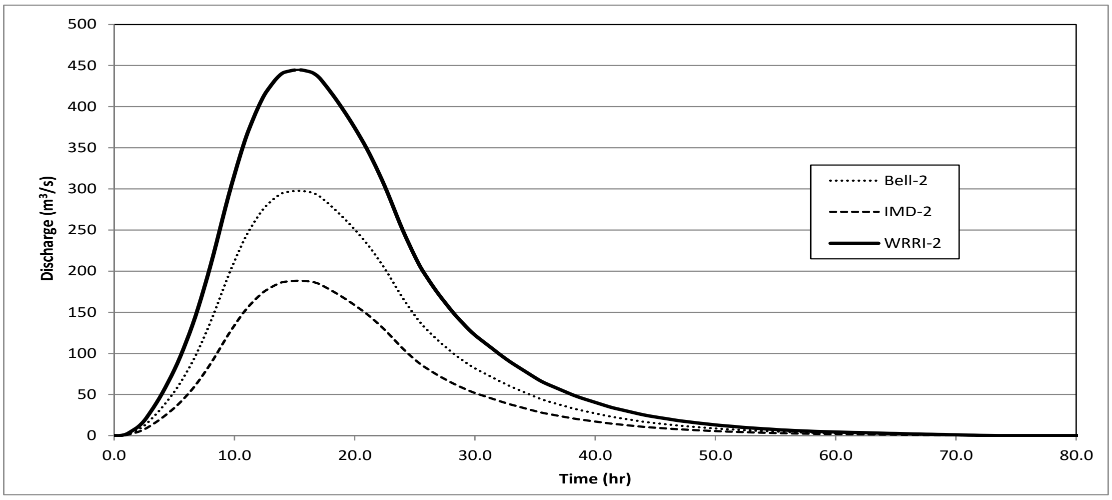

Figure (5): Runoff Hydrograph of 120 min Rainfall Depth Using Different Reduction Ratios

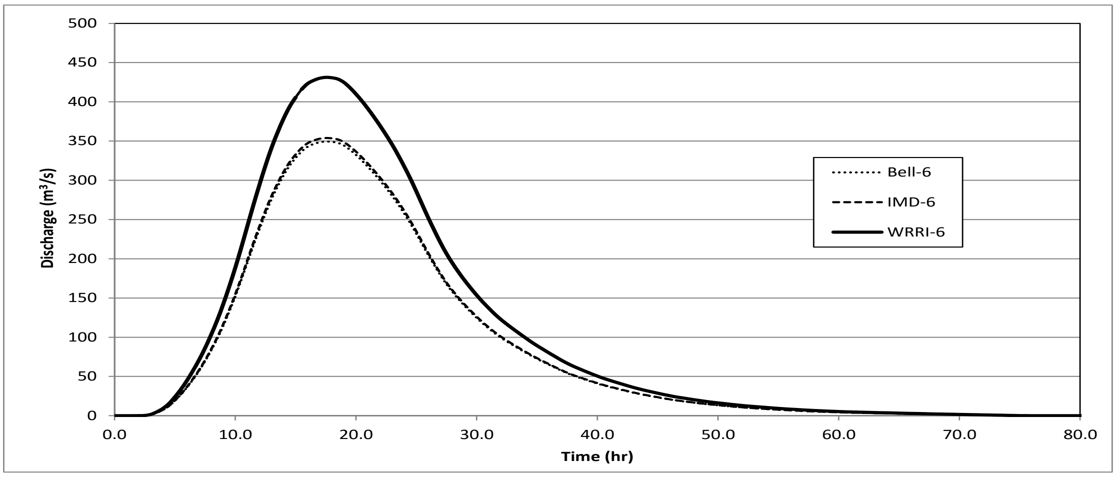

Figure (6): Runoff Hydrograph of 360 min Rainfall Depth Using Different Reduction Ratios

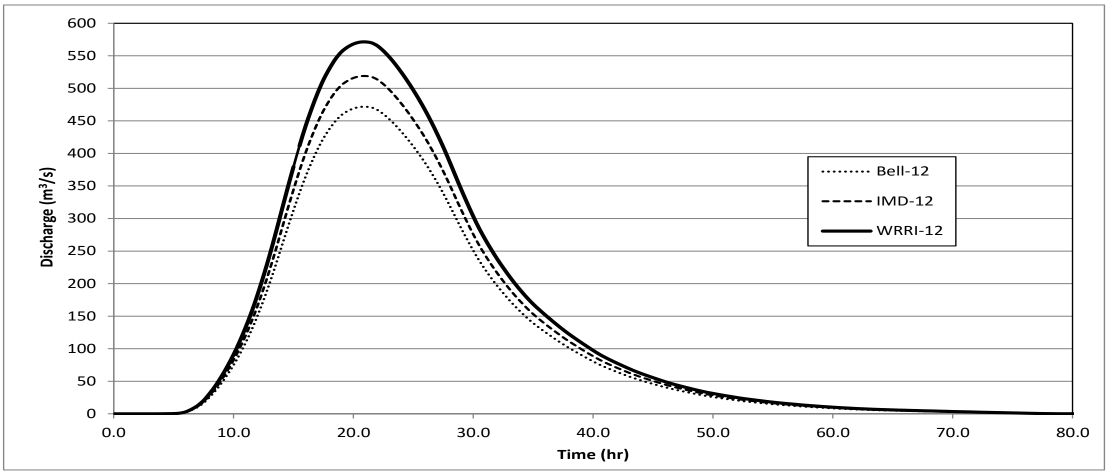

Figure (7): Runoff Hydrograph of 720 min Rainfall Depth Using Different Reduction Ratios

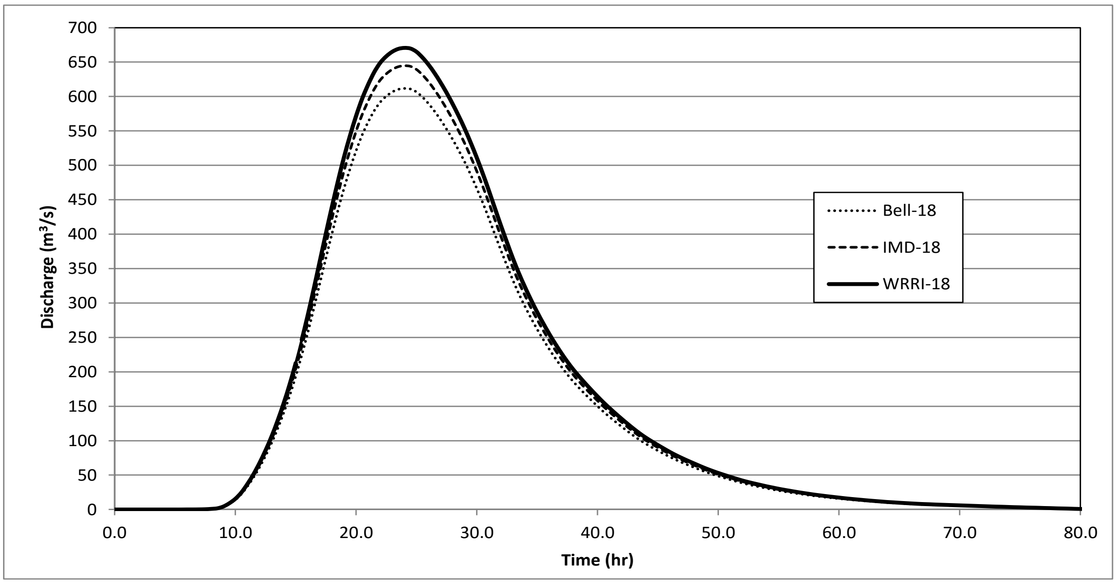

Figure (8): Runoff Hydrograph of 1080 min Rainfall Depth Using Different Reduction Ratios

Also, the maximum discharge values and runoff volumes are compared as presented in **Table (6)**. For 2-hr duration, the estimated runoff using different reduction ratios are highly varying but for higher duration it becomes closer due to the high variation between different reduction ratios. In general, the estimated runoff using developed WRRI ratios is higher than that of Bell's ratio and IMD equations. This means that both Bell's ratios and IMD equation produce under estimate values for runoff discharge and volume.

Table (6): Comparison Between Runoff Discharges and Volumes Produced Using Different Reduction Methods

Reduction method	Q (m3/s)				V (million m3)			
	2-hr	6-hr	12-hr	18-hr	2-hr	6-hr	12-hr	18-hr
Bell's ratios	297.6	349.4	471.7	611.7	20.7	24.4	33.2	43.3
IMD ratios	188.3	353.9	518.9	644.7	13.1	24.7	36.5	45.7
WRRI ratios	444.7	498.8	571.3	670.6	31.0	34.8	40.2	47.5

4. CONCLUSION AND RECOMMENDATION

Twelve stations in Sinai are used to develop reduction ratios for Sinai area. The study area ratios are used to develop general reduction formula for duration up to two hours. The developed ratios were compared with other common ratios such as Bell's ratios and Indian Meteorological Department (IMD) empirical reduction formula. The result shows that there is a considerable difference between the study area ratios and other common ratios. Also, these ratios were used to estimate the rainfall depth for the hydrological model to compute the runoff. Comparing the produced runoff using the developed ratios and other Bell's and IMD ratios, there are a significant difference in both runoff discharge and volume. The developed ratio is based on field records and it can be considered more accurate than using the other reduction ratios. It is recommended to use the developed WRRI ratios for Sinai to reduce the available 24 hr rainfall values and obtain the required short duration rainfall.

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