HYDROLOGICAL INVESTIGATIONS IN SEMI-ARID AREAS CASE STUDY: RAILWAY CULVERT DESIGN IN LIBYA

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ABSTRACT

Libya is planning to construct a railway system along the coastline to serve the cities and towns as part of the infrastructure for the country.

Since no direct runoff measurement records for the wadis located in the study area are available, statistical and probability methods using the available precipitation data were employed in combination with empirical equations to determine maximum probable discharges through wadis based on 100-year return period.

Available daily precipitation data for a record of 41 years by three meteorological stations along the coastline covering the railway segment under consideration was collected and used. Due to the unavailability of hourly precipitation data from the three meteorological stations, hourly rainfall records from Tripoli meteorological station were used. A model is developed to establish a relationship between the daily and hourly precipitation for Tripoli station and was utilized to generate similar relationships for the other three stations.

Key words: Semi desert, Surface runoff, Statistical modelling, Hydrological investigation

INTRODUCTION

The coastline of Libya is classified under the semi arid areas. The precipitation is generally scares and has random and erratic behavior such that; mean monthly and yearly rainfall data are unreliable. Almost all precipitation occurs on October through March along the coastal areas of the country. Occasional violent downpours often result in flash floods (torrential flows).

The objective this paper is to provide the hydrological input and to perform the design of storm water needed for flood protection structures for the railway. The meteorological records of the study area are analyzed for extreme events and the 100 year return period rainfall was extrapolated. With rainfall extremes and determined catchments areas the extreme runoff events were determined, for which in turn the required culvert sizes were designed.

SOURCES OF METEOROLOGICAL DATA

In the coastal area from Sirt to Benghazi three major meteorological stations of the General Directory of Civil Aviation and Meteorology (GDCAM) exist. Daily precipitation readings are available at the stations in Sirt, Ajdabiya and Benina. The data covers 41 years from 1960 to 2000. Because extreme rainfall and runoff values are known to be associated with flash floods, where the rainfall usually lasts only for one day or shorter, preference was given to the evaluation of the daily reading records, even though the monthly summaries cover occasionally a longer time span. Data of hourly maximum precipitations for Tripoli meteorological station for a 20-year period was obtained from the (GDCAM) and also used in the analysis.

DATA ANALYSIS

The random behaviour of rainfall patterns in arid or semiarid regions such as Libya makes predication of the some variables difficult. However, probability and statistical methodologies provide the tools for such predictions. In a first step, the data was tabulated and, frequency distributions of rainfall records at each available meteorological station were established. Furthermore, a theoretically convenient Probability Distribution Function was fitted to the recorded data in order to obtain the population distribution of the rainfall amounts for each station (Table 1).

Table 1: **Probabilities of daily rainfall amounts**

Station Name	10 mm	25 mm	50 mm	100 mm
Tripoli	0.67	0.34	0.14	0.02
Sirt	0.62	0.20	0.03	0.00
Ajdabiya	0.41	0.10	0.01	0.00
Benghazi	0.81	0.41	0.10	0.00

Hundred years was selected as a return period for determining the different events of the study. The probabilities for the number of occurrences of the 100-year event within any given 100 year period are as follows (Table 2).

Table 2: Probability of occurrence of a 100-year-event within 100 years

Number of occurrences	0	1	2	3	4	5
Probability % age	**36.6**	**37.0**	**18.5**	**6.1**	**1.5**	**0.3**

Figure 1 shows that an event with a return period of 100 years has a risk of 63.4% occurring at least once in a 100 year period. The same Figure can be further used to determine the risk for other combinations of return period and design life

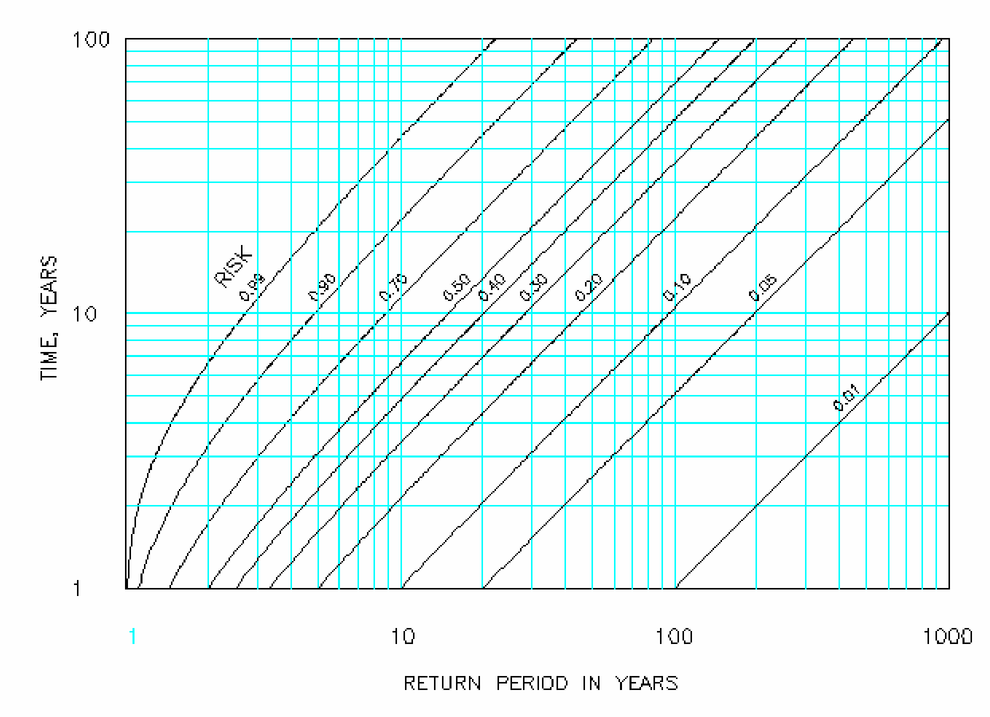

Figure 1: Hydrologic risk, design life and return period

From the general pattern of the actual rainfall data records of different meteorological stations, it is clear that there is an inverse relationship between the probability of occurrence and the amount of rainfall: Small amounts of rainfall occur relatively more frequently than large amounts. Furthermore, rainfall with values of 25mm and 50mm may occur, but the probability of 100mm rainfall occurrence is quite low.

FREQUENCY ANALYSIS AND COMPUTIONAL METHODS

Many times interest exists in extreme events such the maximum values of rainfall of a storm. There are several types of continuous distributions from which various parameters could be estimated. Among these distributions is the Gumble Extreme Probability Distribution. This distribution was found to be an appropriate distribution for fitting to the precipitation data of the three meteorological stations Sirt, Ajdabia and Benina.

Graphical Distribution of the maximum Daily rainfall data with the reference to the procedure explained in the previous section, the maximum daily rainfall from each year for the meteorological stations Sirt, Ajdabia, Benina and Tripoli was utilized to establish a relationship between the maximum daily precipitation and its return period.

For evaluation of the accuracy of the computed values of the precipitation, for return periods up to 100 years confidence intervals are calculated and presented in Table 3 for Sirt, Ajdabia, Benina and Tripoli meteorological stations.

Table (3) Confidence levels

L.C.L: Lower Confidence Limit, U.C.L: Upper Confidence Limit

Percentage			**95%**		**90%**		**80%**		**68%**	
Station	**Return period (years)**	**P (mm)**	**L.C.L**	**U.C.L**	**L.C.L**	**U.C.L**	**L.C.L**	**U.C.L**	**L.C.L**	**U.C.L**
Benina	100	85	64.84	105.96	68.15	102.65	71.95	98.85	74.91	95.89
Ajdabia	100	70	52.89	86.51	55.59	83.81	58.70	80.70	61.12	78.28
Sirt	100	98	72.86	122.14	76.82	117.65	81.39	113.62	84.93	110.07

Figure (2), shows the Gumbel extreme probability distribution fitted to the daily precipitation data for one of the four mentioned stations (Benina).
Hourly precipitation data obtained from Tripoli station was also plotted as Gumbel extreme probability distribution (Figure 3).

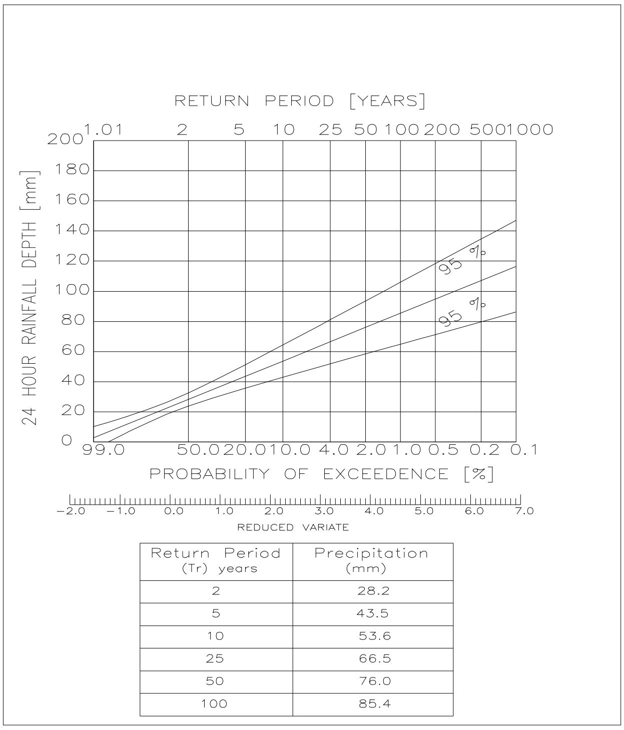

Figure (2): Gumbel extreme probability paper – Benina station

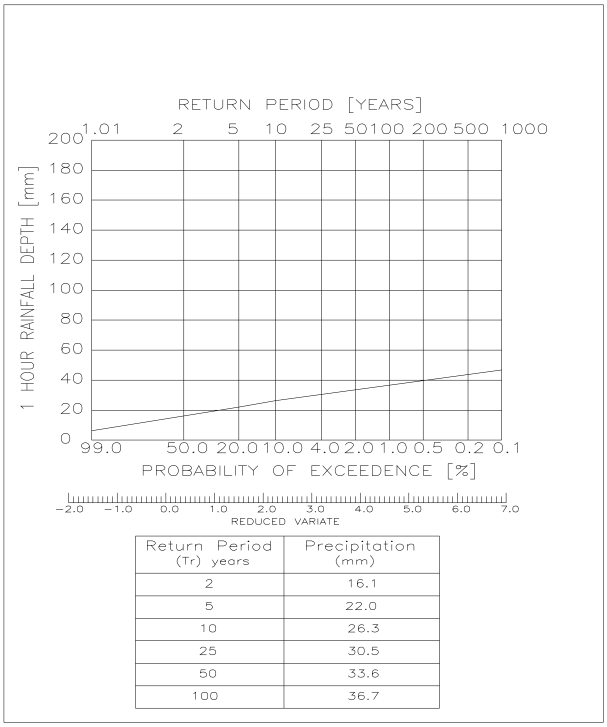

Figure (3): Gumbel extreme probability paper –Tripoli station (hourly data)

The relationship between the maximum hourly and daily precipitation can be established for Tripoli station as shown in Table 4.

Table (4): Hourly and Daily Maximal Precipitation Relationship Tripoli Station

Occurrences every n year	Max. Daily Precip. (mm) H_d	Max. Hourly Precip. (mm) H_h	$\frac{H_h}{H_d}$
2	40.2	16.1	0.400
5	63.5	22.0	0.346
10	78.9	26.3	0.333
25	98.3	30.5	0.310
50	112.8	33.6	0.298
100	129.2	36.7	0.284

The average of $\frac{H_h}{H_d}$ is: 0.329

where: H_d is the Max. Daily Precipitation in (mm)
H_h is the Max. Hourly Precipitation in (mm)

A regional constant can be obtained for later use on the basis of the relationships between the hourly and daily precipitation with duration of 1 and 24 hours respectively as follows:

$$\frac{H_1}{H_{24}} = \left(\frac{1}{24}\right)^{1-r}$$

$$0.329 = \left(\frac{1}{24}\right)^{1-r}$$

$$r = 0.650$$

where r is the regional constant.

Considering the established relationship between the daily maximum and hourly maximum precipitation for Tripoli station, values of hourly maximum precipitation of the other three stations (Sirt, Ajdabia and Benina) can be determined assuming that the recorded rainfall from the four stations having same pattern, since they are occurring on the same region. They are presented in Table 5.

Table 5 Maximum Hourly Precipitation Heights for different return periods

Return period (years)	Maximum Hourly Precipitation in mm		
	Sirt	Ajdabiya	Benina
2	10.1	7.5	9.3
5	16.0	11.6	14.3
10	19.9	14.4	17.6
25	24.8	17.8	21.9
50	28.5	20.4	25.0
100	32.1	22.9	28.1

ESTIMATION OF RUNOFF DISCHARGE

The zone that extends between Sirt and Benghazi was divided into two general areas; the first one extends for about 200 km eastward of Sirt. It is characterized by a number of wadis and streams. These wadis flow from south to north in direction towards the coast. Most of these wadis cross the Railway Alignment. The total number of these wadis is 57. The second zone extends about 300 km eastward further to Benghazi. This part is characterized as plain area covered by sand and sparse vegetation with local humps and depressions with almost no defined water courses or streams. There are some scattered sabkhas along the north side of this part, and the railway alignment crosses even through some sabkhas.

Generally in hydrology, there is a greater degree of approximation in applying physical laws because hydrologic systems are large and complex in nature, and may involve several working media. Moreover, most hydrologic systems are inherently random because their major input is precipitation, which is a highly variable and unpredictable phenomenon. Consequently, statistical analysis plays a large role in hydrologic analysis.

Various methods have been used for estimating runoff discharge. Some of them are based on characteristics of the catchment's area, others are based on the theory of the probabilities by using the known different meteorological data, and lastly still others are based on study of rainfall and runoff. Several of these methods are often employed together and a value of the design runoff is chosen so as to suit an individual problem.

In the design of a structure, the likelihood that its capacity was exceeded during its design life which must be accessed. Based on the importance of the structure and the risks involved with its failure, a design return period was selected. In our case, for the railway culverts a return period of 100 years was reasonable like in similar cases where great danger of damage to property and danger of loss of lives was involved. A safety factor should be applied when using the predicted estimated 100 year return period flood, taking into consideration the confidence limits for those predicted values and the approximations involved in establishing the input.

No direct runoff measurements records for the wadis that were located in the study area or its vicinity were available. This left fewer means for predicting the needed estimates of the runoffs. Combination of the empirical equations with the statistical or probability methods was selected as the most reasonable technique, especially with the limited data available that consist only of precipitation data and the data concerning the characteristics of the wadi watershed areas.

Rational Method

This method is generally adopted in the international practice and it was developed from precipitation modelling and accumulation procedures.
Its general form is, Chow [4]:

$$Q = q.\ C.\ A \tag{1}$$

where:

Q: The total critical discharge (m^3/s) (Peak runoff flow)
q: Discharge per unit area of the catchments ($m^3/s.km^2$)
C: Runoff coefficient
A: Catchments area (km^2)

The rational method is based on the assumption that the critical flood wave is originated from precipitation of same duration as the duration of accumulation.

The flood wave path was established for determining the duration of accumulation and the runoff conditions. The time of accumulation is dependable on the condition of the valley-bed, which determines the water speed.

The rational method, which can be traced back to the mid-nineteenth century, is still probably the most widely used method for design of storm drainage systems. The idea behind the rational method is that, if rainfall of intensity (I) begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration (t_c), when all of the watershed is contributing to flow at the outlet. The product of rainfall intensity and watershed area (A) is the inflow rate for the system; (IA), and the ratio of this rate to the rate of peak discharge Q which occurs at time (t_c) is termed the runoff coefficient (C) ($0 < C \leq 1$). In this case the rational formula will take the form, Chow [4]:

$$Q = CIA \tag{2}$$

The duration used for the design precipitation intensity (I) in the above equation is the time of concentration of the watershed. Drainage area usually consists of sub areas or sub catchments of different surface characteristics .As a result, a composite analysis is required that must account for the various surface characteristics. The areas of the sub catchments are denoted by (A_j), and the runoff coefficients of each subcatchment are denoted by (C_j). The peak runoff is then computed using the following form of the rational formula, Chow [4]:

$$Q = I\sum_{j=1}^{m} C_j A_j \tag{3}$$

where: (m) is the number of subcatchment drained parts.

The assumptions associated with the rational method are:

1) The computed peak rate of runoff flow at the outlet point is a function of the average rainfall rate during the time of concentration, in other words: the peak discharge doesn't result from more intense storm of shorter duration when only a portion of the watershed is contributing to runoff at the outlet.
2) The time of concentration employed is the time for the runoff to become established and flow from the most remote part of the drainage area to the inflow point of the structure being designed.
3) Rainfall intensity is constant throughout the storm duration.

Runoff Coefficient

The runoff coefficient (C) is the least precise variable of the rational method. Its use in the formula implies a fixed ratio of peak runoff rate to rainfall rate for the drainage basin, which in reality is not the case. Proper selection of the runoff coefficient requires judgment and experience on the part of the hydrologist. The proportion of the total rainfall that will reach the outflow depends on the percent of imperviousness, slope, and ponding character of the surface. Impervious surfaces will produce nearly 100 percent runoff after the surface has become thoroughly wet, regardless of the slope. Field inspection and aerial photographs are useful in estimating the nature of the surface within the drainage area. The runoff coefficient is also dependent on the character and condition of the soil .The infiltration rate decreases as rainfall continues, and is also influenced by the antecedent moisture condition of the soil. Other factors influencing the runoff coefficient are rainfall intensity, proximity of the water table, degree of soil compaction, porosity of the subsoil, vegetation, ground slope, and depression storage. A reasonable coefficient must be chosen to represent the integrated effects of all these factors.

The coefficient of discharge (C) can be calculated using the following equation, Kuo [6]:

$$C = 0.72\left[0.6C_0 + \frac{0.4C_0}{tc}\right] \qquad (4)$$

where *tc:* is the concentration time
C_0: is a coefficient depends on the catchment's surface cover

The above equation for finding C is for the case where tc is greater than 1 hour. If tc is less than or equal to 1 hour then the value of C can be calculated using the equation, Kuo [6]:

$$C = 0.72C_0 \qquad (5)$$

Rainfall Intensity

The rainfall intensity (I) is the average rainfall rate in millimetres per hour for a particular drainage basin or sub basin. The intensity is selected on the basis of the design rainfall duration and return period. The design duration is equal to the time of concentration for the drainage area under consideration. The return period is established from design standards or chosen by the hydrologist as a design parameter (in our case a 100 year return period is applied as was explained earlier).

Runoff is assumed to reach a peak at the time of concentration (t_c) when the entire watershed is contributing to flow at outlet. The time of concentration is the time for a drop of water to flow from the remotest point of the watershed to the outflow point, which in our case the crossing of the flow channel with the railway alignment. A trial and error procedure has to be used to determine the critical time of concentration where there are several possible flow paths to be considered.

Drainage Area

The size and shape of the catchments or subcatchment under consideration was determined by inspection of the topographic maps. The area was determined by planimetering the maps; the drainage area contributing to the system being designed and the drainage sub area contributing to each inlet point was measured. The outline of the established drainage divide is following the actual watershed boundary derived from the maps.

On the basis of all the data collected from various sources, topographical maps, aerial photos, false colour landset satellite pictures and field trips of the catchment's area for each wadi and its tributaries were attributed to five groups according to their vegetative cover, type of soil and topography.

RUNOFF PARAMETERS

If the surface and soil of a watershed are examined in greater detail, the number of possible flow paths becomes enormous. Along any path, the shape, slope, and boundary roughness may be changing continuously from place to place and these factors may also vary in time as soil becomes wet. Also, precipitation varies randomly in space and time. Because of these great complications, it is not feasible to describe some hydrologic processes in detail with exact physical laws.

Speed of Runoff

The speed of flow in valley bed can be calculated by various different equations available in the literature[1]*, for our case the following equation is used, Kuo [6]:

$$V=20\ S^{0.6} \qquad (6)$$

where V: the water speed on the valley bed (m/s)
S: slope of the valley bed (m/m)

The travel time of flow from one point of a watershed to another can be deduced from the flow distance and velocity. The time at which the entire watershed begins to contribute is the time of concentration (t_c); this is the time of flow from the farthest point on the watershed to the outlet.

The flow of water over a watershed surface is a complicated process varying in all three dimensions of space and with time. It begins when water becomes pounded on the surface at sufficient depth to overcome surface retention forces and begins to flow. Two basic flow types may be distinguished, overland flow and channel flow. Overland flow consists of a thin layer of water flowing over a wide surface. Channel flow has a much narrower stream flowing in a confined path. On a natural watershed, overland flow is the first mechanism of surface flow but it may persist for only a short distance before irregularities in the watershed surface concentrating the flow into tortuous channels. Gradually, the outflows from these small channels combine to produce recognizable stream channel flows, which accumulate going downstream to form stream flow at the watershed outlet.

Concentration Time

The time of concentration (t_c) can be calculated for a watershed using the above mentioned principles with the help of one of the available equations.
For definite valley bed, the concentration time (t_c in hours) can be calculated by the equation, Kuo [6]:

$$t_c = 0.0167 \frac{L}{S^{0.6}} \quad \text{(where bed slope < 3\%)} \qquad (7)$$

where: t_c: time of concentration in hours, L: length of the main valley in (km).

For alluvial valley beds where the bed slope is >3%, the time of concentration can be calculated using the equation, Kuo [6]:

$$t_c = \frac{1}{2}(0.0167 \frac{L}{S^{0.6}} + 0.556L) \qquad (8)$$

Specific Runoff Discharge

The discharge per unit square kilometer of the catchments area (q) is a function of the 24 hours precipitation duration of precipitation (t) and the regional constant. It can be calculated using the equation, Uvaterv [10]:

$$q = 0.278 H_{24} \left(\frac{1}{24} \right)^{1-r} . t^{-r} \qquad (9)$$

where: q: discharge per unit square kilometer ($m^3/s.km^2$).

H_{24}: The height of precipitation in 24 hours (mm).

t: duration of precipitation (hours): corresponds to time of concentration.

r: regional constant (for our case r =0.650 as established before).

The relationships between precipitation per unit square kilometer (q) and duration of precipitation in hours (t) are plotted for the meteorological station Sirt on Figure (4). After calculating the time of concentration for each wadi, the discharge per unit square kilometer of the catchment's area can be obtained for 2, 5, 10, 25, 50, and 100 year return periods from these figures.

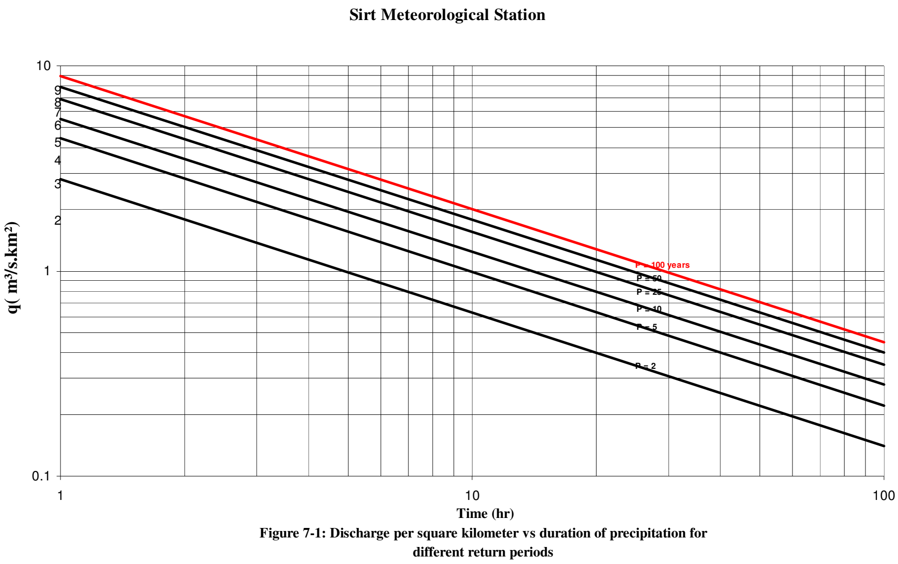

Figure 4. Discharge per square kilometer versus duration precipitation for different return periods

DISCHARGE OF WADIS

As described before, the rational formula was selected for calculating the runoff discharge for each wadi. The topographic maps were evaluated to identify the catchment's area boundaries as well as their features.

The main features of the catchment's area for each wadi were investigated as discussed in the previous section. An estimated value of the runoff coefficient was obtained for each wadi

The other effective parameters that contribute to the runoff for each catchment's area and its wadi, such as soil infiltration, proximity to water table, degree of soil compaction, porosity of the subsoil and slope, etc., were utilized to determine the concentration time and therefore indirectly the specific discharge. All the above parameters were used to determine the total runoff discharge at the wadi intersection with railway alignment.

CONCLUSIONS

In the hydraulic design of culverts, interest exits in extreme events such as the maximum values of rainfall of a storm, where in semi-arid areas occasional violent downpours might result in flash floods (torrential flows).

Due to the unavailability of hourly records of precipitations data for the meteorological stations in the study area, a model was developed to establish a relationship between the daily and hourly precipitation for Tripoli station "has similar hydrological characteristics" and was utilized to generate hourly precipitation data for the other concerned three stations.

There are no direct runoff measurement records in the study area. Statistical and probability methods have been employed in combination with the empirical equations to determine the maximum design discharges through wadis.

REFERENCES

(1) HAAN, Charles T. "Statistical Methods in Hydrology" Iowa State University Press, 1979.

(2) Surveying Department, Tripoli, Libya "Topographical Data"; ….etc.

(3) Ven Te Chow, Open-Channel Hydraulics, McGraw-Hill Inc, (1958).

(4) Ven Te Chowed, Handbook of Applied Hydrology, McGraw-Hill Inc. 1988.

(5) Ven Te Chow, David R. Maiolment and Larry W. Mays, Applied Hydrology, McGraw-Hill Inc., 1988.

(6) Chin, Y. Kuo, Engineering Hydrology. American Society of Civil Engineers.

(7) U.S. Dept. of Interior, Bureau of Reclamation, Design of small Dams, (1977).

(8) Abu grain-Benghazi Railway Line, (Techno-Economic study and preliminary Design) Volume 5.

(9) General Directorate of Civil Aviation and Meteorology, Tripoli, Libya, "Meteorological Data".

(10) TESCO UVATERV, Maintenance, Geotechnical, hydrological and economical Studies, Abuqrin – Benghazi Railway line, Volume 5, February 1986.