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Frequency Analysis of Outflow from Kufa Barrage by using Probability Distributions for Flood Estimation

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Abstract:

This research aims to evaluate the suitability of several probability distributions to represent the discharge data from Kufa barrage, and to estimate the maximum hydrological values using the frequency factor method. In this research, three probability distributions were used to characterize the discharge data: the normal distribution, the lognormal distribution, and the gamma distribution. To estimate the maximum hydrological discharge values over different recurrence intervals (25, 50, 75, and 100 years), the frequency factor method was adopted. The relationship between the frequency factor and the recurrence interval was found to be a direct relationship, meaning that the frequency factor increases with the increase in the recurrence interval. Four distributions were used to calculate frequency factor, the normal, the lognormal, the extreme values (Gumbel), and the log Pearson type III distributions. The chi-square and Kolmogorov-Smirnov indices were applied, in addition to graphical consistency tests. According to the chi-square test, the lognormal distribution (using the maximum likelihood method) was found to be the best fit to the data, and according to the k-s index test, the lognormal distribution (using the method of moments) was found to be the best fit to the data.

Keyword : Probability distributions , Frequency factor , Recurrence periods, Kufa barrage.

Introduction

Statistical analyses play a vital role in understanding and estimating extreme hydrological phenomena such as floods and droughts, due to their pivotal role in water resource management and the design of engineering structures such as dams and drainage stations. [1] .To select the most appropriate distribution to represent hydrological data, a set of probability distributions must be analyzed and compared for their suitability to the data . The most popular of these distributions are the normal , log-normal , and gamma distributions, due to their ability to represent the statistical properties of drainage data , which are typically characterized by asymmetry and high dispersion [2][3]. To ensure the reliability of the results, the data fit to each distribution must be tested using standard statistical tests the chi-square test, the Kolmogorov-Smirnov (K-S) test. These tests are standard tools for testing the null hypothesis that the data follow a specified distribution by comparing the calculated statistical value to the critical value at a given significance level [4].

Frequency analysis it based on the assumption that hydrological events follow a probabilistic pattern that can be represented by a statistical distribution. This distribution can then be used to estimate the values of future events with long recurrence intervals [5]. This methodology has become an essential tool in applied hydrology, particularly when designing critical water infrastructure such as dams, culverts, and bridges .To achieve the best statistical representation, the coefficients of these distributions are estimated using two main methods: the method of moments and the maximum likelihood estimation method. Numerous studies have demonstrated that the choice of estimation method directly affects the results of recurrence analysis, especially for extreme data [6][7]. In the next step, the extreme values are calculated using the frequency factor method, which allows the event to be estimated at a specific recurrence interval based on the mean, standard deviation, and Kt factor associated with the chosen probability distribution. Extreme Value and Log-Pearson III distributions are among the most common distributions used to derive Kt in hydrological studies [8].

1 - Fitting Probability Distributions to the Data

In this paper, statistical analysis will be conducted the selection of an appropriate probability model depends on a goodness-of-fit test. A variety of probability distribution models have been applied in discharge studies. In this study, three probability distributions were selected. the normal and lognormal, and the gamma distributions.

The data were obtained from the National Center for Water Resources Management [9] in this paper, the total annual flow data of Kufa barrage for a period of thirty-one years (1994 to 2024)

1-2 Data use

In this paper, the outflow data was used (figure 1) of the Kufa barrage , the image of which is shown in Figure 2, located in the city of Kufa in the Najaf Governorate .

Figure (1) total outflow data of kufa barrage

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Figure (2) kufa barrage

1-3 Probability distributions

1-3-1 Normal distribution

The normal distribution is widely used in hydrology because aggregated variables—such as outflows at structures like Kufa barrage—tend to approximate normality under the Central Limit Theorem. This has been demonstrated empirically through statistical quantile plots and goodness-of-fit assessments using hydrological data [10]

However, it has drawbacks: it allows negative values and assumes symmetry, while hydrologic data are often nonnegative and skewed [11]

1-3-2 Log normal distribution

A random variable X is said to follow a lognormal distribution if its logarithm, Y = log(X), is normally distributed. This distribution is relevant in hydrology because many natural processes are multiplicative in nature; when the product of independent and identically distributed variables is taken, their logarithms sum to a variable that tends toward the normal distribution by the Central Limit Theorem [12]. Lognormal distributions are especially suitable for modeling positively skewed hydrologic variables, such as rainfall intensity, peak discharges, and sediment loads. Their ability to represent non-negative data with long upper tails makes them a common choice in probabilistic flood and soil property analyses [11].

1-3-3 Gamma distribution

The gamma distribution it commonly used in hydrology to model positively skewed variables. It describes the waiting time until β events occur in a Poisson process and results from summing β independent, exponentially distributed random variables [11]. Its flexibility makes it useful for representing non-negative and right-skewed hydrologic data without requiring a log transformation.

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1-4 Goodness-of-Fit Tests

Three probability distributions were developed for the data generated by the Kufa barrage. It is now important to determine which of these distributions best fits the data. The appropriate probability distribution is typically selected using goodness-of-fit tests, a decision-making method for assessing the fit of sample and population data to a specified probability distribution [13] . These tests offer an objective measure for identifying inadequate models, but they do not provide definitive evidence that a model is correct. A non-rejection of the null hypothesis merely indicates insufficient evidence to conclude a poor fit, not confirmation of model validity. [14]. two goodness-of-fit tests were used. Chi-square, Kolmogorov–Smirnov Test (K-S Test).

The finale results of the chi-square test are shown in Table 1 and the finale results of the k-s test are shown in Table 2.

Table (1) presents the chi-square statistic calculated for the Kufa barrage discharge data

	value of(Xc)^2		
	normal	log normal	**gamma**
moment method	7.3160	3.1370	**3.3926**
Maximum-likelihood method	7.3160	3.1042	**34.2930**

Table (2) the values of the K-S index for kufa barrage

	value of(Xc)^2		
	normal	log normal	**gamma**
moment method	0.1397	0.00008	**0.095108917**
maximum - likelihood method	0.1397	0.074725	**0.162650205**

2- Frequency analysis using frequency factors.

The value xt for a hydrological event we can expressed as an average μ added to the deviation Δxt of the variable,

XT=u+ΔXT ………………………………………………………….(1-1)

The deviation can be considered equivalent to the multiplication1 of the standard deviation and the frequency factor Kt, which means that the equation expresses the relationship as follows: (ΔXt = Kt * σ). The deviation ΔXt and the frequency factor Kt are related The Re-visit period along with the corresponding probability distribution model applied in the analysis influence the formulation. Accordingly, Equation (1-1) can be expressed as follows:

XT=¯X+Kt*s……………………………………………………………….. (1-2)

If a data being analyzed is (Y = ln x), the same Methodology it Highlights to a statistical analysis of a ln values for a variables, utilizing

Yt= ¯Y+Kt*Sy ………………………………………………………..….. (1-3)

The desired value of (Xt) can be obtained by calculating the anti-ln of yt.

2.1 Data and Analysis

In this paper the maximum annual outflow data for thirty-one years (1994 to 2024) for Kufa barrage were analyzed. shown in figure (3)

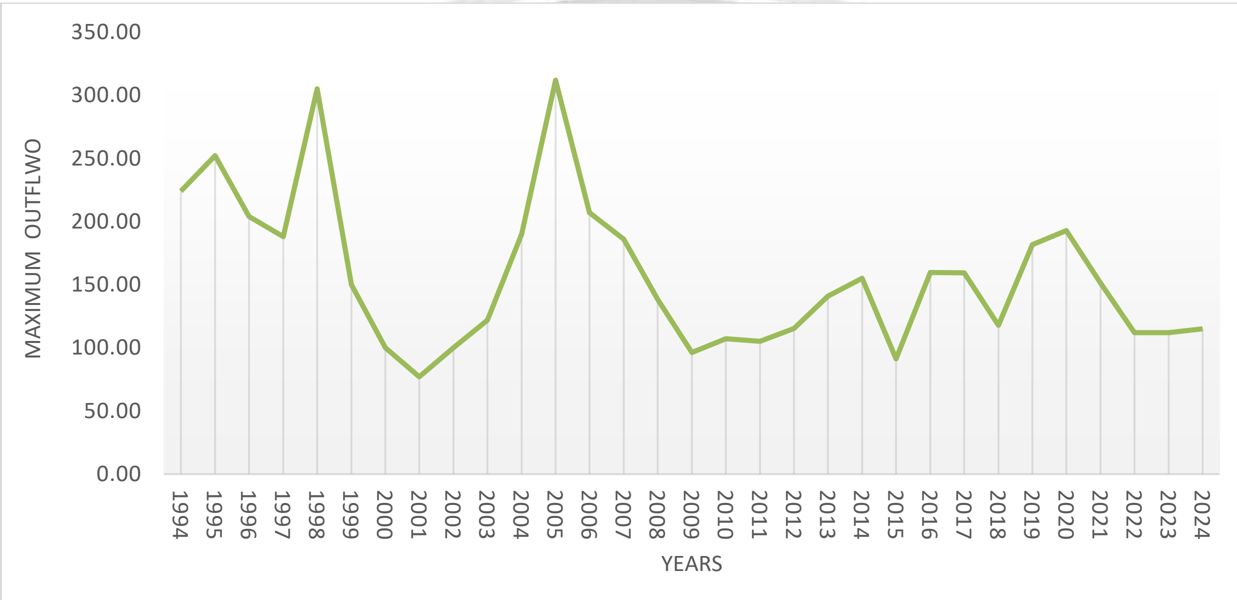

Figure (3) maximum annual outflow data for Kufa barrage

2.2 Normal distributions

Using equation (1-2) we can derive the recurrence coefficient follows

$$Kt = \frac{xt-\mu}{\sigma} \quad \text{………………………………………………………………….. (1-4)}$$

This is an it self typical normal variable z that was Found in Equation (1-6).

The value of z debate to an Probability Distribution of P (P= 1/T) can be calculated by finding the amount of the intermediate variable W **[15]**

$$W = \left[\ln\left(\frac{1}{P^2}\right)\right]^{\frac{1}{2}} \qquad (0 < P \leq 0.5) \text{ ……………………………………………………….(1-5)}$$

Next, determine the value of z by used the approximate methods.

$$z = w - \frac{2.515517+0.802853w+0.010328w^2}{1+1.432788w+0.189269w^2+0.001308w^3} \text{ ……………………………………….......(1-6)}$$

As previously noted, The recurrence coefficient kt. for a normal distribution corresponds to the amount of z .

2-3 Log normal distribution

In this distribution, the same steps are followed that were used in the normal distribution, where if the variable under analysis is (y = ln x), the same procedure is used in the statistical analysis of the values by following the same methodology

2-4 Extreme Value Distributions.

For the Extreme Value Type I distribution, **[16]** derived the expression

$$Kt = -\frac{\sqrt{6}}{\pi}\left\{0.557 + \ln\left[\ln\left(\frac{T}{T-1}\right)\right]\right\} \quad \text{...(1-7)}$$

To Express T as a function of Kt, the previous the equation might be. Reformulated as follows:

$$T = \frac{1}{1-exp\left\{-exp\left[-\left(y+\frac{\pi Kt}{\sqrt{6}}\right)\right]\right\}} \quad \text{... .... (1-8)}$$

2-5 Log Pearson Type III Distribution

The first step of this distribution involves calculating ln for the hydrological data (where y = ln X). Next, the arithmetic mean (Ȳ), standard deviation (σ), and coefficient of skewness (Cs) of the ln values are determined. The frequency factor it based on both the recurrence period T and the coefficient of skewness Cs. When Cs equals zero, the frequency factor corresponds to the standard normal variable (z). However, when Cs is not equal to zero, the frequency factor (Kt) it estimated using the equation

(1-9) proposed by Kite (1977) [17].

$$Kt = z + (z^2-1)k + \frac{1}{3}(z^3-6z)k^2 - (z^2-1)k^3 + zk^4 + \frac{1}{3}k^5 \quad \text{............................. (1-9)}$$

$$where\ k = \frac{Cs}{6}$$

$$Cs = \frac{n\sum_{i=1}^{n}(Xi-\overline{x})^3}{(n-1)(n-2)s^3}$$

Theoretically, there are no specific values for (cs), in other words (it has no fixed limit), but from the practical side, its values can be between (-3_+3), and if they are outside this range, this means that the samples are very small, or there are outlier values, or that the distribution has a very heavy tail that does not fit the distribution. [17].

. Table 5 shows the amount of the frequency factor of (normal and Log normal and extreme value and Log Pearson type III) distribution, for several different amount of the recurrence interval (25,50,75,100) years.

3- Results and Discussion

3-1-1 According to the chi-square test, After comparing the results with the critical value (11.07) Which was calculated based on the degree of freedom (5) and the significance level of 0.05. it found that the log normal distribution (using the maximum likelihood method) is the most appropriate for

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the data. According to the k-s index distribution, and after comparing the results with the critical value (0.268) ,After comparing the results with the critical value (0.268) that was calculated based on the sample size (31) and the significance level (0.05) it found that the log normal distribution (using the moment method) is the most appropriate for the data.

3-1-2 In this paper The distribution coefficients were estimated using the method of moments, and the probability values F(x) were calculated for the three selected distributions used , corresponding to the method of moments shown in table (3). The distribution coefficients were also estimated using the maximum likelihood method, and the probability values F(x) were calculated for the three selected distributions (normal, lognormal, and gamma) used in this study, corresponding to the maximum likelihood method shown in table (4).

3-1-3 Q-Q plots were drawn for log normal distribution and for both methods, the method of moments and the maximum likelihood method, as shown in Figures 4 and 5. The rest of the distributions are drawn in the same way.

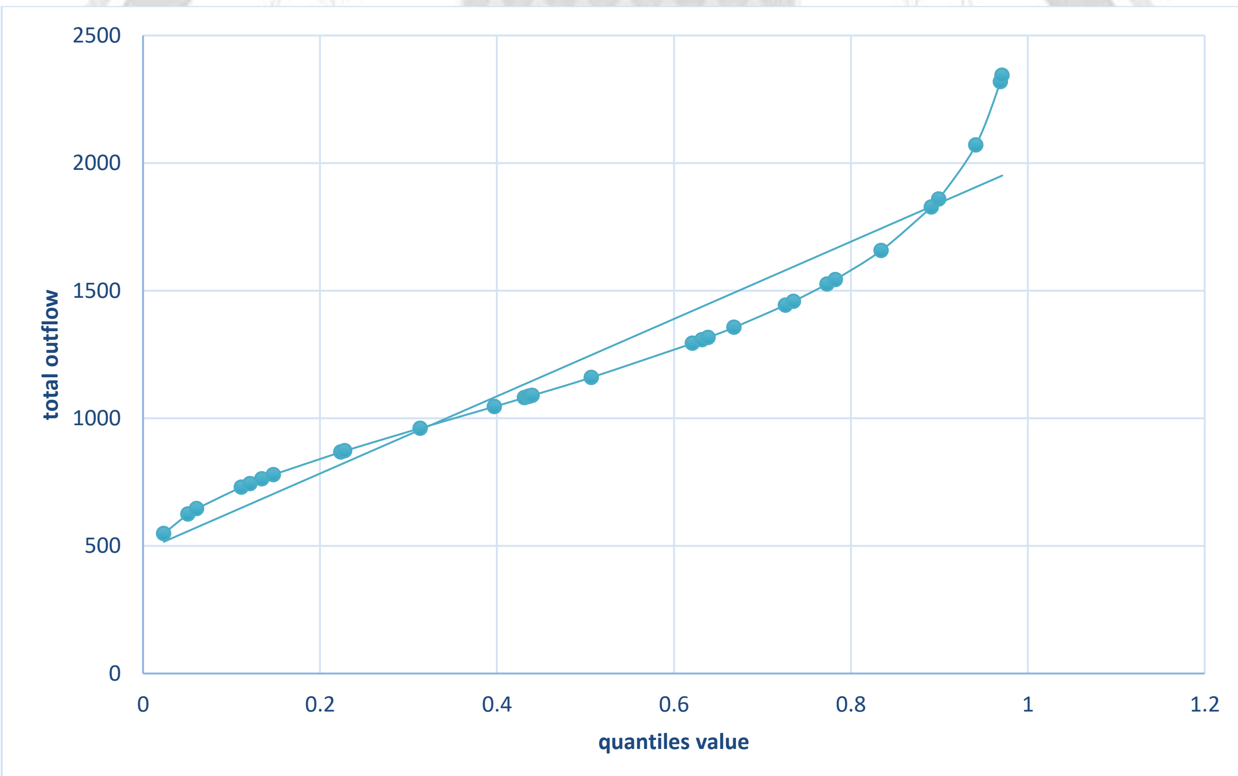

Figure (4) Q-Q plot for log normal distribution for moment method

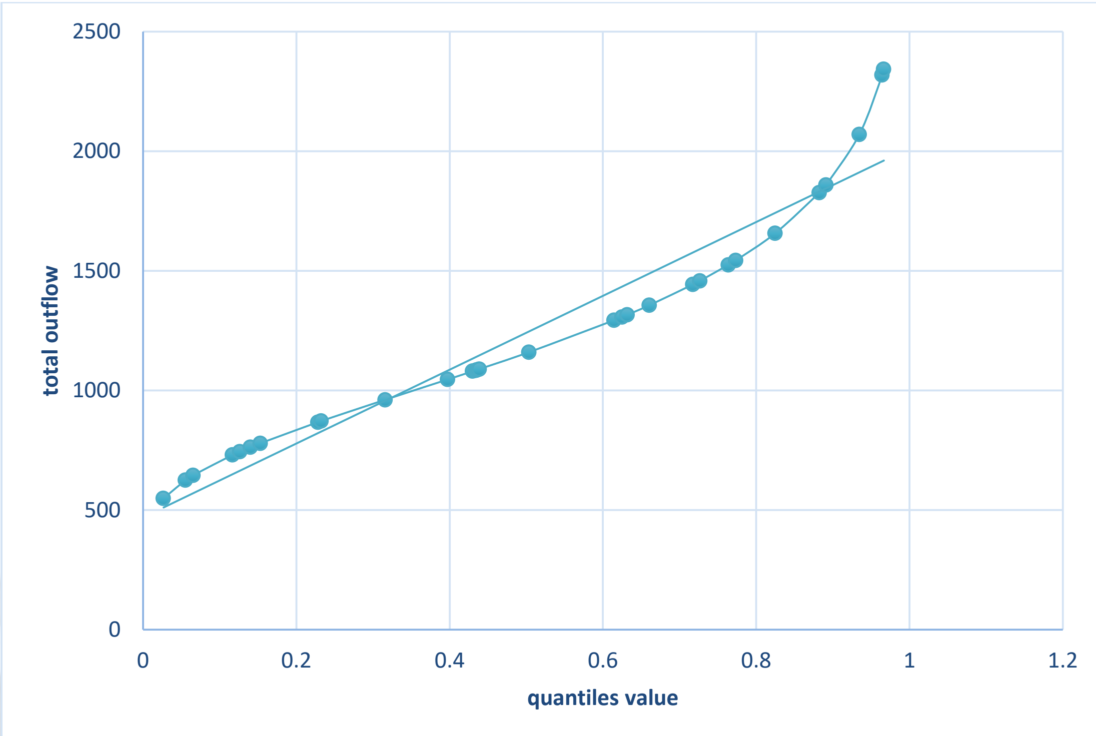

Figure (5) Q-Q plot for log normal distribution for Max. Likelihood

Table (3): Calculations of probability values F(x) by using method of moments

Rank	Total outflow	normal -dis	LOG-normal -dis	GAMMA-dis
1	548	0.074654846	0.023374665	0.042576692
2	625	0.099956869	0.05082756	0.072965763
3	645.17	0.107517402	0.060340408	0.082586866
4	729.95	0.143782479	0.110914891	0.130371786
5	743.78	0.150402365	0.120704606	0.139237184
6	761.99	0.159423888	0.134196342	0.151335582
7	779	0.168164489	0.147384535	0.163055955
8	867.25	0.218324345	0.223430108	0.229576161
9	872	0.221248398	0.227818781	0.23339161
10	960.71	0.279795946	0.313164751	0.307823165
11	1045.47	0.341956762	0.397145965	0.382354965
12	1080	0.368699874	0.431002335	0.412972188
13	1083.66	0.37157487	0.434561187	0.416212879
14	1085	0.372629268	0.435862488	0.41739895
15	1086.35	0.3736925	0.437172578	0.418593633

16	1089.06	0.375829738	0.439799615	0.420991083
17	1159.76	0.432748624	0.506688777	0.482914438
18	1293.35	0.543206613	0.621106624	0.59339055
19	1307	0.55444922	0.631742172	0.603991947
20	1315.8	0.561674633	0.638488134	0.610747919
21	1355.6	0.594062946	0.66790292	0.640501153
22	1442.82	0.662554717	0.726054138	0.700802416
23	1458	0.674013588	0.735298558	0.710578031
24	1525	0.722537984	0.773100448	0.751113916
25	1543	0.734946155	0.782446908	0.761277531
26	1657	0.806476858	0.834262933	0.818642908
27	1827	0.888506379	0.891099059	0.883401428
28	1859	0.900637074	0.899523134	0.89312444
29	2070	0.957656536	0.94137414	0.941466751
30	2318	0.987454851	0.969194988	0.972695673
31	2343	0.989047613	0.971137886	0.974789659

Table (4) Calculations of probability values F(x) by using method of Max. Likelihood

Rank	total	normal -dis	LOG-normal -dis	GAMMA-dis
1	548	0.074654846	0.026435864	**0.417462438**
2	625	0.099956869	0.055367979	**0.451752017**
3	645.17	0.107517402	0.065203724	**0.460294411**
4	729.95	0.143782479	0.116588649	**0.494394722**
5	743.78	0.150402365	0.126410689	**0.499697169**
6	761.99	0.159423888	0.139898614	**0.506573888**
7	779	0.168164489	0.153035352	**0.512892098**
8	867.25	0.218324345	0.228104372	**0.544128086**
9	872	0.221248398	0.232409607	**0.545739465**
10	960.71	0.279795946	0.315755157	**0.574619981**
11	1045.47	0.341956762	0.397329167	**0.600212012**
12	1080	0.368699874	0.43015883	**0.610120898**
13	1083.66	0.37157487	0.433608982	**0.611154448**
14	1085	0.372629268	0.434870516	**0.611532061**

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15	1086.35	0.3736925	0.436140559	**0.611912064**
16	1089.06	0.375829738	0.438687266	**0.612673593**
17	1159.76	0.432748624	0.503538864	**0.631947127**
18	1293.35	0.543206613	0.614740088	**0.665461491**
19	1307	0.55444922	0.625110381	**0.668687621**
20	1315.8	0.561674633	0.631692181	**0.67074898**
21	1355.6	0.594062946	0.660432294	**0.679894563**
22	1442.82	0.662554717	0.717491019	**0.698964107**
23	1458	0.674013588	0.726597665	**0.702152612**
24	1525	0.722537984	0.76396294	**0.715787664**
25	1543	0.734946155	0.773236792	**0.719332782**
26	1657	0.806476858	0.824967295	**0.740691964**
27	1827	0.888506379	0.88254919	**0.769331646**
28	1859	0.900637074	0.891188001	**0.774330347**
29	2070	0.957656536	0.934703887	**0.804517958**
30	2318	0.987454851	0.964487522	**0.834601336**
31	2343	0.989047613	0.966609621	**0.837349795**

3-2 the outflow data of Kufa barrage were used, and the frequency factor was found for the four probability distributions and for the recurrence interval (25-50-75-100) years, as shown in Table (5). Substituting the frequency factor value in Equation (1-2) (for the normal and extreme value distributions) to obtain the extreme event (xt). Substituting the frequency factor value in Equation (1-3) (for the lognormal and Log Pearson type 3 distributions), then taking the inverse of ln to obtain the extreme event (xt). The extreme event (Xt) was found, as shown in Table (6).

Table (5) value of frequency factor for al distributions

	frequency factor(kt)			
recurrence interval	25 year	50 year	75 years	100 year
normal	1.751	2.054	2.2265	2.358
log normal	1.751	2.054	2.2265	2.358
extreme value	2.04	2.59	2.91	3.14
log – Pearson type (|||)	1.49	1.618	1.676	1.712

For the normal and lognormal distributions, the value of kt depends on the recurrence interval and does not depend on the value of the outflow. Therefore, the values of kt are the same for each recurrence interval for both distributions.

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Table (6) value of extreme event (Xt) for al distributions

	(m^3/s) extreme event(Xt)			
recurrence interval	25 year	50 year	75 years	100 year
normal	261.127	279.14	289.4	297.21
log normal	276.165	304.844	323.76	339.61
extreme value	279.497	311	330	343.7
log – Pearson type (|||)	249.635	261.125	266.4	269.886

The previous tables and reveal a relationship between the recurrence interval and the frequency factor, which is fundamental to statistical distribution methods, especially when estimating rare events such as floods and heavy rainfall. This relationship is directly proportional. The higher the recurrence interval, the higher the frequency factor, and consequently, the higher the estimated value xt, reflecting the rarity and severity of the event.

4-conclusion

4-1 The results from two tests K–S index, and Chi-Square support the conclusion that the monthly or annual outflow data from Al- Kufa barrage do not significantly deviate from the normal distribution. Therefore, the normal distribution is statistically appropriate for modeling this hydrologic variable, which is crucial for future water resources planning, hydraulic structure design, and reliability assessments under different flow scenarios. Two tests K–S index, and Chi-Square strongly support the Lognormal distribution as a suitable model for the outflow data from Al- Kufa barrage. The test statistics are significantly below their corresponding critical values. This suggests that the Log normal distribution offers an even better fit than the Normal distribution, which is consistent with the typically skewed nature of hydrologic flow data. Such a fit enhances the reliability of frequency analysis, return period estimation, and the hydraulic design of infrastructure under extreme flow conditions. Two tests K–S index, and Chi-Square show that the Gamma distribution fits the outflow data from Al- Kufa barrage very well. The test statistics are below corresponding critical values. This suggests that the Gamma model, like the Log normal distribution, is a strong candidate for use in hydrologic frequency analysis, particularly where positively skewed flow behavior is expected. Such a fit is crucial for accurate estimation of design flows and risk-based assessments

4.2 Frequency analysis using a frequency factor is a vital tool for estimating rare or extreme events based on historical data. This method is widely used in fields such as hydrology and civil engineering, where it contributes to infrastructure design and mitigating risks associated with climate events .The application results show that each statistical distribution produces different results for the same Outflow data, especially over long recurrence intervals. Therefore, choosing the most appropriate distribution depends on the nature of the data being studied and its general shape. Based on the values in Table 6, it was found that the Gamble distribution is the most appropriate because it gives a higher discharge than others for all revisit periods, meaning that it gives a greater safety factor than others in the case of designing dams or hydraulic structures in general.

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الخلاصة

تهدف هذه الورقة إلى تقييم مدى ملاءمة عدة توزيعات احتمالية لتمثيل بيانات التصريف من سد الكوفة، وتقدير القيم الهيدرولوجية القصوى باستخدام طريقة عامل التردد. في هذه الورقة، استُخدمت ثلاثة توزيعات احتمالية لتوصيف بيانات التصريف: التوزيع الطبيعي، والتوزيع اللوغاريتمي الطبيعي، وتوزيع جاما. ولتقدير قيم التصريف الهيدرولوجي القصوى على مدى فترات تكرارية مختلفة (25، 50، 75، و100 عام)، تم اعتماد طريقة عامل التردد. واستُخدمت أربعة توزيعات لحساب عامل التكرار التوزيع الطبيعي، والتوزيع اللوغاريتمي الطبيعي، والقيم القصوى من النوع الأول(Gumbel) ، وتوزيع لوغاريتم بيرسون من النوع الثالث. وطُبقت مؤشرات مربع كاي وكولموغوروف–سميرنوف، بالإضافة إلى اختبارات التوافق البياني. وفقًا لاختبار مربع كاي، وُجد أن التوزيع اللوغاريتمي الطبيعي (باستخدام طريقة الاحتمال الأقصى) هو الأنسب للبيانات، ووفقًا لاختبار مؤشر k-s ، وُجد أن التوزيع اللوغاريتمي الطبيعي (باستخدام طريقة العزوم) هو الأنسب للبيانات.

الكلمات الدالة: توزيعات الاحتمالات، عامل التكرار ، فترات التكرار ، سد الكوفة.