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# Analysis of Rainfall and Runoff Flood Frequency Based on Statistical and Hydrological Models

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## Abstract

This study aims to design ten-hour rainfall and runoff storms using the Chicago, Weibull, and Gumbel models for periods of 2, 10, 25, and 100 years of the planned dam in the Makhoul Basin of northern Iraq. The design storms are based on thirty years of historical data on flow rates from Mosul Dam, Dukan Dam, the Greater Zab, and the Little Zab Streams, as well as rainfall data from stations in Kirkuk, Mosul, Baiji, and Tikrit, from 1994 to 2024. Intensity-duration-frequency curves, along with the Chicago method, were employed to design the rainfall storms. The planning of the Makhoul Dam Basin is influenced by the diverse characteristics of incoming water from multiple sources, including the Greater and Little Zab Streams and the Tigris River. The analysis indicates a significant increase in discharge volume for the 100-year return period at Mosul Dam, which has the highest discharge rate of 3,000 m³/s, while the maximum discharge at Dukan Dam does not exceed 800 m³/s. The study concludes that constructing the Makhoul Dam in the near future is essential for managing floods resulting from heavy rainfall and runoff exacerbated by climate change, particularly given the lack of control over the Greater Zab Stream.

*Keywords:* Makhoul Dam; Climate Change; Design Storms; Intensity-Duration-Frequency (IDF); Gumbel Method; Chicago Method.

## 1. Introduction

Recently, the world has accelerated climate change, affecting hydrological cycles, rainfall, and flooding. Global warming has increased the average temperature and contributed to the change in evaporation and condensation rates, that cause the distribution intensity of rainfall [1-3]. This change is not limited to moist regions; it has also become clear in dry and semi-dry areas such as the Middle East [4], where extreme weather occurrence increases [5, 6]. In this context, Iraq is one of the weakest countries for the effects of climate change, according to recent international reports, ranking it as the land most at risk in the coming decades [7, 8]. These reports indicate the growing possibility of the country experiencing severe rainfall, followed by flash floods, especially in northern and western regions, which are characterized by diverse topography and climate [9]. Recent studies conducted in Iraq, which focus on areas such as Baghdad, Kirkuk, and Erbil, show the significant changes in the intensity and distribution of rainfall using Intensity-Duration-Frequency (IDF) curves, including Gumbel and Weibull distributions [10] in order to analyze floods. A study from the Makhoul dam has shown that the effect of climate change threatens surface runoff change, increased risk of sedimentary accumulation and converted top discharge, and water infrastructure [11, 12]. In its global report, the Interdiction Climate Panels have confirmed that the future predictions vary on the basis of the Climate Care model (optimistic or pessimistic), but the general trend indicated an increase in irregular rainfall and increased frequency of

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exceptions. Analysis techniques, such as Gumbel Distribution, normal distribution, and climate-down cell models (Lars-WG, CMIP 6), were used to analyze rainy behavior and design structures that are flexible for potential changes [13].

Statistical and hydrological models are essential tools for analyzing the impacts of climate change on rainfall and floods, including the use of IDF curves, precipitation, duration, and frequency. The design of drainage systems and dams widely utilizes these models [14]. The Chicago method is a geometric approach to spread out the intensity of rain during storms. This method aims to accurately identify the peak moment of rainfall, which is crucial for designing an effective drainage network [9]. Weibull method is another one that estimates the probability of rainfall based on historical data. It serves as a useful tool for initial data analysis. Additionally, the Gumbel method leverages the probability distribution of extreme values and is commonly used to analyze significant floods and rare events. Its accuracy in representing extreme cases makes it particularly suitable for designing flood-resistant structures [15]. Among the key studies, the International Energy Agency [1] reports on the National Climate Risk Assessment for Iraq, it addresses climate change issues, notably the anticipated increase in temperature and rainfall intensity. This assessment underscores the vulnerability of Iraq's rivers to flooding. To make Iraq's energy system more resilient to climate change, more political action is needed, and ideas about climate flexibility need to be used in more general ways. Investments should prioritize the reconstruction and development of infrastructure to mitigate the impacts of climate change; safeguarding against physical and cyber threats.

Şensoy et al. [10] in Turkey, who dealt with the ice rink and flood changes in Northern Iraq, analyzed the effect of climate change when the ice melted in the upper Tiger-Euphrates basins and showed that rising temperatures would quickly runaway. The most important result is that rising temperatures and precipitation variability will significantly affect the overall environment of the Upran pool; however, their study mainly focuses on the effect of climate change on discharge and snow conditions [2]. The dangers of weathering regional climate change scenarios [16–18] presented a climate profile for Iraq, which included landscapes for future rainfall changes based on greenhouse gas emissions. Adaptation for climate change requires increased regional cooperation in the management of water resources. Elsebaie et al. [19] studied the IDF relationships in dry regions of Saudi Arabia, focusing on the variation of IDF reduction in the Al-Lith region, indicating that the desert climate is also a subject to heavy rainfall. Kareem et al. [20] has shown a significant difference in the intensity of rainfall between regions, and the areas of rainfall compared to the spatial analysis of Iraq, and in the IDF reduction between Erbil and other Iraqi cities. Hussein & Kasim [21] developed IDF curves for Kirkuk using several statistical distributions, emphasizing the importance of accurate models in hydrological designs.

The current study focuses on flow and rainfall coming to the Makhoul Dam Basin, which is a planned dam to be constructed in the near future in the northwest of Biji City, Iraq. Numerous studies have concentrated on the hydraulic design, sedimentation, and dam safety aspects of Makhoul Dam. But none of these studies or others focus on estimating the flood frequency of both runoff and rainfall design storms. Sadiq et al. [22] provided an extensive review and analysis of the literature about the Makhoul Dam, observed as a vital structure for future development in Iraq. The spillway operation of the Makhoul Dam was analyzed using computational fluid dynamics simulation software. Ali [23] studied the hydraulic assessment of the proposed spillway in Makhoul Dam. He analyzed the flow capacity of the spillway for potential floods and ensured the dam's safety under changing hydrological conditions. Abdulsalam [24] studied the climate change influence and dams upstream of the Tigris River on the hydrological characteristics of Makhoul Dam. He examined changes in water flow, storage levels, and hydrological patterns resulting from human activities and climate change. Rasheed et al. [11] studied the effect of climate change on sediment in the Makhoul Dam reservoir and connected discharge changes with silt. They found that climate change will increase water shortages, high temperatures, and floods in the Tigris River pool. Ghdhban & Irzooki [25] quantified the total sediment influx from the Tigris and Little Zab Rivers into the Makhoul Dam Basin. They found that the total sediment load entering Makhoul Dam Basin from the Tigris River and Lower Zab Stream was 4.4 million tons annually. Al-Fahal et al. [26] examined the hypothetical consequences of the simultaneous failure of the Makhoul dam in Iraq by focusing on advanced hydrodynamic modeling to simulate flood behavior. Their findings highlight the greater hazard posed by the cascading dam failures compared to a single dam break.

The basin of Makhoul Dam receives the runoff that comes from the Tigris River (controlled by Mosul Dam), the Dukan Dam (constructed on the Little Zab Stream), and the Greater Zab Stream. Previous studies failed to investigate the flood analysis risk for both runoff and rainfall storms coming from above rivers and streams that influence the Makhoul Dam Basin. Therefore, this research aims to design 10-hour rainfall and runoff storms using Chicago, Weibull, and Gumbel models at return periods of 2, 10, 25, and 100 years in the Makhoul Dam Basin in northern Iraq based on flow rate data from Mosul Dam, Dukan Dam, Greater Zab, and Little Zab Streams and rainfall data from stations at Kirkuk, Mosul, Baiji, and Tikrit. Thirty years of historical data from 1994 to 2024 were analyzed and performed. The study also aims to strengthen planning capabilities in the field of water security and to address projected climate scenarios at both local and regional levels. The structure of the research includes the following: collecting historical data from 1994 to 2024 for rainfall and flow rates; using Weibull and Gumbel methods for 2, 10, 25, and 100-year return periods of flow rates and rainfall; construction of IDF curves for rainfall storms; using the Chicago method to design 10-hour rainfall storms; and finally, using the SCS hydrograph triangular method to design 10-hour flow rate storms. The structure methodology of the current study is presented in Figure 1.

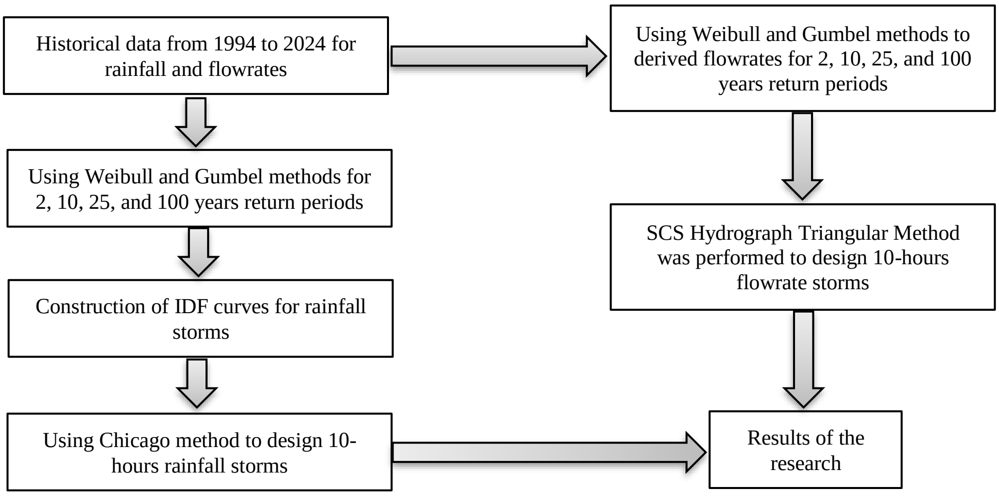


**Figure 1. Methodology process of the current research**

## 2. Materials and Methods

### 2.1. Study Area

The rain wave data from the General Authority for Meteorology and Seismic Monitoring for the stations Baiji, Tikrit, Mosul, and Kirkuk were analyzed and used in this study. The runoff wave data from the Ministry of Water Resources, which includes Mosul Dam, Dukan Dam, Little Zab Stream, and Great Zab Stream, were also analyzed to develop runoff storms. Makhoul Dam is situated at coordinates 35°10' 00"N and 43°20' 00"E, in northwest of Baiji, downstream from the confluence of the Tigris River and the Lower Zab Stream. The location of Makhoul Dam in Salah al-Din Governorate makes it within the climate zones classified as hot/dry in summer and cold/humid in winter, with some influence of the Mediterranean climate, as shown in Figure 2. The Makhoul Dam is located in northern Iraq, 30 km northwest of Baiji and 8 km south of the confluence of the Little Zab Stream with the Tigris River [18]. The planned dam is approximately 3.6 km long and 80 meters high and has an estimated storage capacity of billions of cubic meters of water. The project aims to generate hydropower with the design capacity of around 250 MW [21, 27]. In addition to supporting watering and flood protection in the central region of Iraq, the Makhoul dam is considered an important project, which is planned to increase water security for decades and manage the water resources of the Tigris River [19]. It is worth noting that the natural environment of the central Tigris River pool (where the Makhoul dam is located) is characterized by its sensitivity to the erosion and the current flow of the river under flood. Recent studies have shown that the sediment sources deposited in the Makhoul Dam reservoir come from the Tigris River, Greater Zub, and Little Zub Streams, which means that any change in the flow pattern will also affect the silt speed of the reservoir [21].

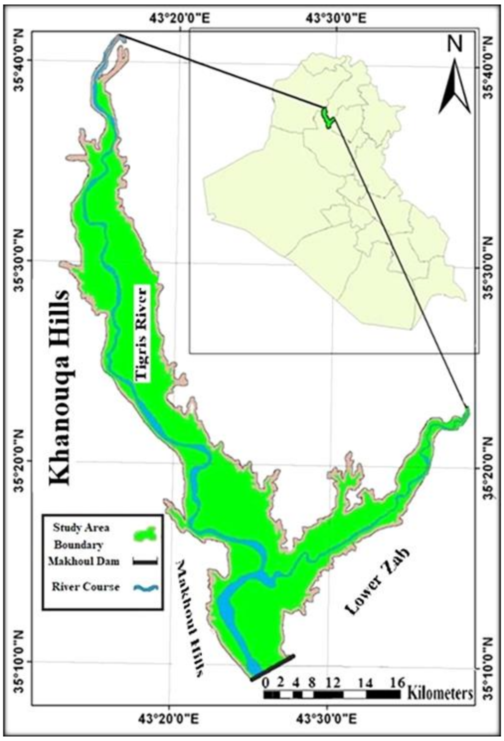


**Figure 2. Study area of Makhoul Dam Basin, located in Northern Iraq**

## 2.2. Developed IDF Curves

In this study, hydrological engineering measurement methods were used to calculate and analyze rainfall and flood frequencies. The Chicago Method was employed to determine maximum rainfall intensity based on historical data, as it relies on empirical equations that link intensity, duration, and frequency [21, 28]. The available rainfall data for Mosul, Tikrit, Baiji, and Kirkuk are 24-hour annual maximum measurements over a 30-year period (Figure 3). In fact, there are two ways to develop IDF curves for standard periods: either by obtaining detailed rainfall data from meteorological stations over short periods (such data can only be obtained from automated rain gauges) or by downscaling the annual maximum rainfall from classical rain gauges to shorter periods [28]. In order to obtain IDF curves for the study area, data on annual maximum rainfall are required for standard periods of 5, 10, 15, 30, 60, 120, 180, 360, and 720 minutes. Since these standard times are not available and not recorded in Iraq, the Mononobe formula (Equation 1) was employed to ascertain rainfall data for durations less than 24 hours. The IDF approach involves applying an empirical formula to convert daily or 24-hour rainfall totals into shorter-duration rainfall amounts [21]. Rainfall analysis via the IDF technique can be conducted at stations lacking automated rain gauges capable of simultaneously recording both rainfall and duration data, provided that rain gauges are available to capture cumulative rainfall data over a 24-hour period:

$$P_i = P_{24}\left[\frac{t}{24}\right]^{\frac{1}{3}} \tag{1}$$

where, $P_i$ is the depth of precipitation for less than 24 hours, mm, $P_{24}$ is the depth of precipitation for 24 hrs., mm, and $t$ is the required duration time in hours. The Mononobe formula (Equation 1) is a simple empirical method to estimate rainfall intensity from daily rainfall data when shorter periods are not available. It assumes uniform rainfall distribution, ignores local climatic variability, and cannot capture short-duration extreme storms, which are considered the limitations of this method [28].

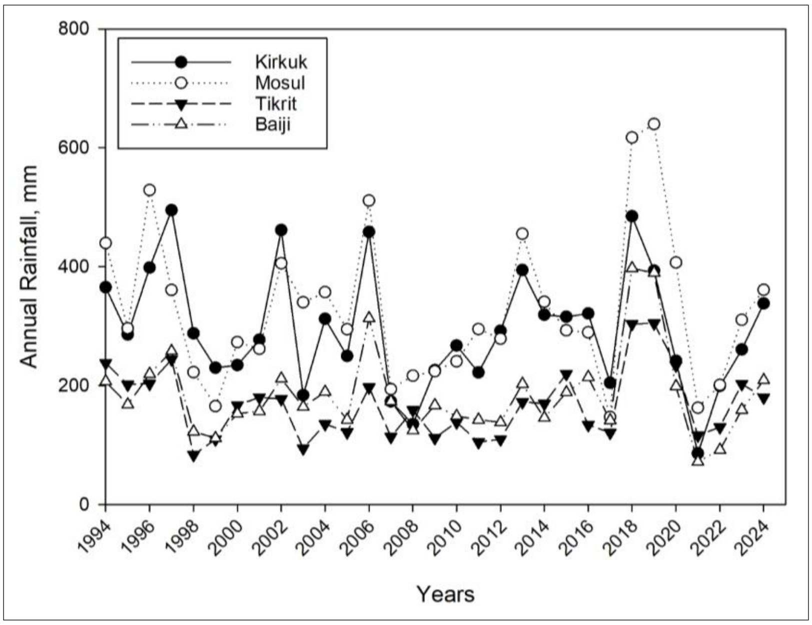


**Figure 3. Historical data of Rainfall for four stations at Kirkuk, Mosul, Tikrit, and Baiji in Iraq, for the period from 1994 to 2024**

The official national authorities were provided rainfall data from Kirkuk, Mosul, Baiji, and Tikrit meteorological stations and discharge data from Mosul Dam, Dukan Dam, the Greater Zab Stream, and the Little Zab Stream. This data covers a continuous period from 1994 to 2024. During this time, all of the stations and flow gauges keep records of being the same every year. There was no missing or inconsistent data during the required periods. However, the rainfall data was provided for 24 hours and not for shorter periods. Therefore, Equation 1 was used to perform rainfall for shorter periods as required in this study.

The frequency distribution method is a statistical technique used to analyze historical rainfall data, aiming to predict the likelihood of various rainfall intensities occurring over time. This method relies on the extremes of rainfall defined by known probability distributions, such as the Gumbel distribution. The intensity of expected rainfall can be calculated for each time and frequency interval. These results contribute to the creation of IDF curves, which are essential tools in hydrological project design and flood risk management. These rainfall patterns illustrate the relationship between rainfall intensity, duration, and frequency intervals, assisting engineers and planners in designing urban drainage systems, sewers, and dams. The accuracy of this method is contingent upon the quality and duration of the rainfall collected data, as well as the suitable selection of the statistical distribution employed [28-30].

### 2.2.1. Gumbel Method

The Gumbel procedure, invented by German mathematician Emil Gumbel, is extensively utilized for modeling severe occurrences in hydrology and various other disciplines. This procedure is a prevalent technique for extreme value analysis, utilized to ascertain maximal rainfall intensity [31]. Phenomena such as accelerated life tests, earthquakes, floods, rains, ocean currents, wind speeds, and track records are all included in this category. The Gumbel method is a simple and effective approach for addressing extreme events, such as maximum or peak rainfall. The subsequent formula calculates the rainfall frequency $P_T$ (in mm), that each duration corresponding to a specific return period $T$ (in years) [32]:

$$P_T = P_{ave.} + K * S \tag{2}$$

where, $P_T$ is the rainfall frequency, $P_{ave.}$ is the mean of the maximum precipitation corresponding to a specific duration, and $K$ is the Gumbel frequency factor, which is expressed as follows:

$$K = -\frac{\sqrt{6}}{\pi}\left[0.577 + ln\left[Ln\left[\frac{T}{T-1}\right]\right]\right] \tag{3}$$

where, $T$ is the return periods. The individual extreme value of rainfall is $P_i$, and $n$ is the number of events or years of record. The following equation is used to calculate the standard deviation $S$:

$$S = [\frac{1}{n-1}\sum_{i=1}^{n}(pi - pave)]{}^\wedge 1/2 \tag{4}$$

where, $S$ is the standard deviation of $P_T$ data. The frequency factor ($K$), which is a function of the return period and sample size, when multiplied by the standard deviation gives the departure from the average rainfall of a desired return period. The rainfall intensity $i_t$ (mm/h) for the duration period $T_d$ is then calculated as follows [33]:

$$i_t = \frac{P_T}{T_d} \tag{5}$$

### 2.2.2. Weibull's Method

This method is used to analyze rainfall data and determine the probability distribution, which helps in estimating the rainfall intensity for different frequencies. Firstly, the Weibull equation calculated the return period. Values (such as maximum annual rainfall or flood discharge) are arranged in descending order, and then the rank of each value was calculated. The return period ($T$) is expressed as follows [34]:

$$T = \frac{N+1}{m} \tag{6}$$

where, $N$ is the maximum rank, and $m$ is the rank of the event in descending order (1 for largest, 2 for second, and so on).

### 2.2.3. Chicago Method

The IDF curves were first derived based on different return periods (2, 10, 25, and 100 years) that estimated from Gumbel distribution. The Chicago method employed the Sherman equation as follows [35]:

$$i_t = \frac{a}{\langle t_d + b\rangle^c} \tag{7}$$

where, $i_t$ is the rainfall intensity, $t_d$ is the storm duration, $a$, $b$, and $c$ are the parameters that represent the local conditions and the return period. These parameters were found from fitting curve of IDF curves that obtained from Gumbel method. To develop the peak intensity of the design hyetograph over its duration, the following formulas were employed to find rainfall intensity at time before the peak ($t_1$) and time after the peak ($t_2$) [36, 37]:

Before peak

$$i_{t_1} = \frac{a\left[\frac{t_1}{y}(1-c)+b\right]}{\left[\frac{t_1}{y}+b\right]^{1+c}} \tag{8}$$

After peak

$$i_{t_2} = \frac{a\left[\frac{t_2}{y}(1-c)+b\right]}{\left[\frac{t_2}{1-y}+b\right]^{1+c}} \tag{9}$$

where, $i_{t1}$ is the rainfall intensity before the peak, $i_{t2}$ is the rainfall intensity after the peak, $t_1$ is the time before the peak, $t_2$ is the time after the peak, and $y$ is the time factor to determine the peak time of the storm. The Chicago method assumed that the factor *y* ranges from 0.4 to 0.5. This study assumed a *y* of 0.43 that obtained a peak of storm occurred at 260 minutes.

In this study, the Gumbel and Weibull distributions were selected for rainfall and flood frequency analysis due to their common use in hydrological studies and their effectiveness with annual maximum series. The Gumbel distribution was utilized to derive IDF curves for the Chicago method in designing rainfall storms. To maintain consistency, the Gumbel distribution was also employed to determine flow rates for various return periods. On the other hand, the Weibull distribution served as a general comparison method for evaluating the rainfall and flow rates derived from the Gumbel distribution. Other distributions, such as the Log-Pearson Type III and Generalized Extreme Value distributions, are frequently applied in extreme value analysis. However, small sample sizes can hinder the effectiveness of these distributions, as they require precise estimates of additional parameters, particularly skewness. Given the 30-year record length and the study's emphasis on design, these alternative distributions were not utilized.

### 2.3. SCS Hydrograph Triangular Method

The U.S. Soil Conservation Service (SCS), now referred to as the Natural Resources Conservation Service (NRCS), developed a dimensionless unit hydrograph derived from the analysis of numerous watersheds. The X-axis represents dimensionless time units, while the Y-axis indicates dimensionless discharge units. This dimensionless unit hydrograph diagram is highly valuable for creating synthetic unit hydrographs applicable to a diverse range of watersheds [38]. Many agencies endorse dimensionless unit hydrographs based on extensive studies of various unit hydrographs to assist the development of synthetic unit hydrographs. A standard flow hydrograph generated by the U.S. Soil Conservation Service (SCS) indicates that 37.5% of the total runoff volume transpires prior to peak discharge, while the residual volume occurs subsequent to peak discharge. This study advocates for a simplified "triangular" flood hydrograph. Maximum flow rates were evaluated using Gumbel and Weibull distributions, considering return periods of 2, 10, 25, and 100 years. The time to peak flow is established at 260 minutes, consistent with values used for rainfall storms. Figure 4 illustrates the flow rates for Mosul Dam, Great Zab Stream, and Dukan Dam, covering the period from 1994 to 2024.

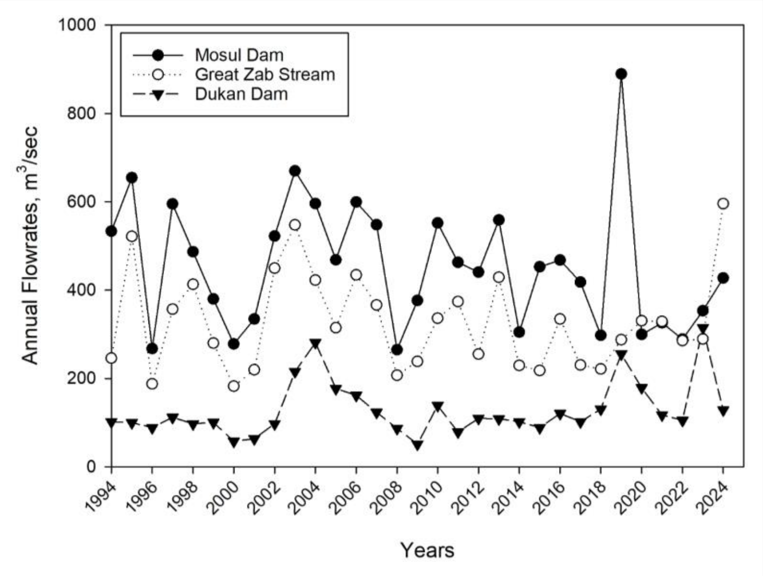


**Figure 4. Historical flow rates data over the years of Mosul Dam, Great Zab, and Dukan Dam for the period from 1994 to 2024**

## 3. Results and Discussions

### 3.1. Rainfall Frequency Analysis

In the study, rainfall intensity curves using Weibull's method were created in four Iraqi stations as shown in Figure 5. These curves are used in hydrological and engineering studies to estimate expected rainfall intensity based on rainfall duration (in minutes) and recurrence interval (number of years between similar events). Equations 1 and 6 were used to develop the curves for the four stations at different duration times. The study area at Kirkuk and Mosul stations showed approximately the highest rainfall intensity, with 5-minute rainfall intensity and a 100-year recurrence interval of approximately 900–1200 mm/h. This indicates a high probability of sudden and heavy rainfall in these cities. The Kirkuk curve also features a wide range of values covering most time dimensions, from 5 minutes to 1440 minutes (24 hours). In addition, the curve covers all time periods, making it highly suitable for detailed studies in fields such as infrastructure, urban drainage design, and hydrological analysis. The curve features a wide range of intensity in Mosul city, similar to Kirkuk, but the time scale only covers up to 720 minutes (12 hours), meaning it misses some long periods (such as 1440 minutes). Such values may limit the accuracy of the assessment in cases of prolonged rainfall or long-term planning. Similarly, the study area of Baiji Station records lower rainfall intensity than Kirkuk and Mosul for the same period and duration. Its intensity range can be described as average compared to other cities. However, the time scale covers the entire day (up to 1440 minutes), and the data includes all times. This makes the Baiji curve useful for analyzing general conditions, but it may not be sufficient for studying heavy rainfall events or designing structures that require resistance to very heavy rainfall.

The study area of Tikrit also exhibits the lowest rainfall intensity among all cities, with a marked decrease in rainfall intensity even at high-frequency intervals. Its range of values is also narrower, meaning that the variation in intensity is less pronounced, reducing the curve's usefulness in studies based on extreme weather events. However, the curve covers the entire day (1,440 minutes) and includes all times, making it suitable for general studies, but less accurate and precise in critical situations compared to other cities. The Kirkuk and Mosul curves provide the highest accuracy and scientific significance in flood and heavy rainfall analysis, particularly for engineering design purposes, while Tikrit and Baiji are relatively less accurate and are typically used for regional comparison or general studies. Hussein & Kasim [21] constructed IDF curves utilizing maximum daily precipitation for durations of 24, 12, 6, 4, 2, 1, and 0.5 hours in Kirkuk city from 1981 to 2023, employing various distributions. The logarithmic distribution was determined to be the optimal model for representing the correlation between the annual maximum rainfall at Kirkuk station and the length of the rainfall.

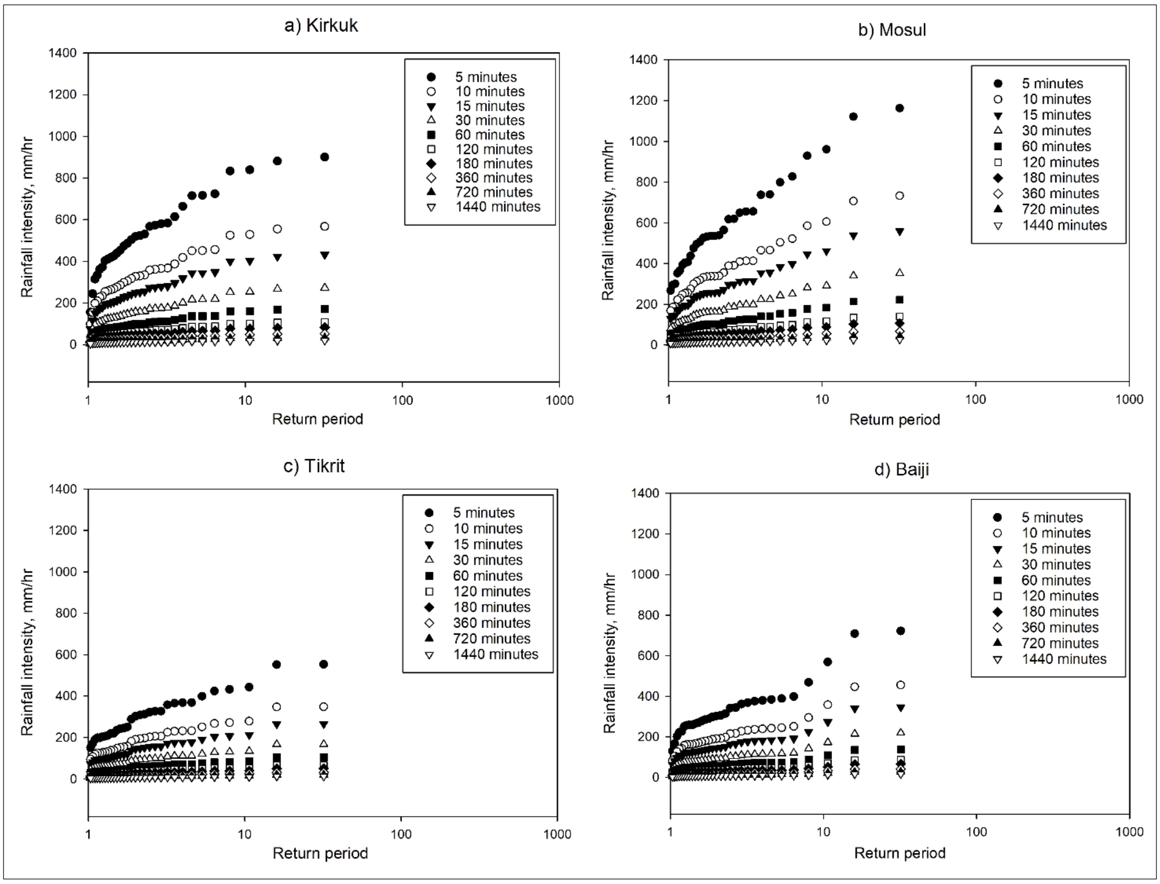


**Figure 5. Analysis of rainfall frequencies using Weibull's Method for stations a) Kirkuk, b) Mosul, c) Tikrit, and d) Baiji, for a period of 30 years and for duration times of 5, 10, 15, 30, 60, 120, 180, 360, 720, and 1440 minutes**

All station results follow the same pattern (logarithmic and standard axes). Intensity decreases with increasing rainfall duration and increases with increasing frequency interval (Figure 5). This trend is evident in all graphs. In terms of accuracy and data relevance, Kirkuk and Mosul provide more relevant and accurate data due to accurate temporal coverage (as short as 5 minutes and as long as 1,440 minutes in Kirkuk), a wide range of recurrence periods, and high rainfall intensity, allowing for a more detailed assessment of flood risk. Tikrit and Baiji are less accurate due to lower overall rainfall intensity, data convergence, and lack of horizontal axis expansion. Most importantly, when studying and analyzing extreme rainfall for hydrological facility design or studying climate change and its impact on flooding, the Kirkuk and Mosul data provide a stronger baseline. On the other hand, Tikrit and Baiji can be used as secondary comparison areas for regional analysis.

Figure 6 shows the IDF curves for four Iraqi stations based on Gumbel's method. The figure indicates that Kirkuk has the highest maximum intensity among the study areas, with rainfall intensity reaching approximately 1000 mm/hr in short periods (5 minutes), indicating the potential for very heavy rainfall over a short period. In terms of time scale, the curves show a clear and wide time scale, meaning there is a clear difference in intensity between different time periods, making the analysis more accurate. They cover almost the whole-time range, from 5 minutes to 1440 minutes (24 hours), which makes it easy to use the curve for different kinds of analysis. This curve is very useful in designing structures that must withstand high densities in short periods, such as road drains and tunnel entrances. The Kirkuk and Mosul stations had much higher rainfall intensities than the Baiji and Tikrit stations. This disparity is mostly due to climatic factors as well as topography levels (both Kirkuk and Mosul have higher levels compared to Baiji and Tikrit). During the wet season, Mediterranean frontal systems and upper-level disturbances that cause convective rainfall affect Kirkuk and Mosul more often. Furthermore, because they are close to the northern Iraqi highlands, orographic lifting and atmospheric instability are stronger, which leads to higher short-duration rainfall intensities. Baiji and Tikrit, on the other hand, are in the relatively flat central Tigris alluvial plain, which has a semi-arid climate and less synoptic forcing. This means that the rainfall is less intense and varies less over time. Kareem et al. [20] and Hussein & Kasim [21] found similar results to the present study that Kirkuk and Mosul get more rainfall than cities in the center of the country. The parameters *a*, *b*, and *c* of Equation 7 in the current study were derived from Figure 6 by fitting the lines of IDF curves. The values of *b* were zero for all stations. The values of *c* were 0.667 for all return periods and for all stations. The value of *a* range from 1472.9 to 3253.0, from 1625.4 to 3840.2, from 836.2 to 1853.1, and from 915.6 to 2204.7 for the Kirkuk, Mosul, Tikrit, and Baiji stations, respectively.

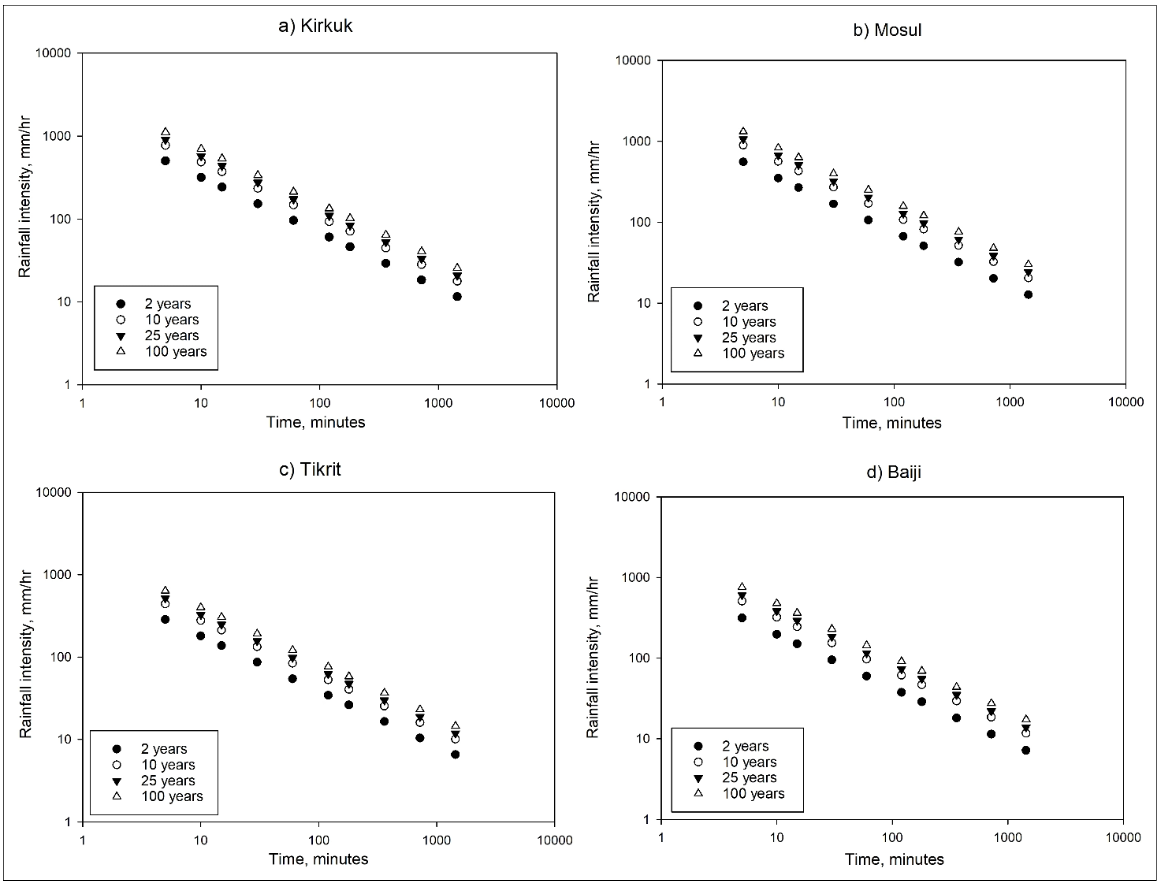


**Figure 6. Analysis of IDF curves using Gumbel's Method for stations a) Kirkuk, b) Mosul, c) Tikrit, and d) Baiji for return periods of 2, 10, 25, 100 years**

The study also indicated that Kirkuk is close to Mosul in terms of maximum intensity but slightly lower overall, yet still within the heavy rainfall range. The temporal gradient is strong and regular, showing a clear difference in intensity between different time periods. The time range also covers up to 1,440 minutes, making it useful for analyzing prolonged events. This curve strikes a balance between accuracy and scalability, making it suitable for urban infrastructure studies. Tikrit's maximum intensity is lower than Kirkuk's and Mosul's but still within the relatively high range. The temporal gradient is good, as the difference between time periods is clear but not as sharp as Kirkuk's. The deadline covers 5 to 1440 minutes, a wide time limit. There is a significant vacancy between different curves (2, 10, 25, and 100 years), which facilitates the interpretation of the repetition’s effect period on the intensity of precipitation. Baiji's maximum rainfall intensity is the lowest of the four cities, reaching around 800 mm/hr or less, indicating a low probability of very heavy rainfall. The temporal gradient shows a constant but less steep slope than other cities, indicating similarity between time periods. The time scale extends up to 1,440 minutes, making it suitable for long-term rainfall analysis. The curves are close together, indicating that the variation in intensity between time frequencies (such as 2 and 100 years) is not large, which could indicate relative stability in the rainfall pattern or a lack of high-quality data. If you are looking for an accurate and comprehensive analysis based on representing realistic extreme rainfall scenarios, the Kirkuk and Mosul curves are the best in terms of scientific accuracy and detail. The Tikrit and Baiji curves may be suitable for studies on a local scale or with lower risks, but they are less useful when studying extreme frequency scenarios or the impacts of climate change.

In northern Iraq, the rainfall storms have uneven rainfall patterns with quick intensification and a longer recession phase. The Chicago method assumes that the storm structure is symmetrical around the peak rainfall intensity. Even so, it is still a widely used tool in hydrological design because it is consistent with IDF relationships and shows peak rainfall conditions in a conservative way. This study utilized the method for design and comparative objectives rather than for the replication of specific storm events. Storm asymmetry may affect short-duration rainfall dynamics; however, its impact on peak discharge estimation diminishes when utilizing long-duration design storms and return-period-based intensities. The design rainfall storms of 10 hours for the four stations using the Chicago Method for different recurrence periods of 2, 10, 25, and 100 years are presented in Figure 7. They are used in the design of stormwater drainage networks, culverts, gutters, dams, and open and closed sewers. They are used as inputs for runoff models to estimate flood magnitude and design flood protection systems. Assessing climate risk is a crucial task. They are used to assess flood risk with varying duration or frequency.

They play a crucial role in urban and engineering planning, used to identify safe sites for construction and estimate the impact of flooding on urban areas. Scientifically speaking, a station that provides a clearer representation and a strong realistic peak (such as Mosul or Kirkuk) is better suited for studies that require accurate risk assessment or the design of effective drainage networks. Mosul outcomes provide the highest intensity and are therefore suitable for extreme risk studies. It is suitable for evaluating climate change scenarios and the frequency of extreme events. Kirkuk outcomes also provide balanced and high-intensity data, but more realistic than Mosul (not too exaggerated). It is ideal for design applications that rely on "worst-case reality." According to the current study, using data from Kirkuk or Mosul is preferable, as the Kirkuk station offers a balance between realism and accuracy, while Mosul is used to estimate extreme scenarios and risks. Tikrit and Baiji are less severe and may not be ideal for high-risk urban design, but they are useful for agricultural or rural studies. For high-resolution studies and potential hazards, the Mosul curve is best in showing the highest peak value and the most severe hazard. For balanced and realistic design studies, the Kirkuk curve is very suitable for designing efficient infrastructure, whereas low-risk areas or agricultural studies, the Tikrit or Baiji curve may be most appropriate.

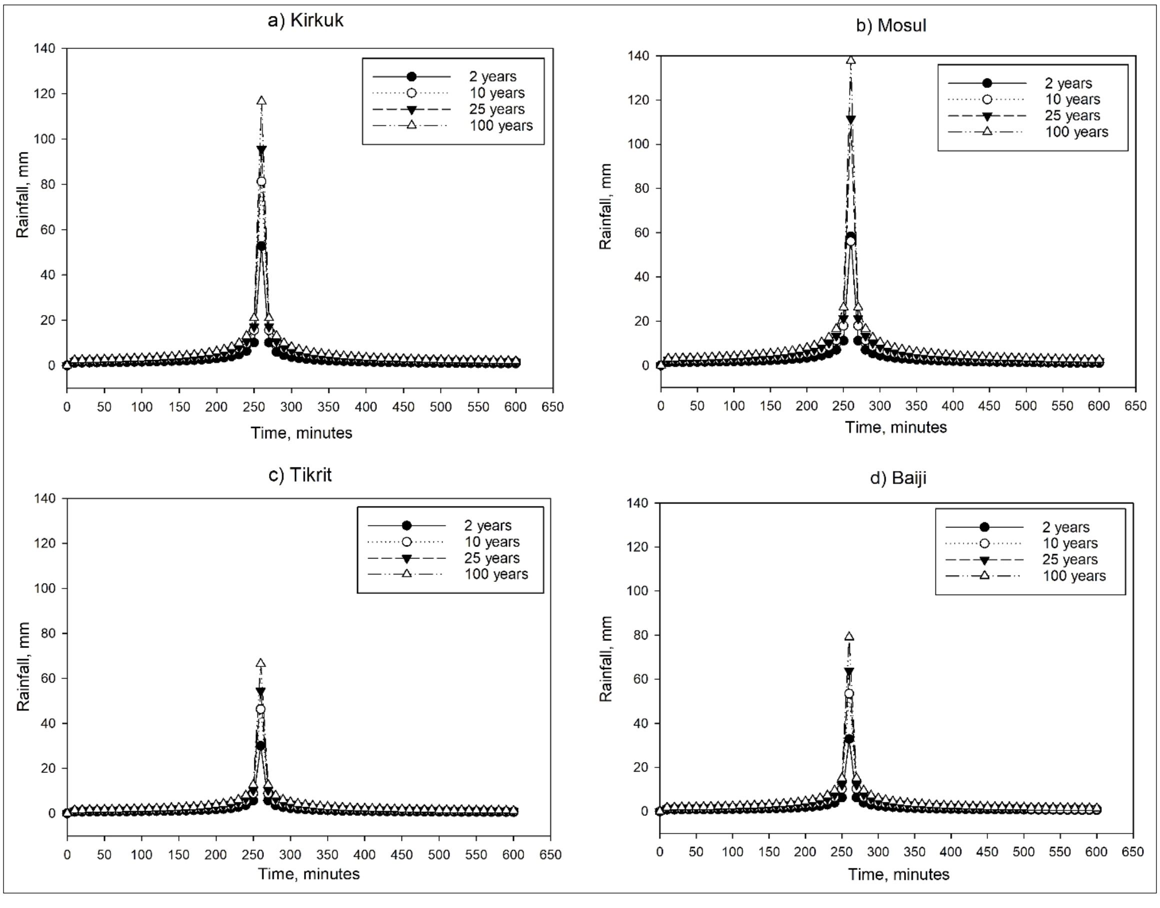


**Figure 7. Design rainfall storms of 10-hrs duration using Chicago Method for return periods of 2, 10, 25, 100 years**

### 3.2. Flood Frequency Analysis

Flow routings and reservoir operations were analyzed to aggregate the inflows to the Makhoul Dam Basin. The Tigris River, located downstream of the Mosul Dam, and the Greater Zab Stream intersect upstream of the Makhoul Dam Basin. Both the Tigris River and the Little Zab Stream contribute inflows to the Makhoul Dam Basin. The operation of the Mosul Dam impacts the inflow of the Tigris River, while the operation of the Dukan Dam affects the inflow of the Little Zab Stream. In this study to analyze the flood recurrences, the water released from Mosul Dam and Great Zab from the flood waves towards Makhoul Dam was calculated and analyzed (Figure 8-a), as well as the water released from Dukan Dam on Little Zab towards Makhoul Dam (Figure 8-b). This study analyzed flood discharge values for different return periods (2, 10, 25, and 100 years) using both the Gumbel and Weibull methods to evaluate the performance of statistical models in representing surface runoff resulting from extreme rainfall and linking them to climate change in the region. The analysis results showed that the Gumbel method was more accurate and realistic in representing extreme discharges, especially over long return periods such as 100 years. The peak discharge at Mosul Dam was 3,406 m³/s approximately, while it did not exceed 905 m³/s at Dukan Dam for the same return period.

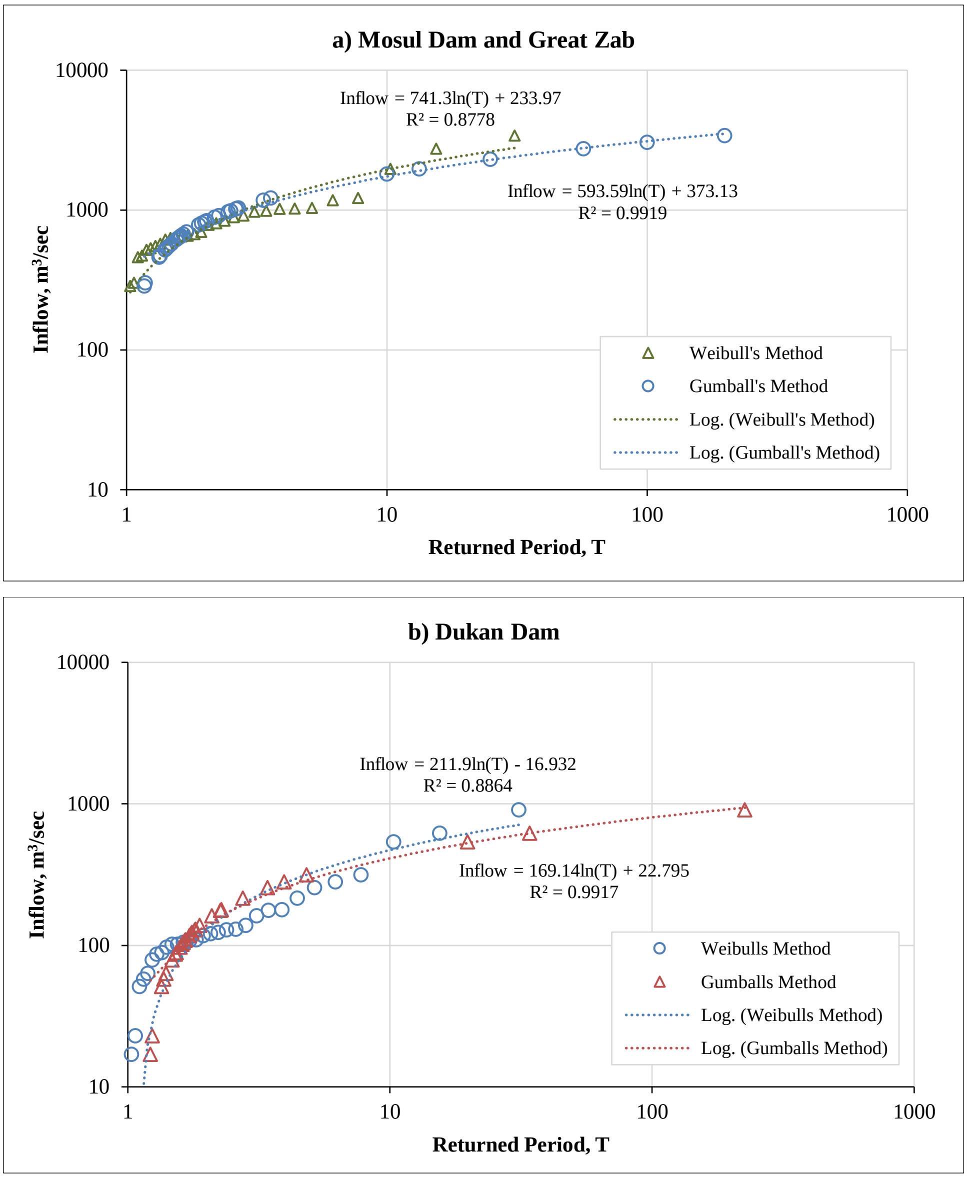
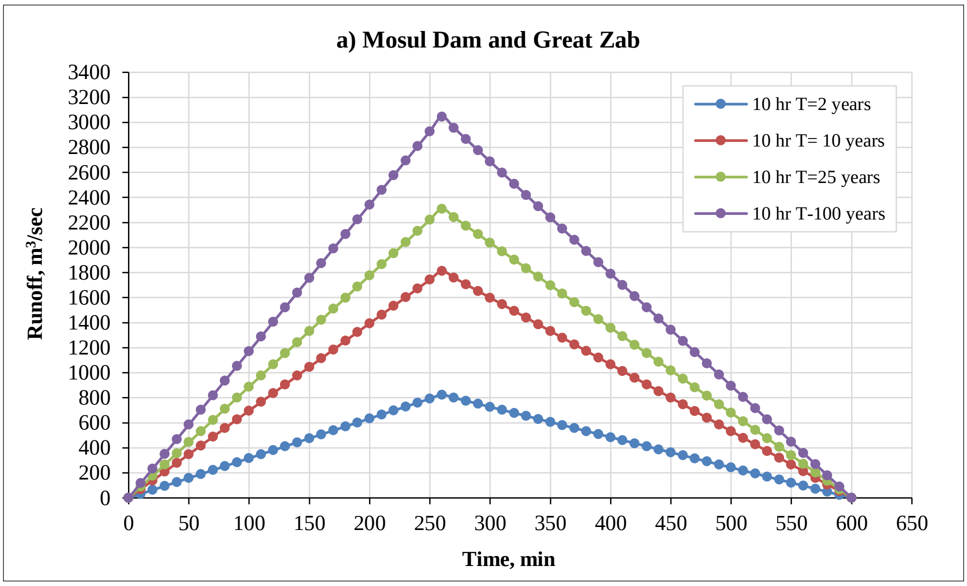


**Figure 8. Analysis of inflow recurrence rates for the flowrates of a) Mosul Dam and Great Zab and b) Dukan Dam using the Weibull's and Gumbel's Methods from data period of 30 years**

Conversely, the Weibull method was only accepted at a period of short return (less than 10 years), but the limited fitness to represent extreme landscapes by reducing high discharge by 15-20% compared to the Gumbel method in a long return period. This deviation between the two methods is due to their mathematical and statistical foundations. Gumbel relies on an extreme value distribution, making it more suitable for analyzing rare and severe events such as severe floods, while Weibull relies on a non-distributive arrangement of data, making it less representative of extreme cases. Gumbel's superiority has been supported by statistical indicators such as a high coefficient of determination ($R^2 > 0.95$) and a low standard deviation ($RMSE < 13$). When linking rainfall discharges to rainfall intensity, a direct correlation was established between rainfall intensity and the resulting discharges. This means that an increase in rainfall intensity leads to an increase in discharge volume, especially with long return periods. The Gumbel distribution's effectiveness in modelling extreme rainfall and flooding events corresponds with the findings of Elsebaie et al. [19] and Hussein & Alfatlawi [31], who highlighted the inadequacies of empirical ranking methods like Weibull for extended return periods.

The analysis of data from the Kirkuk and Mosul stations showed that rainfall can be more than 1000 mm/hr. for a very short time (5 minutes) over a 100-year return period. This is one of the highest values ever recorded in Iraq. This phenomenon is evident in the high discharge levels observed at the Mosul Dam, which is characterized by its large area, steep slopes, and rapidly responding soil due to the hydrological factors. In contrast, the Dukan Dam exhibits a more stable response, benefiting from its more gradual terrain and greater soil retention. The hydrograph indicates that the Mosul Dam maintains high discharge values throughout storm events, necessitating the design of drainage structures with high capacity, such as spillways and drainage channels, to mitigate flood risk. Although the Dukan Dam experiences lower discharge intensity, an effective drainage system is still essential to manage extreme weather events. These findings highlight the importance of employing accurate models, such as the Gumbel distribution, in the design of hydrological structures. The model needs to be updated to reflect the climate change impacts, which have led to an increase in rainfall intensity by over 22% in the past 40 years. Therefore, the study recommends adopting the Gumbel method as the primary approach for flood analysis in hazard-prone areas, particularly for critical infrastructure, as it offers a realistic and reliable depiction of extreme weather events. Additionally, it underscores the necessity of integrating climate change effects into contemporary design models, utilizing more precise rainfall data from long-term monitoring stations to ensure design efficacy and the sustainability of water facilities in the future.

The hydrograph of Mosul Dam demonstrates a sharp and rapid hydrological response, especially under high recurrence scenarios ($T = 100$ years), where peak discharge reaches elevated levels within a short time frame (Figure 9). The design of high-capacity spillways and discharge structures are necessary to manage sudden floods. In contrast, the hydrograph of Dukan Dam shows a more gradual and less intense response, indicating a more stable upstream watershed. While the flood risk is comparatively lower, adequate discharge infrastructure is still essential, particularly for extreme events. The hydrographs of the Mosul and Dukan dams show that each basin reacts very differently to a 10-hour storm event over different periods of time, such as 2, 10, 25, and 100 years. The maximum discharge at Mosul Dam was 3,000 m³/s approximately for the 100-year recurrence period, reflecting an intense rainfall event and a rapid hydrological response resulting from the basin's large area, steep terrain, and low-permeability soils. In contrast, the maximum discharge at Dukan Dam did not exceed 780 m³/s for the same period, indicating a lower runoff volume and likely the presence of more permeable soils, a smaller basin, or a greater absorption and storage capacity. The hydrographs also show that the values at Mosul Dam are higher throughout the storm, reflecting a significantly larger total flow volume. This means that the area under the curve (which represents the volume of water flowing) is larger at Mosul Dam, requiring a more accurate design of the dam and its associated structures, such as spillways and drainage channels. The size of the hydrograph is the same in both dams, indicating the use of an integrated model in hydrological simulation. However, the slope indicates a rapid response to the incidence of rainfall. These results highlight the necessity of evaluating the hydrological properties of the Makhoul Dam Basin while designing water structures and updating flood models to ensure alignment with potential climate change.



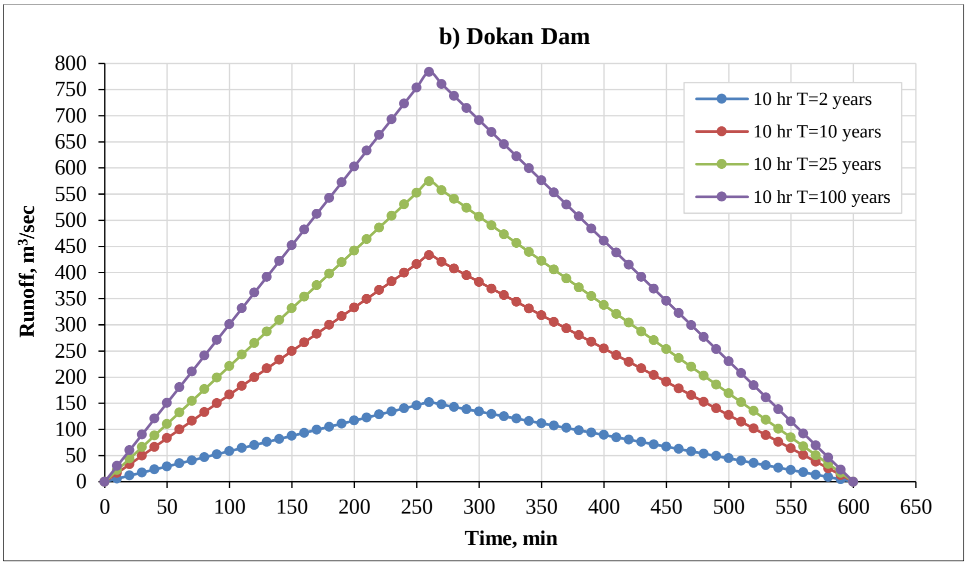


**Figure 9. Design 10 hours hydrograph storm for a) Mosul Dam and Greater Zab, and b) Dukan Dam at four return periods of 2, 10, 25, 100 years**

## 4. Conclusion

Worldwide observations of the rapid climate change have directly impacted hydrological cycles, rainfall intensity, and flood frequency. This research aims to provide a scientific evaluation of these changes' influence on the Makhoul Dam region in Northern Iraq, recognized as a crucial hydrological area. The primary objective is to analyze the climate change effect on rainfall and flood frequency in the Makhoul Dam Basin by designing 10-hour rainfall and runoff storms for return periods of 2, 10, 25, and 100 years. Rainfall data over a span of 30 years was collected from weather stations in Kirkuk, Mosul, Baiji, and Tikrit. The IDF curves were estimated using rainfall intensity methods such as Gumbel and Weibull. The Chicago method was employed to determine the distribution of peak rainfall within a storm. Flow rates from the Mosul Dam, Greater Zab Stream, and Dukan Dam were analyzed to assess how surface runoff volumes entering the Makhoul Dam Basin have changed. Notable scientific findings indicate a direct impact of climate change on Iraq's hydrology, with significant alterations in the intensity and temporal distribution of rainfall, thereby increasing the likelihood of flooding.

The Makhoul Dam is influenced by various incoming water characteristics from multiple sources, including the Greater and Little Zab Streams and the Tigris River, making it vulnerable to abrupt changes in flow and discharge. The analysis of IDF curves for all stations revealed an inverse relationship between rainfall duration and intensity, as well as a direct relationship between intensity and recurrence period. The Gumbel method demonstrated superior accuracy compared to the Weibull method in representing rare and extreme rainfall events, making it preferable for sensitive engineering designs. A notable increase in expected discharges at longer recurrence periods (100 years or more) indicates a need to update the designs of flood control facilities and dams. The Chicago method has shown a high degree of realism in depicting rainfall intensity and timing during storms, which enhances its application in designing storm drainage networks. This study is significant as it provides essential information on the quantities of both rainfall and runoff entering the Makhoul Dam Basin, which can be utilized in planning research for electricity generation under the influence of climate change.

## 5. Declarations

### 5.1. Author Contributions

Conceptualization, M.M. and A.A.; methodology, M.M. and A.A.; software, M.M. and A.M.; validation, M.M. and A.M., formal analysis, M.M. and A.A.; investigation, M.M.; resources, M.M. and A.M.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, A.A.; visualization, M.A.; supervision, A.A.; project administration, A.A.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

### 5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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### 5.5. Conflicts of Interest

The authors declare no conflict of interest.

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