HYDROLOGICAL FLOOD FREQUENCY ANALYSIS OF THE CHENAB RIVER BETWEEN QADIRABAD AND TRIMMU BARRAGES, PAKISTAN

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ABSTRACT: Floods are considered among the most frequent and devastating natural disasters in Pakistan, particularly in the Indus Basin and its tributaries. Every year, especially during the late monsoon season, the Chenab River basin is prone to flood inundation, which has a devastating effect on human life and infrastructure. Pre-disaster estimation of flood magnitudes for various return periods is of vital importance to flood risk management and hydraulic infrastructure design for water sustainability. This study employed flood frequency analysis to estimate exceptional flood events by using yearly peak downstream discharge data gathered over 50 years (1975–2024) on two barrages of the Chenab River- Qadirabad and Trimmu. Five frequency distributions, including the Gumbel, Pearson Type 3, Log Pearson Type 3, Normal, and Log Normal, were fitted to the historical annual maximum discharge series for each site to estimate the corresponding flood magnitudes to return periods of 2, 5, 10, 25, 50, 75, 100, and 200 years. The Chi-square (χ^2) test was used to assess the goodness-of-fit; 95% confidence intervals were computed to quantify estimation uncertainty. Modelled results showed that the magnitude consistently increases with the return period, with model differences being greater for more extreme events (≥50 years). In almost all cases, a Log Pearson Type III distribution provided the best balanced and reliable statistics of fit for all sites (lowest χ^2 values) that produced the highest discharge estimates for very rare floods. Confidence intervals widen significantly for longer return periods, a range of potential flood magnitudes expands, indicating an increase in uncertainty and anticipating less frequent occurrences. These results present the main importance of selecting an appropriate distribution pre-disaster assessment. The findings are helpful in floodplain management, flood control, climate-resilient infrastructure planning, and disaster preparedness across the Chenab River basin.

Keywords: Barrage-Based Discharge Analysis, Chenab River Basin, Flood Frequency Analysis, Flood Risk Assessment, Hydrological Extremes, Return Period Estimation.

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INTRODUCTION

Floods represent some of the most recurrent and destructive natural hazards globally, causing heavy losses in human life, the economy, and to the environment as a whole (Singh *et al*., 2024). Their frequency and intensity have increased due to climate variability, extreme precipitation, changes in land use, and rapid melting of glaciers changes. All these factors, singly and together, act to increase flood hazards in prone regions (Shrestha *et al*., 2021; Malik *et al*., 2023). Unplanned changes in land use and land cover (LULC) and anthropogenic activities are also the primary drivers of hydrological Hazards (Mahmood and Hamayon., 2021) The main reasons are deficient conditions in terms of housing, poverty, low adaptation, and reduction in infrastructure or developing vulnerable structures. The most major obstacle for less developed areas to always have created an efficient flood risk mitigation measure (Sayari *et al*., 2025).

South Asia, particularly, is highly prone to these events because over 80% of annual rainfall is received during the monsoon season, which leads to repeated riverine flooding. Pakistan is prone to extreme flood events every year during the late monsoon season. Recently, flood events have become more devastating as their occurrence and intensity have increased due to climate change (Rizwan *et al*., 2023)

Over recent decades, Pakistan has been through many large-scale floods, including the floods of 2010, 2011, 2012, 2015, and 2022. These resulted in large-scale displacements, agricultural losses, and permanent damage to overall physical infrastructures (Sajjad *et al*., 2024).

The Chenab River is a major tributary within the Indus system and is very prone to flooding during the monsoon season. Its wide, low-gradient floodplain allows widespread flooding, thus being a perennial threat to settlements and infrastructures therein. The basin geometry restricts the construction of major flood-control reservoirs, developing an urgent need for the best possible flood frequency estimation and spatial risk assessment (Shahid *et al*., 2023).

HFA forms the basis for the estimation of design floods for hydraulic structures, floodplain zoning, and disaster preparedness (Mahmood *et al*., 2019; Islam & Sarkar, 2020). Traditional probability distributions include Gumbel, Normal, Log-Normal, and Log-Pearson Type III, which have been widely applied across monsoon-dominated river basins, though their performance varies with hydrological conditions (Farooq *et al*., 2018; Handique *et al*., 2024).

Most of these studies are site-specific and consider only a narrow set of distributions; moreover, very few comparative studies related to the goodness-of-fit metrics or quantification of uncertainty have been carried out, especially within the Chenab River basin (Malik *et al*., 2023). In order to fill this gap, the present work examines the flood behavior of the Chenab River by fitting five of the most common statistical distributions-Gumbel, Normal, Log-Normal, Log-Pearson Type II, and Log-Pearson Type III-to annual maximum discharge data from two barrages. Distribution performance is considered using the Pearson Chi-Square test in order to identify the most suitable model at each station; estimates of discharge for return periods from 2 to 200 years are obtained along with confidence intervals for capturing the associated uncertainty. The resulting spatial variability in design floods provides important insights for evidence-based flood management, the design of hydraulic infrastructure, and sustainable planning of water resources in one of the most flood-prone river basins in Pakistan.

Study area: The Chenab River is one of the major western tributaries of the Indus River System. Originating from the Himalayan glaciers of the Jammu and Kashmir region, it traverses complex mountainous terrain before entering the alluvial plains of Punjab, Pakistan. Its catchment encompasses both high-altitude glacier- and snow-fed tributaries as well as agriculturally rich plains, creating pronounced seasonality in its flow regime (Butt *et al*., 2019). The river is approximately 1,200 km long, of which about 240 km lies in India and nearly 960 km flows through Pakistan, beginning at Marala and extending to its confluence at Panjnad (Umair *et al*., 2019). Under the 1960 Indus Waters Treaty, the Chenab is allocated to Pakistan and is regulated by a cascade of major barrages—Marala, Khanki, Qadirabad, Trimmu, and Panjnad—which play critical roles in irrigation supply, flow regulation, and flood routing (Butt *et al*., 2019).

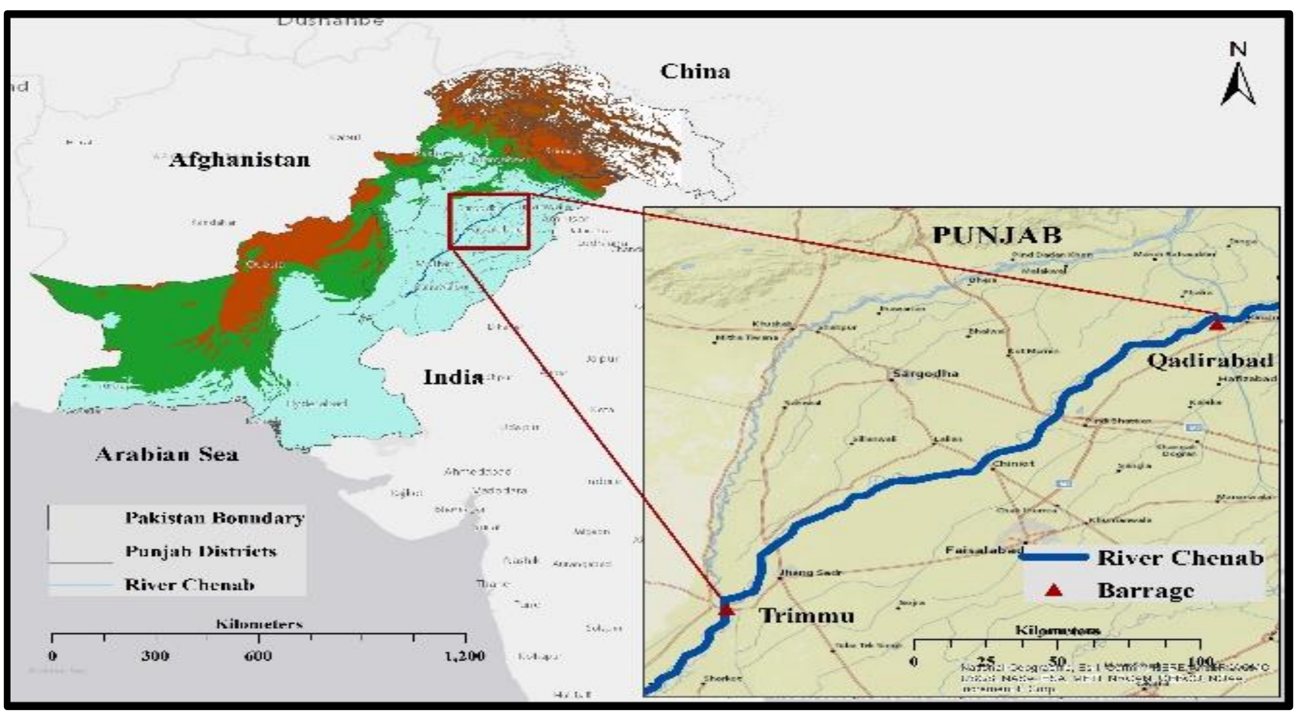

Figure 1: Study Area Map showing location of Qadirabad and Trimmu Barrage

The hydrology of the Chenab is strongly seasonal. More than 60% of summer discharge is produced by snow and glacier melt, supplemented by monsoon rainfall that abruptly raises flows during the period July to September (Hayat *et al*. 2019). This double impact makes for a hydrologically complex system in which temperature increase, increased snow melting, and increased intensity of monsoon events—associated with climate change—are raising flood risk within the basin. In this study, two barrages across the river were selected: Qadirabad and Trimmu(Figure 1). Qadirabad Barrage (32°18′27.902″N, 73°39′5.013″E) has a significant role in diverting the flood waters to Rasul–Qadirabad Link Canal. On further downstream, Trimmu Barrage (31°8′44.308″N, 72°7′27.003″E) is of prime importance while joining near the confluence of Jhelum–Chenab as one of the essential links for the purpose of peak monsoon flow management Beyond its hydrological importance, the Chenab basin is economically and socially vital. Punjab constitutes the agricultural hub of Pakistan and relies greatly on Chenab waters for irrigation, domestic, and industrial purposes. On the other hand, the same river poses a serious threat to the settlements on the riverbanks, agricultural land, and infrastructure. The combined effect of glacier melting and monsoon rainfall often produces rapid discharge increases, which surmount embankment and flood-control capacities. The flood season, spanning from June 15 to October 15, poses significant risks to this densely populated and agriculturally significant area (Mustafa *et al*., 2025) Events like the 2014, 2022 and 2025 flood inundated vast areas of Punjab and caused severe agricultural and infrastructural damage, thus underlining the need for reliable flood forecasting and hazard assessment in this basin.

METHODOLOGY

Data Collection: This study utilized annual maximum peak discharge records from the Chenab River at selected key barrage stations. Annual maximum discharge (AMD) data were collected over a 50-year period (1975–2024) at two key barrages: Qadirabad and Trimmu. These sites were selected due to their hydrological significance and downstream influence on flood-prone regions

Long-term peak flow datasets are fundamental for reliable flood frequency analysis, as they capture the variability and extremity of hydrological behavior over time. Consistent with established hydrological practices, the acquired data were carefully screened for completeness, consistency, and potential anomalies prior to statistical analysis to ensure the robustness of subsequent modeling efforts (Li *et al*., 2023).

Selection of Statistical Distributions: The Gumbel distribution is widely applied in extreme value analysis and is particularly effective for estimating high-magnitude flood events, making it suitable for assessing rare but potentially catastrophic floods (Alam *et al*., 2023).

Gumbel Distribution

$$f(x) = \frac{1}{\alpha} exp\left[-\frac{x-u}{\alpha} - exp\left(-\frac{x-u}{\alpha}\right)\right]$$

The Normal and Log-Normal distributions serve as baseline models, representing symmetric flow behavior and positively skewed flood data, respectively, and are often used for comparative evaluation in hydrological studies (Kundzewicz *et al*., 2019).

Normal Distribution

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$$

Log-Normal Distribution

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{-\frac{[\ln x - \mu]^2}{2\sigma^2}\right\}$$

Pearson Type III and Log-Pearson Type III distributions are well-established tools in flood hydrology; notably, the Log-Pearson Type III distribution is recommended by the U.S. Water Resources Council and is extensively used in flood frequency analysis due to its ability to effectively model skewed flood datasets (Shrestha *et al*., 2021).

Pearson Type III

$$f(x) = \frac{a^{\lambda}}{\Gamma(\lambda)} (x-m)^{\lambda-1} e^{-\alpha(x-m)}$$

Log-Pearson Type III

$$f(x) = \frac{a^{\lambda}}{x\Gamma(\lambda)} (lnx-m)^{\lambda-1} e^{-\alpha(lnx-m)}$$

Goodness-of-Fit Assessment: To evaluate the suitability of each probability distribution, the Chi-Square (χ^2) goodness-of-fit test was applied. This statistical test enables an objective comparison between observed and modeled flood frequencies and has been extensively adopted in flood frequency analyses worldwide. The distribution yielding the lowest χ^2 value was considered to provide the best representation of the observed flood data (Sharma & Poonia, 2021; Li *et al*., 2023).

Return Period Estimation and Uncertainty Analysis: Flood magnitudes corresponding to return periods of 2, 5, 10, 25, 50, 100, and 200 years were estimated for each barrage station using the fitted probability distributions. In addition, confidence intervals were calculated to quantify the uncertainty associated with long-return-period flood estimates (Alam *et al*., 2023).

RESULTS AND DISCUSSION

This study aims to provide a more comprehensive picture of flood risk at the two key barrages mentioned above by analyzing long-term river discharge data and using multiple statistical methods to estimate how often large floods are likely to occur, supports vigorous statistical estimation up to 200-year return periods, and enables model evaluation and uncertainty quantification. The purpose is to support better decision-making for infrastructure design, sustainable water management, and flood preparedness.

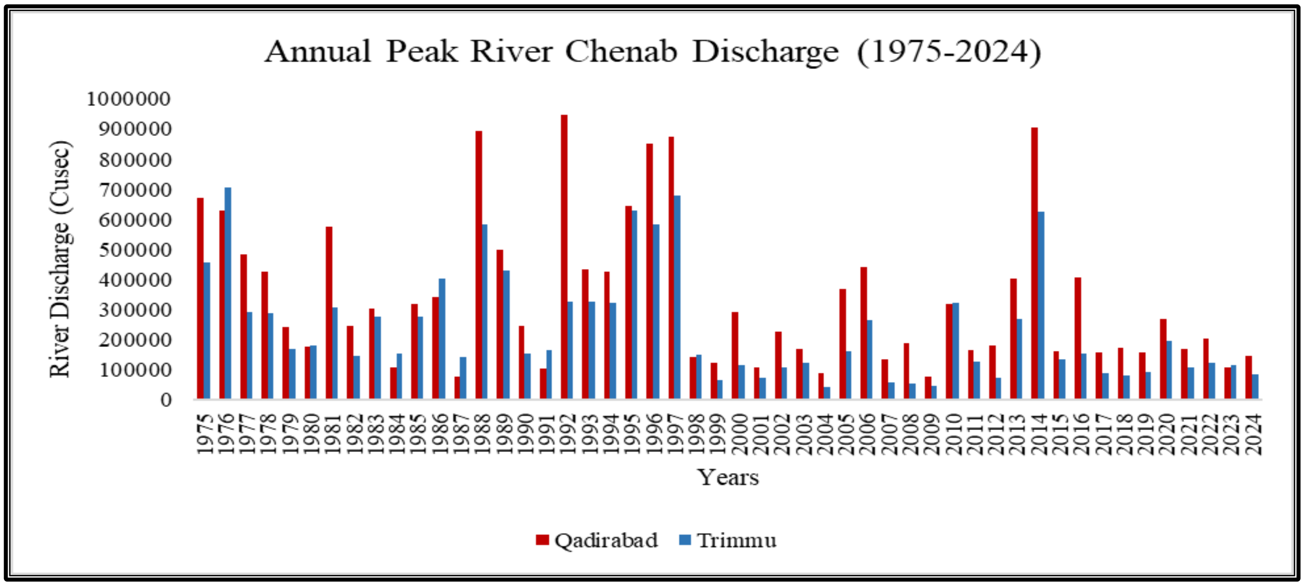

Figure 2: Annual peak discharge of River Chenab at Qadirabad and Trimmu.

Table 1: Basic Statistical parameters of annual peak discharge

Sr No.	Variables	Qadirabad	Trimmu
1	**No of observations**	50	50
2	**Minimum**	76366	42756
3	**Maximum**	948520	706433
4	**Average**	336035.94	237407.16
5	**Standard Deviation**	243842.99	181277.23
6	**Median**	244651	158474.5
7	**Coefficient of variation [Cv}**	0.72564556	0.76357104
8	**Skewness coefficient [Cs]**	1.1917902	1.22813
9	**Kutosis coefficient [Ck]**	3.209941	3.284837
10	**Confidence level**	95%	95%

Table 1 determine basic statistical parameters of annual peak discharge data for Qadirabad and Trimmu Barrages provide a crucial impression of the hydrological behavior of the Chenab River at two sites. This preliminary analysis helps in understanding the symmetry, variability and extremity of flood events before applying probability distribution models.

Qadirabad Barrage

Table 2: Flood Frequency Estimates at Qadirabad Barrage

Sr No.	Return Period (Years)	Gumbel	Pearson Type 3	Log Pearson Type 3	Normal	Log Normal
1	2	290148.3	288648.67	259262.7	336035.9	263892.6
2	5	476187.7	514904.35	466076.5	541219.3	476745.4
3	10	599362	662905.27	639752	648576.5	649653.7
4	25	754992	844639.11	903778.9	763023.7	903541.9
5	50	870449.1	975604.31	1134657	836935.4	1118097
6	75	937556.5	1050362.1	1283751	876588.5	1253485
7	100	985052.6	1102722.7	1396330	903406.2	1354226
8	200	1099238	1226924.8	1692453	964233	1613754
Chi-sqr (x^2)		**11.92**	**13.36**	**9.76**	**22.36**	**9.76**

The flood frequency analysis for the Chenab River's two barrages—Qadirabad and Trimmu was performed using five statistical probability distributions: Gumbel, Pearson Type III, Log-Pearson Type III, Normal, and Log-Normal. The results are presented for various return periods ranging from 2 to 200 years, along with their confidence intervals and goodness-of-fit (Chi-square) statistics.

Table 3: Confidence interval of Flood Return Period at Qadirabad

Sr No.	Return Period	Gumbel		Pearson Type 3		Log Pearson Type 3		Normal		Log Normal	
		Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
1	**2**	236858.3	343438.3	205993.41	371303.92	206253.3	312272	268432.5	403639.4	212468.7	315316.5
2	**5**	393867.1	558508.4	411231.86	618576.84	358630.5	573522.5	462344.6	620094	368354.4	585136.4
3	**10**	493430.4	705293.7	521148.35	804662.2	459844.2	819659.8	556920.1	740232.9	478015.8	821291.7
4	**25**	617398.8	892585.2	618821.96	1070456.3	560107.2	1247451	654764.8	871282.6	621828.9	1185255
5	**50**	708701.3	1032197	671616.03	1279592.6	601654.4	1667659	716895.9	956974.9	731220.4	1504974
6	**75**	761612.3	1113501	697065.88	1403658.3	609357.7	1958145	749982.9	1003194	796071.7	1710898
7	**100**	799009.4	1171096	713222.05	1492223.3	628473	2164187	772279.8	1034533	842367.1	1866085
8	**200**	888781.7	1309694	746864.68	1706984.9	630113	2754793	822649.1	1105817	955156.3	2272352

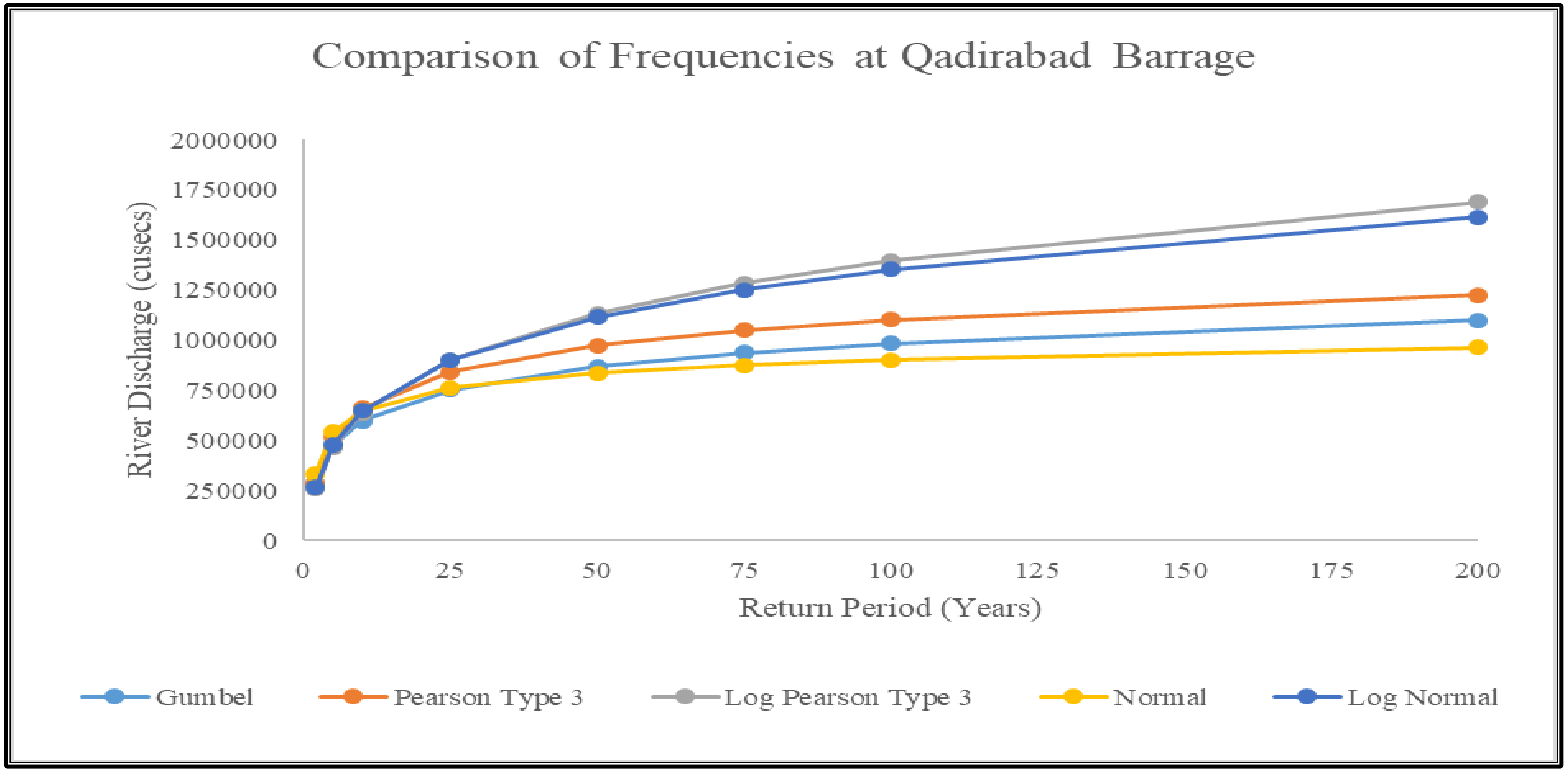

Figure 3: Comparison of Frequencies at Qadirabad Barrage

The flood frequency analysis at Qadirabad Barrage (Table. 2), based on increasing return periods of all five statistical distributions, has indicated a regular rise of discharge. While the general upward trend is similar, the magnitude of estimated peak flows varies considerably among models, reflecting their sensitivity to the skewed nature of the hydrological record. Log-Pearson Type III (LP-III) produced the highest estimates for medium to high return periods, including a 200-year flood of 1.69×10^6 cusecs, far in excess of those by Gumbel and Normal distribution estimates. This pattern indicates that the historical dataset includes extreme flows that logarithmic transformations like LP-III and Log-Normal capture more effectively. At lower return periods, the distribution estimates vary less significantly, though the Normal distribution consistently overestimates moderate floods and underestimates extreme ones due to its poor accommodation of skewness. The goodness-of-fit statistics support this interpretation. LP-III and Log-Normal provided the lowest Chi-square values (χ^2 = 9.76), which showed the best overall agreement with the observed data, while the Normal distribution indicated the weakest fit. This confirms the suitability of logarithmic and skew-sensitive models for monsoon-dominated rivers. The confidence intervals (Table. 3) further underscore the uncertainty inherent in extrapolation beyond the range of observed data. For the 200-year discharge at Qadirabad, LP-III yields a confidence range from 0.63×10^6 to 2.75×10^6 cusecs, substantially wider than either Gumbel or Pearson Type III, and shows the way extreme events and data variability influence high-return-period predictions. The spread between distributions becomes more pronounced in Figure 3, where LP-III and Log-Normal display sharply increasing curves compared to the moderate slopes of Gumbel and Pearson III.

Trimmu Barrage

Table 4: Flood Frequency Estimates at Trimmu Barrage/

Sr No.	Return Period (Years)	Gumbel	Pearson Type 3	Log Pearson Type 3	Normal	Log Normal
1	2	203304.28	201161.62	179413.58	237407.16	180993.3
2	5	340338.95	369510.27	333773.19	389944.1	340677.68
3	10	431067.83	480337.23	463899.5	469755.4	474311.9
4	25	545704.69	616901.89	661364.15	554837.46	674946.42
5	50	630747.67	715556.8	833316.53	609784.78	847660.96
6	75	680178.09	771943.2	943926.62	639263.55	957868.43
7	100	715163.38	811463.68	1027209.5	659200.36	1040416.9
8	200	799271.07	905287.97	1245318.4	704420.1	1254980.3
Chi-sqr (x^2)		**13.36**	**14.8**	**7.96**	**31.36**	**8.32**

At Trimmu Barrage (Table. 4), the pattern is similar. All distributions show an increase of flows with higher return periods, but the rate of growth is noticeably different. LP-III gives again the highest estimates and provides a 200-year flood of 1.24×10^6 cusecs, which is closely matched by Log-Normal, while Gumbel and Normal remain lower. Similar to the pattern at Qadirabad, the Normal distribution overestimates low return period flows but increasingly underestimates the rarer events. The Chi-square test reveals that LP-III (χ^2 = 7.96) and Log-Normal (χ^2 = 8.32) have been the best-fitting models, in contrast with the poor fit of the Normal distribution. Confidence intervals (Table. 5) become much wider at higher return periods. LP-III gives a wide 200-year range of 0.51×10^6 to 1.97×10^6 cusecs, indicating a high level of uncertainty in estimating extreme flows. The uncertainty spreads of Trimmu are slightly wider than those for Qadirabad, reflecting additional hydrological complexity at the Jhelum–Chenab confluence. Figure 4 clearly illustrates such divergence with LP-III and Log-Normal steeply rising at high return periods. Comparing both barrages reveal several spatial patterns. LP-III consistently generates the highest peak flows at all return periods and demonstrates superior statistical performance. Log-Normal follows closely, reinforcing the value of logarithmic transformations for positively skewed hydrological data. On the other hand, the Normal distribution performs poorly at both locations, underlining its unsuitability for monsoon-fed rivers with sporadic extreme floods. In general, Trimmu presents wider confidence bands than Qadirabad, indicating a greater hydrological variability and, not less important, dual inflows from the Jhelum and Chenab Rivers. Besides, design floods increase downstream in accordance with cumulative catchment contributions.

These findings have important implications for flood hazard assessment and hydraulic modeling. Since the Chenab flows across a flat and densely populated floodplain, underestimation of extreme events can result in major design failures. The consistent statistical superiority of LP-III suggests it should form the prime basis of selecting design discharges for 25-, 50-, 100-, and 200-year simulations. The large uncertainty widths

Table 5: Confidence interval of Flood Return Period at Trimmu Barrage

Sr No.	Return Period	Gumbel		Pearson Type 3		Log Pearson Type 3		Normal		Log Normal	
		Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
1	**2**	164051.45	242557.12	139256.18	263067.06	140326.97	218500.19	187149.55	287664.77	143276.59	218710.02
2	**5**	279702.43	400975.47	291786.82	447233.72	253128.81	414417.58	331307.24	448580.97	257848.39	423506.98
3	**10**	353039.72	509095.94	373978.89	586695.57	329630.49	598168.51	401616.43	537894.37	340304.39	608319.42
4	**25**	444355.26	647054.12	446479.96	787323.82	408048.06	914680.24	474355.86	635319.07	449960.92	899931.92
5	**50**	511605.95	749889.38	485332.84	945780.77	439401.37	1227231.7	520545.27	699024.29	534008.36	1161313.6
6	**75**	550579.49	809776.69	503957.25	1039929.2	439401.37	1227231.7	545142.72	733384.38	584086.81	1331650
7	**100**	578125.98	852200.77	515738.46	1107188.9	479145.8	1575273.2	561718.62	756682.11	619883.72	1460950
8	**200**	644251.3	954290.85	540145.02	1270430.9	511703.0,	1978933.8	599164.06	809676.15	707266.72	1802693.9

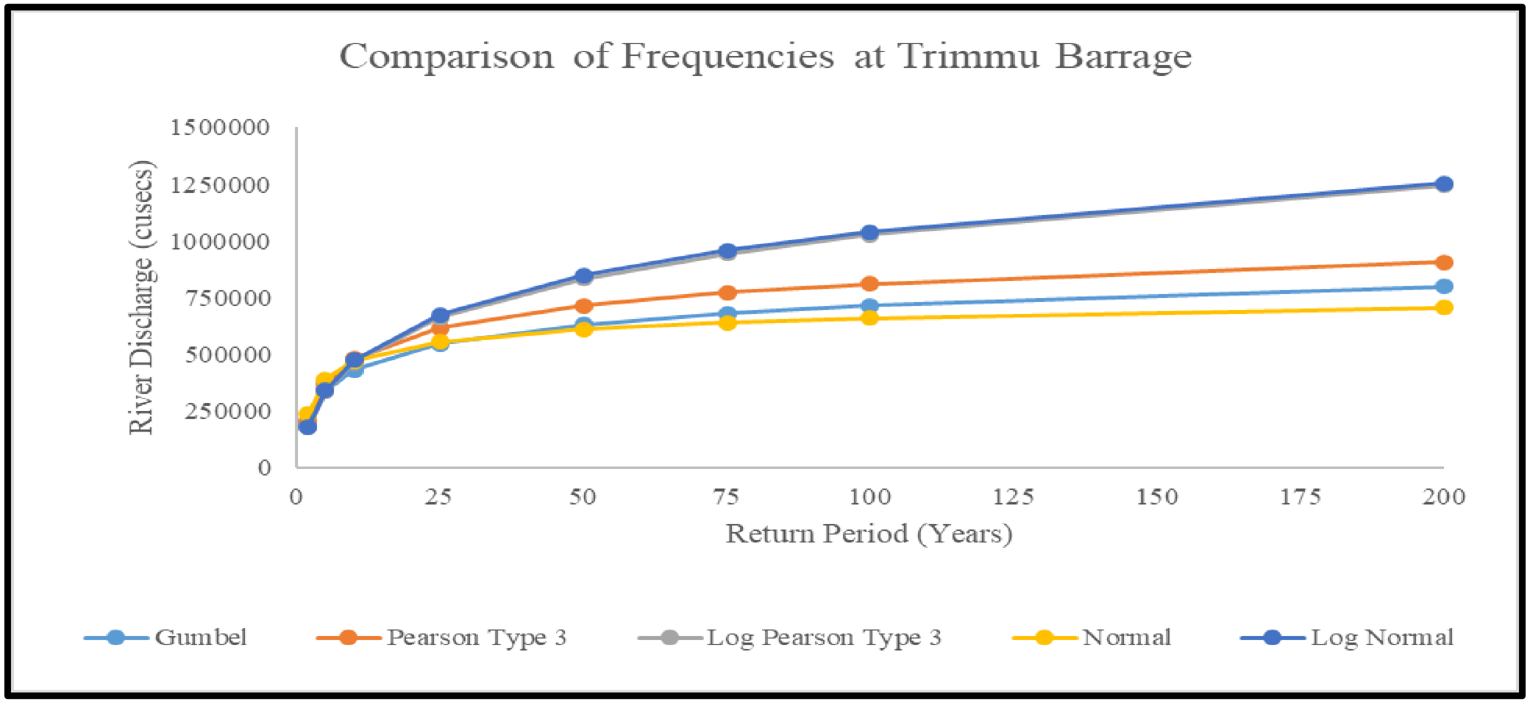

Figure 4: Comparison of Frequencies at Trimmu Barrage

attached to most of these estimates suggest that sensitivity analysis is imperative, particularly for lowermost sites like Trimmu where hydrologic variability tends to be larger. Overall, the results emphasize the requirement for strong, skew-sensitive statistical frameworks in flood-dominant river basins influenced by glacier melt and monsoon rainfall.

Conclusion: This study demonstrates the importance of applying multiple statistical models in flood frequency analysis for complex river systems such as the Chenab River, which is influenced by both monsoon rainfall and glacier melt. A comparative hydrological assessment was conducted at two key barrages—Qadirabad and Trimmu, and to estimate flood magnitudes for return periods up to 200 years. The results revealed a non-linear increase in peak discharges with increasing return periods, highlighting spatial variability in flood risk and sensitivity to model selection. Among the tested models, the Log Pearson Type III distribution consistently provided the best statistical performance, exhibiting the lowest Chi-square values and producing higher estimates for extreme floods, along with relatively narrower confidence intervals. However, widening uncertainty at longer return periods underscores the need for cautious interpretation, particularly for infrastructure design and flood management planning. Future research should incorporate non-stationary approaches and climate change scenarios to better capture evolving hydrological extremes. Overall, the findings offer valuable guidance for engineers, planners, and policymakers in improving flood risk mitigation, land-use planning, and disaster preparedness, emphasizing the necessity of uncertainty-aware, pre-disaster assessments to safeguard lives and infrastructure in Pakistan's flood-prone regions.

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