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Research Article

Frequency Analysis of Daily Reservoir Inflow for Dam-Break Boundary Conditions: A Case Study of the Cirata-Ir. H. Djuanda Serial Dam System

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Abstract

Dam-break modeling requires reliable design inflow hydrographs as upstream boundary conditions. This study performs frequency analysis of daily historical inflow data from two serial dams in the Citarum River Basin, Indonesia; Cirata Dam (1991–2025, 35 years) and Ir. H. Djuanda Dam (2016–2025, 10 years); using the Gumbel and Log Pearson III distributions under a daily-calendar frequency approach. Goodness-of-fit was evaluated using the Kolmogorov-Smirnov (K-S) test at $\alpha = 0.05$ significance level. For Cirata Dam, the Gumbel distribution was accepted for all 365 calendar days (100%), whereas Log Pearson III was accepted for 295 days (80.8%) with 70 days rejected. For Ir. H. Djuanda Dam, with its limited 10-year record, Gumbel was accepted for all 365 days (100%) and Log Pearson III for 363 days (99.5%). The derived Q_{100} design hydrograph yields peak discharges of 894.21 m^3/s for Cirata Dam (March 19) and 1,254.46 m^3/s for Ir. H. Djuanda Dam (November 12) based on the Gumbel distribution. The consistent superiority of the two-parameter Gumbel model, particularly evident in the longer Cirata record where the K-S test has stronger discriminatory power, demonstrates that the additional skewness parameter of Log Pearson III introduces estimator instability rather than improved fit for daily reservoir inflow series at moderate sample sizes ($n \leq 35$). These synthetic hydrographs provide a hydrologically defensible upstream boundary condition for subsequent two-dimensional dam-break simulations using HEC-RAS.

Introduction

Dam failure, whether induced by overtopping during extreme storm events or by internal erosion through the embankment, represents one of the most severe scenarios in water resources engineering. A breach-generated flood wave can inundate settlements, destroy critical infrastructure, and claim lives within hours, making dam-break modeling essential for emergency action planning, inundation mapping, and downstream risk assessment (Mattas et al., 2023; Bharath et al., 2021). Every dam-break simulation hinges on a credible design inflow hydrograph serving as the upstream boundary condition. While rainfall-runoff modeling using watershed hydrology models remains the conventional pathway for generating design floods, many tropical watersheds, including parts of Indonesia, lack the dense, long-term rain gauge records required for reliable calibration of such models. Reservoir inflow data, by contrast, are systematically recorded as part of routine dam operations and offer a practical, observation-driven alternative for frequency-based design flood estimation (Naghettini, 2017).

The Citarum River Basin in West Java hosts three large reservoirs in series with a combined hydropower capacity exceeding 1,800 MW: Saguling, Cirata, and Ir. H. Djuanda (also known as Jatiluhur Dam). This serial configuration introduces a specific hydraulic threat in which breach of an upstream dam can generate a flood wave that overtops the downstream dam, triggering a cascading failure far more destructive than any single-dam breach (Říha et al., 2020; Bharath et al., 2021). A further methodological challenge lies in the data asymmetry between the two dams under study: Cirata Dam has 35 years of continuous daily inflow records (1991-2025), while Ir. H. Djuanda Dam has only 10 years of accessible data (2016-2025). Extrapolating a Q_{100} design flood from just 10 annual observations introduces uncertainty that can exceed 40% of the estimated value (Farooq et al., 2018).

The choice of probability distribution compounds this uncertainty. The Gumbel (Extreme Value Type I) distribution requires only two parameters estimated from the sample moments and is theoretically grounded in extreme value theory (Anghel, 2024). The Log Pearson III distribution adds a third parameter, the coefficient of skewness, which in principle provides greater flexibility but introduces an estimator that is notoriously unstable at moderate sample sizes (Kousar et al., 2020; Handique et al., 2024). In head-to-head comparisons for river systems in Pakistan and Sweden, the simpler Gumbel distribution often outperformed Log Pearson III where record lengths were under 30 years (Farooq et al., 2018; Kousar et al., 2020). Whether this pattern holds for daily reservoir inflow series in tropical serial dam systems has not been tested.

This study adopts a daily-calendar frequency approach, a methodological variant in which statistical parameters are fitted separately to each of the 365 calendar days across the period of record (Amiruddin et al., 2020). Unlike the conventional annual maximum series method, the daily-calendar approach produces a complete 365-day synthetic hydrograph that preserves the seasonal rhythm of the reservoir inflow regime, a decisive advantage for two-dimensional unsteady flow simulations in HEC-RAS where the timing and shape of the hydrograph matter as much as its peak (Brunner, 2020). Amiruddin et al. (2024) demonstrated the effectiveness of HEC-RAS for simulating discharge-driven hydraulic changes in Indonesian catchments, reinforcing the value of integrating frequency-based hydrographs with routing models.

The two-dimensional HEC-RAS unsteady flow module has been extensively validated for dam-break applications, including flood hazard mapping (Mattas et al., 2023), inundation assessment (Bharath et al., 2021; Patel et al., 2017). Dam breach parameter estimation remains a critical uncertainty source in these simulations (Sammen et al., 2017), with empirical breach width and formation time relationships (Froehlich, 1995; Zhong et al., 2021) providing the most widely adopted framework for breach parameterization. The application of HEC-RAS for multi-reservoir systems (Urzică et al., 2020) and flood discharge analysis in Indonesian watersheds (Gunawan, 2021) further supports the methodology adopted in this study. Recent dam-break simulations using HEC-RAS 2D have confirmed that two-dimensional hydrodynamic modeling has become the standard approach for cascade dam failure analysis (Mo et al., 2023).

The objectives of this study are to perform frequency analysis on 365 calendar days using the Gumbel and Log Pearson III distributions at Cirata Dam (n = 35) and Ir. H. Djuanda Dam (n = 10), to evaluate goodness-of-fit via the Kolmogorov-Smirnov test, and to generate the Q_{100} design inflow hydrograph for subsequent HEC-RAS dam-break simulations. The primary contribution is an empirical, head-to-head comparison of two widely used distributions on real operational inflow data from a major tropical cascade system with notably unequal record lengths. The finding that the simpler Gumbel distribution outperforms Log Pearson III across both sample sizes, and that the three-parameter model's performance declines as more data become available, offers a cautionary note against the uncritical preference for complexity in hydrological frequency analysis.

Research Method

Study Area

The study focuses on two serial dams located on the Citarum River, West Java Province, Indonesia: Cirata Dam (6°48' S, 107°21' E) and Ir. H. Djuanda Dam (6°34' S, 107°23' E). Cirata Dam, completed in 1987, has a reservoir capacity of 2,165 million m³ and a catchment area of 4,119 km². Ir. H. Djuanda Dam, located approximately 26 km downstream, began construction in August 1957 and was completed in 1967, with a normal reservoir capacity of 2,514 million m³ at a maximum storage level of 107 m above sea level and a flood storage capacity of 2,854 million m³, serving irrigation, hydropower, municipal water supply, and flood control functions. The spatial configuration, with a river reach of approximately 26 km between the two dams, creates the potential for a cascading failure mechanism in which a breach hydrograph from upstream Cirata Dam propagates downstream and potentially overtops Ir. H. Djuanda Dam. The Citarum River exhibits a dynamic geomorphic setting where channel morphology responds to both natural flow variability and reservoir regulation, making geomorphic analysis essential for understanding flood routing behavior. The spatial configuration, with a river reach of approximately 26 km between the two dams, creates the potential for a cascading failure mechanism in which a breach hydrograph from upstream Cirata Dam propagates downstream and potentially overtops Ir. H. Djuanda Dam. The Citarum River exhibits a dynamic geomorphic setting where channel morphology responds to both natural flow variability and reservoir regulation, making geomorphic analysis essential for understanding flood routing behavior. The spatial relationship between the two dams, the intervening watershed, and the Citarum River network is illustrated in Figure 1.

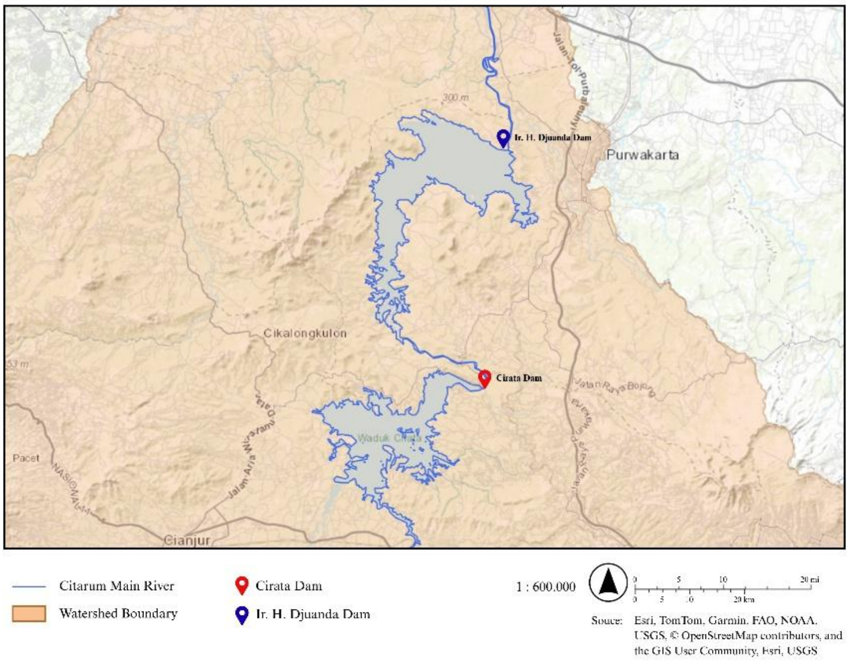

Figure 1. Map of the Citarum River Basin showing the locations of Cirata Dam and Ir. H. Djuanda Dam

Data

Daily historical reservoir inflow data were obtained from the reservoir operations records. For Cirata Dam, 35 years of daily inflow data were available (January 1991 through January 2025). For Ir. H. Djuanda Dam, 10 years of daily inflow data were available (January 2016 through January 2025). Missing data were limited to fewer than 1% of the total daily records across both dams, predominantly consisting of isolated single-day gaps attributable to instrument maintenance periods. At Cirata Dam, two such instances were identified: May 31, 1994 (filled by averaging the adjacent values of 11.62 m³/s and 11.75 m³/s) and August 31, 1993 (filled by averaging 23.67 m³/s and 99.14 m³/s). Missing data points were filled using the arithmetic average of the immediately adjacent days, a method considered appropriate for daily inflow series where the autocorrelation between consecutive days is high and missing values occur as isolated gaps rather than extended outage periods. No formal outlier detection or removal procedure was applied prior to the frequency analysis, as the daily-calendar approach treats each calendar day as an independent statistical series, and extreme values within a given calendar day represent legitimate hydrological events rather than observational artifacts.

Frequency Analysis

Frequency analysis was performed using the daily-calendar approach. For each calendar day (January 1 through December 31, excluding February 29 for non-leap years), a separate frequency analysis was conducted using the available years of record. This produced 365 individual frequency curves per dam, each with n = 10 data points for Ir. H. Djuanda and n = 35 data points for Cirata. Two probability distributions were fitted.

Selection of Distributions. The Gumbel (Extreme Value Type I) and Log Pearson III distributions were selected based on the criteria established in SNI 2415:2016 (Badan Standardisasi Nasional, 2016), the Indonesian national standard for design flood calculation, which specifies these two distributions as the recommended probability models for flood frequency analysis when observed discharge data are available. The Gumbel distribution is theoretically appropriate for extreme value analysis and is widely applied in Indonesian dam safety evaluations (Kementerian PUPR, 2015). The Log Pearson III distribution, recommended by the U.S. Water Resources Council (Bulletin 17B) for flood frequency analysis, was included as a comparative three-parameter alternative to evaluate whether the additional complexity improves distributional fit for tropical reservoir inflow data.

Gumbel Distribution (Extreme Value Type I). Parameters were estimated using the method of moments (Naghettini, 2017). The scale parameter, α, and the location parameter, u (mode), were calculated as follows:

$$\alpha = \frac{\sigma\sqrt{6}}{\pi} \tag{1}$$

$$u = \bar{x} - 0.5772\alpha \tag{2}$$

where $\bar{x}$ is the sample mean, σ is the sample standard deviation, and 0.5772 is the Euler-Mascheroni constant. The design discharge corresponding to a return period T was calculated using:

$$X_T = u + \alpha Y_T \tag{3}$$

where X_T denotes the design discharge associated with return period T, while Y_T is the reduced variate, defined as:

$$Y_T = -\ln\left[-\ln\left(1 - \frac{1}{T}\right)\right] \tag{4}$$

with T representing the return period in years.

Log Pearson III Distribution. The data series was first log-transformed (base-10), after which the mean (μ_{log}), standard deviation (σ_{log}) and coefficient of skewness (C_s) of the log-transformed series were computed. The design discharge for return period T was obtained using the frequency factor K_T, which is a function of Cs and the return period, based on the Wilson-Hilferty approximation (Naghettini, 2017):

$$\log X_T = \mu_{log} + K_T\sigma_{log} \tag{5}$$

Goodness-of-Fit Test

The Kolmogorov-Smirnov test was applied to evaluate the suitability of each distribution. The test compares the maximum absolute difference (D_{max}) between the empirical cumulative distribution function $F_e(x)$ and the theoretical cumulative distribution function $F_t(x)$:

$$D_{max} = \max|F_e(x) - F_t(x)| \quad (6)$$

The null hypothesis (data follow the specified distribution) is accepted when $D_{max} < D_{critical}$ at the chosen significance level (α = 0.05). For n = 10, $D_{critical}$ = 0.41; for n = 35, $D_{critical}$ = 0.23. This test was applied to all 365 calendar days for both distributions at both dams.

The Kolmogorov-Smirnov test was selected in accordance with SNI 2415:2016, which specifies both the Chi-Square and Kolmogorov-Smirnov methods as acceptable goodness-of-fit tests; the K-S test was preferred for this application because it does not require arbitrary class interval selection and is suitable for continuous daily inflow data.

All computations were performed in Microsoft Excel using Visual Basic for Applications (VBA) macros. Parameter estimation, frequency factor computation using the Wilson–Hilferty approximation, and the Kolmogorov-Smirnov test were implemented programmatically to handle the 1,460 individual frequency analyses (365 calendar days × 2 distributions × 2 dams) required by the daily-calendar framework.

Design Discharge Determination

For each calendar day, design discharges were computed at return periods of 2, 5, 10, 20, 50, 100, and 1000 years for both distributions. The Q_{100} return period was selected as the design flood for dam-break modeling, consistent with dam safety evaluation criteria (Kementerian Pekerjaan Umum dan Perumahan Rakyat, 2015). The derived 365-day Q_{100} hydrograph serves as the upstream boundary condition for subsequent two-dimensional HEC-RAS simulations (Brunner, 2020).

Results and Discussion

Statistical Parameters of Fitted Distributions

The statistical parameters for representative high-flow days in January are presented in Table 1 for Ir. H. Djuanda Dam and Table 2 for Cirata Dam.

Table 1. Distribution parameters for selected January days, Ir. H. Djuanda Dam (2016-2025, n = 10)

Date	Mean (m^3/s)	St Dev (m^3/s)	α (Gumbel)	u (Gumbel)	μ log (LP3)	σ log (LP3)	Cs (LP3)
Jan 1	141.47	140.97	109.92	78.02	1.9185	0.5124	-0.2046
Jan 15	151.59	78.48	61.19	116.27	2.1096	0.2934	-1.3419
Jan 31	119.25	78.52	61.20	83.91	1.9451	0.4134	-1.1460

Table 2. Distribution parameters for selected January days, Cirata Dam (1991-2025, n = 35)

Date	Mean (m^3/s)	St Dev (m^3/s)	α (Gumbel)	u (Gumbel)	μ log (LP3)	σ log (LP3)	Cs (LP3)
Jan 1	150.39	81.46	63.52	113.73	2.1169	0.2350	-0.0373
Jan 15	136.53	71.89	56.06	104.17	2.0731	0.2418	-0.1435
Jan 31	134.66	76.09	59.32	100.42	2.0795	0.2019	+0.5533

The standard deviation for Ir. H. Djuanda (140.97 m^3/s on January 1, CV = 1.00) is substantially larger relative to its mean than for Cirata (81.46 m^3/s, CV = 0.54), reflecting both the shorter record length and inherently greater flow variability in the downstream reservoir. The negative skewness coefficients observed in most Ir. H. Djuanda days (Cs = -0.20 to -1.34) indicate left-skewed log-transformed distributions, suggesting that extreme high-flow days are less frequent than would be expected under a symmetric distribution. For Cirata, the skewness ranges from near zero (-0.037) to moderately positive (+0.553), indicating a more balanced distribution shape attributable to the longer period of record.

Goodness-of-Fit: Kolmogorov-Smirnov Test

The Kolmogorov-Smirnov test results for representative January days are summarized in Table 3 for Ir. H. Djuanda Dam and Table 4 for Cirata Dam.

Table 3. Kolmogorov-Smirnov test results for selected days, Ir. H. Djuanda Dam
($n = 10$, $D_{critical} = 0.41$, $\alpha = 0.05$)

Date	Dmax Gumbel	Verdict	Dmax LP3	Verdict
Jan 1	0.1264	Accepted	0.1304	Accepted
Jan 15	0.1353	Accepted	0.2387	Accepted
Jan 31	0.0944	Accepted	0.2090	Accepted

Table 4. Kolmogorov-Smirnov test results for selected days, Cirata Dam
($n = 35$, $D_{critical} = 0.23$, $\alpha = 0.05$)

Date	Dmax Gumbel	Verdict	Dmax LP3	Verdict
Jan 1	0.0764	Accepted	0.0871	Accepted
Jan 15	0.1377	Accepted	0.1564	Accepted
Jan 31	0.1247	Accepted	0.1613	Accepted

For all representative January days, both distributions were accepted at both dams. However, the Dmax values for the Gumbel distribution were consistently lower than those for the Log Pearson III across all examined days, indicating a quantitatively better fit for the simpler two-parameter model. The comprehensive 365-day evaluation is summarized in Table 5.

Table 5. Comprehensive 365-day Kolmogorov-Smirnov evaluation summary

Dam	n	Distribution	Accepted	Rate (%)	Rejected
Ir. H. Djuanda	10	Gumbel	365	100.0	0
Ir. H. Djuanda	10	Log Pearson III	363	99.5	2
Cirata	35	Gumbel	365	100.0	0
Cirata	35	Log Pearson III	295	80.8	70

The comprehensive 365-day evaluation reveals a clear and consistent pattern. For both dams, the Gumbel distribution was accepted for all 365 calendar days (100% acceptance rate). The Log Pearson III distribution performed comparably for Ir. H. Djuanda (363 out of 365 days, 99.5%) but demonstrated notably lower performance for Cirata, with 70 days rejected (80.8% acceptance rate). This finding contradicts the conventional expectation that three-parameter distributions universally outperform two-parameter alternatives in hydrological frequency analysis.

The differing K-S acceptance rates between the two dams must be interpreted with attention to the test's statistical properties. The critical value $D_{critical}$ depends on sample size: 0.41 for $n = 10$ versus 0.23 for $n = 35$ at $\alpha = 0.05$. This fivefold difference in sample size produces a nearly twofold difference in the critical threshold, making the Cirata test substantially more stringent than the Ir. H. Djuanda test. Consequently, the higher rejection rate for Log Pearson III at Cirata (70 days, 19.2%) relative to Ir. H. Djuanda (2 days, 0.5%) partially reflects the greater sensitivity of the test at the larger sample size rather than an intrinsic deterioration of model performance with additional data. Under a correctly calibrated hypothesis test at $\alpha = 0.05$, approximately 18 rejections per dam (5% of 365 days) would be expected by chance alone if all null hypotheses were true, though neighboring calendar days are not fully independent.

An important methodological caveat is that the K-S critical values used in this study (0.41 for $n = 10$ and 0.23 for $n = 35$) are derived under the assumption that distribution parameters are known a priori. In the present analysis, parameters were estimated from the same data being tested, which makes the test more conservative than its nominal significance level would suggest (Naghettini, 2017). This may partially explain the 100% acceptance rate for the Gumbel distribution at both dams. A more rigorous approach would employ Lilliefors-corrected critical values or simulation-based goodness-of-fit tests that account for parameter estimation uncertainty.

Furthermore, the Kolmogorov-Smirnov test places emphasis on the central portion of the distribution and is relatively insensitive to discrepancies in the upper tail. Since the Q_{100} design discharge is governed primarily by upper-tail behavior, the K-S test alone may not provide a complete basis for distribution selection in the context of extreme flood estimation. The Anderson-Darling test, which assigns greater weight to tail observations, would offer complementary information more directly relevant to design flood quantile selection. The application of such tail-sensitive tests is recommended for future extensions of this work, particularly for the Ir. H. Djuanda Dam where the small sample size (n = 10) limits the power of any single test to discriminate distributional fit in the extrapolation region.

Distribution Selection

Based on the Smirnov test evaluation, the Gumbel distribution is recommended as the primary distribution for design flood estimation at both Cirata and Ir. H. Djuanda Dams under the daily-calendar frequency approach. This recommendation is supported by four factors. First, superior acceptance rate: Gumbel achieved 100% acceptance at both dams, while Log Pearson III showed reduced performance (80.8%) at Cirata. Second, parsimony: Gumbel is a two-parameter distribution, requiring estimation of only the mean and standard deviation, compared to the three parameters of Log Pearson III. The principle of parsimony favors the simpler model when it performs equally well or better. Third, estimator stability: the Gumbel parameters (α and u) are estimated directly from the sample moments without the high-variance skewness estimator required by Log Pearson III. Fourth, consistency with extreme value theory: the Gumbel distribution is derived from the asymptotic theory of extremes, making it theoretically appropriate for modeling extreme hydrological events (Anghel, 2024; Kousar et al., 2020).

The Log Pearson III distribution produced 2 rejected days at Ir. H. Djuanda and 70 rejected days at Cirata, predominantly during the dry season months (July to October) when inflow variability is low and the distribution shape is less well-defined. Since the primary concern in dam-break analysis is the extreme high-flow scenario during the wet season, the distribution performance during the critical flood months (December through March) is of primary importance. During these months, both distributions were accepted at both dams.

Q_{100} Design Inflow Hydrograph

The Q_{100} design inflow hydrographs were generated using the Gumbel distribution for both dams. Table 6 presents the peak Q_{100} discharge values for each calendar month.

Table 6. Peak Q_{100} design discharge by month (Gumbel distribution)

Month	Cirata (m^3/s)	Day	Ir. H. Djuanda (m^3/s)	Day
January	699.49	22	915.17	12
February	495.80	29	1,165.73	8
March	894.21	19	1,020.59	3
April	621.07	23	957.36	10
May	453.23	1	1,066.53	19
June	378.91	2	840.04	23
July	300.32	13	769.41	27
August	281.79	14	841.67	6
September	340.78	25	817.81	27
October	434.53	28	845.96	14
November	714.99	2	1,254.46	12
December	538.66	14	1,054.25	8

For Cirata Dam, the annual peak Q_{100} design discharge is 894.21 m^3/s, occurring on March 19. The seasonal distribution shows two prominent peaks, one in January (699.49 m^3/s) and the dominant peak in March, followed by a steady decline through the dry season months (June to September), where the design discharge drops below 400 m^3/s. The lowest monthly peak occurs in August (281.79 m^3/s), consistent with the driest period of the Citarum Basin's hydrological calendar.

For Ir. H. Djuanda Dam, the annual peak Q_{100} design discharge reaches 1,254.46 m^3/s on November 12, reflecting the early wet-season inflow pattern characteristic of the downstream catchment. The Ir. H. Djuanda peaks are consistently higher than Cirata across all months, which is expected given the cumulative drainage area increase (from 4,119 km^2 at Cirata to approximately 4,500 km^2 at Ir. H. Djuanda) and the contribution of intermediate sub-basins between the two dam sites. Notably, the highest monthly peaks at Ir. H. Djuanda occur in November (1,254.46 m^3/s) and February (1,165.73 m^3/s), suggesting that rainfall in the lower catchment, rather than upstream releases, drives the extreme inflow events at the downstream dam. Notably, the highest monthly peaks at Ir. H. Djuanda occur in November (1,254.46 m^3/s) and February (1,165.73 m^3/s), suggesting that rainfall in the lower catchment, rather than

upstream releases, drives the extreme inflow events at the downstream dam. Figure 2 illustrates the derived Q_{100} design inflow hydrograph for January, the peak month for Cirata Dam, showing the daily discharge variation for both dams under the Gumbel distribution.

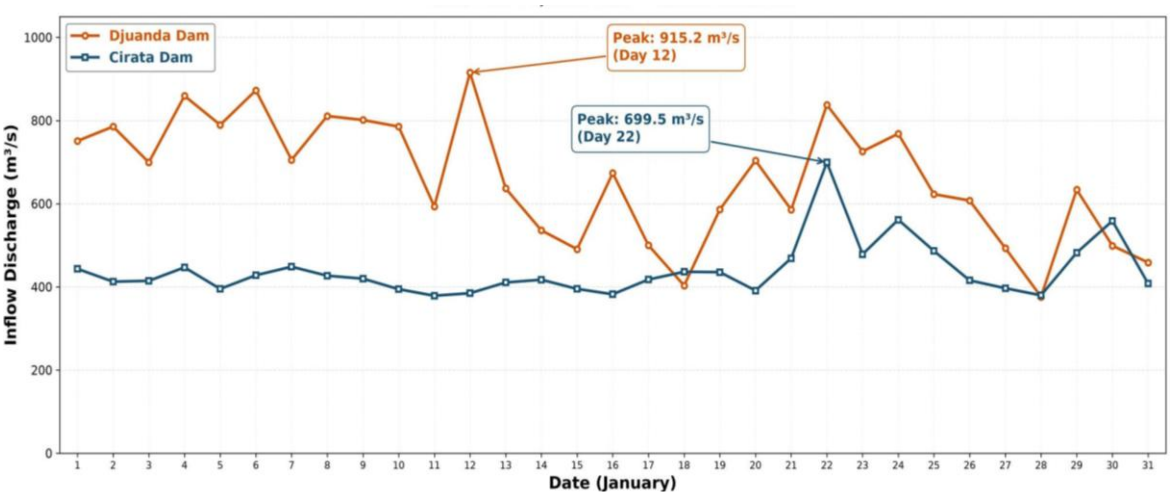

Figure 2. Q_{100} design inflow hydrograph for January (31 days) for Cirata Dam and Ir. H. Djuanda Dam using the Gumbel distribution

Figure 3 summarizes the monthly peak Q_{100} design discharge pattern across the full calendar year for both dams, highlighting the contrasting seasonal peak timing described above. with the driest period of the Citarum Basin's hydrological calendar.

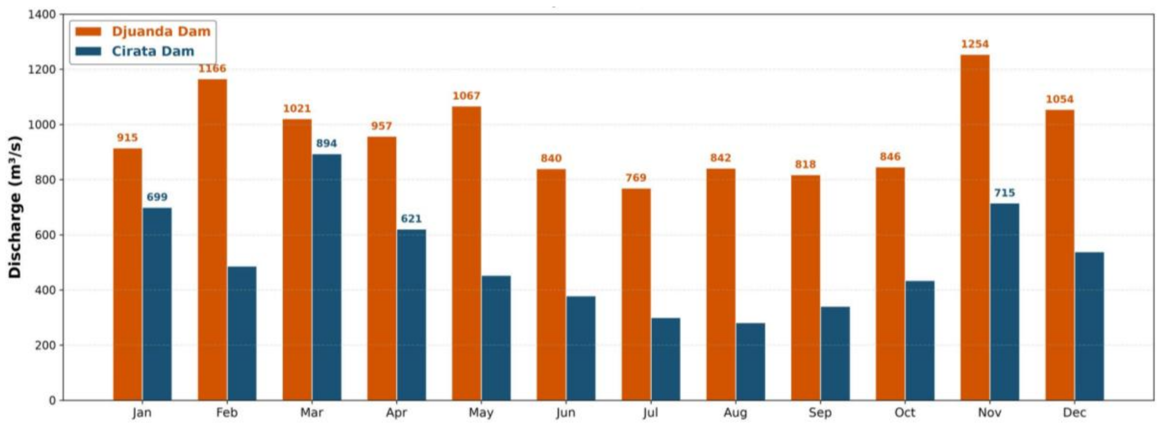

Figure 3. Monthly peak Q_{100} design discharge for the full calendar year Cirata Dam and Ir. H. Djuanda Dam, Gumbel distribution.

Implications for Dam-Break Modeling

The selection of the Gumbel distribution over Log Pearson III carries direct practical implications for dam-break modeling. The Gumbel-based Q_{100} design hydrograph provides a hydrologically defensible upstream boundary condition that can be directly input into two-dimensional HEC-RAS unsteady flow simulations. Because the daily-calendar approach preserves the full seasonal inflow pattern, including the timing, shape, and recession characteristics of wet-season inflow events, multiple breach initiation scenarios can be evaluated. A wet-season breach occurring when reservoirs are at or near full supply level can be contrasted with a dry-season breach at lower storage levels, producing more realistic and scenario-specific inundation predictions than would be possible with a single-peak, single-event design flood (Brunner, 2020; Mo et al., 2023).

For the Cirata-Ir. H. Djuanda cascade specifically, the November peak at Ir. H. Djuanda (1,254.46 m³/s) presents the most critical scenario because it coincides with the early wet season when Ir. H. Djuanda reservoir storage is being rapidly replenished following the dry season drawdown. A breach under these conditions would release a reservoir volume approaching the full 2,448 million m³, with the breach hydrograph routed through the densely populated downstream floodplain that includes the city of Purwakarta and agricultural areas of Karawang Regency. The contrasting peak timing between the two dams, Cirata peaking in March (894.21 m³/s) and Ir. H. Djuanda in November, indicates that the worst-case cascading failure scenario may not coincide with the peak inflow to either individual dam, but rather with a condition of simultaneous high reservoir storage at both dams. This finding highlights the value of the daily-calendar approach in identifying temporal windows of heightened cascade vulnerability that would be invisible to an annual-maximum-based analysis.

The study by Amiruddin et al. (2024) on discharge-driven channel morphology changes in Indonesian catchments using HEC-RAS further supports the integration of frequency-based inflow hydrographs with hydraulic routing models for cascade dam systems in tropical environments.

Together with Gunawan (2021), who demonstrated the effectiveness of HEC-HMS for flood modeling in Indonesian watersheds, these studies establish a methodological precedent for the approach adopted here: frequency analysis of operational reservoir inflow data as the hydrological foundation for physics-based, two-dimensional dam-break routing through serial reservoir systems.

Limitations and Uncertainty

Several limitations must be considered when applying these design hydrographs to dam-break modeling. The 10-year inflow record (2016-2025) at Ir. H. Djuanda is at the minimum acceptable threshold for frequency analysis. Extrapolating a 100-year return period from only 10 years of data carries substantial statistical uncertainty, with confidence intervals that may exceed 40% of the estimated value. This is particularly critical for the November peak of 1,254.46 m³/s, where the high month-to-month variability suggests that even moderate sampling errors could significantly shift the estimated quantile (Farooq et al., 2018).

Regarding the daily-calendar approach, while this method preserves intra-annual variability, it treats each calendar day as an independent statistical series, thereby omitting the autocorrelation structure inherent in daily flow sequences. Consecutive high-flow days, which are common during tropical cyclone events, are modeled as independent realizations, which may underestimate the persistence of extreme inflows. For the Smirnov test sensitivity, at the small sample size for Ir. H. Djuanda ($n = 10$), the critical D value (0.41 at $\alpha = 0.05$) is relatively large, making the test less powerful at detecting departures from the hypothesized distribution. Both distributions pass the test at nearly 100%, not necessarily because they fit well, but because the test has limited discriminatory power at small sample sizes.

A further limitation concerns the absence of formal outlier screening. While the daily-calendar framework mitigates the influence of individual extreme values by treating each calendar day independently, the presence of anomalously high or low inflow readings could affect the estimated distribution parameters, particularly the coefficient of skewness in the Log Pearson III model. Future work could incorporate systematic data quality screening procedures, including Grubbs' test for outlier detection and Pettitt's test for change-point detection, to enhance the robustness of the frequency estimates.

Finally, the reliance on the Kolmogorov-Smirnov test as the sole goodness-of-fit criterion represents a methodological limitation. As noted in the Discussion, the K-S test is less sensitive to discrepancies in the upper tail of the distribution, which is precisely the region that governs the Q_{100} design discharge. The inclusion of a tail-sensitive test, such as the Anderson-Darling (A-D) test, would strengthen the basis for distribution selection by providing complementary information about model fit in the extreme-value region. The unavailability of raw data in a format amenable to A-D test computation during this study precluded its application; future research should incorporate both central-tendency and tail-sensitive goodness-of-fit measures when selecting distributions for design flood estimation.

Conclusion

This study performed a comprehensive frequency analysis of daily historical inflow data from two serial dams, Cirata (35 years) and Ir. H. Djuanda (10 years), using the Gumbel and Log Pearson III distributions evaluated by the Kolmogorov-Smirnov test. The daily-calendar approach generated 365 individual frequency curves per dam, preserving intra-annual variability for use as boundary conditions in dam-break simulations. The key finding is that the Gumbel distribution consistently outperformed the Log

Pearson III across both dams. For Cirata Dam (n = 35), the Gumbel distribution was accepted for all 365 days (100%), while Log Pearson III was accepted for only 295 days (80.8%), with 70 days rejected. For Ir. H. Djuanda Dam (n = 10), both distributions performed nearly equivalently (Gumbel 100%, Log Pearson III 99.5%), where the small sample size limits the discriminatory power of the test. This result provides empirical evidence that the simpler two-parameter Gumbel distribution is more appropriate than the three-parameter Log Pearson III for the daily-calendar frequency approach in tropical reservoir inflow analysis. The instability of the sample skewness estimator at moderate sample sizes (n = 35) appears to degrade rather than improve the Log Pearson III's distributional fit, particularly during dry-season months when inflow variability is low. The peak Q_{100} design discharge is 894.21 m^3/s for Cirata Dam (March 19) and 1,254.46 m^3/s for Ir. H. Djuanda Dam (November 12) based on the Gumbel distribution. These values serve as the upstream boundary condition for subsequent HEC-RAS simulations of cascading dam failure scenarios. The 10-year record at Ir. H. Djuanda remains the primary limitation; extrapolating a 100-year return period from such a limited sample introduces uncertainty that propagates through all downstream modeling outputs. The synthetic Q_{100} design hydrographs generated in this study form the basis for two-dimensional dam-break simulations of the Cirata-Ir. H. Djuanda serial dam system under overtopping and piping breach scenarios, to be reported separately.

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Author Contributions

Conceptualization, J.F.H and R.Y.; Methodology, O.S.; Software, J.F.H.; Validation, J.F.H and O.S.; Formal Analysis, J.F.H.; Investigation, J.F.H.; Resources, J.F.H and R.Y.; Data Curation, R.Y.; Writing – Original Draft Preparation, R.Y.; Writing – Review & Editing, J.F.H.; Visualization, O.S.; Supervision, J.F.H.; Project Administration, J.F.H.; Funding Acquisition, J.F.H.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability

The datasets generated during and/ or analyzedduring the current study are available from the corresponding author on reasonable request.

Use of Generative AI

No generative AI was used.

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