

# Implementation of an early warning system for the management of hydrological extremes at the Singrobo-Ahaouaty hydroelectric dam on the River Bandama (Côte d'Ivoire)

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**Abstract:** Against a backdrop of increasing climate variability, hydraulic infrastructure is becoming increasingly vulnerable in the last decades. The Singrobo-Ahouaty hydroelectric dam, situated in the Bandama catchment in Côte d'Ivoire, is particularly exposed to hydrological variations. The study therefore aims to characterise extreme flows and define appropriate warning thresholds. Hydrometric data for the period 1981-2017 were analysed to evaluate hydrological extreme. The methodology is based on a frequency analysis of maximum annual flows (QMAX) and minimum annual flows (QMNA). The assumptions of homogeneity, stationarity and independence of the time series were tested using the Wilcoxon, Kendall and Wald-Wolfowitz tests. Six probability distributions (Exponential, Lognormal, Gumbel, Gamma, Weibull and Pearson Type III) were then compared on the basis of graphical fit, the chi-squared ( $\chi^2$ ) test, and the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). The results show that the log-normal distribution is the best model for peak flows, whilst the Gumbel distribution is the most suitable for low-water flows. The estimated quantiles indicate that the 100-year flood reaches 643 m<sup>3</sup>/s and the 200-year flood 712 m<sup>3</sup>/s. For low water levels, the 5-year return period flow (QMNA-5) is estimated at 20.7 m<sup>3</sup>/s. Based on these reference values, operational thresholds have been defined: for high water levels, a watch threshold of 578.7 m<sup>3</sup>/s and a crisis threshold of 707 m<sup>3</sup>/s; for low water levels, a watch threshold of 22.7 m<sup>3</sup>/s and a crisis threshold of 18.6 m<sup>3</sup>/s.

## 1. Introduction

Climate change manifests itself in the form of more or less unpredictable anomalies and crises, sometimes as successive periods of extreme events (floods) and, in other cases, as water shortages (droughts). Between 2010 and 2016, 715 projects aimed at reducing hydro-climatic risks, adapting to and building resilience against climate change were launched in West Africa, with a total budget of 7.3 billion US dollars (Tiepolo et al., 2018). Côte d'Ivoire, which has not been spared, has also been suffering for several decades from the effects of changes caused by extreme weather events. Indeed, the

population is severely affected by flooding, which impacts around 60,000 people each year, representing 0.3 per cent of the Ivorian population (CIMA and UNISDR, 2018).

The construction of the Singrobo-Ahaouaty dam on the River Bandama is essential for power generation. However, its vulnerability to extreme flow rates highlights the importance of determining the maximum hydrometric values. The aim of this study is to develop an Early Warning System (EWS) for this dam. The study therefore seeks to characterise hydrological variability and to define an early warning system for the management of extreme flows.

Furthermore, the analysis of hydrological extremes can be approached using several complementary methods. However, the statistical approach remains the most frequently used method in studies on extreme flows in Côte d'Ivoire (Goula, 2007; Kouassi et al., 2018; Assoko, 2022).

However, this is a difficult task, given that extremes are rare and observation series are short in most cases (Souanef, 2015). Furthermore, a series of at least ten years' worth of observations is required to ensure the validity of a statistical analysis (J. F. Miller et al., 1982). Frequency analyses were therefore carried out using time series comprising 10, 12, 15 and 62 years of data respectively (Kouider, 2003; Souanef, 2015). The reliability and robustness of the results depend heavily on the length of the observation series. Several probability distributions are commonly used to model extreme values, notably the generalised extreme value (GEV) distribution, the log-normal distribution, the log-Pearson type III distribution, the Gumbel distribution and the Gamma distribution (Achite et al., 2004; Assoko, 2022).

Thus, the availability of data on past events makes it possible to use frequency analysis. This allows these past events to be analysed and their probability of recurrence to be assessed.

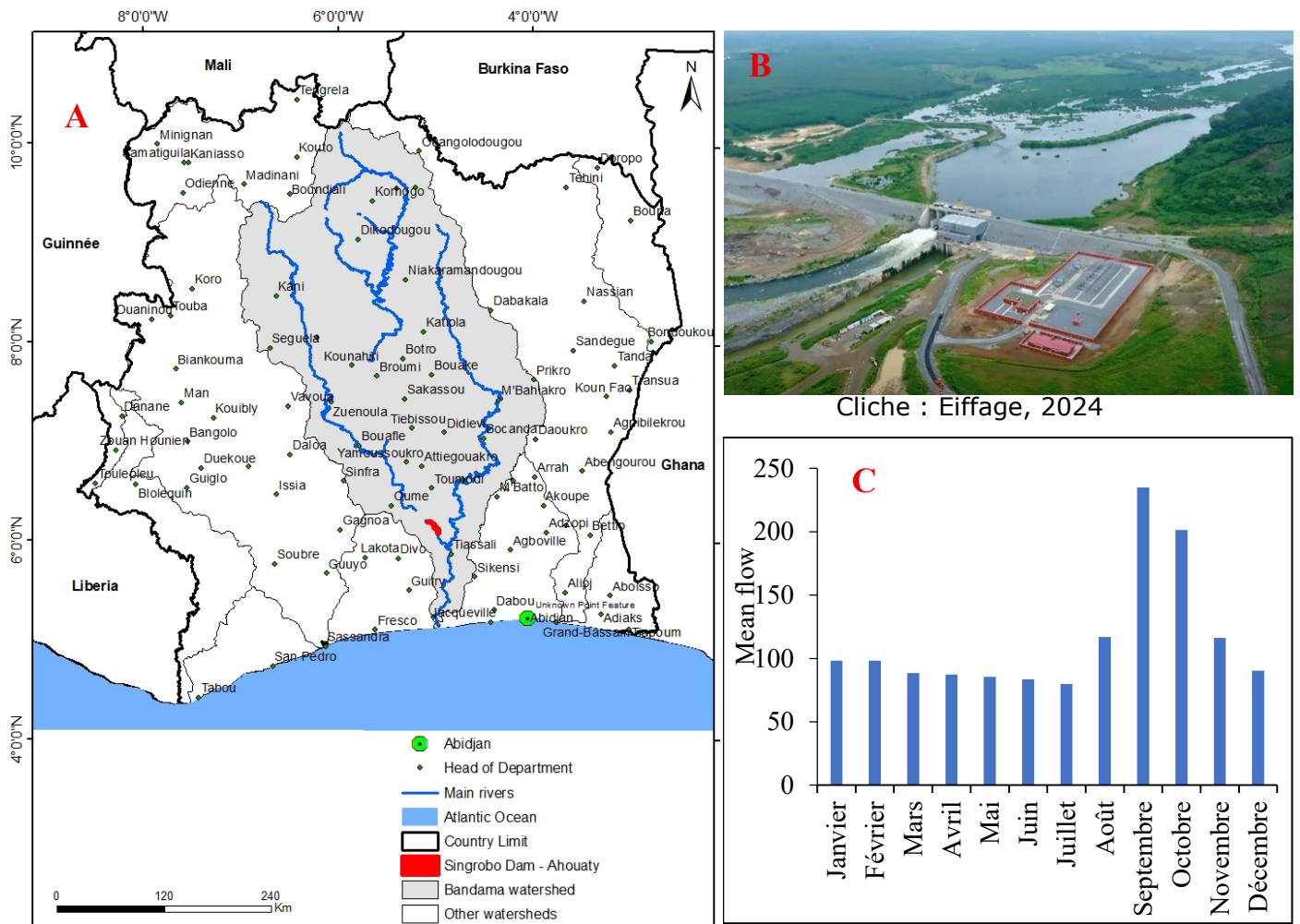
This study demonstrates the value of frequency analysis in defining statistically robust hydrological warning thresholds. The proposed system serves as a decision-support tool for flood and drought risk management, as well as for the safe operation of the Singrobo-Ahouaty dam.

## 2. Materials and Methods

### 2.1. Description of the study area

The Singrobo-Ahouaty hydroelectric dam is situated on the Bandama River, between the villages of Singrobo and Ahouaty, in south-central Côte d'Ivoire (Figure 1A). Its geographical coordinates are 6°6'11.15" north latitude and 4°56'54.72" west longitude. The Singrobo-Ahouaty Project is a 44 MW hydroelectric development. The five (05) localities directly affected by the project are Singrobo, Ahouaty, Pacobo, Ahérérou 2 and N'dénou. It is situated downstream of the Taabo dam, which was commissioned in 1979 (Kaisers Engineers and Constructors, 1980).

The Bandama River at Singrobo-Ahouaty exhibits a unimodal hydrological regime, characterized by a single annual flood peak, centered in September (235 m<sup>3</sup>/s) and October (200 m<sup>3</sup>/s) (Figure 1C). In fact, the high-water period extends from August to November. A gradual decline in flow is observed in November (115 m<sup>3</sup>/s). This phase represents the basin's response to rainfall during the main rainy season (June through October), with a time lag due to the time it takes for water to move through the watershed.



**Figure 1.** (A) Location, (B) aerial view, and (C) annual hydrological regime of the Singrobo-Ahouaty hydroelectric dam on the Bandama River.

The high-water period extends from August to November, with the rise in water levels beginning in August ( $117 \text{ m}^3/\text{s}$ ), a clear peak in September-October, followed by a gradual decline in November ( $115 \text{ m}^3/\text{s}$ ). This phase represents the catchment's response to rainfall during the main rainy season (June to October), with a time lag due to the time taken for water to move through the catchment. From December through July, flows remain relatively stable and moderate, ranging between  $80$  and  $98 \text{ m}^3/\text{s}$ . This stability over eight consecutive months, with no particularly low flows, indicates good support for low-flow conditions.

## 2.2. Data base

The monthly hydrometric data obtained from the Compagnie Ivoirienne d'Électricité (CIE) covers the period from 1981 to 2017 and relates to the Taabo station, upstream of the Singrobo-Ahouaty dam.

The characterisation of extreme flows is based on the extraction of the annual minimum monthly mean flows (QMNA) and the annual maximum monthly mean flows (QMXA). The QMNA values are used as a monthly reference for characterising low-water conditions (Lang, 2011; Assoko, 2022). As for the QMXA, these are used to characterise floods (Segui et al., 2018).

## 2.3. Statistical modelling method and early warning thresholds for extreme flows

### 2.3.1. Statistical assumptions prior to frequency analysis

Before any adjustment is made, the quality of the time series is assessed using three non-parametric tests. The principle common to these tests is the test of goodness of fit between a null hypothesis ( $H_0$ ) and the observations, against an alternative hypothesis ( $H_1$ ). Acceptance of  $H_0$  indicates a likely random effect, whilst its rejection reveals a statistically significant structure, requiring further interpretation. Each test produces a statistical statistic-p-value pair. This p-value is compared with the chosen significance threshold. It enables the null hypothesis  $H_0$  to be accepted or rejected.

The first is the Wilcoxon rank test (1945). It tests the hypothesis of homogeneity. Its null hypothesis  $H_0$  assumes that the means of two subsamples are equal. Thus, suppose that, due to a change in station location, the overall sample consists of two subsets of data on annual maximum flows, denoted respectively by  $x_1, x_2, \dots, x_n$  and  $x_{n+1}, x_{n+2}, \dots, x_m$ , whose means are  $\mu_1$  and  $\mu_2$  respectively. The objective is then to test whether these two means are equal. Its mathematical formulation is as follows (Assoko, 2022):  $H_0: \mu_1 = \mu_2$ ;  $H_1: \mu_1 \neq \mu_2$

Thus,  $H_0$ : the means of the two subsamples are equal;  $H_1$ : the means of the two subsamples are different.

The second is Kendall's test. It tests the hypothesis of stationarity. It is based on rank correlation and enables trends in time series to be detected (Goula, 2007). Its null hypothesis  $H_0$  assumes the absence of a trend.

The third is the test proposed by Wald and Wolfowitz (1943). It tests the hypothesis of independence. Its null hypothesis  $H_0$  assumes that the observations are independent. A flood is said to be independent if its intensity is not influenced by that of the previous year (Kouider, 2003).

### 2.3.2. Selection of the frequency model

Six probability distributions, consistent with those proposed by the HYFRAN software and used in previous studies (Koumassi et al., 2014; Kouassi et al., 2018; Kouassi et al., 2019), were selected for flood and low-water events. These include the exponential, log-normal, Weibull, gamma, Gumbel and Pearson Type III distributions. The characteristics of the various distributions are set out in the table 1.

**Table 1:** Characteristics of the various frequency distributions used.

| Law              | Key feature                                                                                                                                                                                                   |
|------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| exponential      | A simple law, combined with Maillet's runoff coefficient for predicting discharge rates (Lang, 2007)                                                                                                          |
| log-normal       | Suitable if the logarithm of the variable follows a normal distribution; 2- or 3-parameter version; provides a good fit for time series spanning around twenty years (Gailliez, 2013)                         |
| Gumbel           | The founding law of the theory of extreme values (Gumbel, 1954); widely used for adjusting maximum and minimum flow rates in hydrology                                                                        |
| Weibull          | Widely used for low water levels since Gumbel's seminal work (1954) on the theory of extreme values; it provides a good representation of distributions with a negative skewness coefficient (Gailliez, 2013) |
| Gamma            | A special case of Pearson's third law when the position parameter $m = 0$ (Assoko, 2022)                                                                                                                      |
| Pearson type III | Commonly used for flood flows, or incomplete gamma (Kouider, 2003; Goula, 2007); also used for minimum annual flows (Assoko, 2022)                                                                            |

The flow rates, sorted in descending or ascending order, are associated with an empirical exceedance frequency, according to a general formula parameterised by a constant  $\alpha$  (0 to 0.5). Hazen's formula (1914), with  $\alpha = 0.5$ , the traditional choice in humid tropical regions (Soro, 2011 and Kouassi et al., 2019), was adopted in this study.

### 2.3.3. Selection of the best fits.

Several complementary approaches have been used to select the most appropriate distribution (Soro et al., 2016; Kouassi et al., 2019).

A visual check of the graphical fit is an essential step (Kouassi et al., 2018). This involves plotting the experimental data points on probability paper and visualising how well they fit the theoretical curve. However, this method is subject to interpretative bias in the presence of outliers (Gailliez, 2013). It is therefore advisable to apply more robust statistical approaches.

Thus, the chi-squared ( $\chi^2$ ) test, introduced by Karl Pearson in the early 20th century, is used to verify the fit of a sample to a theoretical distribution. A fit is considered satisfactory if the p-value is less than 0.05. However, this test does not allow for the comparison of several distributions with one another (Assoko, 2022).

Furthermore, the Akaike information criteria (AIC) (Akaike, 1974) and the Bayesian information criteria (BIC) (Schwarz, 1978), which are based on maximised log-likelihood (S. Gailliez, 2013; WMO, 2009), were applied. The values of these criteria are estimated for each distribution at different levels. The associated model is selected based on the fit to the variable in question when the AIC and BIC values are low (Goula, 2007).

The distribution selected following these tests for a data series is used to determine the quantiles of the return periods.

### 2.3.4. Determination of flood and low-water thresholds

Frequency-based QMNA and QMAX values were used to determine early-warning thresholds for low water and floods (GIEC, 2013; Kouadio, 2016; Kouassi et al., 2019).

With regard to QMAX values, the reference flood selected is the highest known flood. If this is lower than the hundred-year flood, the latter is used (GEI, 2013). Thus, operational thresholds are set in relation to the reference flow (CEPRI, 2017):

- Warning threshold = 90 % of the reference flow rate;
- Crisis threshold = 110 % of the reference flow rate.

The thresholds used are colour-coded (SODEXAM, 2018): yellow (low risk), orange (medium risk), red (high risk, imminent flooding).

The QMNA provides information on the severity of low water levels. The Framework Plan for Drought, which sets out a national framework for water resource management, distinguishes between four levels of severity: vigilance, alert, crisis, and heightened crisis (A. V. S. Assoko, 2022). The indicator used for low water levels is the QMNA-5, the annual minimum monthly flow with a five-year return period, a regulatory value prescribed by the French Act of 3 January 1992 on water management (Sauquet et al., 2009) and already applied to rivers in Côte d'Ivoire (Kouassi et al., 2018). The thresholds are calculated as follows:

- Vigilance threshold =  $1.1 \times \text{QMNA-5}$ ;
- Crisis threshold =  $0.9 \times \text{QMNA-5}$ .

A similar colour-coding system is used: yellow for dangerous flow rates but without significant damage, orange for significant low water levels, red for major low water levels.

## 3. Results

### 3.1. Statistical analysis of the temporal variability of hydrological extreme flow rates

Analysis of the hypothesis tests applied to the annual maximum and minimum flows (QMNA) of the Bandama River at the Singrobo-Ahouaty gauging station reveals different patterns (Table 2). For the QMAX values, the Wilcoxon homogeneity test yields a p-value of 0.0293, which is below the 5% significance threshold, thus indicating that the time series is non-homogeneous. The QMNA time series has a p-value of 0.094, which is above the 5% threshold, allowing this time series to be considered homogeneous.

However, Kendall's stationarity test does not detect any significant time-series trends, either for QMAX ( $p = 0.170$ ) or for QMNA ( $p = 0.24$ ). Similarly, the Wald-

Wolfowitz independence test confirms the absence of significant autocorrelation in both data series. Indeed, the p-values obtained are 0.104 and 0.082 respectively, both of which are above the 0.05 threshold. These results allow for a frequency analysis.

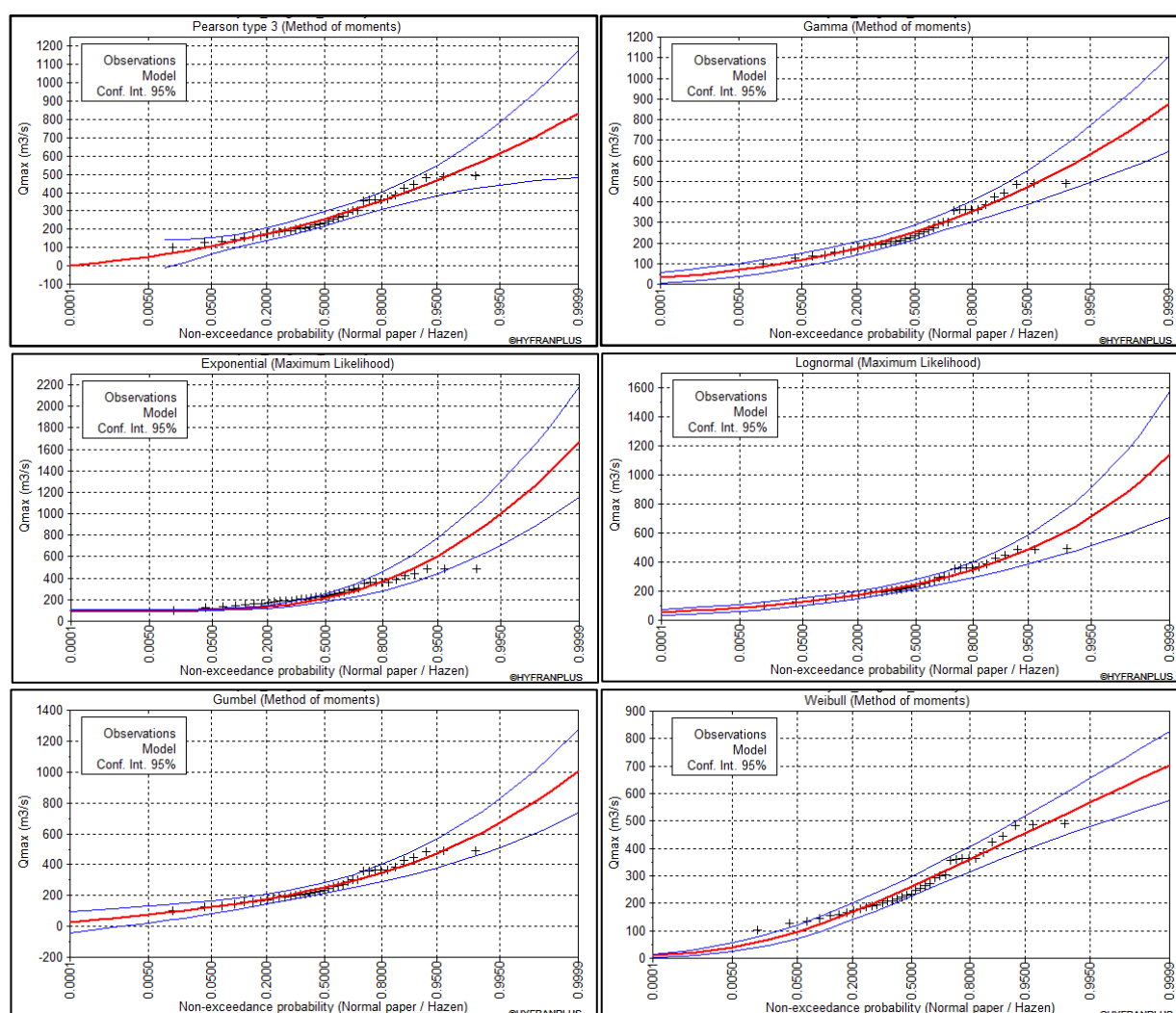
**Table 2:** Results of the hypothesis tests applied to QMNA and QMAX

|             | Homogeneity test |        | Stationarity test |       | Independence test |       |
|-------------|------------------|--------|-------------------|-------|-------------------|-------|
|             | W                | P      | K                 | P     | U                 | P     |
| <b>QMAX</b> | 2.18             | 0.0293 | 1.37              | 0.170 | 1.63              | 0.104 |
| <b>QMNA</b> | 1.67             | 0.094  | 1.18              | 0.24  | 1.74              | 0.082 |

### 3.2. Frequency analysis of flood discharge rates

#### 3.2.1. Graphical fitting of QMAX data

Analysis of the graphical fits (Figure 2) reveals contrasting performance depending on the distributions. Indeed, the log-normal, Gamma, Gumbel and Person type 3 distributions show a satisfactory fit. The observation points align well with the theoretical curve. This fit holds true both in the central part of the distribution and at the tails. The Weibull distribution behaves differently. It tends to underestimate extreme values at the upper tail. Its suitability for forecasting rare floods is therefore limited. The exponential distribution stands out clearly from the others. It significantly overestimates high values. Its curve spreads excessively towards high exceedance probabilities. It therefore appears ill-suited to the hydrological context under study.



**Figure 2:** Fitting of QMAX values for the Bandama River at the Singrobo Ahouaty station (1981-2017)

### 3.2.2. Analytical fitting of QMAX data

In order to objectively select the most appropriate distribution for the fit, two complementary approaches were employed: the chi-squared ( $\chi^2$ ) goodness-of-fit test and the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC).

Analysis of the p-values from the  $\chi^2$  goodness-of-fit test (Table 3) reveals that the Gamma and Gumbel distributions show the strongest fit to the data, with an identical probability of exceeding 0.76. The log-normal distribution ranks third, with a p-value of 0.485. The Pearson Type 3 ( $p = 0.36$ ) and Weibull ( $p = 0.30$ ) distributions show intermediate levels of goodness of fit, whilst the exponential distribution has the lowest p-value ( $p = 0.10$ ). This value confirms its poorer goodness of fit, which had already been observed graphically.

**Table 3:** Chi-squared test applied to the QMAX values

| Laws of probability   | $\chi^2$ | P     |
|-----------------------|----------|-------|
| <b>Gamma</b>          | 2.57     | 0.76  |
| <b>Gumbel</b>         | 2.57     | 0.76  |
| <b>Log-normal</b>     | 2.16     | 0.485 |
| <b>Pearson type 3</b> | 4.30     | 0.36  |
| <b>Weibull</b>        | 6.03     | 0.30  |
| <b>Exponential</b>    | 9.05     | 0.10  |

The AIC and BIC criteria confirm and support this ranking (Table 4). The log-normal distribution yields the lowest values (AIC=449.90; BIC=453.12), making it the best-fitting model. It is followed by the Gamma distributions (AIC=450.41; BIC = 453.63) and Gumbel distributions (AIC = 450.47; BIC = 453.70), which perform very similarly. The exponential distribution has the highest values for these criteria (AIC = 458.38; BIC = 461.60), as well as an estimated quantile of 882.7 m<sup>3</sup>/s, which is significantly higher than those of the other distributions (538 to 643 m<sup>3</sup>/s), confirming its tendency to overestimate extreme flows.

Following this comparative analysis based on graphical fit, the chi-squared test, the AIC and the BIC, the log-normal distribution emerges as the statistically optimal distribution for modelling the annual maximum flows of the Bandama River at the Singrobo-Ahouaty station over the period 1981-2017. The Gamma distribution, traditionally used in extreme hydrology, constitutes a robust alternative that could be considered for comparison within the framework of the flood early warning system.

**Table 4:** AIC and BIC criteria applied to probability distributions for QMAX

| Model                 | Estimated quantiles XT (m <sup>3</sup> /s) | BIC     | AIC     |
|-----------------------|--------------------------------------------|---------|---------|
| <b>Log-normal</b>     | 642.619                                    | 453.12  | 449.898 |
| <b>Gamma</b>          | 585.145                                    | 453.632 | 450.41  |
| <b>Gumbel</b>         | 610.57                                     | 453.695 | 450.473 |
| <b>Weibull</b>        | 538.218                                    | 456.096 | 452.874 |
| <b>Pearson type 3</b> | 571.721                                    | 458.295 | 453.462 |
| <b>Exponential</b>    | 882.662                                    | 461.598 | 458.376 |

### 3.2.3. Determination of extreme hydrometric thresholds for flood risk

The return periods (T) assessed range from 2 to 200 years, with associated maximum flows varying from 246 m<sup>3</sup>/s to 712 m<sup>3</sup>/s (Table 5). yearly flood with low impact, correspond to return periods of between 2 and 5 years, have discharge rates

ranging from 246 m<sup>3</sup>/s to 348 m<sup>3</sup>/s. These events, with an annual probability of exceedance of between 50 per cent and 20 per cent, constitute ordinary floods.

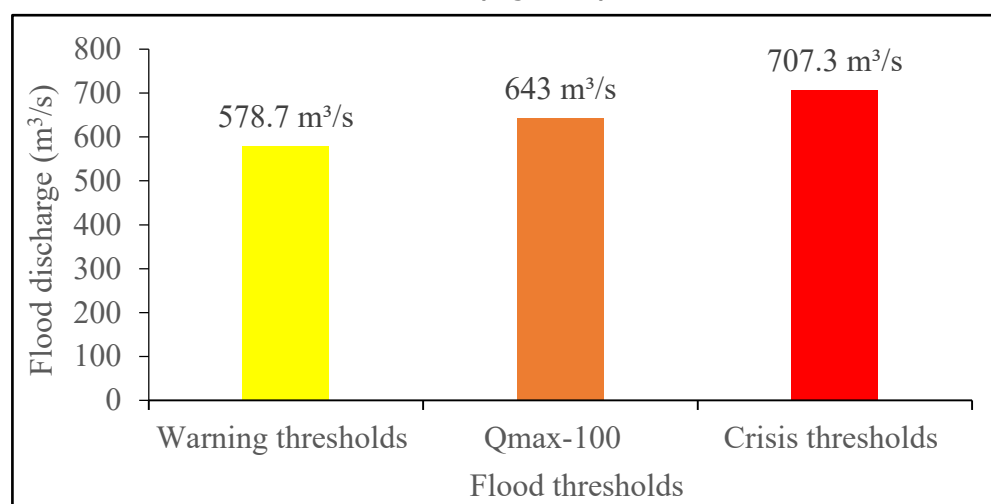
Moderate to severe floods, associated with return periods of 10 to 20 years, are characterised by discharge rates of between 418 m<sup>3</sup>/s and 485 m<sup>3</sup>/s. These events, which are rarer, can cause local flooding.

**Table 5:** Quantiles (XT) and confidence intervals for QMAX

| T (years)  | Estimated quantiles XT<br>(m <sup>3</sup> /s) | Confidence interval<br>(95%) |
|------------|-----------------------------------------------|------------------------------|
| <b>200</b> | 712                                           | 513 - 911                    |
| <b>100</b> | 643                                           | 477 - 809                    |
| <b>50</b>  | 574                                           | 438 - 710                    |
| <b>20</b>  | 485                                           | 385 - 585                    |
| <b>10</b>  | 418                                           | 342 - 493                    |
| <b>5</b>   | 348                                           | 294 - 402                    |
| <b>2</b>   | 246                                           | 213 - 279                    |

Exceptional floods, corresponding to return periods of 50 to 200 years, have discharge rates ranging from 574 m<sup>3</sup>/s to 712 m<sup>3</sup>/s. The 50-year flood is estimated at 574 m<sup>3</sup>/s, the 100-year flood at 643 m<sup>3</sup>/s and the 200-year flood at 712 m<sup>3</sup>/s. These events have respective annual exceedance probabilities of 2 %, 1 per cent and 0.5 %.

Consequently, at the Singrobo-Ahouaty station, the reference flood selected is therefore QMAX-100 (643 m<sup>3</sup>/s). The calculated warning threshold is 578.7 m<sup>3</sup>/s and the calculated crisis threshold is 707 m<sup>3</sup>/s (Figure 3).



**Figure 3:** Flood thresholds relative to QMAX-100 at the Singrobo-Ahouaty station

### 3.3. Frequency analysis of low-water flows

#### 3.3.1. Graphical fitting of QMNA data

The figure 4 illustrates the fit of the QMNA data using the various models selected. The Gumbel distribution provides the best visual fit. The data fall well within its confidence interval. The Weibull distribution and the Pearson Type 3 distribution also perform well, although the confidence interval widens significantly for high non-exceedance probabilities. The Gamma distribution provides an acceptable fit, but its calibration is less satisfactory at high non-exceedance probabilities. Conversely, the Exponential distribution significantly underestimates the QMNA values. The Log-normal distribution, meanwhile, is characterised by an overestimation of the extreme values. Indeed, the fit plot shows that the log-normal distribution correctly reproduces the observed minimum flow rates for low and intermediate non-exceedance probabilities.

However, for high non-exceedance probabilities, the simulated data deviate from the observations and tend to overestimate the extreme values of the minimum flow rates.

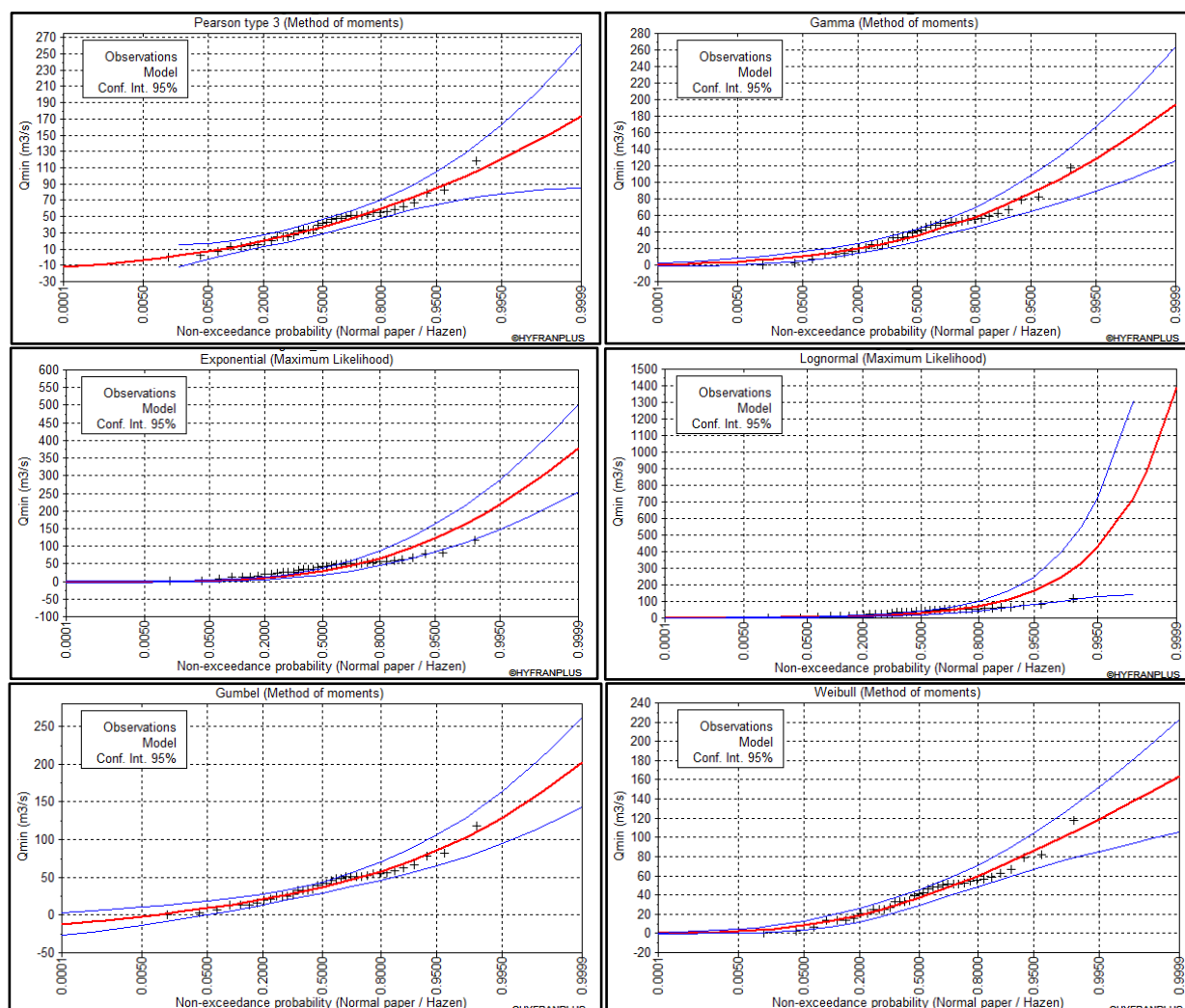


Figure 4: Adjustment of Bandama's QMNA values at the Singrobo Ahouaty station (1981-2017)

### 3.3.2. Analytical fitting of QMNA data

The results of the chi-squared goodness-of-fit test (Table 6) indicate that the Gamma and Gumbel distributions provide the best fit. Their p-value, equal to 0.39, is well above the critical significance threshold of 5 per cent. The Weibull distribution ranks next ( $\chi^2 = 6.46$ ;  $p = 0.26$ ), followed by the Pearson Type 3 distribution with a p-value of 0.16. Conversely, the null hypothesis of goodness of fit is rejected for the log-normal and exponential distributions, whose p-values are 0.0011 and 0.0004 respectively, well below the 5% significance threshold.

**Table 6:** Chi-squared test applied to QMNA

| Laws of probability   | $\chi^2$ | P      |
|-----------------------|----------|--------|
| <b>Gamma</b>          | 5.16     | 0.39   |
| <b>Gumbel</b>         | 5.16     | 0.39   |
| <b>Weibull</b>        | 6.46     | 0.26   |
| <b>pearson type 3</b> | 6.46     | 0.16   |
| <b>Log-normal</b>     | 20.30    | 0.0011 |
| <b>Exponential</b>    | 22.89    | 0.0004 |

The information criteria also show that the model that best fits the QMNA time series is the Gumbel distribution. It has the lowest values for both the Bayesian criterion (BIC = 344.49) and the Akaike criterion (AIC = 341.27) (Table 7).

The Weibull distribution ranks second, with very similar values (BIC = 344.92; AIC = 341.70), followed by the Pearson Type 3 distribution (BIC = 347.05; AIC = 342.21). The Gamma distribution occupies an intermediate position (BIC = 352.54; AIC = 349.32), whilst the Exponential distribution shows significantly higher values (BIC = 356.34; AIC = 353.11).

The log-normal distribution, meanwhile, records the least favourable values of all the distributions tested (BIC = 365.42; AIC = 362.20). Following this comparative analysis based on graphical fit, the goodness-of-fit test, the AIC and the BIC, the Gumbel distribution emerges as the statistically optimal distribution for modelling the annual minimum flows of the Bandama River at the Singrobo-Ahouaty station. The Weibull distribution constitutes a robust alternative.

**Table 7:** AIC and BIC criteria applied to probability distributions for QMNA

| Model                 | Estimated quantiles XT ( $\text{m}^3/\text{s}$ ) | BIC     | AIC     |
|-----------------------|--------------------------------------------------|---------|---------|
| <b>Gumbel</b>         | 116.088                                          | 344.49  | 341.268 |
| <b>Weibull</b>        | 109.742                                          | 344.919 | 341.697 |
| <b>Pearson type 3</b> | 110.241                                          | 347.047 | 342.214 |
| <b>Gamma</b>          | 116.264                                          | 352.54  | 349.318 |
| <b>Exponential</b>    | 188.9                                            | 356.335 | 353.114 |
| <b>Lognormal</b>      | 330.79                                           | 365.418 | 362.196 |

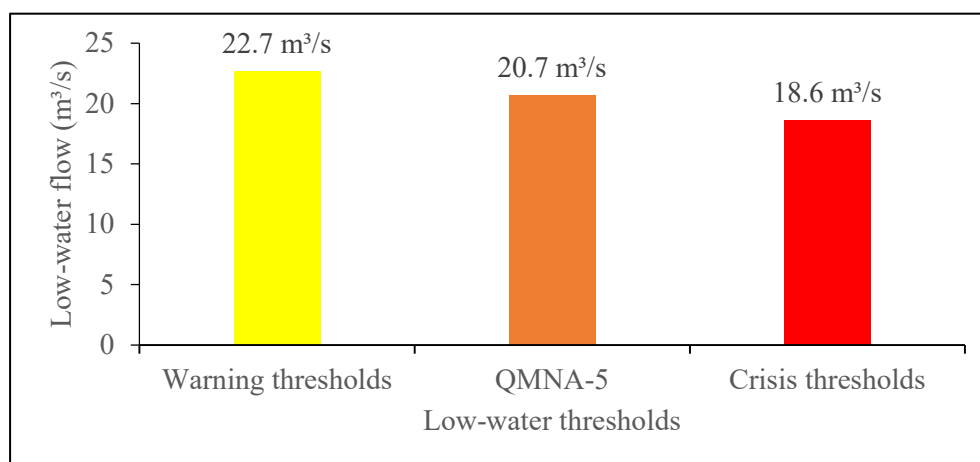
### 3.3.3. Determination of low-water thresholds

The quantiles of low-water flows are calculated using the Gumbel distribution. Their confidence intervals are shown for return periods of 2 years, 5 years, 10 years, 20 years and 50 years (table).

**Table 8:** Quantiles (XT) and confidence intervals for QMNA

| T (years) | Estimated quantiles XT ( $\text{m}^3/\text{s}$ ) | Confidence interval (95%) |
|-----------|--------------------------------------------------|---------------------------|
| <b>50</b> | 3.98                                             | -20.83                    |
| <b>20</b> | 8.99                                             | -18.256                   |
| <b>10</b> | 13.9                                             | 5.87 - 22.0               |
| <b>5</b>  | 20.7                                             | 13.7 - 27.6               |
| <b>2</b>  | 36.5                                             | 29.4 - 43.6               |

The five-year low-water flow (QMNA-5), used as the reference flow at the Singrobo-Ahouaty station, is estimated at 20.7  $\text{m}^3/\text{s}$  (Figure 5). On this basis, two low-water thresholds have been calculated. The calculated vigilance threshold stands at 22.7  $\text{m}^3/\text{s}$ . The crisis threshold is 18.6  $\text{m}^3/\text{s}$ . Thus, when the observed flow falls below 22.7  $\text{m}^3/\text{s}$ , increased vigilance is recommended. The situation is considered critical and calls for enhanced water resource management measures when the flow falls below 18.63  $\text{m}^3/\text{s}$ .



**Figure 5:** Low-water thresholds in relation to the QMNA-5 values at the Singrobo-Ahouaty station

#### 4. Discussion

An analysis of hydrological extremes on the Bandama River at the Singrobo-Ahouaty station reveals a distinct statistical behaviour between maximum and minimum flows. For QMAX values, the log-normal distribution proved to be the best fit. These results are consistent with those of the research carried out by Goula et al. (2007) on maximum annual rainfall in Côte d'Ivoire (1947-1995). According to the authors, fitting an extreme value distribution and quantile kriging (return periods of 2 to 100 years) show that the log-normal distribution is better suited to equatorial transitional and attenuated transitional regimes, particularly in the west and centre of the country. In this context, the work by Kouassi et al. (2019), focusing on the N'zi-Bandama catchment (Côte d'Ivoire), yields similar results.

For QMNAs, on the other hand, Gumbel's distribution has emerged as the most robust. In Côte d'Ivoire, this distribution has already been applied to exceptional daily rainfall in the work of Goula et al. (2007). The adjustments made yield satisfactory results for the mountain, transitional equatorial, particularly in the northern part and a small portion of the southern part of the region. Similarly, Koumassi et al. (2014) conducted a frequency analysis of the mean daily discharges at the Couberi and Gbassè stations. This study covers the period 1965-2008 in the Sota catchment in Benin. The results show that peak flows are best fitted to the Gumbel and Log-Pearson III distributions. The associated margin of error ranges from 1 to 5 per cent.

However, several studies have produced results that differ from those obtained in this study. The work by Kouassi et al. (2019), which focused on the N'zi-Bandama catchment (Ivory Coast), yielded divergent results. The authors fitted four distribution laws (log-normal, exponential, gamma and Weibull) to the average monthly low-water flows (January, February, March). Their results show that the log-normal distribution fits best, followed by the exponential, gamma and Weibull distributions. In this regard, Mekhloufi's (2014) study on the prediction and forecasting of low-water flows in the wadis of northern Algeria shows that the log-normal distribution fits the low-water flow data best. It emerges from this work that three distributions are frequently used in the study of low-water flows (the log-normal, Weibull and exponential distributions).

This divergence between the two hydrological regimes confirms that no single statistical law can adequately describe the entire range of extreme behaviour of a watercourse. It therefore justifies the differentiated treatment of high-water and low-water conditions adopted in this study.

The operational thresholds were defined on the basis of the 100-year flood (QMAX-100 = 643 m³/s) and the 5-year low-water flow (QMNA-5 = 20.7 m³/s). This method is commonly used in hydrological risk management (Assoko, 2022). It is based on robust statistical references rather than arbitrary empirical thresholds.

This approach is in line with the recommendations from early warning systems in Côte d'Ivoire (Kouassi et al., 2023). It favours vigilance thresholds based on frequency analysis. These thresholds constitute an essential step in characterising risks before they are integrated into operational systems.

However, there are several limitations worth discussing. Firstly, there is the lack of homogeneity detected in the QMAX time series ( $p = 0.0293$ ). This non-homogeneity could result from changes in the Bandama's hydrological regime linked to the filling of dams located upstream of the catchment, notably the Taabo dam, which came into operation in 1979, at the start of the study period under consideration (1981–2017). Furthermore, the study conducted by Koumassi et al. (2014) presents similar results. At the Kalalé station, the rainfall time series were found to be non-independent, non-homogeneous and non-stationary. Despite this finding, a frequency analysis was carried out. Indeed, the series shows minimal correlation from one year to the next. Its impact on the estimated flood quantiles therefore remains relatively small (WMO, 2009).

Assoko (2022) reaches a similar conclusion in his study of the Marahoué. The null hypothesis ( $H_0$ ) of the Wilcoxon homogeneity test was rejected at the 1 per cent significance level. The same result is observed for Kendall's stationarity test. The Wald–Wolfowitz independence test, however, was accepted at the 1% significance level. The time series from these stations therefore do not fully satisfy the basic assumptions of frequency analysis. Nevertheless, they were fitted using this method.

Furthermore, the marked widening of the confidence intervals for long return periods highlights the limitations of statistical extrapolation. This limitation extends beyond the available observation period. For QMAX values, the range increases from 66 m<sup>3</sup>/s at  $T=2$  years to 398 m<sup>3</sup>/s at  $T=200$  years. For QMNA values, the widening is even more pronounced. The lower bounds even become negative at  $T=20$  and 50 years. This finding is consistent with the general principles of frequency analysis, according to which the reliability of estimates decreases as the return period moves further away from the length of the historical time series (Assoko, 2022; Kouassi et al., 2023). For the most critical applications of the SAP, particularly the crisis threshold, it would be advisable to prioritise regular updating of the adjustment parameters as new data become available. This approach is preferable to setting thresholds definitively from the 1981–2017 series alone, as this series is too short and may not be fully representative of the hydrological variability.

## 5. Conclusions

A frequency analysis of annual maximum flows (QMAX) and annual minimum flows (QMNA) over the period 1981–2017 enabled the identification of the most suitable statistical models and the definition of operational hydrological thresholds.

The results show that the log-normal distribution provides the best fit for maximum flows, whilst the Gumbel distribution performs best for low-water flows. The estimated quantiles enabled a 100-year flood flow of 643 m<sup>3</sup>/s to be selected as the reference flow for flooding and a 5-year low-water flow of 20.7 m<sup>3</sup>/s as the reference for low water levels. Based on these values, warning and crisis thresholds were proposed to improve the monitoring of flood and drought risks.

It thus helps to strengthen the resilience of water infrastructure in the face of the effects of climate variability and extreme hydrological events.

However, further research is still needed to improve the performance of the proposed system. This includes, in particular, the integration of weather forecasts, the use of hydrological models coupled with climate forecasts, and the regular updating of thresholds based on new observations. The operational validation of the system and its extension to other dams and catchment areas in Côte d'Ivoire will also help to strengthen national strategies for the prevention and management of hydro-climatic risks.

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**Appendix:** The appendix is an optional section that can contain details and data supplemental to the main text.

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