

Evaluation of Water Resources in the confront of Climate Variability in the N'Zi Watershed at M'Bahiakro (Central-East Côte d'Ivoire)

21 ABSTRACT

22

This study evaluates the availability and management of water resources in the N'Zi watershed at M'Bahiakro, in central-east Côte d'Ivoire, under the influence of climate variability. Water resources play a crucial role in water supply, the development of irrigated rice cultivation, and the preservation of local ecosystems. The analysis is based on rainfall series (1944-2016) and hydrological data (1960-2004). Climatic breaks were identified using the Pettitt test and the Lee & Heghinian test. The methods of precipitated and runoff water depths, the recession coefficient, and the volume of water mobilized by aquifers were applied to characterize hydrological dynamics and water availability. The results show significant breaks in 1968, 1973, 1989, and 2005, associated with rainfall deficits (11.7% to 18.8%) and a notable decline in streamflow and volumes mobilized by aquifers. Monthly analysis reveals a strong correlation between precipitation and runoff, with some localized anomalies indicating a complex hydrological response. The recession coefficient highlights a progressive drying of aquifers starting from the 1970s. These changes indicate a particularly high-water vulnerability in M'Bahiakro, which could threaten the sustainability of irrigated rice cultivation, food security, and water availability. Therefore, the study has been carried out to incorporate both historical climate variations and anthropogenic factors in the analysis of water resources, with the aim of ensuring sustainable and secure management of water systems, which is essential for agricultural production and drinking water supply.

Keywords: *Climate variability, Water resources, Groundwater recharge, Hydrological fluctuations, N'Zi Watershed, M'Bahiakro, Côte d'Ivoire*

24 1. INTRODUCTION

25

26 Water resources play a central role in the socio-economic development of developing
27 countries, particularly in West Africa, where agricultural, industrial, and domestic activities
28 are heavily dependent on local hydrological systems (Bossa et al., 2020; Owusue et al.,
29 2022). However, for several decades, climate variability has been placing increasing

30 pressure on watersheds, altering the availability and distribution of water resources.
31 Numerous studies highlight that rainfall fluctuations, temperature increases, and the
32 intensification of extreme weather events are major factors disrupting regional hydrology
33 (**Obahoundje et al., 2021 ; Konaté et al., 2023**). In Côte d'Ivoire, studies on hydroclimatic
34 dynamics highlight a succession of years with rainfall deficits and a general downward trend
35 in the flow rates of the main rivers since the 1970s (**Kouassi et al., 2019a; Kouao et al.,
2024; Coulibaly et al., 2025**). Located in the central-eastern part of the country, the town of
36 M'Bahiakro is crossed by the N'Zi River, one of the main tributaries of the Bandama River.
37 This river is an essential source of water for local populations and agricultural activities. It is
38 also considered a strategic resource for the development of irrigated rice farming, supplying
39 the population, and preserving ecosystems (**Bai et al., 2019; Bai et al., 2025**). However,
40 climate variability, combined with human pressures and population growth (**Ullah et
al., 2024**), is already threatening the balance of the hydrological system. These
factors lead not only to a reduction in water availability but also to a deterioration in the
quality of water resources. Preliminary studies have been conducted by several authors
on this subject (**Goula et al., 2006; Kouassi et al., 2013; Fossou et al., 2020; Kouassi
et al., 2022**). However, these studies remain rudimentary and do not take into account
the impacts of climate variability on water resource availability in M'Bahiakro. Given the
strategic importance of this locality, which is home to Côte d'Ivoire's first inflatable dam
designed to combat food insecurity and support irrigated rice farming (**Bai et al.,
2019**), it is essential to conduct a precise assessment of water resources. Such an
assessment would not only allow for anticipating the risks associated with climate
fluctuations but also for optimizing resource management, improving agricultural planning,
and ensuring the long-term sustainability of water use. Such an assessment will make it
possible to anticipate risks, optimize resource management, and ensure the sustainability
of their uses. It is within this context that the present study is situated.

41 **2. MATERIAL AND METHODS**

42 **2.1 Material**

43 **2.1.1 Study Area**

44 The N'Zi watershed at M'Bahiakro is located between longitudes 4° and 5° West and
45 latitudes 6° and 9°27' North (Figure 1). This basin is drained exclusively by the N'Zi River,
46 which is the only major watercourse in the study area. The N'Zi rises in northern Côte
47 d'Ivoire in the Ferkessedougou region at an altitude of 400 m and flows generally in a north-
48 south direction to its outlet at M'Bahiakro. The south of the basin is characterized by a humid
49 tropical regime (Baouléan climate) with annual rainfall between 1200 and 1600 mm/year
50 (**Kouassi et al., 2022**). The main soil types are moderately desaturated ferralitic soils (North)
51 and highly desaturated ferralitic soils (Center and South) (**Kouassi et al., 2019b**).

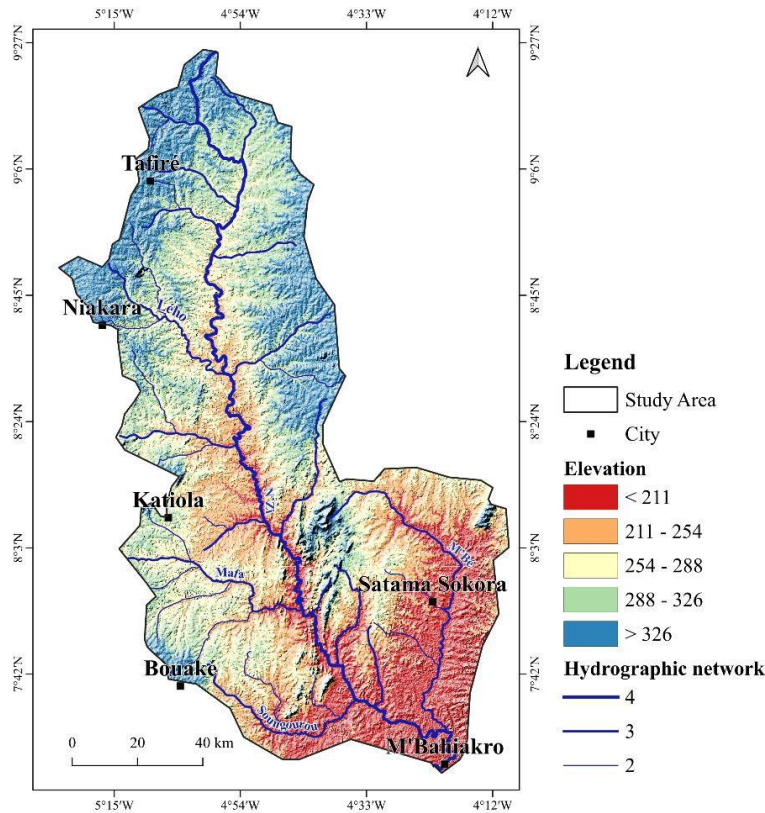


Figure 1: Presentation of the Study Area

67
68
69
70

2.1.2 Data

71 The data acquired for this study concern the daily flow rates from the M'Bahiakro station,
72 which allowed for the study of the N'Zi River's hydrological regime through the determination
73 of the runoff depth, the recession coefficient, and the volume of water mobilized by the
74 aquifers. This data covers the period from 1971 to 1998. Daily rainfall data from the stations
75 of Tafiré, Katiola, Ouéllé, Niakaramandougou, Dabakala, Bouaké, Tiébissou, Bocanda,
76 M'Bahiakro, Daoukro, Bongouanou, and Dimbokro enabled the calculation of the average
77 annual and monthly surface rainfall of the N'Zi River watershed at M'Bahiakro using the
78 Hydracess software. This data covers the period from 1971 to 2016. The climatological data
79 was provided by the management of the Société de Développement et d'Exploitation
80 Aéroportuaire, Aéronautique et Météorologique (SODEXAM). Data processing was carried
81 out using the following software: XLSTAT 2019 for statistical analyses, and Hydracess for
82 determining average rainfall over the basin.

83
84

2.2 Methods

2.2.1 Detection of Breaks in Precipitation

86 Two tests were used in conjunction: the **Pettitt test (Pettitt, 1979)** and the Bayesian method
87 of **Lee and Heghinian (1977)** over the reference period. The Pettitt test, which detects a
88 break date at most, was considered a stationarity test: "the series under study is stationary"
89 constitutes the null hypothesis of this test. If its application rejects the null hypothesis, then
90 the Bayesian method of **Lee and Heghinian (1977)**, which aims to confirm or refute the
91 hypothesis of a change in the mean of the series, is used. If several break dates in opposite

92 directions (rising and falling) or in the same direction (rising and falling) are detected in the
 93 series, then the overall trend of the means of the sub-periods corresponding to these breaks
 94 is considered.

95 **2.2.1.1 Pettitt Test**

96 The Pettitt test, described by several authors (**Pettitt, 1979; Lubes-Niels et al., 1998**), is a
 97 modified version of the Man-Whitney test. It is non-parametric and allows verification of the
 98 stationarity of the rainfall series. The Pettitt test consists of dividing the main series of N
 99 elements into two subseries at each time point (t) between 1 and N-1. The main series
 100 shows a break at time (t) if the two subseries have different distributions. The variable to be
 101 tested is the maximum absolute value of the variable U_t, N defined by equation 1:

102
$$U_t, N = \sum_i^t t = 1 \sum_j^N t + 1 \quad (\text{Éq.1})$$

103
$$D_{ij} = \text{sgn}(X_i - X_j), \text{ with } \text{sgn}(X) = 1 \text{ if } X > 0 \text{ si } X = 0 \text{ et } -1 \text{ if } X < 0$$

104 The approximate probability of exceeding a value k is defined and allows us to assess the
 105 importance of the break (equation 2):

106
$$\text{Prob}(K_N > k) \approx 2 \exp(-6k^2 / (N^3 + N^2)) \dots\dots\dots (\text{Éq.2})$$

107 The absence of a break in the series (X_i) of size N constitutes the null hypothesis. If the null
 108 hypothesis is rejected, an estimate of the break date is given by the time t defining the
 109 maximum in absolute value of the variable $U_{-}(t, N)$. The implementation of the test assumes
 110 that for any time t between 1 and N, the time series (X_i)_{i=1 to t} and t + 1 at N belong to the
 111 same population.

112
 113 **2.2.1.2 Lee and Heghinian Bayesian Test**

114 The Lee and Heghinian Bayesian method (1977) aims to confirm or refute the hypothesis of
 115 a change in the mean within a series. It is a parametric approach whose application to a
 116 series requires a normal distribution of its values. The absence of a break in the series
 117 constitutes the null hypothesis. The procedure is based on the following model:

118
$$X_i = \begin{cases} \mu + \epsilon_i & i=1, \dots, T \\ \mu + \delta + \epsilon_i & i=T+1, \dots, N \end{cases} \quad (\text{Éq.3})$$

119 where the ϵ_i are independent and normally distributed, with a mean of zero and variance σ^2 .
 120 The variables T, μ , δ , and σ are unknown parameters.

121 T represents the break date, and δ the magnitude of the change in the mean. The potential
 122 change (its position and magnitude) corresponds to the mode of the posterior distributions of
 123 T and δ . The method therefore provides the probability that the break will occur at time τ in a
 124 series where it is assumed a priori that a change will indeed occur at an undetermined time.

125 **2.2.2 Determining Rainfall and Water Deficits**

126 Determining climatic and water deficits allows us to quantify the rainfall and water deficits for
 127 a given period. This determination applies to climatic and water variables where the time
 128 series exhibits a break. Therefore, it is useful to calculate the average variations on either
 129 side of the break using the following formula (**Ardoin, 2004**):

130
$$D = \frac{X_m}{X_i} - 1 \quad (\text{Éq. 4})$$

131 Where:

132 X_m : average rainfall over the period after the breach (mm);

133 X_i : average rainfall over the period before the breach (mm).

134 If $D \geq 0$: excess rainfall or runoff for the period after the breach compared to the period
 135 before the breach.

136 If $D < 0$: deficit rainfall or runoff for the period after the breach compared to the period before
 137 the breach.

138 **2.2.3 Study of Variations in the Hydrological Regime**

139 **2.2.3.1 Calculation of Runoff Depth**

140 Runoff depths are calculated using stream flows and allow for the assessment of a basin's
 141 surface water potential. They can be daily, monthly, or annual, depending on the study's
 142 objective. The daily runoff depth at time i is calculated as follows:

143
$$Le \text{ (daily)} = \frac{Q \times 86,4}{s} \quad (\text{Éq. 5})$$

144 Avec: Le : sheet of flowing water (mm); Q : flow rate (m^3/s); S : catchment area (km^2) and 86.4:
 145 time coefficient, in seconds.

146 **2.2.3.2 Calculation of the Recession Coefficient**

147 Recession is defined as the decrease in groundwater flow into surface waters during periods
 148 without recharge, as expressed by the recession curve. In other words, it is the period during
 149 which the depletion of groundwater is the sole contribution to the flow of watercourses in a
 150 basin. The recession coefficient allows us to assess the state of water "inflows" that
 151 contribute to the apparent modification of rainfall/runoff relationships observed in river basins
 152 (Amoussou, 2012). The calculation of the recession coefficient is based on the Maillet
 153 model, which has already been used by several authors (Savané et al., 2001; Vissin, 2007;
 154 Amoussou, 2012 ; Yao et al., 2012 ; Kouassi et al., 2013). This method is based on the
 155 following equation (Savané et al., 2003):

156
$$Q = Q_0 \times e^{-kt} \quad (\text{Éq.6})$$

157 Where: Q_t : flow rate at a given time t (m^3/s); k : Maillet recession coefficient;
 158 Q_0 : initial flow rate (flow rate at the beginning of the recession) (m^3/s);
 159 t : recession time (days).

160 The expression for the drying-off period T can be formulated as follows:

161
$$T = \frac{1}{k} \quad (\text{Éq.7})$$

162  **Construction of the Reduction Curve**

163 To represent the reduction curves, we start with the highest daily flow of the year (Q_0) and
 164 plot the flow rates measured every 10 days on the x-axis until they increase significantly.
 165 The 10-day time step was chosen because this step has already yielded good results
 166 (Savané et al., 2001 ; Savané et al., 2003). The reduction curves will correspond to periods
 167 during which the flow rate decreases more or less regularly (uninfluenced regime), that is, in
 168 the absence of any precipitation (Kouassi et al., 2013).

169 **2.2.3.3 Calcul du volume d'eau mobilisée par les aquifères**

170 The volume mobilized by all the aquifers in the basin is obtained by solving the integral over
 171 the interval 0 to $+\infty$ of the following equation:

172
$$V_{\text{mobilisee}} = \int_0^{+\infty} Q_0 \times e^{-kt} dt = \frac{Q_0}{k} (1 - e^{-k\Delta t}) \quad (\text{Éq.8})$$

173 When the drainage time Δt is large, then the entire volume of water received by the aquifer
 174 drains completely, and the drained volume is expressed by the following equations:

174
$$V_{\text{mobilisé}} = \frac{Q_0}{k} = 0 \text{ car } e^{-k\Delta t'} \quad (\text{Éq.9})$$

175 With Q_0 : initial flow rate (flow rate at the start of the recession) (m^3/s);

176 K : Maillet recession coefficient (days^{-1})

177 Maillet's method makes it possible to determine, on the N'Zi watershed, the temporal evolution of
 178 the volumes of water mobilized by the aquifers and to assess the duration of drying up of the N'Zi
 179 watercourse at M'Bahiakro under the effect of climatic variations.
 180

184 **3.1 Results**

185 **3.1.1 Break Detection**

186 **3.1.1.1 Pettitt Test**

187  Rainfall Series

188 Table 1 presents the results of the Pettitt test. A classification of the significance level of this
 189 test shows that the observed breaks are highly significant at the different study stations
 190 (M'Bahiakro, Ouéllé, and Bouaké). The null hypothesis of no break is rejected at the 99%,
 191 95%, and 90% confidence levels at all study stations (M'Bahiakro, Ouéllé, and Bouaké).
 192 Analysis of the results shows that the M'Bahiakro station experienced a break in 1973 and
 193 the Bouaké station in 1989. The break at the Ouéllé station was observed in 2005.
 194
 195

Table 1: Pettitt's failure test applied to rainfall series

Stations	Study period	Year of Break	Probability of Exceedance	Level of Significance	Hypothesis of Absence
M'Bahiakro	1944 à 2016	1973	0/09%	Break Highly significant	Rejected at the confidence levels of 99%; 95% and 90%
Bouaké		1989	0.03%		
Ouéllé	1971 à 2015	2005	0.0007%		

196  **Flow series**

197 Table 2 presents the results of the Pettitt test applied to the flow series. Analysis of this table
 198 indicates the absence of a break in the pattern over the period from 1960 to 2004. Thus, the
 199 null hypothesis of no break is accepted at the 99%, 95% and 90% confidence levels.

Table 2: Pettitt's rupture test applied to flow rate series

Station	Study period	Year Break	Level of Significance	Hypothesis of Absence
M'Bahiakro	1960 à 2004	No breaks	No breaks	Accepted at the following confidence levels: 99%, 95% and 90%.

201 **3.1.1.2 Lee and Heghinian Test**

202  Rainfall Series

203 Table 3 presents the results of the Lee and Heghinian test applied to rainfall series from the
 204 different study stations over the period 1944 to 2016. According to the analysis of the test

205 results, a break in the rain series was detected at each station studied. However, with the
 206 exception of the M'Bahiakro station, where the break period is observed in 1968, the Bouaké
 207 and Ouéllé stations have break dates (2000 and 2005) almost identical to those given by the
 208 Pettitt test (1989 and 2005).

209 Table 3: Lee and Heghinian Break Test on Rainfall Series

210

Stations	Study Period	Year break	Probability
M'Bahiakro	1944-2016	1968	0.13
Bouaké		2000	0.53
Ouéllé	1971 2015	2005	0.01

211  **Flow Series**

212 Table 4 presents the results of the Lee and Heghinian test applied to the flow series from
 213 1960 to 2004. Analysis of this table indicates the presence of a break in 1968 at the study
 214 station.

215 Table 4 : Lee and Heghinian rupture test applied to flow series

216

Station	Study Period	Year break	Probability
M'Bahiakro	1960-2004	1968	0.15

217

218 **3.1.2 1.2 Rainfall and Water Deficits**

219  **Rainfall Deficits**

220 The rainfall deficit results calculated on either side of the break date at each station are
 221 recorded in Table 5. Analysis of this table shows that the rainfall deficit is higher at the
 222 M'Bahiakro station (18.78%) than at the Bouaké (17.26%) and Ouéllé (11.69%) stations.
 223 However, all stations recorded a deficit of more than 10%.
 224

225 Table 5: Rainfall Deficits

Stations	Year Break	Average before break (mm)	Stations Average after break (mm)	Deficit (%)
M'Bahiakro	1973	1163.62	945.06	18.78
Ouéllé	1970	1197.42	1057.45	11.69
Bouaké	1960	1222.59	1011.61	17.26%

226
 227

 **Water Deficit**

228 The water deficit results, calculated on either side of the break date, are recorded in Table 6.
 229 Analysis of this table indicates the presence of a break in 1973 at the study station, with a
 230 water deficit of approximately 32%. The average flow rate observed before the break (55.57
 231 m³/s) is higher than that obtained after the break (37.66 m³/s).
 232

233 Table 6: Hydrometric deficits at the M'Bahiakro station (1960-2004)

Stations	Year Break	Average before break (mm)	Stations Average after break (mm) (m ³ /s)	Deficit (%)
M'Bahiakro	1973	55.57	38.07	53.45 %

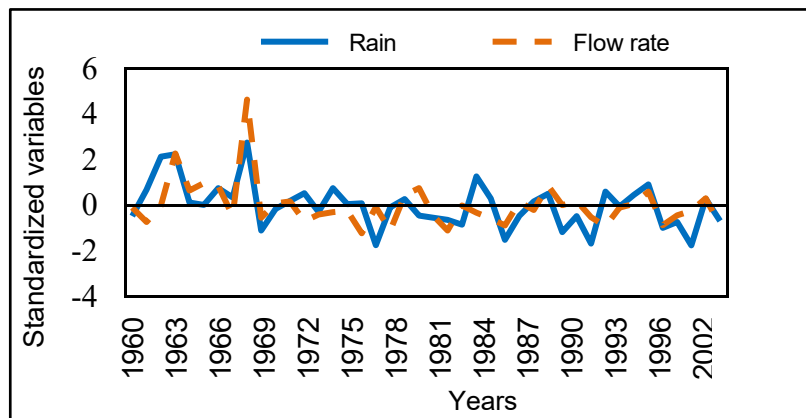
234
 235
 236

237 **3.1.3 Variations in the Hydrological Regime**

238 **3.1.3.1 Annual Evolution of Rainfall and Flows of the N’Zi River**

239 The annual evolution of rainfall, coupled with flows of the N’Zi River over the period 1960 to
 240 2004, is illustrated in Figure 2. The analysis of fluctuations in rainfall and flow rates shows a
 241 strong correlation between rainfall and flow. Indeed, the increase in flow rate observed
 242 during the period 1960 to 1972 is marked by above-average rainfall, and the decrease in
 243 flow rate during the period 1973 to 2004 is observed during a rainfall deficit.

244



245

246 Figure 2: Rainfall-runoff relationship at the M’Bahiakro station from 1960 to 2004

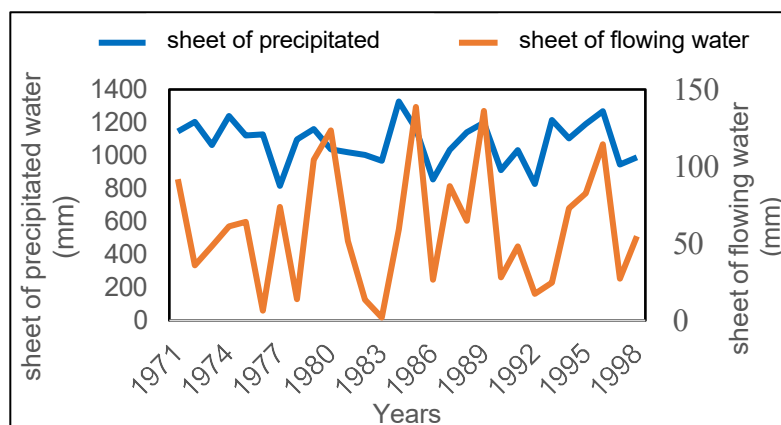
247

248

249 **3.1.3.2 Annual Evolution of Rainfall and Runoff**

250 Figure 3 shows the annual evolution of rainfall and runoff over the period 1971 to 1998. It
 251 can be seen that the runoff curve varies in the same direction as the rainfall curve over the
 252 entire study period (1971-1998). Generally, the runoff remains below the rainfall, except for
 253 the year 1985 when the runoff was above the rainfall. The lowest value of rainfall was
 254 observed in 1977 with 815.90 mm and the highest value of 132.20 mm was obtained in
 255 1984. As for the runoff, the highest value was observed in 1988 with 138.65 mm and the
 256 lowest value was 1.91 mm in 1983.

257



258

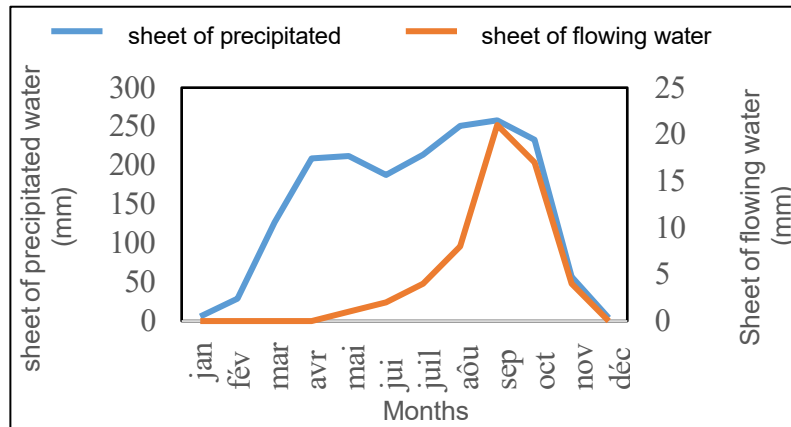
259 **Figure 3:** Annual evolution of runoff and precipitation from 1971 to 1998 M’Bahiakro

260

261 **3.1.3.3 Monthly Evolution of Rainfall and Runoff**

262 On a monthly scale, rainfall and runoff (Figure 4) fluctuate similarly, with respective values of
 263 0 and 300 mm and 0 and 25 mm over the period 1971 to 1998. However, monthly rainfall
 264 remains higher than runoff, except in November and December. September receives the
 265 maximum rainfall (258 mm) and runoff (21 mm). Conversely, November and December are
 266 characterized by a slight increase in runoff at the expense of rainfall.

267



268

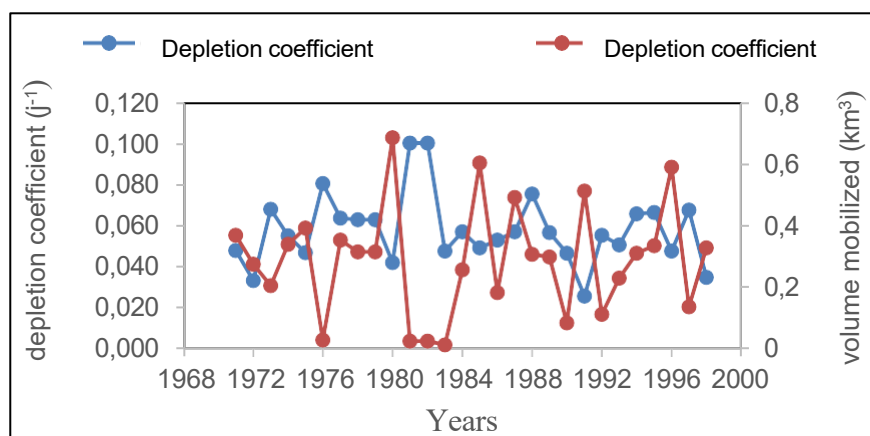
269 Figure 4: Monthly evolution of runoff and precipitation from 1971 to 1998 in M'Bahiakro

270

271 **3.1.3.4 Annual Evolution of the Reduction Coefficient and Mobilized Water Volumes**

272 Figure 5 shows the coupled evolution of the reduction-mobilized volume curves of the
 273 aquifer over the period 1971 to 1998 at M'Bahiakro (outflow). Looking at the evolution of the
 274 reduction-mobilized volume curves of the aquifer, we observe that the reduction curve varies
 275 inversely with that of the mobilized volume throughout the study period. Indeed, when the
 276 reduction coefficient increases, the mobilized volume decreases, and vice versa. The
 277 reduction coefficient, with a sawtooth pattern of annual variation, increased steadily during
 278 the 1970s and 1980s, particularly in 1976 ($8.1 \times 10^{-2} \text{ d}^{-1}$) and 1983 (10^{-1} d^{-1}). As for the
 279 average volumes mobilized by the aquifer, they vary from 0.01 km^3 to 0.69 km^3 with an
 280 average of 0.29 km^3 over the period from 1971 to 1998. However, from the years 1976 (2.9
 281 $\times 10^{-2} \text{ km}^3$), 1981 ($2.5 \times 10^{-2} \text{ km}^3$) and 1983 ($1.3 \times 10^{-2} \text{ km}^3$), the quantity of volumes
 282 mobilized by the aquifers of the study area decreases sharply to reach its minimum in 1983.
 283 This indicates that during these years 1976 and 1983, surface runoff was well supported by
 284 the groundwater.

285



286

287 Figure 5: Interannual evolution of the depletion coefficient and the volume mobilized by the
 288 aquifers at M'Bahiakro from 1971 to 1998

289

290 **3.2 Discussion**

291 **3.2.1 Detection of Breaks**

292 Analyses of rainfall and hydrological series from the M'Bahiakro, Ouéllé, and Bouaké
 293 stations using the Pettitt and Lee-Heghinian tests reveal the presence of significant climatic
 294 breaks at different periods. The Pettitt test indicates breaks in 1973 for M'Bahiakro, 1989 for
 295 Bouaké, and 2005 for Ouéllé, while the Lee-Heghinian test identifies breaks close to these
 296 dates for Bouaké (2000) and Ouéllé (2005), as well as an earlier break in 1968 for
 297 M'Bahiakro. These results confirm the existence of abrupt changes in rainfall patterns in the
 298 region, linked to the climate variability observed in West Africa since the 1970s (Goula et al.,
 299 2006 ; Kouassi et al., 2019a ; Obahoundje et al., 2021 ; Konaté et al., 2023). The breaks
 300 identified in Bouaké and Ouéllé reflect phases of rainfall reorganization and persistent
 301 interannual fluctuations over the last few decades (Kouassi et al., 2013; Kouassi et al.,
 302 2022). In M'Bahiakro, the break observed in 1968 using the Lee-Heghinian test suggests a
 303 direct impact of rainfall changes on local hydrology, while the Pettitt test places this break in
 304 1973, illustrating the sensitivity of statistical methods to different detection periods. Indeed,
 305 the Pettitt test, based on the rank of values, primarily detects abrupt changes in the mean,
 306 while the Lee-Heghinian test can identify gradual or damped breaks.

307 Regarding the N'Zi River flow series (1960–2004), the two tests reveal contrasting results.
 308 Rather than a contradiction, these discrepancies reflect the complexity of the climatic and
 309 hydrological series. In fact, the Pettitt test indicates no significant break, suggesting relative
 310 stability in the hydrological regime despite rainfall fluctuations. Conversely, the Lee-
 311 Heghinian test detects a break in 1968 at the M'Bahiakro station, which could indicate a
 312 direct impact of rainfall fluctuations on local hydrology. These results confirm the
 313 observations of several authors (Mahé & Paturel, 2009; Soro et al., 2013; Kouassi et al.,
 314 2022; Amichiatchi et al., 2023), according to whom tropical rivers often exhibit a non-linear,
 315 damped, or delayed response to rainfall disruptions. Thus, abrupt changes in rainfall
 316 patterns do not systematically translate into immediate hydrological disruptions, due to the
 317 inertia of hydrological systems, the characteristics of watersheds, and increasing
 anthropogenic pressures.

323 **3.2.2 Rainfall and Water Flow Deficits**

324 Analysis of the rainfall deficit calculated before and after the break date reveals that the
325 M'Bahiakro station is the most affected, with a deficit of 18.78%, followed by Bouaké
326 (17.26%) and Ouéllé (11.69%). These values, exceeding 10%, confirm that climate
327 variability has led to a significant reduction in rainfall in central-eastern Côte d'Ivoire. This
328 rainfall deficit reflects not only the general downward trend in rainfall since the 1970s, but
329 also the increased interannual irregularity that characterizes the West African climate
330 (Konaté et al., 2023 ; Kouakou et al., 2016).

331 From a hydrological perspective, flow analysis at M'Bahiakro indicates a break in 1973,
332 accompanied by a water flow deficit of 32%. The average flow rate before the breach (55.57
333 m³/s) is significantly higher than that observed afterward (37.66 m³/s), indicating a
334 substantial decrease in water availability. These results corroborate those of Koukou et al.
335 (2014), who emphasize that this rainfall decrease has direct repercussions on aquifer
336 recharge and water availability for agricultural and domestic uses. This decrease in flow
337 rates confirms the observations of Amichiatchi et al., 2023 and Kouassi et al. (2022), who
338 documented a progressive reduction in runoff in the basins of central-eastern Côte d'Ivoire.
339 The causes are multiple: climate variability, reduced rainfall, but also anthropogenic
340 pressures such as deforestation, the expansion of cultivated areas, and urbanization.
341

342 **3.2.3 Variations in the Hydrological Regime**

343 **3.2.3.1 Annual Evolution of Rainfall and Flows of the N'Zi River**

344 An examination of the time series of rainfall and flow rates over the period 1960–2004
345 reveals a close correlation between the two variables. The period 1960–1972, characterized
346 by above-average rainfall, corresponds to a significant increase in river flows. Conversely,
347 the period 1973–2004, marked by a rainfall deficit, is accompanied by a notable decrease in
348 flows. This direct relationship between rainfall and flow confirms the crucial role of rainfall in
349 supplying watercourses, particularly in tropical regions where rainfall constitutes the main
350 source of recharge for watersheds. These results corroborate the work of Roudier et al.
351 (2014), which showed that runoff changes are strongly linked to rainfall changes in West
352 African basins (correlation $R=0.49$). Similarly, in the Ivorian context, Kouassi et al. (2019a)
353 highlighted that streamflow losses were linked to decreased rainfall and anthropogenic
354 pressures in the Bandama basin.

355 **3.2.3.2 Annual and Monthly Evolution of Rainfall and Runoff**

356 Rainfall and runoff are two fundamental indicators of the hydrological cycle, particularly in
357 tropical regions such as West Africa, where rainfall is the main source of river water.
358 Analysis of data from 1971 to 1998 shows a strong correlation between these two variables,
359 with annual and monthly fluctuations moving in the same direction, illustrating the direct
360 relationship between rainfall and runoff in the N'Zi basin. Generally, runoff remains lower
361 than rainfall, indicating that only a fraction of precipitation contributes to runoff, the remainder
362 being absorbed through infiltration, evapotranspiration, and storage in soil and vegetation
363 (Mahé & Paturel, 2009). However, some anomalies are observed, notably in 1985, when the
364 runoff exceeded the rainfall. This hydrological paradox could be explained by changes in
365 surface conditions due to soil crust formation and land degradation leading to unsustainable
366 land use in the basin (Amogu et al., 2010). This result was also observed in the Agneby
367 watershed in Agboville (Côte d'Ivoire) by Kouakou (2016) during the period 1955 to 2012,
368 and in certain Sahelian basins of Nakanbé (Burkina Faso) and Sirba (Niger) by Descroix et
369 al. (2009). Furthermore, some authors attribute this phenomenon to soil saturation, rainfall
370 concentrated over a short period, or a hydrological shift effect (Op de Hipt et al., 2019; Kouassi et
371 al., 2019b).

372 On a monthly scale, analysis of rainfall and runoff over the period 1971–1998 shows a
373 strong correlation between the two variables, indicating that runoff is directly related to
374 rainfall. Monthly values fluctuate between 0 and 300 mm for rainfall and 0 and 25 mm for
375 runoff, respectively, illustrating the seasonal variability typical of the region. Generally,
376 rainfall exceeds runoff, reflecting losses due to infiltration, evapotranspiration, and temporary
377 storage in the soil and vegetation. September saw the highest rainfall (258 mm) and runoff
378 (21 mm), corresponding to the rainy season when the soil reaches its saturation capacity,
379 thus promoting runoff. Conversely, November and December show a slight reversal, with
380 runoff exceeding rainfall. This phenomenon can be explained by delayed runoff resulting
381 from the release of water stored in soils or upstream basins, a phenomenon frequently
382 observed in tropical basins subject to climate variability (Kouassi et al., 2019a). Furthermore,
383 from November to January, the monsoon regime is replaced by the harmattan regime. This
384 is often referred to as a weakening of the monsoon. The harmattan, being a dry air mass,
385 hot during the day and cool at night, does not generate rainfall. Consequently, during its
386 duration, the watershed experiences a significant rainfall deficit (Boko, 1992). This leads to a
387 reduction in precipitation at the expense of runoff.

388

389 **3.2.3.3 Annual Evolution of the Reduction Coefficient and Water Volumes Mobilized**

390 Analysis of the evolution of annual reduction coefficients over the period 1971-1998
391 indicates a significant variation in these coefficients during the 1970s and 1980s, particularly
392 in 1976 ($8.1 \times 10^{-2} \text{ d}^{-1}$) and 1983 (10^{-1} d^{-1}). The average value around which this coefficient
393 fluctuates is $5.2 \times 10^{-2} \text{ d}^{-1}$. This result highlights a significant depletion of groundwater
394 reserves, likely due to climate variability manifested by a decrease in rainfall and an increase
395 in temperature at M'Bahiakro. As for the average volumes mobilized by the aquifer, they vary
396 from $1 \times 10^{-2} \text{ km}^3$ to $6.9 \times 10^{-2} \text{ km}^3$, with an average of $2.9 \times 10^{-2} \text{ km}^3$ over the period from
397 1971 to 1998. However, starting in 1976 ($2.9 \times 10^{-2} \text{ km}^3$), 1981 ($2.5 \times 10^{-2} \text{ km}^3$), and 1983
398 ($1.3 \times 10^{-2} \text{ km}^3$), the volume of water mobilized by the aquifers in the study area decreased
399 sharply, reaching its minimum in 1983. This indicates that the decline in rainfall observed
400 from the 1970s onward also led to a decrease in the volume of water mobilized by the
401 aquifers that normally supply streams during periods of drought. It therefore appears that the
402 groundwater reserves in M'Bahiakro are sensitive to fluctuations in rainfall. The decrease in
403 mobilized volumes following the reduction in rainfall corroborates the observations of
404 Assémien et al. (2013) and Soro et al. (2017), who demonstrated a similar impact of climate
405 variability on the aquifers and hydrology of several Ivorian basins. These findings highlight
406 the importance of integrated groundwater resource management, particularly for securing
407 water supplies for irrigated crops and local populations in the face of climate hazards.

408

409

4. CONCLUSION

410 The study conducted on the N'Zi watershed in M'Bahiakro highlights the significant impact of
411 climate variability on the availability and dynamics of water resources. Analyses of rainfall
412 and hydrological records, supported by Pettitt and Lee & Heghinian break tests, identified
413 periods of marked climate change, with breaks observed in 1968, 1973, 1989, and 2005,
414 depending on the station studied. These breaks result in significant rainfall and hydrological
415 deficits, affecting both surface runoff and the volumes mobilized by aquifers. The observed
416 deficits, in both rainfall and runoff, confirm a trend toward reduced water resources, with
417 potential impacts on water availability, food security, and socio-economic activities. The
418 monthly analysis reveals a consistent dynamic between the two variables, while also
419 highlighting occasional anomalies that reflect the complexity of hydrological responses to
420 climate variations. This water vulnerability, which can threaten the sustainability of
421 agricultural activities and lead to water scarcity risks, is particularly pronounced in
422 M'Bahiakro

423

424 Therefore, water resource managers must integrate both historical climate variations and
425 anthropogenic factors to ensure the sustainable and secure management of water systems,
426 essential for agricultural production and drinking water supply. Such an approach will help
427 prevent the risk of scarcity, optimize water use, and support the sustainability of agricultural
428 systems and associated ecosystems.

429 However, despite the significant results obtained, this study has some limitations. Indeed,
430 the analysis relies primarily on historical rainfall and flow records, which may underestimate
431 the recent impacts of climate variability and anthropogenic pressures on the watershed.
432 Furthermore, socio-economic data on water use by the population and agriculture remain
433 limited, restricting the overall assessment of water resource management. It would be
434 beneficial to supplement this study with:

- 435 1. The integration of hydrological models (SWAT, HEC-HMS, or HBV) coupled with
436 future climate scenarios (RCP4.5, RCP8.5) or SSP models to simulate the likely
437 impact of climate change on water availability.
- 438 2. A detailed assessment of soil and water quality to better plan irrigated rice cultivation
439 and ensure agricultural sustainability.
- 440 3. Consideration of human uses, particularly agricultural practices and urbanization, to
441 propose sustainable management strategies adapted to the local context.
- 442 4. Expanding the study to other neighboring watersheds to establish regional
443 comparisons and identify general trends.

455 **DISCLAIMER (ARTIFICIAL INTELLIGENCE):**

456 Author(s) hereby declare that NO generative AI technologies such as Large Language Models
457 (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of
458 this manuscript.

459 **COMPETING INTERESTS**

460 Authors have declared that no competing interests exist.

461 **FUNDING**

462 No funding was received for conducting this study

463 **AUTHORS' CONTRIBUTIONS**

464 All authors contributed to the design and development of the study. Material preparation, data
465 collection, and analysis were carried out by Santé Natacha, Aké Gabriel Etienne, and Ruth Baï.
466 The first draft of the manuscript was written by Ruth Baï and the authors, including Séraphin K.
467 Konan; Lazare Kouakou Kouassi and Innocent Kouassi Kouamé provided feedback on previous
468 versions of the manuscript. All authors read and approved the final version of the manuscript.

469 **REFERENCES**

- 470 **Amichiatchi, N. J. M. C., Soro, G. E., Hounkpè, J., Goula Bi, T. A., & Lawin, A. E.**
471 **(2023).** Evaluation of Potential Changes in Extreme Discharges over Some Watersheds in
472 Côte d'Ivoire. *Hydrology*, 10(1), 6. <https://doi.org/10.3390/hydrology10010006>
- 473 **Amogu O., Descroix L., Yéro K.S, Le Breton E., Mamadou I., Ali A., Belleudy P (2010).**
474 Increased river flows in the Sahel? *Water*, 2 :170-199.
- 475 **Amoussou E, Camberlin P, Mahé G (2012).** Impact of climate variability and the Nangbéto dam
476 on the hydrology of the Mono-Couffo system (West Africa). *Hydrological Sciences Journal*, 57(4),
477 805–817. <https://doi.org/10.1080/02626667.2011.643799> (in French)
- 478
479 **Ardoin, B. S. (2004).** Variabilité hydroclimatique et impacts sur les ressources en eau de grands

- 480 bassins hydrographiques en zone soudano-sahélienne. *Université de Montpellier II (France),*
481 *Montpellier*, 441. <https://theses.hal.science/tel-00568025/>
- 482 **Assemian, E. A., Kouame, F. K., Djagoua, É. V., Affian, K., Jourda, J., Adja, M., Lasm, T. &**
483 **Biemi, J. (2013).** Étude de l'impact des variabilités climatiques sur les ressources hydriques d'un
484 milieu tropical humide : cas du département de Bongouanou (Est de la Côte d'Ivoire). *Revue des*
485 *sciences de l'eau / Journal of Water Science*, 26(3), 247–261. <https://doi.org/10.7202/1018789ar>
486
- 487 **Baï, R., Konan, S.K., N'Cho, H.A., Oga, M.S., Kouassi, L.K. and Kouame, I.K. (2025)**
488 **Microbiological Characterization of Irrigation Water and Risk Assessment for Rice**
489 **Production: Application of the Biological Quality Index (IBQ6) in the M'Bahiakro Irrigated**
490 **Agricultural Perimeter (Central-Eastern Côte d'Ivoire). Open Journal of Modern**
491 **Hydrology**, 15, 294-307. <https://doi.org/10.4236/ojmh.2025.154018>
- 492 **Baï, R., Kouame, I.K., Kouassi, L.K., Konan, S.K. and N'Cho, H.A. (2019)** C. Assessment of the
493 Physicochemical Quality of Irrigation Water and Soil for Sustainable Irrigated Rice Cultivation: Case
494 of Irrigated Perimeter of M'Bahiakro (Central-East of Côte d'Ivoire). *Journal of Environmental*
495 *Protection*, 10, 1536-1552. <https://doi.org/10.4236/jep.2019.1011091>
- 496 **Boko, M. (1992).** Saisons et types de temps au Bénin : analyse objective et perceptions populaires.
497 *Espace Géographique*, 21(4), 321-332
- 498 **Bossa, A. Y., Hounkpè, J., Yira, Y., Serpantié, G., Lidon, B., Fusillier, J. L., Sintondji, L. O.,**
499 **Tondoh, J. E., & Diekrüger, B. (2020).** Managing New Risks of and Opportunities for the
500 Agricultural Development of West-African Floodplains: Hydroclimatic Conditions and Implications
501 for Rice Production. *Climate*, 8(1), 11. <https://doi.org/10.3390/cli8010011>
- 502 **Coulibaly, L., Ouattara, I., Yao, K. A. F., Ouedraogo, M., Diallo, S., Dao, A., Soro, G. E., &**
503 **Kamagate, B. (2025).** Rainfall variability in Western Côte d'Ivoire: A case study of the Mountain
504 District (1961–2020). *American Journal of Water Resources*, 13(4), 121–128.
505 <https://doi.org/10.12691/ajwr-13-4-1>
- 506 **Descroix L., Mahé G., Lebel T., Favreau G., Galle S., Gautier E., Olivry J. C., Albergel J.,**
507 **Amogu O., Cappelaere B., Dessouassi R., Diedhiou A., Le Breton E., Mamadou I &**
508 **Sighomnou D (2009).** Spatio-Temporal variability of hydrological regimes around the boundaries
509 between Sahelian and Sudanian areas of West Africa: a synthesis. *Journal of Hydrology*, 375 (1-2):
510 90-102.
- 511 **Fossou N. M-R., Soro T. D., Soro G., Orou K. R., Goné D. L (2020).** Modélisation de la Relation
512 Pluie-Débit dans un Contexte de Gestion en Eau : Cas du Sous Bassin Versant du N'Zi en Côte
513 d'Ivoire. *Europe. Science. Journal*, 16 (21) : 62-88.
- 514 **Goula BTA., Savané I., Konan B., Fadika V. et Gnamien K. B (2006).** Impact de la variabilité
515 climatique sur les ressources hydriques des bassins de N'Zo et N'Zi en Côte d'Ivoire (Afrique
516 tropicale humide). *Vertigo*, 7 (1) :1-12
- 517 **Konate, D., Didi, S. R., Dje, K. B., Diedhiou, A., Kouassi, K. L., Kamagate, B., Paturel, J.-E.,**
518 **Coulibaly, H. S. J.-P., Kouadio, C. A. K., & Coulibaly, T. J. H. (2023).** Observed Changes in
519 Rainfall and Characteristics of Extreme Events in Côte d'Ivoire (West Africa). *Hydrology*, 10(5), 104.
520 <https://doi.org/10.3390/hydrology10050104>
- 521 **Kouakou, A. B. P., Lawin, E. A., Kamagaté, B., Dao, A., Savané, I., & Srohourou, B. (2016).**
522 **Rainfall Variability across the Agneby Watershed at the Agboville Outlet in Côte d'Ivoire, West**
523 **Africa.** *Hydrology*, 3(4), 43. <https://doi.org/10.3390/hydrology3040043>
- 524 **Kouakou, E., Koné, B., N'Go, A., Cissé, G., Ifejika Speranza, C., & Savané, I. (2014).** Ground
525 water sensitivity to climate variability in the White Bandama basin, Ivory Coast. *SpringerPlus*, 3,
526 226. <https://doi.org/10.1186/2193-1801-3-226>
- 527 **Kouassi, A., Nassa, R.-K., Kouakou, K., Kouame, K. & Biemi, J. (2019a).** Analysis of the impacts
528 Of climate change on hydrological standards in West Africa: Case of Abidjan District (South of Ivory
529 Coast). *Revue des Sciences de l'Eau / Journal of Water Science*, 32(3), 207–220.
530 <https://doi.org/10.7202/1067305ar>

- 531 **Kouassi, A. M., Assoko, A. V. S., Kouakou, K. E., & Biémi, J. (2019b).** *Analyse des impacts des*
532 *changements climatiques sur les normes hydrologiques en Afrique de l'Ouest : cas du district*
533 *d'Abidjan (sud de la Côte d'Ivoire). Revue des Sciences de l'Eau / Journal of Water Science, 32(3),*
534 257-272. <https://www.erudit.org/fr/revues/rseau/2019-v32-n3-rseau05058/1067305ar/>
- 535 **Kouassi, A. M., Kouamé, K. F., Saley, M. B., & Biémi, J. (2013).** Application du modèle de
536 Maillet à l'étude des impacts des changements climatiques sur les ressources en eau en Afrique
537 de l'Ouest : Cas du bassin versant du N'Zi-Bandama (Côte d'Ivoire). *Journal of Asian Scientific*
538 *Research, 3 (2), 214-228.*
- 539 **Kouassi, J.-L., Wandan, N., & Mbow, C. (2022).** Observed climate trends, perceived impacts and
540 community adaptation practices in Côte d'Ivoire. *Environmental & Socio-economic Studies, 10(3),*
541 43–58. <https://doi.org/10.2478/environ-2022-0016>
- 542 **Kouao, J.-M., Tagnon, B. O., Koffi, B., Kouassi, A. M., Kouassi, K. A., & Gone, D. L. (2024).**
543 Variabilité et tendances interannuelles du climat à l'échelle de la Côte d'Ivoire sur la période 1961-
544 2016. *European Scientific Journal, ESJ, 20(33), 218.* <https://doi.org/10.19044/esj.2024.v20n33p218>
- 545 **Lee, A. F. S., & Heghinian, S. M. A. (1977).** Shift of the mean level in a sequence of independent
546 normal random variables: A Bayesian approach. *Technometrics, 19 (4), 503–506.*
- 547 **Lubes-Niel, H., Masson, J. M., Paturel, J. E. & Servat, E. (1998).** Variabilité climatique et
548 statistiques. Etude par simulation de la puissance et de la robustesse de quelques tests utilisés
549 pour vérifier l'homogénéité de chroniques. *Revue des sciences de l'eau / Journal of Water Science,*
550 *11(3), 383–408.* <https://doi.org/10.7202/705313ar>
- 551 **Mahé, G., & Paturel, J.-E. (2009).** 1896–2006 Sahelian annual rainfall variability and runoff
552 increase of Sahelian Rivers. *Comptes Rendus. Géoscience, 341(7), 538-546.*
553 <https://doi.org/10.1016/j.crte.2009.05.002>
- 554 **Obahoundje, S., Amoussou, E., Youan Ta, M., Kouassi, L. K., and Diedhiou, A (2021).**
555 Multiyear rainfall variability in the Mono river basin and its impacts on Nangbeto hydropower
556 scheme, *Proc. IAHS, 384, 343–347.* <https://doi.org/10.5194/piahs-384-343-2021>.
- 557 **Op de Hipt, F., Diekkrüger, B., Steup, G., Yira, Y., Hoffmann, T., Rode, M., & Näschen, K.**
558 **(2019).** Modeling the effect of land use and climate change on water resources and soil erosion in
559 a tropical West African catchment (Dano, Burkina Faso) using SHETRAN. *Science of The Total*
560 *Environment, 660, 1234–1250.* <https://doi.org/10.1016/j.scitotenv.2018.10.351>
- 561 **Owusu, S., Cofie, O., Mul, M., & Barron, J. (2022).** The Significance of Small Reservoirs in
562 Sustaining Agricultural Landscapes in Dry Areas of West Africa: A Review. *Water, 14(9), 1440.*
563 <https://doi.org/10.3390/w14091440>
- 564
565 **Pettitt, A. N. (1979).** A non-parametric approach to the change-point problem. *Journal of Applied*
566 *Statistics, 28(2), 126–135.*
- 567 **Roudier, P., Ducharne, A., & Feyen, L. (2014).** Climate change impacts on runoff in West Africa:
568 A review. *Hydrology and Earth System Sciences, 18, 2789–2801.* <https://doi.org/10.5194/hess-18-2789-2014>
- 569 **Savané I., Coulibaly K. M & Gioan P (2001).** Climate variability and groundwater resources in the
570 semi-mountainous region of Man. (In French). *Sécheresse, 12 (4): 231-237.*
- 571 **Savané I., Coulibaly K. M. et Gioan P (2003).** Etude comparative de trois méthodes de calcul du
572 coefficient de tarissement des cours d'eau. *Sécheresse, 14 (1) : 37-42.*
- 573 **Soro, T. D., Kouakou, B. D., Kouassi, E. A., Soro, G., Kouadio, E., Yéi, M.-S. O., & Soro, N.**
574 **(2013).** Hydroclimatologie et dynamique de l'occupation du sol du bassin versant du Haut
575 Bandama à Tortiya (Nord de la Côte d'Ivoire). *Vertigo – la revue électronique en sciences de*
576 *l'environnement, 13-3.* <https://doi.org/10.4000/vertigo.14468>
- 577 **Soro, G. E., Yao, A. B., Kouamé, Y. M., & Bi, T. A. G. (2017).** Climate change and its impacts on
578 water resources in the Bandama Basin, Côte D'ivoire. *Hydrology, 4(1), 18.*
<https://doi.org/10.3390/hydrology4010018>.

579 **Ullah, A., Khan, K., Bibi, N., & Ahmad, S. (2024).** The impacts of land use change on partridge's
580 population in the Marghazar valley of Swat District, Pakistan. *Ornis Hungarica*, 32(1), 16–30.
581 <https://doi.org/10.2478/orhu-2024-0002>

582 **Yao, B., Goula, B. T. A., Kouadio, Z. A., Kouakou, K. E., Kane, S., & Sambou, S. (2012).**
583 Analyse de la variabilité climatique et quantification des ressources en eau en zone tropicale
584 humide : Cas du bassin versant de la Lobo au Centre-Ouest de la Côte-d'Ivoire. *Revue Ivoirienne*
585 des Sciences et Technologie, 19, 136-157.

