Atmospheric and Climate Sciences, 2026, 16(1), 41-70
https://www.scirp.org/journal/acs
ISSN Online: 2160-0422
ISSN Print: 2160-0414

Evaluation of Climatic Variables and Water Requirements of Rice Cultivation, and Their Influence on Irrigation Water Availability Using the CROPWAT 8.0 Model: Case Study of the M'Bahiakro Irrigated Perimeter (Central-Eastern Côte d'Ivoire)

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How to cite this paper: Baï, R., Sante, N., Anouman, D.G.-L., N'Cho, A.H., Konan, K.S., Kouassi, K.L. and Kouame, K.I. (2026) Evaluation of Climatic Variables and Water Requirements of Rice Cultivation, and Their Influence on Irrigation Water Availability Using the CROPWAT 8.0 Model: Case Study of the M'Bahiakro Irrigated Perimeter (Central-Eastern Côte d'Ivoire). *Atmospheric and Climate Sciences*, **16**, 41-70.
https://doi.org/10.4236/acs.2026.161004

Received: November 1, 2025
Accepted: December 2, 2025
Published: December 5, 2025

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Abstract

This study analyzes the impact of climate variability on irrigation water requirements for rice cultivation in M'Bahiakro, located in the Central-Eastern region of Côte d'Ivoire. The dataset includes rainfall (1944-2016), annual temperature records (1964-2015), and flow data from the N'Zi River (1960-2004). The analyses were conducted using the Nicholson rainfall index, the Hanning filter for seasonal smoothing, as well as the Pettitt and Lee & Heghinian tests for the detection of structural breaks, defined as abrupt changes in the statistical properties of a time series such as the mean, variance, or trend. The results indicate that some preliminary signals suggest the onset of a shift as early as 1968, whereas the Pettitt test identifies 1973 as the most statistically significant breakpoint. Consequently, 1973 was selected as the main reference for delineating the climatic periods. Three phases were thus defined: a wet period (1944-1972), a transition phase (1973-1996), and a dry period (1997-2016). The mean annual temperature increased by approximately 0.5˚C, confirming a progressive warming trend. From a hydrological perspective, the mean discharge of the N'Zi River decreased by nearly 47%, from 55.57 m^3/s (1960-1972) to 29.63 m^3/s (1973-2004), highlighting the strong sensitivity of the basin to climate variability. Furthermore, irrigation water requirements for rice increased by about 22% between 2009 and 2016 as a result of rising temperatures and increasing irregularity in rainfall patterns. Overall, these findings underscore the growing vulnerability of the irrigated perimeter to climate variability and emphasize the need for integrated water management, improved irrigation efficiency, and the adoption of sustainable adaptation practices.

Keywords

Climate Variability, Irrigated Rice Cultivation, Water Requirements, CROPWAT, M'Bahiakro, Côte d'Ivoire

1. Introduction

Irrigation plays a fundamental role in agricultural development, particularly for water-demanding crops such as rice. It remains a key strategy in addressing food insecurity, as irrigated agriculture accounts for approximately 40% of global crop production and generally achieves yields twice as high as those of rainfed systems [1] [2]. However, despite its effectiveness, this intensive agricultural model is increasingly challenged by the impacts of climate change, which threaten the availability and sustainable management of irrigation water.

Rising temperatures, as a major climatic driver, act as a catalyst for hydrological imbalances by intensifying water losses through evapotranspiration. Consequently, the water requirements of rice cultivation increase, particularly during critical growth stages such as flowering. These climatic stresses directly affect irrigation water availability—estimated globally at 1277 km^3 per year [3]—which is essential for maintaining stable yields. According to [4] and [5], the global growth rate of rice yields has declined to below 1% per year over the past decade, primarily due to the decreasing availability of irrigation water. Meeting the increasing global food demand would require an annual growth of over 1.2% in irrigated rice production. This situation calls for urgent adaptation of agricultural practices and water management policies to ensure the long-term sustainability of production systems under changing climatic conditions.

In Africa, where rapid population growth and a steadily rising food demand prevail, irrigation emerges as an indispensable solution for enhancing rice production. Nevertheless, the expansion of irrigated agriculture faces several challenges, including the progressive depletion of water resources available for agriculture. This issue is further exacerbated by climate variability and the effects of climate change, which disrupt hydrological regimes and compromise water availability [6]. [7] projected that climate change in West Africa could reduce agricultural yields by 10% - 20% by 2050 due to increased drought frequency and rainfall irregularity. These climatic disruptions directly undermine the performance of irrigated systems, emphasizing the need to adapt agricultural practices and water management strategies to safeguard food security in an increasingly uncertain climate context.

In Côte d'Ivoire, substantial progress has been achieved in the rice sector over the past decade. In 2025, national milled rice production is estimated at approximately 1.8 million tonnes, compared with an annual demand of about 2.1 million tonnes [8]. This progress reflects sustained investment in irrigation development, particularly through the construction of dams across several regions. One notable example is the irrigated perimeter of M'Bahiakro, located in the Centre-East region, which covers 450 hectares of irrigable land supplied by the N'Zi River. Established as part of national food security policies, this scheme supports annual production exceeding 2000 tons of irrigated rice [2]. These infrastructures have contributed to improved yields and expanded cultivated areas, thereby strengthening national production capacity. Despite these achievements, the country continues to face a structural deficit, necessitating substantial rice imports to meet domestic consumption. This persistent gap is partly attributed to climatic constraints, particularly increased rainfall variability and rising temperatures, which directly affect agricultural systems. In irrigated areas, water availability and management have thus become critical issues for ensuring food security. However, despite the strategic importance of rice cultivation in this region and across Côte d'Ivoire, research focusing on climatic variables and the specific water requirements of this crop remains limited. This knowledge gap is particularly concerning given the increasing risks associated with irrigation water scarcity in a context of intensified climate variability and mounting pressure on water resources. The lack of reliable, site-specific data hampers the development of effective adaptation strategies that could ensure the sustainability of rice production under changing climatic conditions.

The objective of this study is therefore to analyze the influence of climatic variables on the water requirements of rice cultivation and to assess their impact on irrigation water availability using the CROPWAT 8.0 model. CROPWAT is widely recognized for its user-friendliness, low data input requirements, and broad applicability in estimating crop water requirements, net irrigation needs, and irrigation scheduling [9] [10]. Numerous studies have successfully employed CROPWAT to evaluate the potential impacts of climate change on water and irrigation requirements [11]-[17], demonstrating its reliability and robustness for agricultural water management research.

2. Methodology

2.1. Study Area Description

The study area is located approximately 6 km northeast of the town of M'Bahiakro, in the Centre-East region of Côte d'Ivoire. It covers an irrigated perimeter of 450 hectares (**Figure 1**). Geographically, the area extends between longitudes 335,000 and 365,000 W and latitudes 815,000 and 842,500 N [2]. The rice-growing perimeter hosts the first inflatable dam in Côte d'Ivoire; a landmark infrastructure developed as part of the country's food security policies. The study area is influenced by a transitional equatorial climate characterized by four distinct seasons: a major rainy season from March to June, followed by a short dry season between July and August. The minor rainy season occurs from September to early November [2]. Monthly rainfall varies between 0 and 160 mm, with an average annual precipitation of about 1000 mm [18]. The mean annual temperature ranges from 25.6˚C to 29.1˚C. The main economic activity of the local population is agriculture.

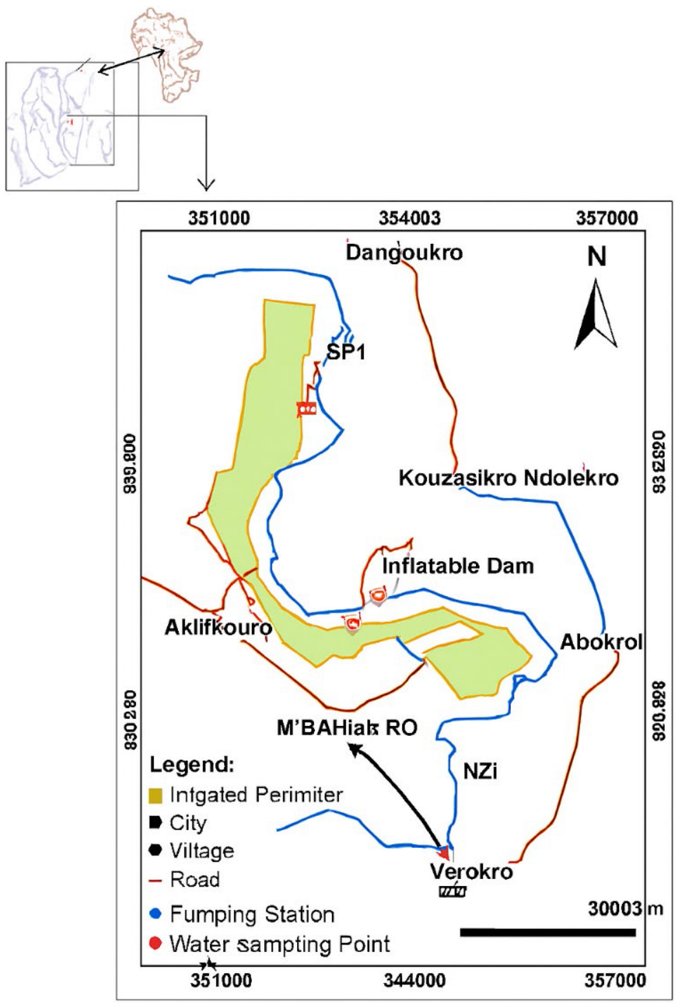

Figure 1. Presentation of the study area [2].

2.2. Description of the Irrigated Perimeter

The M'Bahiakro irrigated rice perimeter extends over a length of approximately 9 km and a width ranging from 300 to 1000 m. It is divided into two sectors (P1 and P2). Pumping station 1 (SP1) supplies water to sector 1, while pumping station 2 (SP2) serves sector 2. The irrigation system is gravity-based, using open channels and two water towers that help overcome the constraints associated with rainfed rice production (**Figure 2**). The basic irrigation unit of the perimeter is the plot, known as a “casier.” Each casier generally measures 100 × 30 m^2, corresponding to an area of 0.30 hectares. The casiers are grouped into hydraulic units, each covering no more than 12 hectares. These hydraulic units are further organized into 12 zones or blocks, six (06) per sector [19].

Figure 2. Intake structures for water supply at the level of the irrigated area of M’Bahiakro: (A) Concrete canal; (B) Earth canal.

2.3. Operation of the Irrigated Perimeter

The irrigation network of the M’Bahiakro perimeter is based on an open-channel system, supplied on a demand-driven basis from upstream. Two pumping stations (SP1 and SP2) deliver water to sectors 1 and 2 through collective discharge pipelines [19]. The water is then distributed via PVC conduits to the main canals, and subsequently conveyed to secondary and tertiary canals and plots through intake structures (**Figure 3**).

Figure 3. First water pumping station in the irrigated area of M’Bahiakro [19].

During the high-water period (August to November), the entire network is fully supplied. Two regulating reservoirs (R1 and R2), installed as bypasses on the discharge lines, are used to manage excess water or interruptions (**Figure 4**). When the supply valves are closed, the pumped water is stored in the reservoirs. Level sensors trigger the gradual shutdown of the pumps through an automated control system. When the valves are opened, the drop in water level activates the pumps again, either automatically or manually, according to demand. The water used for irrigation is sourced from the N'Zi River.

Figure 4. M'Bahiakro rice-growing perimeter regulation reservoir.

2.4. Data Collection

2.4.1. Hydroclimatic Data

The climatic data required for this study were provided by the SODEXAM (Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique). These include rainfall records (1944-2016) and temperature data covering the period from 1964 to 2015. Daily, monthly, and annual streamflow data were obtained from the Hydrology Department and concern the discharge of the N'Zi River at M'Bahiakro. Considering data availability, the study period used extends from 1960 to 2004.

2.4.2. Data on Irrigation Water Requirements for Rice Cultivation

The data used include temperature and decadal potential evapotranspiration (PET) values from the Dimbokro synoptic station, covering the period 1984 to 2016. These data are regular and homogeneous. The choice of this station is justified by its geographical proximity to the M'Bahiakro study area and by the similarity of climatic conditions between the two locations. According to [20], synoptic stations belonging to the same climatic zone can be considered representative of neighboring locations, particularly when thermal and hydrometeorological regimes are comparable. Thus, the Dimbokro station adequately reflects the climatic regime of M'Bahiakro, which guarantees the validity of the data used in the model and the robustness of the results obtained. Regarding agronomic parameters, they include crop coefficients (Kc) and maximum rooting depths for the different crops. These parameters were obtained from FAO Irrigation and Drainage Papers No. 24 and 56 [20]-[22]. Data processing for determining irrigation water requirements for rice cultivation was carried out using the CROPWAT 8.0 software.

2.5. Methods

2.5.1. Determination of the Evolution of Climatic and Hydrometric Variables

The evolution of climatic and hydrometric variables was analyzed using several calculation methods, including the Nicholson Index, the second-order Hanning low-pass filter, rupture (change-point) tests (Pettitt, Bayesian Lee, and Heghinian), and the determination of climatic and hydrometric deficits. All these methods make it possible to highlight periods of deficit and excess in precipitation, temperature, and streamflow at spatio-temporal scales.

1) Nicholson Index Method

The Nicholson Index method [23] is used to highlight rainfall, temperature, and streamflow trends (excess and deficit periods) within a time series. A positive value indicates a wet year, while a negative value indicates a dry year. The Nicholson index is expressed by the following equation:

$$I_i = \frac{X_i - \overline{X}}{\delta} \quad (1)$$

where:

- I_i = Nicholson index for year *i*;
- X_i = observed value of the variable (rainfall, temperature, or discharge) for year *i*;
- $\overline{X}$ = mean of the series;
- δ = standard deviation of the series.

2) Second-Order Hanning Low-Pass Filter Method

The second-order Hanning low-pass filter method helps to better distinguish deficit and excess periods in rainfall or streamflow series. Its principle is to smooth out small fluctuations in a time series to highlight long-term variations. In this case, the totals of annual rainfall or streamflow series are weighted using the following equations [24]:

$$X_t = 0.06X_{t-2} + 0.25X_{t-1} + 0.38X_t + 0.25X_{t+1} + 0.06X_{t+2} \quad (2)$$

$$\text{Pour} \quad 3 \le t \le n-2$$

where:

X_t: weighted total of rainfall or streamflow series at term *t*;

X_{t-2} and X_{t-1}: observed totals of rainfall or streamflow series for the two terms immediately preceding term *t*;

X_{t+1} and X_{t+2}: observed totals of rainfall or streamflow series for the two terms immediately following term *t*.

The weighted totals of the first two ([X_1, X_2]) and the last two ([X_{n-1}, X_n]) terms of the series are calculated using the following expressions (where *n* is the length of the series):

$$X_1 = 0.54X_1 + 0.46X_2 \quad (3)$$

$$X_2 = 0.25X_1 + 0.50X_2 + 0.25X_3 \quad (4)$$

$$X_{n-1} = 0.25X_{n-2} + 0.50X_{n-1} + 0.25X_n \quad (5)$$

$$X_n = 0.54X_n + 0.46X_{n-1} \quad (6)$$

To better visualize the deficit and excess periods in rainfall or streamflow series, the moving averages were centered and standardized using the following formula [24]:

$$Y_t' = \frac{X_t - m}{\delta} \quad (7)$$

where:

- *m*: mean of the weighted moving average series.
- δ: standard deviation of the weighted moving average series.
- Wet period: when the annual mean of rainfall or streamflow exceeds the mean observed over the reference period.
- Normal period: when the annual mean is close to the mean of the observation period.
- Dry period: when the annual mean of rainfall or streamflow is lower than that of the reference period.

3) Change Point Detection

Pettitt Test

The Pettitt test, described by several authors [25] [26], is a modified version of the Mann-Whitney test. It is a non-parametric test used to verify the stationarity of a rainfall series. The Pettitt test consists of dividing the main series of *N* elements into two sub-series at each instant (*t*) between 1 and *N* − 1. The main series exhibits a change point at time (*t*) if the two sub-series have significantly different distributions. The test variable is the maximum absolute value of the statistic $U_{t,N}$, defined by Equation (8):

$$U_{t,N} = \sum_i^t = 1 \sum_j^N t + 1 \quad (8)$$

where $D_{ij} = \text{sgn}\left(X_i - X_j\right)$, with sgn(*X*) = 1 if *X* > 0, 0 if *X* = 0, and −1 if *X* < 0.

The approximate exceedance probability of a given value k is defined and used to evaluate the significance of the change point (Equation (9)):

$$\text{Prob}\left(K_N > k\right) \approx 2\exp\left(-6k^2 / \left(N^3 + N^2\right)\right) \quad (9)$$

The absence of a change point in the series (X_i) of size *N* constitutes the null hypothesis. If the null hypothesis is rejected, the estimated date of the change point corresponds to the time *t* at which the statistic $U_{t,N}$ reaches its maximum absolute value. The application of the test assumes that, for any time t between 1 and *N*, the time series $(X_i)_{i=1 \text{ to } t \text{ and } t+1 \text{ to } N}$ belong to the same population.

Bayesian Lee and Heghinian Test

The Bayesian method of Lee and Heghinian [27] aims to confirm or refute the hypothesis of a mean shift within the series. It is a parametric approach that requires the data series to follow a normal distribution. The absence of a change point in the series constitutes the null hypothesis. The procedure is based on the following model:

$$X_i = \begin{cases} \mu + \varepsilon_i & i = 1, \cdots, T \\ \mu + \delta + \varepsilon_i & i = T+1, \cdots, N \end{cases} \quad (10)$$

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

T represents the change point (break date), and δ represents the magnitude of the shift in the mean.

The potential change (its position and magnitude) corresponds to the mode of the posterior distributions of T and δ.

This method, therefore, provides the probability that the change occurs at time τ in a series where it is assumed *a priori* that a change indeed occurs at some unknown point.

Determination of Hydrometric Deficits

The determination of hydrometric deficits makes it possible to quantify the hydrometric shortfall over a given period. This method is applied to hydrometric variables whose time series exhibits a change point. It is therefore useful to calculate the mean variations on either side of the change point using the following formula [28]:

$$D = \frac{X_m}{X_i} - 1 \quad (11)$$

where:

- X_m: mean value for the period after the change point (mm);
- X_i: mean value for the period before the change point (mm).

If $D \geq 0$: rainfall or streamflow surplus during the period after the change point compared to the period before the change point.

4) Determination of the Monthly Flow Coefficient (MFC)

The Monthly Flow Coefficient (MFC) is defined as the ratio of the mean monthly discharge to the mean discharge (module) over the considered period. The MFC helps identify the periods of high and low flows. Specifically, when the MFC is greater than or equal to 1, it indicates a high-flow period, whereas when it is less than 1, it corresponds to a low-flow period. The formula for calculating the Monthly Flow Coefficient is given by the following equation:

$$\text{MFC} = \frac{Q}{Q_m} \quad (12)$$

where:

- MFC: Monthly Flow Coefficient (dimensionless);
- Q: discharge (m^3/s);
- Q_m: mean discharge (m^3/s).

2.5.2. Calculation of Irrigation Water Requirements for Rice Cultivation

These correspond to the volume of water that must be supplied through irrigation in addition to rainfall. According to [29], water requirements include the water needed for plant growth, soil preparation, and the filling and puddling of rice fields, and are calculated using the following formula:

$$\text{Bi} = \text{Bp} + \text{Bs} + \text{Brb} \tag{13}$$

where:

- Bi: irrigation water requirements (mm);
- Bp: crop water requirements;
- Bs: water needed for soil preparation;
- Brb: water needed for field filling and puddling.

In cases where all the water required for optimal crop growth is supplied by rainfall, irrigation is not necessary [29]:

$$\text{Bi} = 0 \tag{14}$$

- Bi: irrigation water requirements (mm).

In cases where there is no rainfall during the growing season, all the water must be supplied through irrigation [29]:

$$\text{Bi} = \text{Bc} \tag{15}$$

Bi: irrigation water requirement (mm); Bc: crop water requirement (mm).

In most cases, part of the crop water requirement is supplied by rainfall, and the remainder by irrigation [29]:

$$\text{Bi} = \text{Bc} - \text{Pe} \tag{16}$$

where:

- Bi: irrigation water requirement (mm);
- Pe: effective rainfall (mm);
- Bc: crop water requirement (rice cultivation) (mm).

1) Calculation of Water Requirements for Field Ponding and Puddling (Brb)

Table 1. Water depth in rice fields according to the growth stage and development of rice [30].

Crop Stage	Land Preparation		Transplanting		Tillering	Panicle Initiation	Heading	Maturity
Water Depth (mm)	100	100	30	30	100	100	150	0
Days	−25	−4	0	15	20	50	60	100

It refers to the amount of water, or water layer, required to submerge the rice plots. This submersion is carried out intermittently, depending on the different growth stages of the rice plant. In addition to soil saturation, a certain quantity of water is needed to perform puddling and establish the appropriate water depth.

Once this water layer has been established, it must be maintained at a level consistent with the crop's requirements. Reference values have been established to account for all these parameters (**Table 1**).

2) Calculation of Water Requirements for Land Preparation

These correspond to the volume of water needed to saturate the soil before the start of irrigation. The objective is to moisten an initially dry soil up to its field capacity (Hcr), starting from the wilting point (Hpf) or the hygroscopic point. This amount of water is equivalent to the available water capacity (AWC), also known as the wetting dose. The amount of water required for land preparation depends on several factors, including soil texture, porosity, initial moisture condition, groundwater depth, and the thickness of the layer to be saturated, which is generally less than 50 cm and often limited to 25 - 30 cm (De Datta and Barker, 1978, cited by [31]). It is calculated using the following formula [32]:

$$\mathrm{RU} = \mathrm{Zr} \times (\mathrm{Hcr} - \mathrm{Hpf}) \times \mathrm{Da} \tag{17}$$

where:

RU: available water capacity (mm);

Zr: depth of the soil layer saturated with water, in mm;

Da: bulk density or apparent density of the soil = 1.5;

Hcr = HpF2.5: soil water content at field capacity (% by weight);

Hpf = HpF4.2: soil water content at the wilting point (% by weight).

The values of Zr, HpF2.5, and HpF4.2 are presented in **Table 2**.

Table 2. Soil characteristics of the M'Bahiakro irrigation scheme [33].

$HpF_{2.5}$ (% poids)	$HpF_{4.5}$ (% poids)	Da	Zr (mm)
29	17	1.5	180
29.4	17	1.5	220
33.5	18.7	1.5	200

N.B.: A value of 130 mm will be used for the available water capacity during the first cycle (dry season) and 60 mm for the second cycle (rainy season).

3) Calculation of Crop Water Requirements

This represents the volume of water consumed throughout the entire growth cycle of the plant, from field flooding to harvest. The water requirements for rice include the actual, gross, and net water needs of the crop. They are calculated using the following formula:

$$\mathrm{Bp} = \mathrm{Br} + \mathrm{Bb} + \mathrm{Bn} \tag{18}$$

where:

- Bp: crop water requirement (mm);
- Br: gross water requirement (mm);
- Bn: net water requirement (mm).

Calculation of Actual Water Requirements:

The actual water requirements of rice, or the crop's own needs, correspond to the quantities of water necessary for its development. These requirements depend on potential evapotranspiration (ETP), the vegetative stage of the plant, and the water supplied by rainfall [22]. They are governed by the following formulas:

- **At the time of soil saturation:**

$$Br = 0 \text{ (no transplanting)} \quad (19)$$

- **During field filling:**

$$Br = Ru + Cn + ETM + Is \quad (20)$$

where:

- Bp: actual water requirement of rice (mm);
- Ru: readily available water (mm);
- Is: infiltration (mm);
- Cn: change in water level (mm);
- ETM: maximum evapotranspiration (mm).

The maximum evapotranspiration is calculated as:

$$ETM = Kc \times ETP \quad (21)$$

where:

- ETM: maximum evapotranspiration (mm);
- ETP: potential evapotranspiration (mm);
- Kc: crop coefficient (dimensionless), determined experimentally.

Crop Coefficient

The crop coefficient (Kc) expresses the rate of water consumption of a crop. For a given crop, it generally varies according to its growth stage and therefore depends on both the crop type and the climatic conditions. Over one (1) growing cycle, there are four (4) main phases: *Initial*, *Development*, *Mid-season* (*Maturity*), and *Late season* (*Senescence*), associated with three (3) reference Kc values: Kc_ini → Kc_mid → Kc_end [22]. According to the crop cycle, the Kc values adopted for the study area are presented in **Table 3**. The rice variety cultivated in the M'Bahiakro irrigated perimeter is WITA 9, with a growth cycle of 120 days [34].

Table 3. Crop coefficients (Kc) for rice [21].

Decade	1	2	3	4	5	6	7	8	9	10	11	12
Kc	0.6	0.8	1.0	1.0	1.0	1.0	1.05	1.05	1.0	1.0	0.9	0.9

Rice Evapotranspiration (ETrice)

ETrice represents the maximum actual evapotranspiration of a rice field cultivated under optimal conditions and with adequate water supply. It is governed by climatic conditions (influenced by the cropping period) and by the development stage of the rice [35]. ETrice is expressed by the following equation [36]:

$$ETrice = Kc \times Eto \quad (22)$$

where:

- Kc: crop coefficient determined experimentally (dimensionless);

- ETrice: potential evapotranspiration of rice (mm day^{-1}, mm $month^{-1}$, or m^3 ha^{-1} day^{-1});
- ETo: reference potential evapotranspiration (mm day^{-1}, mm $month^{-1}$, or m^3 ha^{-1} day^{-1}).

Reference Evapotranspiration (ETo)

ETo is defined as "the evapotranspiration from a hypothetical reference crop surface with a height of 12 cm, a surface resistance of 70 s/m, and an albedo of 23%." ETo is measured in millimeters (1 mm = 10 m^3 ha^{-1}) and varies with time (month) and region. It is expressed using the Penman-Monteith equation [22] as follows:

$$ETo = \frac{\Delta \times Rn}{\Delta + \gamma'} + \frac{\gamma \times \frac{90}{T_{kmoy}} \times U_2 \times Ea_{T_{moy}} - Ed}{\Delta + \gamma'} \quad (23)$$

where:

ETo: reference evapotranspiration (mm);

Δ: slope of the vapor pressure curve (mb/˚C);

Rn: net daily radiation (mm/day);

γ: psychrometric constant (mb/˚C);

γ': modified psychrometric constant (mb/˚C);

U_2: wind speed at 2 meters above the ground (m/s);

$Ea_{T_{moy}}$: saturation vapor pressure at the mean temperature (mb);

Ed: actual vapor pressure at the dew point temperature (mb);

Tkmoy: mean daily air temperature (˚K) ($T_{kmoy} = T_{moy} + 273.16$).

Potential Evapotranspiration (PET)

Table 4. Average decadal potential evapotranspiration at Dimbokro from 1984 to 2016 (Source: SODEXAM, 2017).

Month	AVERAGE DECADAL ETP (mm)		
	1st Decade	2nd Decade	3rd Decade
January	39.1	40.4	44.6
February	45.7	47.8	46.9
March	48.9	49.0	49.9
April	48.9	49.5	48.4
May	47.6	46.5	44.8
June	41.8	41.3	39.0
July	37.7	36.3	36.7
August	35.2	35.9	37.8
September	38.0	39.4	39.3
October	41.1	42.1	44.2
November	43.1	42.1	40.9
December	39.0	37.6	39.3

PET represents the amount of water that would evaporate from the soil and be transpired by vegetation if there were no limitation in water supply [37]. The approach recommended within the framework of the FAO model is the Penman-Monteith method. The PET values obtained at a ten-day time step (decadal scale) from the Dimbokro station were used in this study (**Table 4**).

- **Actual crop evapotranspiration**

Actual evapotranspiration (ETR) is the amount of water removed from a surface by plants. ETR depends on potential evapotranspiration (ETP—the atmospheric demand) and the state of the soil water reserve (the available supply) [37]. During humid periods, when the soil water reserve is at field capacity (Rcc), it is assumed that ETR = ETP. Conversely, during dry periods (when the soil reserve is below field capacity), ETR < ETP. Furthermore, when the soil water supply equals the readily available water (RAW), ETR = ETM; however, when it falls below RAW, plants close their stomata and ETR < ETM [38]. In practice, irrigation is designed to meet the crop water requirements corresponding to ETc, in order to maintain plants under optimal production conditions, since yield is directly related to the following ratio [36]:

$$\frac{T}{PE} = \frac{\text{Transpiration}}{\text{Pouvoir evaporant de l'air}} = \frac{ETR}{ETo} \tag{24}$$

- **Flooding depth**

The flooding depth of rice fields varies according to the growth stage of the rice crop. The values presented in **Table 5** are those adopted for the irrigated perimeter of M'Bahiakro, based on studies conducted by the Japan International Cooperation Agency [34]. The rooting depth for irrigated rice generally ranges from 0.5 to 0.70 m [21].

Table 5. Flooding depth of rice according to growth stage [34].

Growth Stage	Flooding Depth (mm)
0 to 10 days	30
10 to 30 days	60
30 to 40 days	0
40 to 50 days	50
50 to 70 days	100
70 to 80 days	150
80 to 90 days	90
90 to 100 days	30
100 to 120 days	0

Calculation of Net Water Requirements for Rice:

This represents the amount of water that must be supplied through irrigation to meet the crop's water needs. It is defined by the following formula [29]:

$$Bn = Bp - Pe \quad (25)$$

where:

Bn = net water requirement (mm);

Pe = effective rainfall (mm);

Bp = actual crop water requirement (mm).

- **Effective Rainfall (Pe)**

From an agronomic perspective, effective rainfall (or useful rainfall) represents the amount of rainwater retained in the root zone that can be used by the plant. It can be expressed as follows:

$$Pe = Pt - R - D \quad (26)$$

where:

Pe = effective precipitation (mm);

Pt = total rainfall (mm);

R = surface runoff (mm);

D = deep percolation below the root zone (mm).

Effective rainfall (Peff) can also be estimated using the FAO empirical formula, based on climatic data analysis in arid and semi-humid regions [21] [20]:

$$Pe = 6.0 \times P - 10 \ \text{ if } \ P < 70 \text{ mm/month} \quad (27)$$

$$Pe = 8.0 \times P - 24 \ \text{ if } \ P > 70 \text{ mm/month} \quad (28)$$

where:

Pe = effective rainfall;

P = total rainfall over the plot.

In general, effective rainfall is estimated as 80% (0.80) of the total rainfall actually recorded [36].

Calculation of the Gross Water Requirements for Rice or Head of Network Demand:

This represents the actual amount of water that must be mobilized to meet the net water requirements, taking into account the losses that occur during water transport up to the plant [29]. The gross water requirement is calculated using the following formula:

$$Bb = Bn/EGI \quad (29)$$

where:

Bb: gross water requirement (mm);

Bn: net irrigation water requirement (mm);

EGI: overall irrigation efficiency (dimensionless).

- **Calculation of Overall Irrigation Efficiency**

The overall irrigation efficiency (EGI, %) is obtained by multiplying the different efficiencies [38] [39]. An irrigation efficiency of 50 to 60% is considered good; 40% is reasonable, while an irrigation efficiency of 20 to 30% is poor [29]. It can be defined by the following equation:

$$EGI = EA \times ET \times 100 \quad (30)$$

where:

ET: conveyance efficiency;

EA: application efficiency at the field level (dimensionless).

At the M'Bahiakro irrigated perimeter, given the simplicity of flood irrigation (rice cultivation), an application efficiency of 90% is assumed for this type of irrigation.

An irrigation efficiency of 0.65 was adopted in this study. This value corresponds to the average efficiency generally observed in gravity-fed irrigation systems in rice-growing schemes across West Africa, in accordance with FAO recommendations for networks characterized by moderate distribution and infiltration losses [20].

Calculation of Irrigation Water Requirements for Rice Using CROPWAT 8.0:

The evaluation of irrigation water requirements for rice cultivation was carried out using the CROPWAT 8.0 model, software developed by the FAO in 1992 [9], to support irrigation management. This program integrates agronomic parameters specific to each crop, such as crop coefficients, duration of phenological stages, rooting depth, and others. The calculation of water requirements is based on the modified Penman-Monteith formula for evapotranspiration, the use of the crop coefficient (Kc) according to [22], and the USDA-SCS method for estimating effective rainfall [40]. The adopted methodology relies on the collection and analysis of monthly climatic data, including minimum and maximum temperatures (˚C), precipitation (mm), relative humidity (%), wind speed (m/s), and sunshine duration (hours/day). These data are entered into CROPWAT, which automatically calculates reference evapotranspiration (ET_0), effective rainfall, and radiation. Specific information related to rice cultivation, such as the sowing date and cultivated area, is also input into the model. The results obtained, in tabular form, are then exported to Excel for further analysis and interpretation.

3. Results

3.1. Evolution of Climatic and Hydrometric Variables

3.1.1. Interannual Variation of Rainfall and Streamflow

Rainfall

The analysis of Nicholson's rainfall index, combined with seasonal smoothing using the Hanning filter, reveals three major climatic periods that marked rainfall variability in M'Bahiakro over the observation period from 1944 to 2016 (**Figure 5**):

- **Humid period (1944-1972)**: This phase is characterized by abundant rainfall, with an average annual total of 1163.62 mm, which is significantly higher than the overall mean for the study period (1036.26 mm). It reflects a generally humid climatic regime.
- **Normal or transitional period (1973-1996)**: During this phase, the mean annual rainfall was 1027.53 mm, a value close to the long-term average (1036.26

mm), indicating relative climatic stability.

- **Dry period (1997-2016)**: This last phase is marked by a significant decrease in rainfall, with an average annual total of 862.06 mm, well below the reference mean (1038.31 mm). It reflects a persistent rainfall deficit that continues until the end of the observation period.

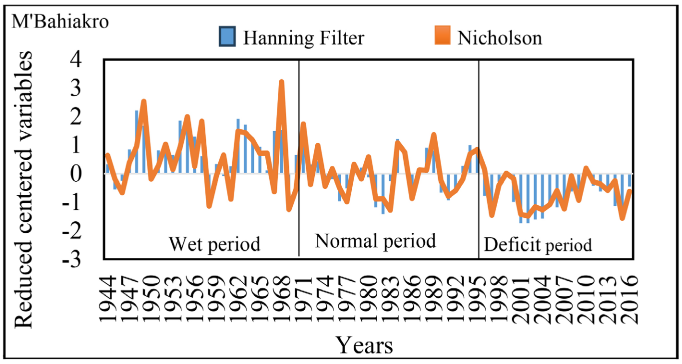

Figure 5. Interannual variation of rainfall in M'Bahiakro (1944-2016).

Discharge

Figure 6 shows the annual evolution of average discharges at the M'Bahiakro station over the period from 1960 to 2004 (*i.e.*, 44 years). This analysis highlights two main phases of flow fluctuation in the N'Zi River:

Surplus period (1960-1972): Characterized by abundant flows, with an annual average of 55.57 m^3/s, well above the overall average for the study period (37.66 m^3/s). This reflects a favorable hydrological context corresponding to a humid period.

Deficit period (1973-2004): Marked by a significant decrease in discharges, with an annual average of 29.63 m^3/s, well below the reference average. The indices filtered using the Hanning method are consistently located below the main axis, indicating a persistent dry period. This trend is particularly pronounced between 1973 and 1979, a decade during which flows experienced a notable decline.

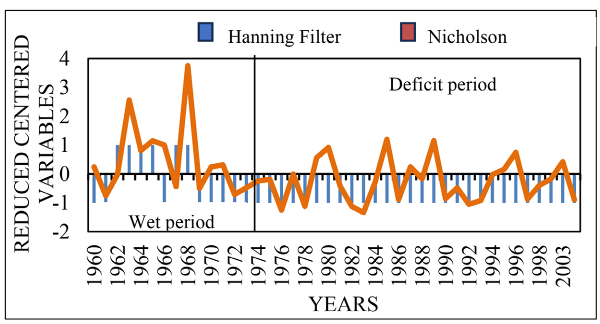

Figure 6. Interannual variation of discharge at the M'Bahiakro station (1960-2004).

3.1.2. Results of Change Point Tests

1) Pettitt Test

The analysis of the rainfall series recorded at the M'Bahiakro station over the

1944-2016 period reveals a highly significant change point that occurred in 1973. The exceedance probability, estimated at 0.09%, is extremely low, indicating strong statistical significance. This value, being below the 1% threshold, allows the rejection of the null hypothesis of no change at the 99% and 95% confidence levels, thereby confirming a marked shift in the rainfall regime at that date.

In contrast, the results of the Pettitt test applied to the discharge series over the 1960-2004 period show no significant change point. The analysis indicates that the null hypothesis of no change is accepted at the 99%, 95%, and 90% confidence levels, suggesting a relative stability in river flows during this period, despite the rainfall fluctuations observed (Table 6).

Table 6. Pettitt change point test.

Station	Study Period	Year of Climatic Break	Exceedance Probability	Significance Level	Null Hypothesis of No Break
M'Bahiakro	1944 to 2016	1973	0.09%	Highly significant break	Rejected at the 99% confidence level
	1960 to 2004	No break detected	0.09%	No break	Accepted at the 99%, 95%, and 90% confidence levels

2) Lee and Heghinian Test

According to the Bayesian test of Lee and Heghinian applied to the rainfall series of M'Bahiakro over the period 1944-2016, a probable change point was detected in 1968, with a probability of 0.13. This result suggests a moderately significant shift in the rainfall regime at that time, indicating a transition toward a different climatic phase. Moreover, the same test applied to the discharge series recorded between 1960 and 2004 confirms the presence of a hydrological break in 1968 at the study station. This concordance between rainfall and streamflow series strengthens the hypothesis of a structural climatic change affecting both precipitation and the flow regime of the N'Zi River (Table 7).

Table 7. Lee and heghinian change point test.

Station		Study Period	Year of Change	Probability
M'Bahiakro	Rainfall	1944-2016	1968	0.13
	Discharge	1960-2004	1968	0.15

3) Monthly Variation of Rainfall and Discharge

The monthly hydrological data from M'Bahiakro reveal strong seasonality closely linked to rainfall patterns. The dry season (January to March, November, and December) is characterized by low discharge and flow volumes. Starting in April, rainfall increases, leading to a rise in river discharge, with a peak occurring between August and October. The maximum flow is recorded in September (128.57 m^3/s), although rainfall peaks in June, indicating a lag between precipitation and runoff. The MFC values greater than 1 confirm the significance of the flood period (Table 8).

Table 8. Summary of monthly rainfall and discharge of the N'Zi River at M'Bahiakro (1971-2004).

Months	Rainfull (mm)	Average Discharge (m^3/s)	MFC	Average Flow Volumes (m^3)
January	7.40	0.72	0.02	1,917,531
February	35.70	0.29	0.01	690,873
March	84.10	0.46	0.02	1,222,179
April	117.20	1.93	0.06	5,000,710
May	133.60	5.63	0.19	15,087,986
June	144.40	13.72	0.46	35,553,318
July	87.60	25.12	0.84	67,294,241
August	79.50	52.78	1.76	141,361,716
September	135.80	128.57	4.28	333,261,921
October	93.00	100.35	3.34	268,765,224
November	28.90	26.63	0.88	69,020,966
December	11.40	4.37	0.14	11,710,369

3.1.3. Interannual Evolution of Temperature

The analysis of annual temperature data from the Bouaké station between 1964 and 2015 reveals a general upward trend, with an increase of approximately 0.5˚C per year (**Figure 7**). Temperatures remained below 26˚C until 1972 but exceeded this threshold from 1973 onward. This trend became more pronounced after the 2000s, reaching 26.9˚C, indicating a gradual climatic warming in the region.

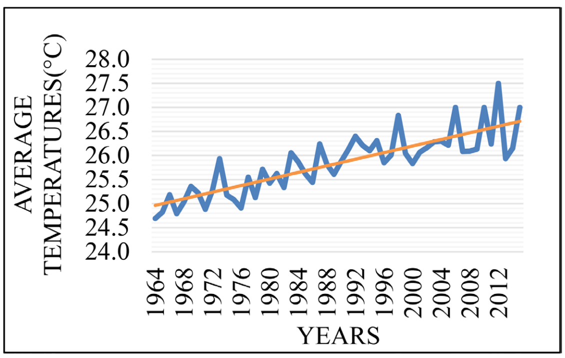

Figure 7. Interannual variation of temperature in Bouaké (1964-2015).

3.2. Irrigation Water Requirements

3.2.1. Annual Irrigation Water Requirements

Table 9 presents the results of the annual irrigation water requirements for the M'Bahiakro irrigation scheme during the years 2009 (before the rehabilitation of the scheme), 2014 (during the rehabilitation), and 2016 (after the rehabilitation). Analysis of this table shows that the irrigation water requirements have increased over the years. Indeed, estimated at 11,614,500 m^3 in 2009, the irrigation water requirements rose to 13,066,200 m³ and 13,121,550 m³ in 2014 and 2016, respectively.

Table 9. Results of irrigation water requirements for the periods 2009, 2014, and 2016 in M'Bahiakro.

	Water Requirement 2009		Water Requirement 2014		Water Requirement 2014	
Description	1st cycle	2nd cycle	1st cycle	2nd cycle	1st cycle	2nd cycle
Period	Jan-May	June-Oct	Jan-May	June-Oct	Jan-May	June-Oct
Net Requirements (mm)	929.18	748.48	1043.06	844.29	1131.3	858.91
Network Efficiency	0.65		0.65		0.65	
Gross Requirements (m^3/ha)	14,295	11,515	16,047	12,989	17,405	13,214
Gross Requirements for 450 ha (m^3)	6,432,750	5,181,750	7,221,150	5,845,050	7,832,380	5,946,350
Total Gross Requirements for 450 ha (m^3)	11,614,500		13,066,200		13,121,550	

3.2.2. Monthly Irrigation Water Requirements

Figure 8 illustrates the monthly irrigation water requirements for the period 1970-2000, showing significant variability according to the seasons of the year. During the main dry season (December to March), water requirements are highest, ranging from 1,862,397 m^3 to 2,244,738 m^3, with an average of 2,056,507 m^3. In contrast, during the main rainy season (April to June), the requirements decrease markedly, with values between 733,846 m^3 and 1,134,000 m^3, and an average of 957,923 m^3. The short rainy season (September to October) is characterized by moderate requirements, with the lowest value recorded in September (929,631 m^3). As for the short dry season (July to August), it shows relatively low requirements, ranging between 864,000 m^3 and 1,157,000 m^3.

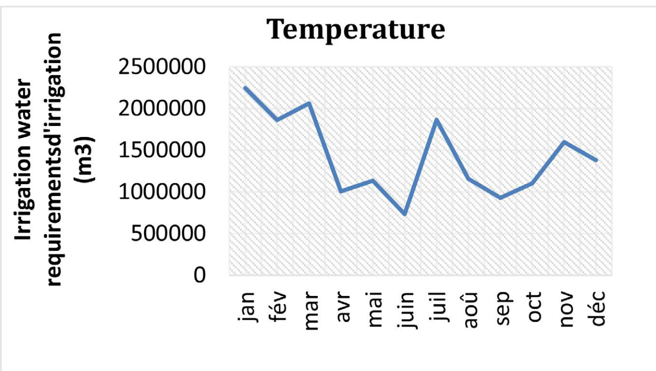

Figure 8. Monthly variation of irrigation water requirements from 1970 to 2000 in M'Bahiakro.

3.2.3. Comparison between N'Zi River Flows and Monthly Irrigation Water Requirements

The results obtained from the comparison between the monthly flows of the N'Zi River over the period 1971-2004 and the monthly irrigation water requirements over the period 1970-2000 made it possible to assess the availability of the M'Bahiakro dam reservoir in meeting irrigation water demands (Table 10). The analysis of the table shows that the reservoir water largely meets the monthly irrigation water requirements for rice cultivation, except for January to March, when irrigation needs are higher. Thus, for two cropping cycles of 150 days each, the first cycle extends from March to July, and the second from August to December.

Table 10. Comparison between N'Zi river flows and irrigation water requirements in M'Bahiakro.

Month	Flow (m^3) (1971-2004)	Water Requirements (m^3) (1970-2000)	Difference Between Flows and Requirements (m^3)
	A	B	Δ = A-B
January	1,917,531	2,244,738	−327,207
February	690,873	1,862,397	−1,171,523
March	1,222,180	2,062,385	−840,205
April	5,000,711	1,005,923	3,994,788
May	15,087,986	1,134,000	13,953,986
June	35,553,318	733,846	34,819,472
July	67,294,242	1,864,038	65,430,203
August	141,361,716	1,156,846	140,204,870
September	333,261,921	929,631	332,332,290
October	268,765,225	1,101,462	267,663,763
November	69,020,967	1,596,462	67,424,505
December	11,710,370	1,380,185	10,330,185

4. Discussion

4.1. Evolution of Climatic Variables

4.1.1. Interannual Variation of Rainfall and River Flow

The analysis of Nicholson's rainfall indices, combined with seasonal smoothing using the Hanning filter, highlights three distinct climatic periods at the M'Bahiakro station between 1944 and 2016.

The first period (1944-1972) corresponds to a wet phase characterized by abundant rainfall, with an annual average of 1163.62 mm, well above the overall mean (1036.26 mm). This period reflects a surplus and favorable climate, consistent with the findings of [23] [41] [42], who reported relatively wet conditions across West Africa during the first half of the 20th century. From a hydrological perspective, the flow series of the N'Zi River (1960-2004) also indicates a surplus phase between 1960 and 1972, with an annual average discharge of 55.57 m^3/s, significantly higher than the general mean (37.66 m^3/s). This situation reflects effective watershed recharge, a phenomenon previously observed in several West African rivers [43] [44].

The second period (1973-1996) corresponds to a transitional or normal phase, with an annual average of 1027.53 mm, close to the overall mean. It marks a transition between the previous wet period and the subsequent dry phase, in agreement with the observations of [45] [46], who highlighted oscillations in West African rainfall regimes without a real return to the surplus conditions observed before 1970.

Finally, the third period (1997-2016) is characterized by a notable decrease in rainfall, with an annual average of 862.06 mm, representing a deficit of about 17% compared to the reference mean. This phase indicates a deficit and irregular rainfall regime, reflecting the persistence of the drought that began in the 1970s [41] [46] [47]. From a hydrological standpoint, this evolution resulted in a marked decline in N'Zi River discharge (29.63 m^3/s between 1973 and 2004), corresponding to a reduction of more than 40%. The Hanning-filtered indices confirm a persistent hydrological drought, consistent with the findings of [48], who reported a generalized decrease in river flows across several West African basins since the late 1990s.

4.1.2. Change-Point Tests

The results of the Pettitt test applied to the rainfall series of M'Bahiakro reveal a highly significant change in 1973, indicating a major climatic discontinuity. This date corresponds to a profound shift in the West African rainfall regime, widely documented in recent literature [41] [49]. Conversely, the Pettitt test applied to the mean discharge series of the N'Zi River (1960-2004) does not indicate any statistically significant change point. This discrepancy between the rainfall break and the absence of a hydrological rupture may be explained by the basin's storage capacity, delayed hydrological response, or anthropogenic modifications of the environment.

Indeed, [44] demonstrated that river flows respond in a buffered and delayed manner to rainfall variability, due to the regulating effects of soils, groundwater, and vegetation, which mitigate the direct impacts of rainfall deficits. Furthermore, [43] and [50] highlighted that land-use changes (deforestation, intensive agriculture, urbanization) have altered the hydrological dynamics of several West African basins, thereby reducing or delaying the streamflow response to rainfall variations.

The Bayesian test of Lee and Heghinian, applied to the same rainfall series, detected a probable break around 1968, suggesting a moderately significant shift in the precipitation regime. This earlier change, also observed in the hydrological series, may represent a transitional phase preceding the 1973 shift, marking the onset of a rainfall deficit before the establishment of the persistent regional drought.

4.1.3. Monthly Evolution of Rainfall and Streamflow

A joint analysis of rainfall, mean discharge, monthly runoff coefficients (MFC), and flow volumes at the M'Bahiakro station reveals a strong hydroclimatic seasonality, typical of the Sudano-Guinean zones of West Africa.

During the dry season (November to March), rainfall remains low (7.4 - 84.1 mm), resulting in very reduced discharges (0.29 - 1.93 m^3/s) and small flow volumes (<5 × 10^6 m^3). This period corresponds to the predominance of the Harmattan winds, maximum evapotranspiration, and an almost complete absence of hydrological recharge. Such low flow conditions reflect the seasonal drying of the basin, a behavior also observed in other West African catchments by [51], who relate it to intra-seasonal rainfall variability and soil dynamics. The resumption of rainfall in April (117.2 mm) leads to an increase in discharge (1.93 m^3/s) and in the MFC (0.06), marking the reactivation of surface flow. Between May and October, rainfall (133.6 - 144.4 mm) induces a clear rise in discharge (up to 128.57 m^3/s in September) and in flow volume (3.33 × 10^8 m^3). The maximum MFC in September (4.28) indicates soil saturation and direct runoff, confirming a strong hydrological response of the basin, as reported by [52] in similar contexts. The gradual decline in streamflow from October onwards marks the end of the wet season and the return to a deficit regime. Overall, the M'Bahiakro basin exhibits a unimodal hydrological regime tightly controlled by rainfall, consistent with the findings of [53] [54] regarding the rainfall-driven nature of river discharge in West Africa.

4.1.4. Interannual Evolution of Temperature

The analysis of annual temperatures recorded at the Bouaké station between 1964 and 2015 reveals a significant climatic warming trend in the region. Mean temperatures, which remained below 26˚C until 1972, exceeded this threshold from 1973 onward, marking a transition to a warmer phase. This increase became more pronounced from the 2000s, reaching approximately 26.9˚C in 2015, representing an average rise of about 0.5˚C per decade. This trend is consistent with the regional dynamics described by several authors, including [54] [55], who reported an average temperature increase of 0.2˚C - 0.4˚C per decade since the 1970s. These thermal changes have major hydrological and agroclimatic consequences, such as intensified evapotranspiration, progressive soil drying, reduced water availability, and declining agricultural yields.

4.2. Irrigation Water Requirements

4.2.1. Annual Irrigation Water Requirements

The analysis of irrigation water requirements for a 450-hectare area between 2009 and 2016 reveals a general upward trend, reflecting the growing impact of climate change on agricultural irrigation demand. Net water requirements increased from 929.18 mm to 1131.3 mm during the January-May period, and from 748.48 mm to 858.91 mm between June and October. This rise also affected gross water requirements, which reached 17,405 m^3/ha in 2016 compared to 14,295 m^3/ha in 2009, representing an increase of about 22%, despite a stable irrigation efficiency of 0.65. These changes directly influence water availability and intensify irrigation needs, particularly for rice cultivation the main irrigated crop in the area. These findings are consistent with those of [55], who reported that increasing temperature and irregular rainfall amplify irrigation water demand in tropical and semi-arid regions, especially for irrigated rice, a crop highly sensitive to water stress. Similarly, [56] highlighted that the decline in rainfall and the shift in seasonal patterns extend irrigation periods, thereby increasing pressure on water resources.

4.2.2. Monthly Irrigation Water Requirements

The analysis of monthly irrigation water requirements between 1970 and 2000 at the M'Bahiakro station reveals strong seasonal variability, closely linked to the alternation of wet and dry seasons. The highest demands are observed during the main dry season (December to March), with volumes ranging from 1.86 to 2.24 million m^3, and an average of 2.06 million m^3. This high demand reflects the combined impact of low rainfall and high evapotranspiration, which intensify water deficits. These observations are consistent with the findings of [48] and [59], who demonstrated that the dry season in central and northern Côte d'Ivoire is characterized by a chronic water deficit, requiring increased reliance on irrigation.

Conversely, during the main rainy season (April to June), irrigation requirements decrease significantly, ranging from 733,846 m^3 to 1.13 million m^3, with an average of 958,000 m^3. This reduction is explained by substantial rainfall inputs and improved soil moisture conditions, which favor a decline in irrigation demand, as also reported by [55] in similar West African contexts. The minor rainy and dry seasons (July to October) show moderate water needs, below 1.16 million m^3, indicating a temporary balance between rainfall inputs and water losses.

4.2.3. Comparison of N'Zi River Flows and Monthly Irrigation Water Requirements

The comparative analysis of the monthly flows of the N'Zi River (1971-2004) and the irrigation water requirements of the M'Bahiakro rice perimeter (1970-2000) reveals a strong interdependence between the river's hydrological dynamics and agricultural water demand. This relationship illustrates the sensitivity of the irrigation system to the seasonal variability of the river regime.

During the main dry season (January to March), N'Zi River flows are particularly low, ranging between 0.69 and 1.91 million m^3, while irrigation requirements reach between 1.86 and 2.24 million m^3. This marked water deficit (up to −1.17 million m^3 in February) indicates an insufficient water supply to meet crop demand, especially for irrigated rice, which is highly dependent on a regular water supply during the vegetative and reproductive growth stages [55]. From April onward, with the onset of rainfall, N'Zi River flows gradually increase, peaking at more than 330 million m^3 in September, while irrigation needs decrease sharply (around 930,000 m^3). This seasonal asymmetry between water availability and demand highlights the need for better synchronization between the cropping calendar and hydrological dynamics.

According to [58] and [59], hydrological variability, exacerbated by climate change, undermines the stability of water supply for irrigated rice cultivation in the Central-Eastern region of Côte d'Ivoire. These authors emphasize that changes in rainfall patterns and the reduction of river flows limit water availability, thereby increasing the vulnerability of irrigation systems to climatic extremes. Therefore, integrated water resource management—based on the mobilization of excess rainfall and improved irrigation efficiency—is essential to ensure water security and the sustainability of rice production in the M'Bahiakro region. Such an approach would enhance the resilience of agricultural systems to climatic variability and the seasonal fluctuations of the N'Zi River's flow.

5. Conclusions and Perspectives

The study conducted on the M'Bahiakro rice irrigation scheme highlights a significant increase in irrigation water requirements over recent decades, closely linked to climate variability and the progressive degradation of the hydrological regime of the N'Zi River. The combined analysis of river discharge and irrigation water demand reveals a marked inverse relationship: low-flow periods coincide with the highest irrigation needs. This mismatch reflects the growing vulnerability of the rice production system to seasonal irregularities, recurrent rainfall deficits, and climate warming. These findings are consistent with regional trends observed across West Africa, where rising temperatures and altered rainfall patterns have profoundly affected water availability for irrigation. In this context, the implementation of integrated and sustainable water resource management is essential. Such an approach should rely on mobilizing excess rainfall, regulating river flows during low-water periods, and improving the technical efficiency of irrigation systems. Concrete adaptation measures suitable for the local context include the adoption of water-saving techniques such as Alternate Wetting and Drying (AWD), as well as the introduction of drought-tolerant rice varieties that are better adapted to the increasingly variable climate in the M'Bahiakro region.

However, this study presents some methodological limitations. The analyses are based on historical datasets of limited duration (1970-2016) and do not incorporate future climate projections or interactions between hydrological and socioeconomic components of the basin. Furthermore, the estimation of irrigation water requirements relies on climatic averages, without accounting for extreme interannual variability that may strongly influence water availability.

In this perspective, future research should focus on:

- The use of Regional Climate Models (RCMs) from CORDEX-Africa and Global Climate Models (GCMs) from CMIP6 to simulate future temperature and precipitation scenarios at the local scale;
- The integration of coupled hydrological models (such as SWAT, WEAP, or HEC-HMS) to assess the impacts of various climate scenarios on N'Zi River flows and irrigation water availability;
- The development of integrated decision-support tools combining climatic, hydrological, and agronomic parameters to support adaptive and sustainable

water management.

Ultimately, strengthening the resilience of the M'Bahiakro irrigation scheme will require better anticipation of future climatic pressures, optimization of irrigation practices, and the proactive implementation of sustainable water management strategies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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