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Assessment of water resources vulnerability to climate change in a tropical region: A case study of the Gbêkê region (Côte d'Ivoire)

T. Kone[1*], M. Kamagate [2,3], K. R. Effebi[4], B. P. Essis[1], P. J. M. Ouattara[1], L. Coulibaly[1]**

[1]*Laboratoire Environnement et Biologie Aquatique, Université Nangui-Abrogoua, 02 BP 801, Abidjan 02, Cote d'Ivoire*
[2]*Département de Sciences et Technologies, Université de Man, BP 20, Man, Cote d'Ivoire*
[3]*Département d'Ingénierie, Agronomique, Foresterie et Environnementale, Université de Man BP 20, Man, Cote d'Ivoire*
[4]*Laboratoire de Géosciences et Environnement, Université Nangui-Abrogoua, 02 BP 801, Abidjan 02, Côte d'Ivoire*

**Corresponding author, Email address: Tiangoua.kone@yahoo.fr*
***Corresponding author, Email address: kamagate.mahamadou@univ-man.edu.ci*

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tiangoua.kone@yahoo.fr
Phone: +2250707267701

Abstract
Climate change threatens human beings with its adverse effects on livelihood, including water resources scarcity. The study based on the analysis of the water resources' exposure level of the sub-watersheds of Gbêkê region aimed to evaluate the evolution of the climate parameters affecting the rivers of this region, to determine the vulnerability index and to identify the most vulnerable zones facing the climatic changes. Indeed, a decrease in rainfall since 1986 generated significant deficits, i.e., 18 to 33%. The application of the methodology of the Vulnerability Index (VI) of the United Nations Environment Program (UNEP), showed a moderate vulnerability on Bandama blanc 1 (VI = 0.36), Bandama blanc 2 (VI = 0.36), Kan 1 (VI = 0.34), Kan 2 (VI = 0.35), Soungourou (VI = 0.37) sub-basins, and a high vulnerability on the Loka (VI = 0.41) sub-basin. Loka is the most vulnerable watershed. This leads to the vulnerability of surface waters through water bodies drying up and the reduction of wetlands. Furthermore, several factors affecting the vulnerability of surface water resources in the Gbêkê region were identified. These include (1) resource stress (water stress and water variation), (2) water use pressure (overexploitation of water resources and accessibility of drinking water supply), (3) ecological health (water pollution and ecosystem deterioration), and (4) management capacity (inefficient water use and inaccessible sanitation improvement). Among all these parameters above-mentioned, ecological health affects most water resource vulnerability, due to the lack of wastewater treatment and deforestation and land degradation, which are accelerating factors of climate change. Therefore, this study determined the climate change vulnerability index of the different sub-watersheds of the Gbêkê region.

1. Introduction
The warming of the climate system is unequivocal and the changes observed since the 1950s are unprecedented in decades and even millennia. Indeed, the atmosphere and the ocean warmed, snow and ice cover decreased, sea levels have rose, and greenhouse gas (GHG) concentrations increased [1]. According to the majority of scientists, these changes, and those projected for the rest of the 21st century, are due to human activity rather than natural changes in the atmosphere [2,3]. Africa, in general, and West Africa in particular, is one of the regions with the lowest GHG emissions (with an

average of 0.69% in 2018). However, due to the poverty of its population, it is one of the region's most strongly affected by the adverse effects of these changes. Indeed, climate change led to a considerable decrease in rainfall and lengthening drought periods [4]. Côte d'Ivoire is no less affected by the adverse effects of climate change. Indeed, like West African sub-region countries, Côte d'Ivoire has seen its rainfall regime decline due to climate change. This has considerably affected water resources, coastal areas, agriculture and forestry [5]. Some authors recently showed that a trend towards drought has been apparent since the end of the 1960s, with an increase in temperature of around 1.6°C and a fluctuation in rainfall with a general downward trend.[6-8]. This phenomenon did not occur homogeneously in time. It first affected the North, then gradually spread to the Center, and finally to the coast. [7]. These rainfall anomalies observed for nearly four decades had an exceptional resonance in this country's northern and central regions. [8]. This study was carried out in the Central region of Côte d'Ivoire because this region has been experiencing increasingly long dry seasons every year for the past few decades. This region is especially marked by intense anthropic pressures due to the high population density (131.3 inhabitants/km^2) compared to an average of 70.3 inhabitants/km^2 [9]. Surface water, the primary resource for drinking water supply, seems to be affected by the manifestations of climate change through the disruption of its normal flow [10]. In Bouaké city, the current average temperature of (i.e., 26-27°C) will increase to 29-30°C in one century in 2110. The current average annual rainfall was 1000-1400 mm/year, which will decrease to 770-1200 mm/year. The aridity index will increase but remain below 2 [11]. To allow an adaptation of the populations to the effects of these climatic changes on the rivers in Ivory Coast, one of the most adapted approaches is the knowledge of the zones vulnerable to these climatic changes and their evolution over time. As a result, several studies have been performed on the influence of climatic events on seasonal rainfall patterns in the N'Zi watershed (Bandama) and the existence of climatic variability and its impact on the supply of water resources in the Grand-Lahou region (southwestern Côte d'Ivoire) [12-14].

However, few studies have focused on the vulnerability to climate change of aquatic ecosystems in the Gbêkê region. It is within this framework that this study proposed to implement a spatial model to assess the vulnerability of river areas to climate change.

Thus, this study aimed to evaluate the degree of exposure of aquatic ecosystems in the GBEKE region to change to determine the most vulnerable area to this phenomenon. Specifically, this study focuses on: (i) evaluating the evolution of climatic parameters affecting the water bodie in the Gbêkê region, (ii) determining the vulnerability index, (iii) and identifying the most vulnerable zones to these changes.

2. Material and Methods

2.1 Material

2.1.1 Study data

The study required several types of data (See **Table 1**). Rainfall data were collected from the rainfall stations in Bouaké, Sakassou, Botro, and Beoumi. Flow data, on the other hand, were collected from the hydrometric stations in Bouaké, Sakassou, and on the Loka, Kan, and Soungourou rivers, covering the period 1986-2017.

2.1.1 Data processing tools

The analysis and processing (i.e. delineation of the sub-basins of the hydrographic network) of the data as well as the elaboration of the document were carried out using Kronostat and QGIS softwares.

Table 1. Different types of data sources

Data	Types	Sources
Rain	Rainfall	Company for Operation and Development, Airports, Aeronautics and Meteorology (CODAAM)
Flow rates	Hydrometric	Directorate of Hydraulics, Standards and Quality Regulation (DHSQR)
Surface water resource	Hydrological	General Directorate of Human Hydraulic Infrastructures (GDHHI)
Populations without access to improved drinking water sources	Demographic	General Directorate of Human Hydraulic Infrastructures (GDHHI)
Populations without access to improved sanitation	Demographic	General Directorate of Human Hydraulic Infrastructures (GDHHI)
Population	Demographic	National Institute of Statistics (NIS)
Areas of land without vegetation cover	Spatial	Land Occupation Map (LOM)

2.2 Methods

2.2.1 Interannual variability of precipitation

The study of the interannual variability of precipitation allows us to characterize the exposure of aquatic ecosystems to climate change. In practice, it consists of studying the degree of variation of precipitation through rainfall trend tests (Nicholson and Hanning test) and carrying out stationarity analysis to determine the break year (Pettitt test). In the Gbêkê region, the time series of climatic data are observed at 4 stations comprising 3 rainfall stations (Béoumi, Botro, Sakassou) and 1 synoptic station at the Bouaké station.

2.2.1.1 Second-order Hanning low-pass filter

This is a method of eliminating seasonal variations in a given time series. The weighted rainfall totals are calculated through equations 1 to 6, as recommended by Tyson et al.[15] quoted by Assani [16].

This allows the estimation of each term of the series:

$$x(t) = 0{,}06X_{(t-2)} + 0{,}25x_{(t-1)} + 0{,}38x_t + 0{,}25x_{(t+1)} + 0{,}06x_{(t+2)} \qquad (1)$$

For $3 \leq t \leq (n-2)$

Where, $X_{(t)}$ the weighted rainfall totals for term t ;

$X_{(t-2)}$ et $X_{(t-1)}$ are the observed main rainfall totals of both terms immediately preceding the term t.

$X_{(t+2)}$ et $X_{(t+1)}$ are the observed rainfall totals of the two terms immediately following term (t).

The weighted rainfall totals of the first two items [$X_{(1)}$, $X_{(2)}$] and the last two items [$X_{(n-1)}$, $X_{(n)}$] of the series are calculated using the following expressions (3-6) (n being the size of the series):

$$X_{(1)} = 0{,}54X_1 + 0{,}46X_2 \qquad (2)$$

$$X_{(2)} = 0{,}25X_1 + 0{,}5X_2 + 0{,}25X_3 \quad (3)$$

$$X_{(n-1)} = 0{,}25X_{(n-2)} + 0{,}5X_{(n-1)} + 0{,}25X_{(n)} \quad (4)$$

$$X_{(n)} = 0{,}54X_{(n)} + 0{,}46X_{(n-1)} \quad (5)$$

To better visualize the periods of rainfall deficit and surplus, the moving averages were centered and reduced using the following formula (6):

$$Y_t = \frac{X(t) - m}{\sigma} \quad (6)$$

Where, m is the average of the weighted average series and σ is the standard deviation of the weighted moving average series. This method appears more efficient because it allows for a discernible breakdown of the series.

2.2.1.2 Stationarity of hydroclimatic series: Pettitt test (1979)

Pettitt's test was used to detect a break. This break must be demonstrated by a change in the probability distribution of the time series at a given time, most often unknown [17, 18]. Pettitt's test was retained in this study for its power and robustness. In addition, it is non-parametric and derives from the formulation of the Mann-Whitney test [19].

The absence of a break in the series (X) constitutes the null hypothesis H0. Pettitt defines the variable $U_{t,N}$ by the following formula (7):

$$U_{t,N} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} D_{ij} \quad (7)$$

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

The approximate probability of exceeding a k-value is defined by the following expression, and is used to assess the significance of the break (8):

$$Prob\ (K_N > k) \approx 2\exp(-6k^2/(N^3 + N^2)) \quad (8)$$

For a risk Q of a given specie, if the estimated probability of overshoot is less than Q, the null hypothesis is rejected. In this case, the series has a break whose date is given by the time t defining the maximum in the absolute value of the variable $U_{t,N}$.

Calculation of average variations

For hydroclimatic variables with a break in the time series, some authors propose to determine the average variations on either side of the break by using the following formula (9) [20]:

$$D = \frac{\overline{X_J}}{\overline{X_\iota}} - 1 \quad (9)$$

Where: D is the hydroclimatic deficit; Xj, the average over the period after the break and Xi, the average over the period before the break.

2.2.2. Estimation of the vulnerability index

The Vulnerability Index (VI) of water resources developed by the United Nations Environment Program (UNEP) and Pekin University was used in this study. This index is expressed as follows:

$$VI= f\,(SR, PW, EH, MC) \qquad (10)$$

Where: SR: Stress on the Resource; PW: Pressure related to Water use; EH: Ecological Health; MC: Management Capacity.

2.2.2.1 Stress on the Resource (SR)

Stress on the Resource (SR) determines the availability of water resources to meet the water demand pressure for the growing population, considering the precipitation variability. Therefore, SR is influenced by the renewable water resource constraint (SRs) and the parameter of water variation resulting from long-term precipitation (SRv). This parameter is estimated as follows:

$$SR= f\,(SRs, SRv) \qquad (11)$$

Where: SRs: water stress and SRv: water variation.

2.2.2.1.1 **Water stress**

Water stress (WS) can be expressed as the per-inhabitant water resource of a basin. In compliance with international agreements, the minimum level of the WS per-inhabitant is generally 1700 m^3 / person [21]. Thus, it is calculated as follows:

$$\begin{cases} WS = \dfrac{1700 - R}{1700}, & (R<1700) \qquad (12) \\ WS = 0, & (R>1700) \end{cases}$$

With, R, Water resource per inhabitant (m^3/person).

The per-inhabitant water resource (R) is the ratio of the surface water resource (Rs) plus the groundwater resource (Res) to the total watershed population (P). R is obtained by the following equation (13):

$$R = \frac{R_s + R_{es}}{P} \qquad (13)$$

2.2.2.1.2 Water Variation (SRv)

Water variation (SRv) is estimated by the coefficient of variation (CV) of precipitations recorded from 1986 to 2017. An upper ceiling of 0.3 (30 %) is defined for CV, which reflects a point above which precipitation variation severely impacts water resource security [22]. SRv is determined according to equation (14).

$$SR_V = \frac{CV}{0.3}, \quad CV<0.3 \qquad (14)$$

$$SR_V = 1, \quad CV \geq 0.3$$

The coefficient of variation is defined by the normal statistical terms, where (Pi) is the precipitation for *i* years (mm), (S) the standard deviation of the precipitation record, and (μ) the avearage precipitation. Thus, the coefficient of variation (CV) and standard deviation of precipitations recorded (s) is unwound according to equation (15).

$$CV = \frac{S}{\mu} \quad ; \quad s = \frac{\sqrt{\sum_{i=1}^{n}(Pi-\beta)^2}}{n+1} \tag{15}$$

2.2.2.2 Pressure related to Water use

Pressure related to Water use (PW) is estimated in terms of overexploitation of water resources (OWR) and the availability and accessibility of drinking water supplies (ADS). This parameter is estimated as follows:

$$PW = f\,(OWR, ADS) \tag{16}$$

With, OWR: Overexploitation of water resources and ADS: accessibility to drinking water.

2.2.2.2.1 Overexploitation of water resources

A natural hydrological process does recharge water resources. This process is disrupted by the overexploitation of water resources, eventually causing difficulties in the recharge of water resources. Thus, the proportion of the resource extracted for use (WRs) and the proportion of the total water resource (TWR) can be used to demonstrate the capacity of the basin water cycle for a healthy renewable process. The Overexploitation of water resources (OWR) is estimated by the ratio of total water demand (domestic, commercial, agriculture) to the total renewable water resource according to equation (17):

$$OWR = \frac{\mathrm{WRs}}{\mathrm{TWR}} \tag{17}$$

With, OWR: Overexploitation of water resources, TWR: total water resource and, WRs: lack resource extracted.

2.2.2.2.2 Improving Access to Drinking Water

The Improving Access to Drinking Water (IADW) parameter is defined as the provision of a sufficient supply of safe drinking water to meet the basic needs of society in terms of how well water development facilities meet the needs of the population [23]. The lack of drinking water accessibility is estimated by the ratio of the percentage of the population without access to drinking water to the total population. Improved access to safe drinking water (IADW) is calculated according to equation (18).

$$\mathrm{IADW} = \frac{Pd}{P} \tag{18}$$

Where, Pd is Population without access to improved drinking water sources and P is Total population of the watershed.

2.2.2.3 Ecological Health (EH)

Ecological Health (EH) is measured by the Water pollution (WP) and Ecosystem impairment (EI) parameters. EH is estimated as follows:

EH = f (WP, EI).

With, WP is water pollution and EI is ecosystem deterioration.

2.2.2.3.1 Water Pollution (WP)

Water pollution (WP) can be estimated by the ratio of the total untreated wastewater flow discharged into water receiving systems to the total renewable water resources. The amount of untreated wastewater is estimated as the difference between the generated wastewater collected by the system and the amount of wastewater that received treatment using equation 19 [24]:

$$WP = \frac{\frac{WW}{R}}{0{,}1}, \qquad (ww<0{,}1*R) \tag{19}$$

$$WP = 1, \qquad (ww \geq 0{,}1*Rt)$$

Where, WW represents the total untreated wastewater; R is water resource per inhabitant and Rt denote total renewable water resources of the watershed.

2.2.2.3.2 Ecosystem Deterioration (ED)

The natural landscape is altered by socio-economic development activities, consequent urbanization, and vegetation removal. This phenomenon alters the hydrological properties of the land surface and can cause severe problems in supporting ecosystem function. Thus, Ecosystem Deterioration (ED) is defined as the ratio of the area of land without vegetation cover (e.g., the total area except that covered by pasture and cultivated areas) to the total land area of the Gbêkê region (9,136 km²). ED is expressed using equation (20):

$$ED = \frac{Ad}{A} \tag{20}$$

With, Ad, the area of land without vegetation cover and A, the total area of the watershed.

2.2.2.3 Management Capacity (MC)

Management Capacity (MC) assesses the vulnerability of water resources to three key issues: (1) water use efficiency, (2) human health regarding the accessibility of adequate services and sanitation, and (3) overall conflict management capacity. Thus, management capacity (MC) is measured with the parameter Inefficient Water Use (IWU), Improved Sanitation Inaccessible (ISI), and the parameter Conflict Management Capacity (CMC). This parameter is estimated as follows:

$$MC = f\,(IWU, ISI \text{ and } CMC) \tag{21}$$

Where, IWU is Inefficient Water Use; ISI represents Inaccessible Sanitation Improvement, and CMC indicates Conflict management capacity.

2.2.2.3.1 Inefficient Water Use

The integrated capacity of water use policy and technological innovation will impact water use in general. Inefficient Water Use (IWU) is estimated in terms of the financial contribution to the gross domestic product (GDP) of a cubic meter of water in one of the water-consuming sectors relative to the global average for a selection of countries [25]. Since the agriculture sector is the main water consumer in the Gbêkê region, it is used to indicate the financial return on water use.
Therefore, Inefficient Water Use (IWU) is calculated using the average watershed water use efficiency (AWWUE) and the value of the ratio of gross domestic product (GDP) produced from 1 m^3 of water and the total annual rainfall (TR) [26].

$$IWU = \frac{AWWUE - WU}{AWWUE} \qquad WE < AWWUE \tag{22}$$

$$\text{IWU} = 0 \qquad\qquad \text{WE} \geq \text{AWWUE} \quad (23)$$

With, AWWUE: Average WU of the watershed water and WU: Value of the ratio of the gross domestic product (GDP) produced from 1 m^3 of water and the total annual rainfall (TR) which represents the total available water resource. Thus, WU is denoted as follows:

$$\text{WU} = \frac{\text{GDP}}{\text{TR}} \quad (24)$$

2.2.2.3.2 Improving Access to Sanitation (IAS)

Access to sanitation is often dependent on the availability of surface water resources. A key objective of surface water management is to make water sources accessible to communities (rural and urban) to support their basic livelihoods. This translates into the inclusion of access to improved sanitation. Thus, the management system must make efforts to increase the availability of water sources to communities to meet their basic livelihood needs. Improved access to sanitation (IAS) is used as a typical value to measure the management system's capacity to address improved livelihoods by reducing pollution levels. Improved sanitation is defined here as facilities that hygienically separate human excreta from human, animal, and insect contact, including sewers, septic tanks, flush toilets, latrines, and simple pits [27]. Improved Access to Sanitation (IAS) is estimated as the ratio of the proportion of the population without access to improved sanitation facilities to the total population of the area and expressed as follows:

$$\text{IAS} = \frac{PWS}{P} \quad (25)$$

PWS is Population without access to improved sanitation and P: Total population of the watershed.

2.2.2.3.3 Conflict Management Capacity (CMC)

Conflict Management Capacity (CMC) demonstrates the ability of a water resources management system to deal with conflict. A good management system can be assessed by its effectiveness in institutional arrangements, policy formulation, communication mechanisms, and implementation efficiency [28]. The metric is defined here as the ability of the watershed to manage competition over water use between different consumptive sectors. The Conflict Management Capacity (CMC) is determined based on the assessment of the water survey and expert consultation using the conflict management capacity scoring criteria ranging from 0 to 0.25, considering the correlation of all variables. These aspects are assigned scoring criteria ranging from 0 to 1 weight given to each parameter.

2.2.3 Vulnerability Index (VI)

According to the guidelines, a weight of 0.25 is assigned to SR, PW, SH, and MC. For the parameters WS, SRv, OWR, IADW, WP, and ED, a weight of 0.5 is applied, while a weight of 0.33 is attributed to the parameters IWU, ISI, and CMC. The total weight assigned to all parameters in each category must equal 1. The vulnerability index (VI) was finally estimated based on the four categories using equation 24, providing an estimated value ranging from zero (not vulnerable) to one (most vulnerable) to determine the severity of stress experienced by the water resources in the study area. A high vulnerability index (IV) value shows high resource constraints, development pressures, ecological health, and low management capabilities. The total weight of the data to all categories must also be equal to 1 [29]. Finally, we have the following equation:

$$VI = \sum_{i=1}^{n} \left[\left(\sum_{j=1}^{mi} x_{ij} * w_{ij} \right) * w_i \right] \quad (26)$$

Where: n is the number of parameter categories;
mi: number of parameters in the category (SR, PW, SH, and MC);
Xij: values of the parameters WS, SRv, OWR, IADW, WP, and ED;
Wij; Weight given to the parameters WS, SRv, OWR, IADW, WP, and ED; and,
Wi: Weight given to the parameters (SR, PW, SH, and MC).

3. Results and Discussion

3.1 Analyses of rainfall indices from 1986-2017

Figure 1 exhibits the interannual variations in rainfall indices in the Gbêkê region, which includes the stations of Bouaké, Béoumi, Botro, and Sakassou. Overall, two major periods of rainfall fluctuations can be noted: a surplus and a deficit period, respectively. The surplus period runs from 1986 to 2004 for the Bouaké, Botro, Béoumi, and Sakassou stations. For each of these periods, the rainfall indices of the stations vary over the years and remain negative overall.

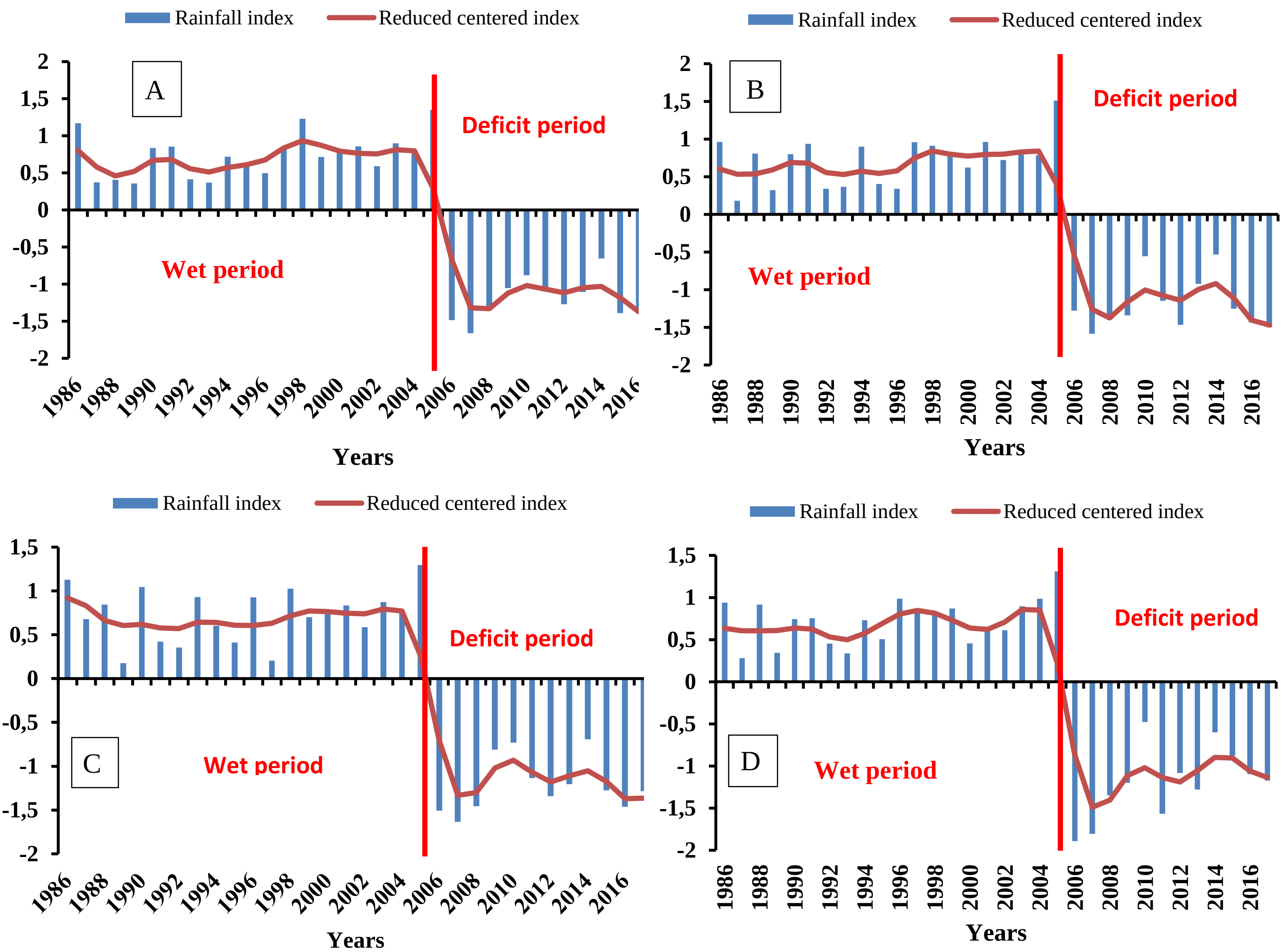

Figure 1. Interannual variation of rainfall index in the Gbêkê region: A: Bouaké station; B: Beoumi station; C: Botro station and D: Sakassou stations.

As for the deficit period, it evolved from 2005-2017 for Bouaké, Botro, Béoumi, and Sakassou. The results of Pettitt's test on rainfall data give 49, 44, 52, and 46% of the rainfall deficit to years. The break year at the stations in the study area is 2005 at the Bouaké, Béoumi Botro, and Sakassou stations.
The wet period can be explained by the models developed by the Intergovernmental Panel on Climate Change (IPCC) to describe climate change in the Bandama Valley, to which the study area belongs, which envisage an increase in temperature of around 3°C by 2030 that will be accompanied by a decrease in rainfall of around 16 to 20% [30-32]. The breaks are characterized by a rainfall deficit estimated at 49% for Bouaké, 44% for Béoumi, 52% for Botro, and 46% for Sakassou. These values are similar to those obtained in studies of which show that deficits vary between 40 and 53% [33-34].

3.2 Study of sub-basin vulnerability

The analysis of the vulnerability parameters of the Bandama Blanc 1, Bandama Blanc 2, Kan 1, Kan 2, Soungourou, and Loka sub-basin is presented in **Figure 2**. In general, the ecological health factor contributes the most to the vulnerability of the watersheds, followed by the water stress, management capacity and water use pressure factors, except for the Kan 1 watershed (**Figure 2 A**). The analysis of these results revealed a similarity between vulnerability levels of all factors in the Bandama Blanc 1 and Bandama Blanc 2 sub-basins, as well as those of Kan 1 and Kan 2 (**Figure 2 B**).

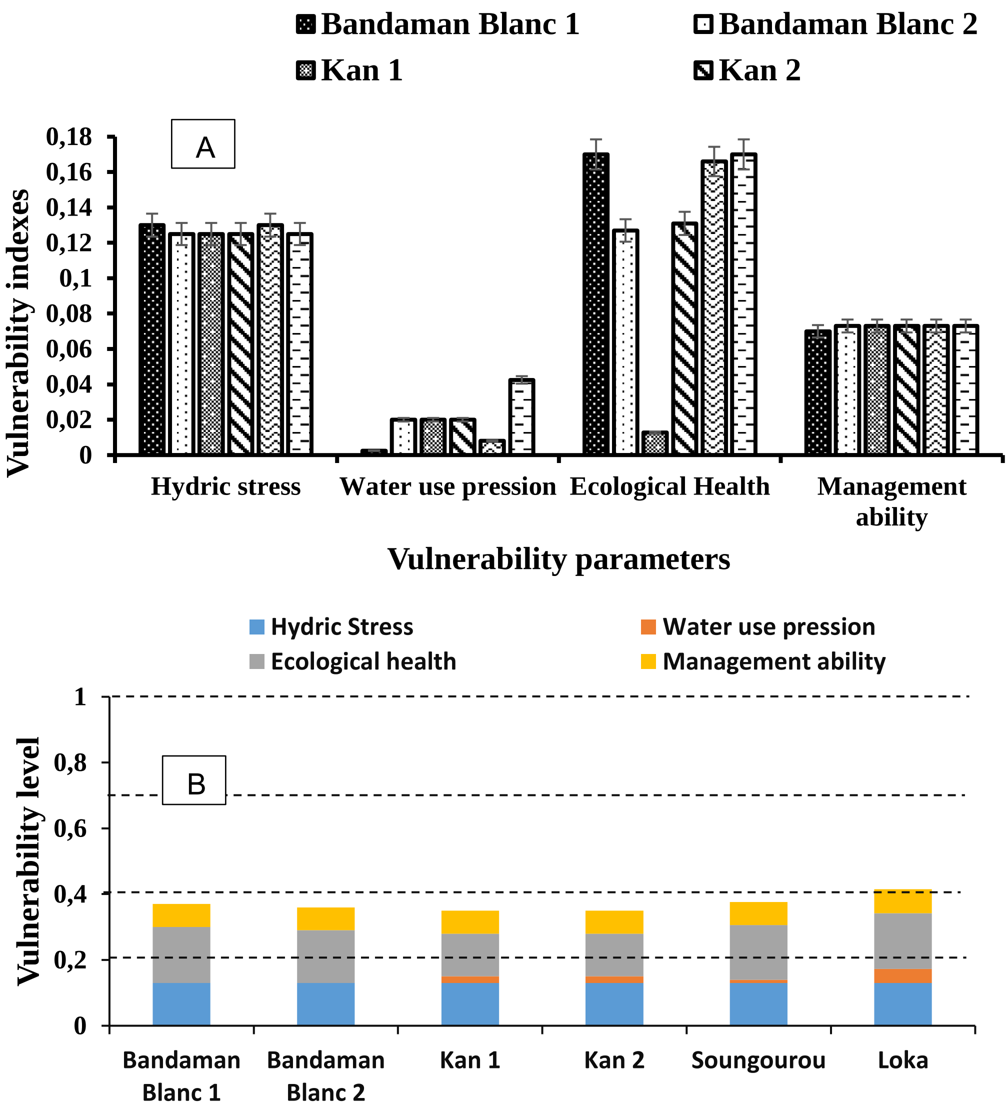

Figure 2. Vulnerability indexes of different sub-basin: A: Vulnerability parameters; B: Vulnerability level.

On the other hand, the results of the vulnerability index within the Soungourou sub-basin denoted that stress on the resource (SR = 0.125) and ecological health (EH = 0.166) has a strong effect on water resources vulnerability, while pressure related to water use (PW = 0.008) had a weak effect. Moreover, resource management capacity (MC= 0.073) contributes moderately to water resource vulnerability. In the Loka watershed, there is a strong influence of resource stress (SR = 0.125) and ecological health (EH = 0.17). At the same time, water use pressure (PW = 0.042) has a weak influence, and management capacity (MC = 0.073) has a moderate effect on water resource vulnerability. Given the analyses of the results of the stress and management capacity indices, the proportions are identical in all the sub-basins studied. The strong influence in the vulnerability of water resources would be explained by significant pollution and deterioration of ecosystems. Indeed, some authors demonstrated that the majority of households in the study area use dumping in nature as the preferred means of wastewater disposal [35]. This wastewater, loaded with pollutants, can be drained into surface waters, leading to pollution of the latter. This pollution can cause the eutrophication of surface waters [36].

3.4. Vulnerability mapping of water resources in the Gbêkê region.

The vulnerability map of water resources in the Gbêkê region is shown in **Figure 3**. Indeed, the analyses of the map showed that the watercourses having their sources in the Gbêkê region have both a moderate vulnerability in some sub-basins and a high vulnerability in others [37].

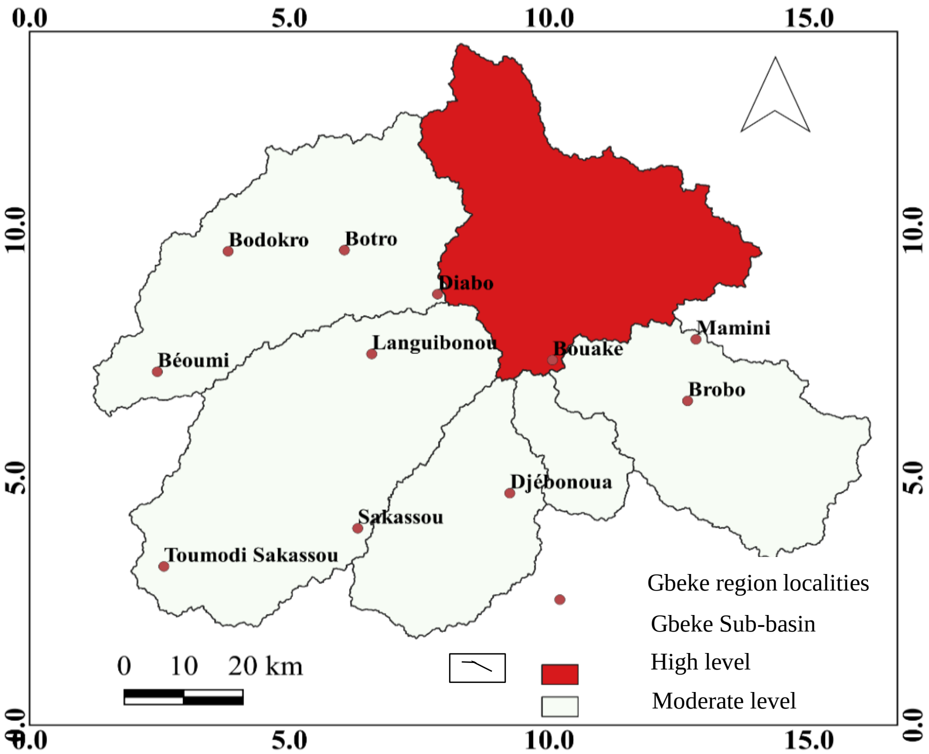

Figure 3. Vulnerability mapping of water resources in the Gbêkê region.

Conclusion

In this study, it emerged that a decrease in rainfall since 1986 generated significant deficits of the order of 18 to 33%. This led to the vulnerability of surface waters through water bodies drying up and the reduction of wetlands. Furthermore, the factors affecting the vulnerability of surface water resources in the Gbêkê region can be classified into four categories: (1) resource stress (water stress and water variation), (2) water use pressure (overexploitation of water resources and accessibility of drinking water supply), (3) ecological health (water pollution and ecosystem deterioration), and (4) management capacity (inefficient water use and inaccessible sanitation improvement). The study showed that ecological health is the most important factor affecting water resource vulnerability. It is reflected in the lack of wastewater treatment and deforestation and land degradation which are accelerating factors of climate change. This study, therefore, determined the vulnerability index to climate change of the different sub-watersheds of the Gbêkê region. The vulnerability index analysis showed that the Loka sub-watershed is the most vulnerable and would be the priority area for any intervention of public policies to adapt the water resources sector to climate change.

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Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

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