



# Hydro-Climatic Variability and Human Activities Impact on the Morphology of the Cavally River Bed, Western Côte d'Ivoire

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## Abstract

The Cavally watershed is covered by a large forest area, where for decades there has been intense agricultural and mining activity (modern and traditional). Anthropogenic pressures and hydro climatic variability can significantly alter the hydrological response of the Cavally River watershed. The objective of this study is to assess the impact of hydro climatic variability and land-use dynamics on the availability of water resources in the Cavally River basin. To achieve this objective, two methodological approaches were used, a first approach was used to calculate the rainfall and hydrometric indices to determine the different hydro-climatic trends of the watershed. The second approach consists in analyzing the inter-annual morphological evolution of the bed of the Cavally River by using Landsat images from 1986s, 2011s and 2018s. The results of this study show that several successive years of drought were observed in the Cavally Basin from 1970 to 1980. Analysis of hydro-climatic trends showed that rainfall has declined, and the land use map analysis showed that the vegetation cover has been significantly degraded (Four common land use classes were finally mapped. They are represented by dense vegetation with 13.11%; degraded vegetation and crops with 72.04%; water with 4.73%; built areas and bare soils with 10.12%). About the evolution of the Cavally River bed, illegal gold miners could be the cause of the increase in the surface area of the water body located between the SMI and the Floleu village (Section 3 where the morphology of the Cavally River bed has increased considerably by 13.70% between 1986 and 2011 and by 55.93% between 2011 and 2018). Indeed, this area is frequented daily by gold miners who carry out their activities both in the minor bed and on the banks of the river.

## Subject Areas

Hydrology

## Keywords

Land Cover, Hydro Climatic Variability, Human Activities, Cavally River, Côte d'Ivoire

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## 1. Introduction

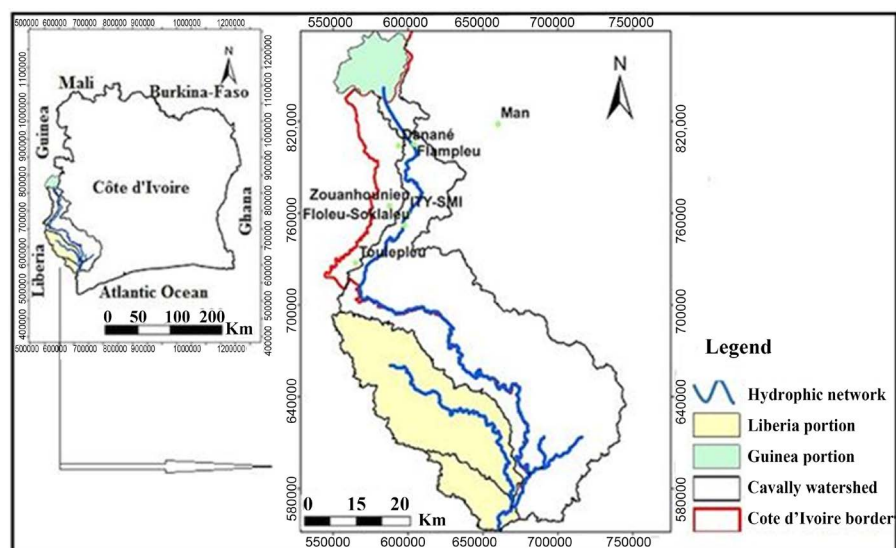
Water environment deterioration is a prominent issue in river basin management throughout the world, which has become a serious threat to water security [1]. Surface water was gradually polluted due to natural and anthropogenic activities [2], such as water-rock interactions [3], industrial and municipal waste water emissions [4], nutrient losses [5], excessive dam and sluice constructions [6]. Water resources are sensitive to climate change and variability [7]. In recent years, the question of hydro-climatic variability is a challenge for the world and for African Countries in particular. It is explained by factors inherent to the climate system and the climatic variability greatly affects water resources with consequences on various sectors of activity [8]. Also, the hydrological cycle and water systems are extensively influenced by climate variability and human activities [9] [10] [11] [12]. Also, changing weather patterns will have complex and nonlinear impacts on many human and environmental systems, including on processes governing the mobilization and transport of sediment within watersheds [13]. Changing climate is an additional stressor that can enhance the effects of these anthropogenic influences [14]. For example, higher temperatures lead to increased evapotranspiration and thus, if not counterbalanced by increased precipitation, to declining streamflow [15] [16]. The Cavally watershed is covered by a large forest area, where for decades there has been intense agricultural and mining activity (modern and traditional). As mining activity is a source of considerable environmental and health impacts and issues, which vary according to the ecological context, extraction methods and type of ore, codes are very important to regulate this sector [17]. Despite the measures taken by the State, this sector is facing several difficulties, particularly those related to gold panning. The illegally artisanal gold mining activity is a very lucrative activity in which many actors, operating at various levels and with specific roles, find their financial benefit [18]. The other causes of the development of clandestine gold mining are the under-selling of traditional agricultural products (cocoa and coffee) and the ignorance of the negative medium and long-term impacts of gold panning on the biophysical and human environment by most of the actors involved in the sector. The latter aspect is observed in Zouan-Hounien, in the west of Côte d'Ivoire where the bed of the Cavally River stream is the place where this activity is developed. Gold panning is not in itself a bad activity, but the tech-

nologies used, the technologies used are not adapted and the tools are rudimentary (“hunter-gatherer” approach). This new way of practicing gold panning raises questions about the impacts of this activity on certain characteristics of the watercourse (velocities, flow, etc.). The objective of this study is to assess the impact of hydro climatic variability and land-use dynamics on the availability of water resources in the Cavally River basin.

## 2. Material and Methods

### 2.1. Study Area

The Cavally River is a lower cross border watershed between Guinea, Ivory Coast and Liberia. Located in the west of Ivory Coast, the Cavally River begins in Guinea, in the North of Mount Nimba with more than 1000 meters as approximate altitude (**Figure 1**). 700 km long, its riverbed constitutes the border between Liberia and Ivory Coast from its middle way (at the South of Toulépleu) on about 330 km. The lower watershed covers a complete area of 28,800 Sq. Km at Tate hydrometric station located at 60 km from the mouth. Côte d’Ivoire doesn’t possess but about 15,000 Sq. km of watershed [19]. In the framework of this study, the chosen outlet is the hydrometric station of Floleu located at downstream of the Ity station in the Zouan-Hounien region. The low watershed has got an area of 3647.53 Sq. km (**Figure 1**). The region of Zouan-Hounien is in the mountain region of Côte d’Ivoire; its relief is hilly. Zouan-Hounien is in the forest area and its climate is the mountain climate with two seasons: one rainy season from May to October and one dry season from November to March. The annual average temperature is 25.6°C. The annual average precipitation is 186 mm. The driest month is January with a precipitation of 15 mm. The most important precipitations are recorded in September and they are 357 mm in average.



**Figure 1.** Study area of sub-watershed of Cavally River.

## 2.2. Data Collection and Analysis

The methodological approach used is based on annual rainfall data. The rainfall data used are those of Danané, Toulepleu and Zouan-Hounien meteorological stations and three (3) hydrometric stations (Flampléu (Danané), Ity (Zouan-Hounien) and Toulepleu). They cover the period 1970-2010. To carry out this study, two methods were used: a first approach was used to calculate the rainfall and hydrometric index to determine the different hydro-climatic trends of the watershed. The study of hydro-climatic variability was carried out by analysing data collected at the stations. Based on the rainfall variability, periods of rainfall deficit over time and space have been identified. The second approach consists in analyzing the inter-annual morphological evolution of the bed of the Cavally River.

## 2.3. Index Precipitation Methods

The evolution of precipitation and runoff was carried out by the method of calculating the NICHOLSON rainfall index (Equation (1)) and the low-pass filter method of "HANNING of order 2" (Equation (2)) where they expressed by the following equations.

$$I = \frac{x_i - \bar{x}}{\sigma} \quad (1)$$

with  $I$ : rainfall or hydrological index,  $x_i$ : annual module of the variable recorded during year  $I$ ,  $\bar{x}$ : interannual mean of the variable over the period of study,  $\sigma$ : standard deviation of the hydro-climatic series over the period of study. For HANNING'S Low Pass filter method, the first step is to filter the data to eliminate seasonal variation. This filter is made using the recommended equations. According to this method, each term in the series is calculated as follows:

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

$X(t)$ :  $X(t)$  is the weighted rainfall total of the term  $t$ ;  $X_{(t-2)}$  and  $X_{(t-1)}$ : total observed flows of two terms immediately preceding the term  $t$ ;  $X_{(t+2)}$  and  $X_{(t+1)}$ : observed rainfall totals of two terms immediately following the term  $t$ . 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 (being the size of the series):

$$X_1 = 0.54x_1 + 0.46x_2 \quad (3)$$

$$X_2 = 0.25x_1 + 0.5x_2 + 0.25x_3 \quad (4)$$

$$X_{n-1} = 0.25x_{(n-2)} + 0.5x_{(n-1)} + 0.25x_n \quad (5)$$

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

To better visualize periods of a deficit and excess flow, moving averages are centered and reduced by the following formula:

$$Y'_i = (x_i - m) / \sigma \quad (7)$$

where:  $m$  is the average of the series of weighted averages and  $\sigma$  is the stan-

dard deviation of the series of weighted moving averages.

#### **2.4. Decadal Variability of Rainfall over the Basin**

The annual average rainfall distribution was calculated by the isohyet method over the period 1970 to 2010.

Rainfall data from stations in the basin and surrounding areas made it possible to trace the isohyets of the 1971-1980, 1981-1990, 1991-2000 and 2001-2010 decades. They are prepared with the maximum likelihood that considers the region, the hydrographic network and the quality of the measurements.

#### **2.5. Morphological Evolution of the Cavally River Bed**

The satellite images are made up of three scenes from the Landsat sensor (Land Satellite) from the website <http://earthexplorer.usgs.gov>. The scenes use the visible (B, R, V) and near infrared bands were taken on January 07, 1986, January 12, 2011 and January 22, 2018 respectively. This month's choice (January) allows the river environment to the same season and to minimize the risk of over-or underestimating the contours of the reservoir. Indeed, the surface area of a water body may also be underestimated by the presence of aquatic vegetation or overestimated by the presence of wet soils surrounding the water bodies during the recession period [20]. In addition, Landsat 4.5 and 8 satellites provide images that include near-infrared spectral bands. This is very important because water surfaces absorb all this type of radiation [20]. The image processing consisted in making the coloured composition of the different images, vectorizing the contours of the plan each year and validating the vectorizations. About the colour composition, the bands used are respectively bands 4; 5 and 6, for the 2018 and 3 satellite images; 4 and 5 for the 2011 and 1986 images. These bands were used for the red, green and blue channels respectively. This classification brings out the different entities of the image as well as possible. The outline of the watercourse was delimited by digitalization (vectorization) using a GIS tool. The digitalization consisted, from each image used, in reviewing the outlines of the watercourse. A validation of the vectorization layers is required after the realization of these layers. Thus, the 2011 and 2018 contour vectorizations were respectively checked with the ortho image of 03/12/2012 and the Google earth image of 19/01/2018. To do this, segments parallel to the horizontal (transverse) were drawn and measured at precise and easily identifiable locations on the map, including areas of curvature. Cross-sectional segments prevent errors related to the length of the segments that could be caused by the existence of different measuring angles. The plots were validated if and only if the difference between the lengths of the segments measured on the reference images and the vectorized layers is less than 5%. Otherwise the vectorizations are taken over and the segments are recalculated. After the map was validated, sections were defined to evaluate the area most affected by the gold panning phenomenon. A total of five sections were defined on the stream; one upstream section of the study area,

three sections in the study area and one downstream section of the study area. The area of each section of the stream for the three years (1986, 2011 and 2018) was determined using the GIS tool. Indeed, the calculation of surfaces is a statistical method for estimating the level of evolution of the river bed [20].

$$I(\%) = \frac{S_f - S_i}{S_i} \times 100 \quad (8)$$

where,  $I$  is increase area (%),  $S_f$  et  $S_i$  (Sq Km) are the surfaces calculated for the final and initial years considered.

**Figure 2** shows a summary diagram of all the activities carried out to achieve the interannual morphological evolution of the Cavally river.

### 3. Results and Discussion

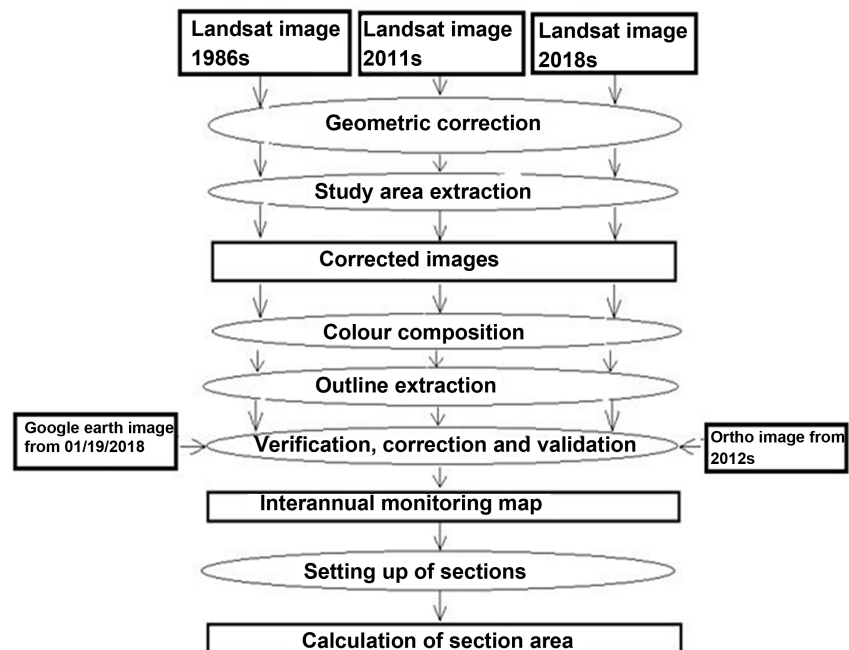
#### 3.1. Distribution of Annual Rainfall from the Cavally Watershed

**Figure 3** shows the distribution of annual rainfall from the Cavally Basin. The average annual rainfall from the Cavally Basin is  $1804.29 \pm 47.63$  mm.

#### 3.2. Decadal Variability of Rainfall of the Cavally Watershed

The study of decadal rainfall variability from the isohyets of the 1971-1980, 1981-1990, 1991-2000 and 2001-2010 decades shows a general increase in rainfall for the 11 rainfall stations (**Figure 4**).

The decade 1971-1980 was made by the presence of isohyets characteristic of rainfall amounts between 1500 mm and 1850 mm. The rainfall stations of Toulepleu, Guiglo and Bangolo are the only ones with the lowest rainfall (1500 mm);



**Figure 2.** Conceptual diagram of the implementation of the inter-annual evolution of the bed of the Cavally River watercourse.

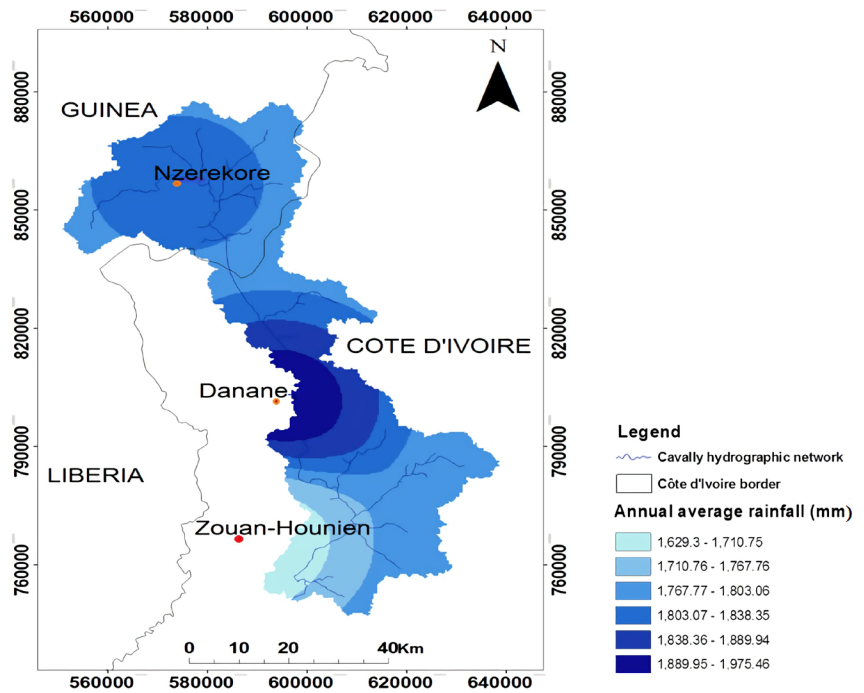


Figure 3. Annual average rainfall of Cavally sub watershed (1970-2010).

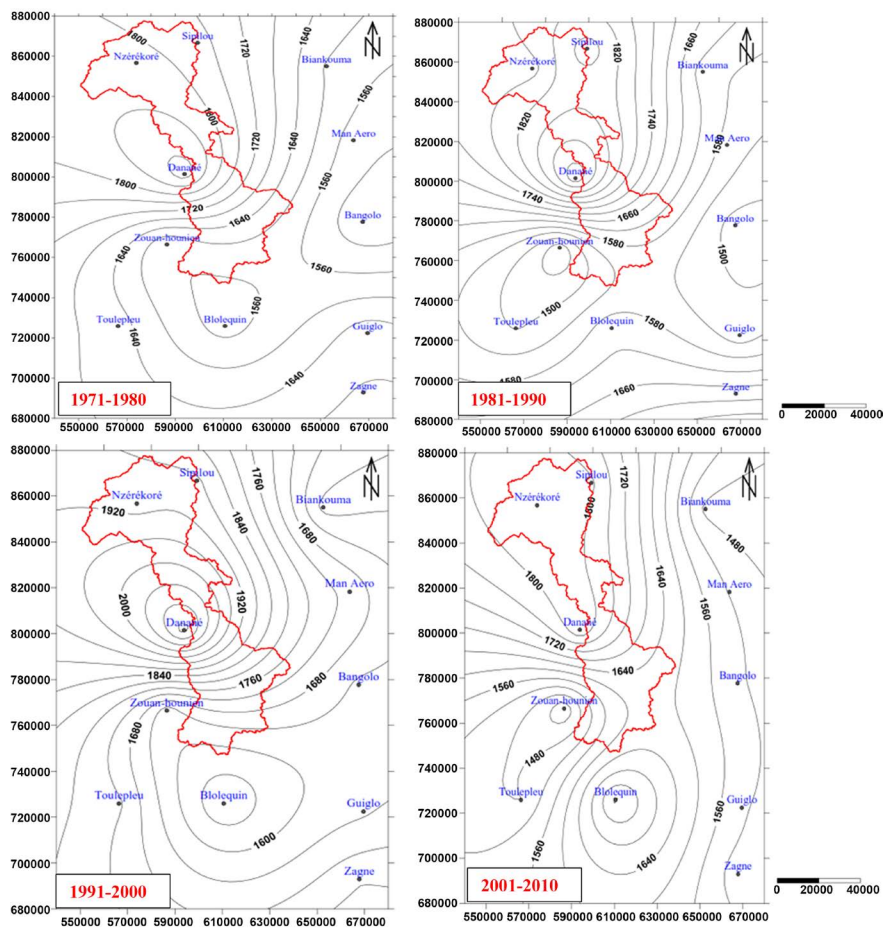


Figure 4. Maps of the decade isohyets 1971-1980, 1981-1990, 1991-2000 and 2001-2010.

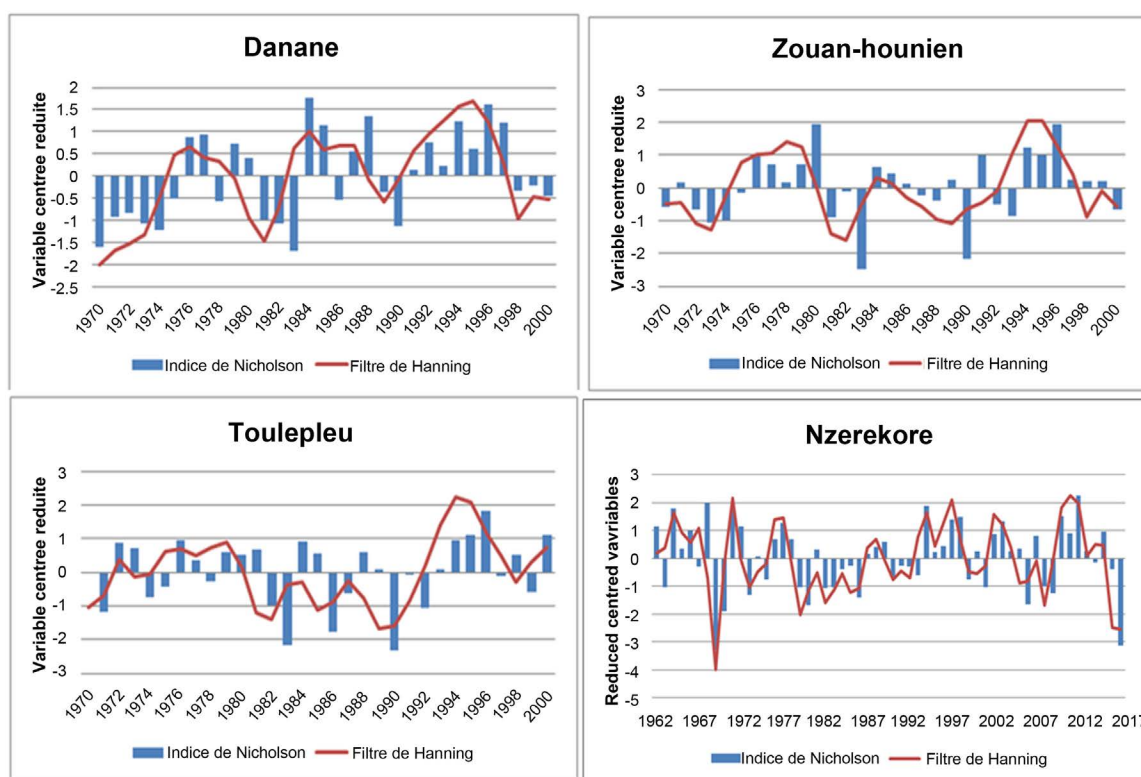
the other stations receive rainfall amounts between 1600 and 1850 mm. The decade 1981-1990 saw an increase in rainfall with the appearance of isohyets 1700 mm, 1850 mm and 1900 mm. The decade 1991-2000 also saw an increase in rainfall with the appearance of isohyets 1950 mm and 2000 mm in the Danané and Taï areas. The decade 2001-2010 also recorded an increase in rainfall similar to the decade 1991-2000 with the appearance of the 1950 mm and 2000 mm isohyets.

This could be explained by the return to normal rainfall in western Côte d'Ivoire, following the major rainfall breaks observed in West Africa from the 1960s and 1970s.

### 3.3. Index Precipitation

The evolution of Nicholson indices associated with seasonal elimination by HANNING filter shows that inter-annual variations in rainfall at the Nzerekore, Danané, Zouan-Hounien and Toulepleu stations are characterized alternating wet, normal years and dry season.

The analysis of the Nicholson indices and the 2nd order HANNING filter makes it possible to distinguish 3 climatic trends at the Toulepleu station: from 1971 to 1980 for wet period, 1981 to 1992 dry season and 1993 to 1994 to 1998 wet season. 3 periods for wet season and 4 dry periods at Danané station. 3 periods for wet season and 4 dry periods at Zouan-Hounien station. Trends at the Nzerekore station vary rapidly from one period to another (**Figure 5**).



**Figure 5.** Annual rainfall for four stations from Cavally watershed.



### 3.4. Inter-Annual Variation in Flows of the Cavally River

Flampleu station was chosen to monitor the hydrological variability of the Cavally watershed for the length of its series. The evolution of the reduced centred indices and Hanning filtering makes it possible to distinguish the periods of fluctuations from the following annual flow modules (**Figure 6**):

- a deficit period from 1974 to 1991, marked by a sharp drop in flows indicating a dry period;
- a surplus period from 1992 to 1999, corresponding to a wet period marked by abundant flows;
- a deficit period from 2001 to 2011, indicating a dry period with a considerable decrease in flows;
- a surplus period from 2012 to 2015, announcing a return of humidity at the end of the observation period.

### 3.5. Morphology of the Cavally River Bed

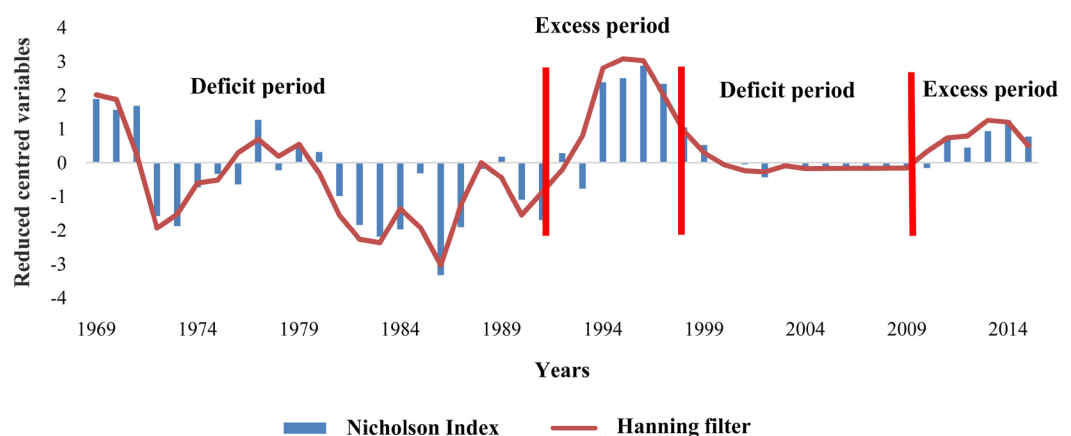
#### 3.5.1. Land Use Map of the Study Area

Four (4) common land use classes were finally mapped (**Figure 7**). They are represented by dense vegetation with 13.11%; degraded vegetation and crops with 72.04%; water with 4.73%; built areas and bare soils with 10.12%. Discrimination between the different thematic classes is statistically significant with overall statistical accuracy ranging from 80.5% to 82.2%.

#### 3.5.2. Dynamic Evolution of the Cavally River Bed

**Figure 8** shows the deformations of the streambed in this area on these three dates. The bed of the Cavally River stream in the Zouan-Hounien area underwent a change from 1986 to 2018. The contours of the Cavally River from 1986 (yellow) and 2011 (red) are very similar. Some deviations from these contours are observed in some areas of the watercourse. However, the contours of the 2018 watercourse (blue) show remarkable deformations.

**Figure 9** shows the illegal gold miners operating and degradation of the bank of the Cavally River due to this activity.



**Figure 6.** Variation of annual modules of the Cavally River flows to Flampleu Station (1969-2015).

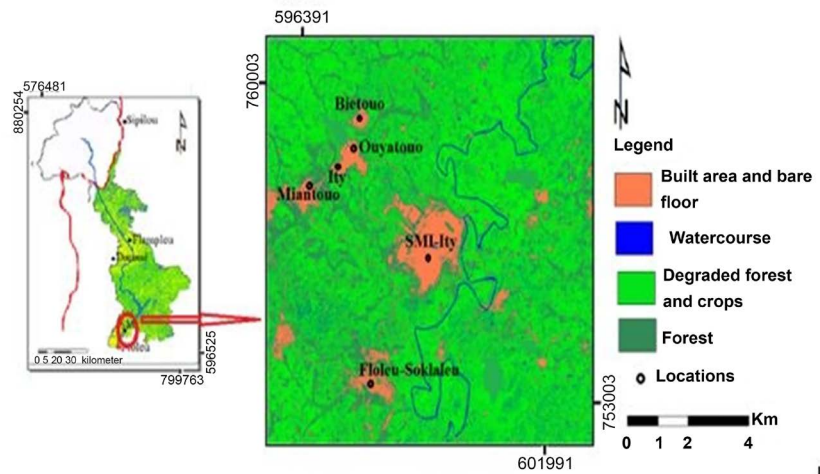


Figure 7. Land use map of the study area.

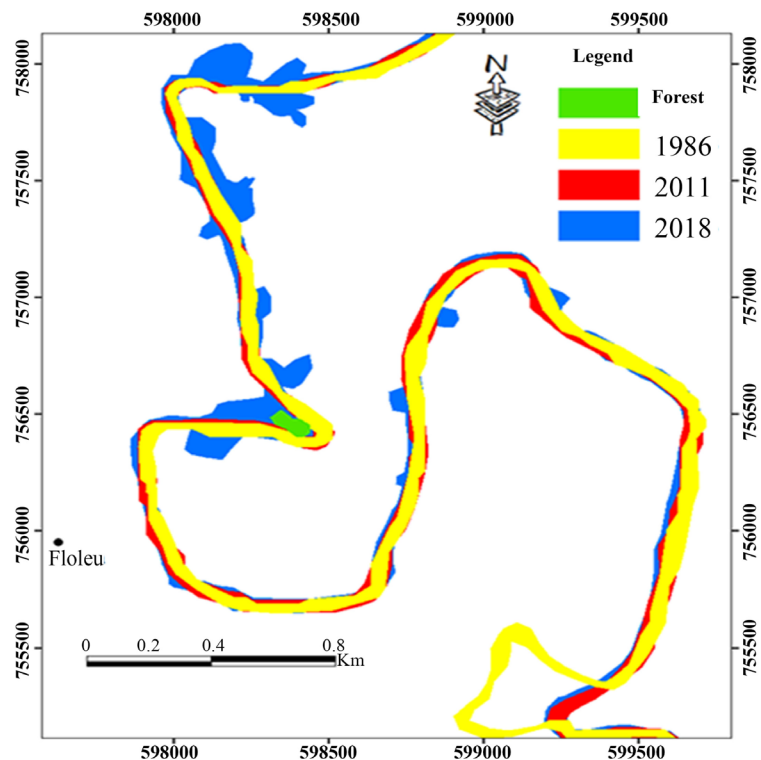


Figure 8. Inter-annual monitoring map of the Cavally River streambed from 1986, 2011 and 2018 in Section 3.

### 3.5.3. Evolution of the River Bed

The areas of the sections of the stream increased from 1986 to 2018. From 1986 to 2011, the surfaces of the sections increased from 3.33% to 18.18%. Sections 2 and 3 have a surface change of more than 10%, which are 18.18% and 17.65% respectively. Between 2011 and 2018, the increase in section surfaces ranged from 19.35% to 55.00%. The rates of increase in Sections 1 and 5, which are 17.65% and 12.50% respectively, are the lowest, while the rate in Section 3 (55.00%) is the highest (Table 1).



**Figure 9.** Degradation of the banks of the Cavally River due to illegal gold panning activities.

**Table 1.** Summary table of section surfaces.

		Area (Sq Km)			Increase area (%)	
		1986	2011	2018	1986-2011	2011-2018
<b>Upstream</b>	Section 1	0.30	0.31	0.37	3.33	19.35
	Section 2	0.11	0.13	0.16	18.18	23.08
<b>Study area</b>	Section 3	0.17	0.20	0.31	17.65	55.00
	Section 4	0.39	0.41	0.51	5.13	24.39
<b>Downstream</b>	Section 5	0.30	0.32	0.36	6.67	12.50

The dynamics of the Cavally River watercourse in the study area were determined using Landsat images. These types of images, with very high resolutions (30 m of resolution), have made it possible to establish, with sufficient precision, the annual interannual monitoring of the Cavally River. Mapping water bodies using Landsat images is an accurate method, both recent and old. Thus, in Burkina Faso and Tunisia, for monitoring the configuration of water bodies over several years, [20] [21] [22] used these types of images. However, the vectorization of the contours of the water body remains a rather tedious task to accomplish because of the quality of the image. This generally leads to an underestimation or overestimation of the volume of the water body. To overcome these consequences, orthophotos and aerial photographs are needed to facilitate the estab-

ishment of water body boundaries [23] [24]. Since these two types of photographs have a relatively low spatial resolution (0.5 m resolution), this would make it possible to differentiate between the different elements of the earth's surface and to highlight water bodies and vegetation clearly.

In general, the validation of results from GIS processing is carried out through field visits [25] [26]. In this study, the data used to validate the different contour layers are of a cartographic type. However, they were very satisfactory because the distances between the distances of the sections measured on the vectorized maps and the validation maps are almost zero, less than 1%. Nevertheless, a field visit would be more advantageous in the context of a more comprehensive study. About the evolution of the riverbed, illegal gold panning could be the cause of the increase in the surface area of the water body located between the SMI and the village of Floleu (Section 3). Indeed, this area is frequented daily by gold miners who carry out their activities both in the minor bed and on the banks of the river. [18] [27] argue that clandestine gold mining weakens soils, gradually destroys Arab lands, destabilizes banks and predisposes the soil to often intense erosion processes. Indeed, artisanal gold mining is generally accompanied by the opening of trenches, wells, scraping and turning the soil. Given the flow rate and flow velocity of the Cavally River, the presence of these trenches would indeed favor the erosion of the banks and therefore the deformation of the bed of the watercourse.

#### **4. Conclusion**

This study showed that the vegetation cover has deteriorated considerably (four common land use classes were finally mapped). They are represented by dense vegetation (13.11%; degraded vegetation and crops (72.04%); water (4.73%); built areas and bare soils (10.12%)), the climate has been highly variable with a succession of dry and wet periods. The Cavally River watershed is subject to significantly hydro-climatic variability. This variability could have a significant impact on the water resources of the watershed. In recent years (2011s to 2018s), the Cavally River bed has undergone very significant modifications due to the massive presence of illegal gold panners operating in the bed with a degradation surface ranging from 13.70% between 1986 and 2011 to 55.00% between 2011 and 2018. Given the importance of the flows and flow rates of the Cavally River, the presence of trenches dug by these illegal gold panners would favor the erosion of the banks and therefore the deformation of the bed of the watercourse.

#### **Conflicts of Interest**

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

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