Full Length Research Paper

Study of the fluctuation of the NDVI in the Casamance River Basin upstream of Kolda using remote sensing data: what impact on flow?

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Abstract. Changes in land use and land cover have attracted considerable scientific interest in recent years because of their marked influence on hydrological cycles. In the tropics, widespread vegetation degradation and changes in land use that occurred from the 1970s onwards have affected the hydrological dynamics of catchments. In this study, land cover changes in the Casamance catchment upstream of Kolda in recent years were analysed and their role in hydrological evolution was estimated. These changes had occurred in environmental conditions between 1987 and 2018. Remote sensing and geographic information system (GIS) techniques were used to monitor changes in the basin as well as changes in NDVI values. Landsat 5 and 8 satellite images were used respectively. The extraction of land cover in the basin was carried out through the application of unsupervised nesting classification processes. The results indicated that a regression of forest cover in the Casamance River Basin upstream of Kolda and the classification of the area into seven main land categories (forest, savannah, slash-and-burn, cultivated areas, habitat, plantations and water) was significant. Like rainfall, the flow rates, which declined during the 1980s, increased from the 2000s onwards, although the trend was not significant. This increase in runoff is the result of vegetation degradation and increased rainfall. The results highlight the importance of integrating land use information into assessments of water availability in a region where water is a strategic resource.

Keywords: Casamance Basin Basin, GIS, NDVI, Remote Sensing, Supervised Classification

1. INTRODUCTION

Climate change indicates the trend towards a global and multi-year increase in the average temperature of the oceans and the atmosphere, a decrease in the amount and duration of rainfall in some regions, and an increase in natural disasters and extreme events (droughts, floods, etc.) (IPCC, 2007; IPCC, 2013). Global warming combined with increased variability in rainfall is leading to an increase in extreme events, particularly floods and low water levels, which will increase in frequency and intensity across the African continent. Various studies highlight the evolution of river flows and the impacts on natural and human systems in the territories during the recent period. The extent and reality of this evolution depends on the regions and hydro-climatic conditions (Faye et al., 2015).

Africa is at the forefront of the issue of the impact of climate fluctuations on water resources (Kanohin et al., 2009). Several studies carried out in West and Central Africa have highlighted, from the 1970s onwards, a decrease in surface and underground runoff following the drop in rainfall (Faye, 2013; Faye et al.. 2015), and, from the 1990s, an increase in runoff (Hountondji et al., 2009; Ouoba, 2013), which augurs well for an improvement in the hydrological regime in this area,

Drought, which is characterized by a reduction or poor distribution, or even absence of rainfall in a given area for a period of time (Bootsma et al., 1996), is primarily meteorological. It is then hydrological and agricultural. Drought is a natural phenomenon that poses many problems throughout the world insofar as it requires enormous demands on natural resources, particularly water resources (Barua et al., 2009). While in the past, drought was associated only

with arid, semi-arid and desert fringes when the definition was based solely on absolute amounts of precipitation (Omonijo and Okogbue, 2014), today it occurs in areas of high and low precipitation and in virtually all climatic regions. Drought is now associated with the onset and cessation dates of rainfall and the length of the rainy season. Thus, it is better defined as the inefficiency of rainfall.

In addition to interest in climatic factors, there has been particular interest in recent decades in land use and land cover changes, because of their potential to alter the hydrological cycle (Kundzewicz et al., 2007). Although the physical properties of River Basins, including topography and lithology, can control the process of water infiltration, they are stationary at the temporal scale over which hydrological analyses are conducted (Mora'n-Tejeda et al., 2012). Nevertheless, vegetation cover and land use evolve on the same temporal scale as human activity and therefore affect the availability of water resources for populations through their influence on runoff. The relationship between vegetation cover and hydrology has been the subject of scientific research since ancient times (Andre'assian, 2004).

In recent years, studies of experimental River Basins have shown that land and forest cover affect the water cycle and water balance by participating in processes associated with infiltration and precipitation distribution (Llorens and Domingo, 2007). At local and global scales, vegetation cover is involved in infiltration, interception and evapotranspiration processes (Zhang et al., 2001; Cosandey et al., 2005), and land use changes that increase vegetation cover generally result in decreased runoff, while vegetation removal tends to increase river flow in basins (Bent, 2001; Gallart and Llorens, 2003). Both natural and anthropogenic land use changes in the Sahel (reduction in vegetation cover, increase in cultivated areas and densification of the drainage network) have led to a faster concentration of water, increased flooding and reduced base flow, despite the decrease in rainfall in the Sahel: this is the "Sahel hydrology paradox" (Descroix et al., 2009).

Prolonged conditions of rainfall and hydrometric deficits since the 1970s have been highlighted throughout the Casamance catchment area (Dacosta, 1989; Faye, 2019). The lands of Casamance are described as rich soils with high productivity due to their physical and chemical conditions and high fertility (Mballo, 2016). This is due to the availability of suitable water for agricultural production. This agricultural land in Casamance is considered one of the most important natural and economic resources. However, the deterioration of agricultural land due to climate change and anthropogenic effects (amendment of agricultural land and fragmentation of plots) is one of the most serious problems noted there (Mballo et al., 2019). The Casamance River Basin upstream of Kolda was chosen in this study because of its agricultural character with rich water bodies. The different land-use units identified on the landscape were monitored and changes in the areas over the last 30 years were interpreted using satellite image processing.

With the development of remote sensing technology, it is possible to monitor changes in land cover. Therefore, it is possible to apply some of the techniques of remote sensing and geographic information systems to monitor the effect of certain climatic factors on land cover deterioration (Al-Obaidy and Al-Baldawi, 2019). This study, which focuses on the Casamance River Basin upstream of Kolda, aims to: identify the changes that have occurred in the landscape, by analysing the results of processing satellite images from the years (1987 and 2018). The process here consists of a multi-temporal analysis of the normalized difference vegetation index (NDVI), which makes it possible to interpret vegetation dynamics and the effect of climatic factors on the environment, particularly the study area (Casamance basin upstream of Kolda). The results of satellite image processing were combined with statistical analysis of hydrological and climatic series using a set of stations located in the Casamance basin.

2. MATERIALS AND METHODS

2.1. Study Area

The Casamance basin, which extends over three administrative regions (Ziguinchor, Sédhiou and Kolda), in the south of Senegal, is situated in latitude between 12°20' and 13°21' North and in longitude between 14°17 1 and 16°47' West. i It covers an area of approximately 20150 km2, stretching from West to East over 270 km, and from North to South over 100 km (Dacosta, 1989). It has an Atlantic Sudanian and South Sudanian climate (Sané et al., 2011) and is strongly influenced by geographical and atmospheric factors (Sagna, 2005). The Casamance basin can be subdivided into three parts: the upper basin (Upper Casamance), the middle basin (Middle Casamance) and the lower basin (Lower Casamance). From a topographical point of view, the Casamance River Basin is characterized by its low relief. Indeed, all the rivers originate from the plateau of the terminal Continental and the weakness of the slopes explains the deep invasion of the sea inside the Casamance basin causing the salinization of agricultural land (PADERCA, 2008).
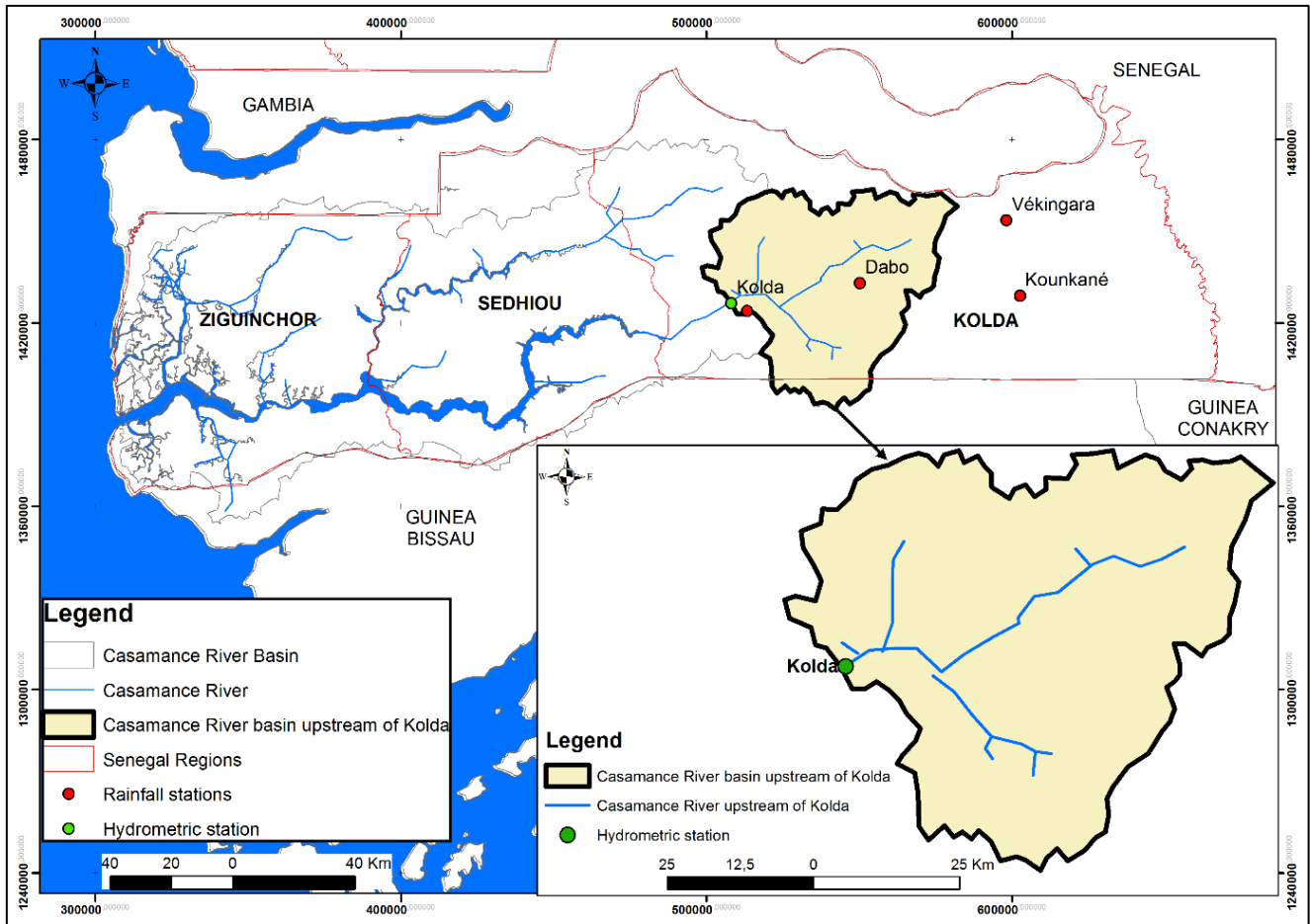
Figure 1. Location of the Casamance River Basin upstream of Kolda and the study stations

The Casamance River Basin upstream of Kolda has a surface area of 3650 km2 with a maximum altitude of 80 m and a minimum altitude of 10 m. An analysis of the data in Table 1 shows that the Casamance basin upstream of Kolda has a relatively elongated shape ($_{KG}$: 2) with gentle slopes (Ig: 0.36 m/km)). In this basin, rainfall is highly variable and its evolution in Kolda makes it possible to distinguish three periods: a relatively wet 1930-1971 period, a relatively dry 1972-2002 period and a third decade characterized by a return to wet conditions (Bodian et al., 2015).

2.2. Data
2.2.1. Satellite data
In order to study land use dynamics in the Casamance catchment upstream of Kolda, two dates of Landsat image capture are used (Table 1). The first date dates back to the dry period (late 1980s), and the second corresponds to the current period considered as relatively wet (2018). Two scenes are required to cover the entire basin (P204r051 and P203r051) with the advantage of covering the entire study area. In addition to their resolution, which is quite sufficient, the images are available for free download on http://earthexplorer.usgs.gov/.
Data processing was carried out using Idrisi TerrSet software for satellite image processing, and ArcGIS 10.5 for area calculation and map layout. A GPS is used to take geographical coordinates in the field.

Table 1. Landsat satellite images used

Year	Date	Path	Row	Satellite	Sensor	Spatial resolution
1987	20 Nov 1987	204	051	Landsat 5	TM	30 m
	15 Dec 1987	203				
2018	09 Jan 2018	204	051	Landsat 8	OLI_TIRS	30 m
	18 Jan 2018	203				

2.2.2. Rainfall and hydrological data

For this study, analysis of rainfall data from Kolda, Velingara, Dabo and Kounkané stations from 1960 to 2016 are used to characterize climate variability in the Casamance basin upstream of Kolda (Table 2). As for the temperature data, they concern only the Kolda Station. All these climatic data come from the National Agency of Civil Aviation and Meteorology (ANACIM). For the impacts of climate variability on water resources in the basin, the hydrological station of Kolda from 1965 to 2008 is used. However, the hydrological data come from the Directorate of Water Resources Management and Planning (DGPRE).

Table 2. Rainfall stations in Senegal selected for the study and their characteristics

Rainfall stations	Latitude	Longitude	Altitude	Study period
Kolda	12°53'	14°58'	35	1980-2016
Velingara	13°09'	14°06'	38	1980-2016
Dabo	12°52'	14°08'	40	1980-2016
Kounkané	12°56'	14°05'	33	1980-2016
Hydrometric station	**Latitude**	**Longitude**	**Altitude**	**Study period**
Kolda	12°53'	14°56'	1,62	1980-81 - 2007-08

For the study of the spatial variability of drought, a number of indices, usually used by forecasting services, have been selected.

2.3. Methods
2.3.1. Methods of processing geospatial data

Land use is a physical description of the space covering the ground (vegetation, bare soil, hard surfaces, wet surfaces and water bodies). The functional dimension refers to the description of areas according to their socio-economic purpose (residential, industrial or commercial, agricultural or forestry, recreational or conservation areas, etc.).); the sequential approach, developed for agricultural statistics, which encompasses a series of human operations aimed at deriving products and/or benefits from soil resources (European Commission, 2001). Image processing started with geometric correction. It consisted in bringing the images back to the same geometry. This step is necessary in order to jointly use images taken by different sensors at different dates (Andrieu, 2008; Solly et al., 2018). Next, georeferencing, with the choice of four bitter points on the 2018 image, is used as a reference. After reducing the images to the same geometry, the bands of the two scenes of each reference date were mosaiced. Finally, the colour composition and the calculation of the Normalized Vegetation Index (NDVI) were carried out.

2.3.1.1. Coloured composition

The color composition of an image is the result of the overlapping bands in the Red, Green, and Blue (RGB) channels. The one used in this study is called false-colour infrared (Figure 2). It combines the bands corresponding to the PIR, R and V wavelengths respectively in the R-G-B channels. It is based on the properties of vegetation that reflect near-infrared radiation very strongly (Girard and Girard, 2010).

2.3.1.2. Classification of land use units

This operation allows the identification of land use classes by photo-interpretation. These are forest, savannah, burnt areas, cultivated areas, habitat, plantations and water. These classes have been coded from 1 to 7.

After identifying the different land use classes, the unsupervised nesting classification was adopted with reference to the work of Andrieu (2008) and Solly et al. (2020). The choice of this method was justified by the lack of suitable reference samples for the 1987 image (Masse, 2013). This classification allows the pixels of an image to be grouped into spectral classes according to their signatures and depends on the spectral signature of the thematic classes composing the surface to be mapped. Validation of the results was based on GPS points taken in the field for each class over the entire basin. This work is supplemented by documentation relating to the topic addressed (Stancioff et al., 1986; Tappan et al., 2004; ANAT, 2018) and associated with the classification of plant formations adopted at the Yangambi conference in 1956 (Aubreville, 1957).

2.3.1.3. Determination of NDVI

NDVI is calculated by the reflectivity of the band channel of Landsat imagery which is red (red) light (0.64-0.67 μm) and near infrared (nir) light (0.85-0.88 μm) (Rouse et al., 1974; Griffith et al., 2002; Kundu et al., 2002). The standard index of vegetation variation was calculated using the following equation (1) (Rouse et al., 1974):

$$NDVI = \frac{(R_{nir} - R_{red})}{(R_{nir} + R_{red})} \qquad (1)$$

The NDVI varies mainly from - 1 to + 1. Generally, areas with no vegetation give a negative value or a value close to zero (meaning no vegetation) and a value close to + 1 (0.8-0.7) represents healthy vegetation (Griffith et al., 2002). In general, values below 0.1 provide information on water, cultivated areas, areas affected by fire and areas with very little vegetation, while values above 0.1 provide information on vegetation cover (Dessay, 2006; Djoufack-Manetsa, 2011; Solly et al., 2020). The closer the value is to 1, the greater the chlorophyll activity and the denser the vegetation.
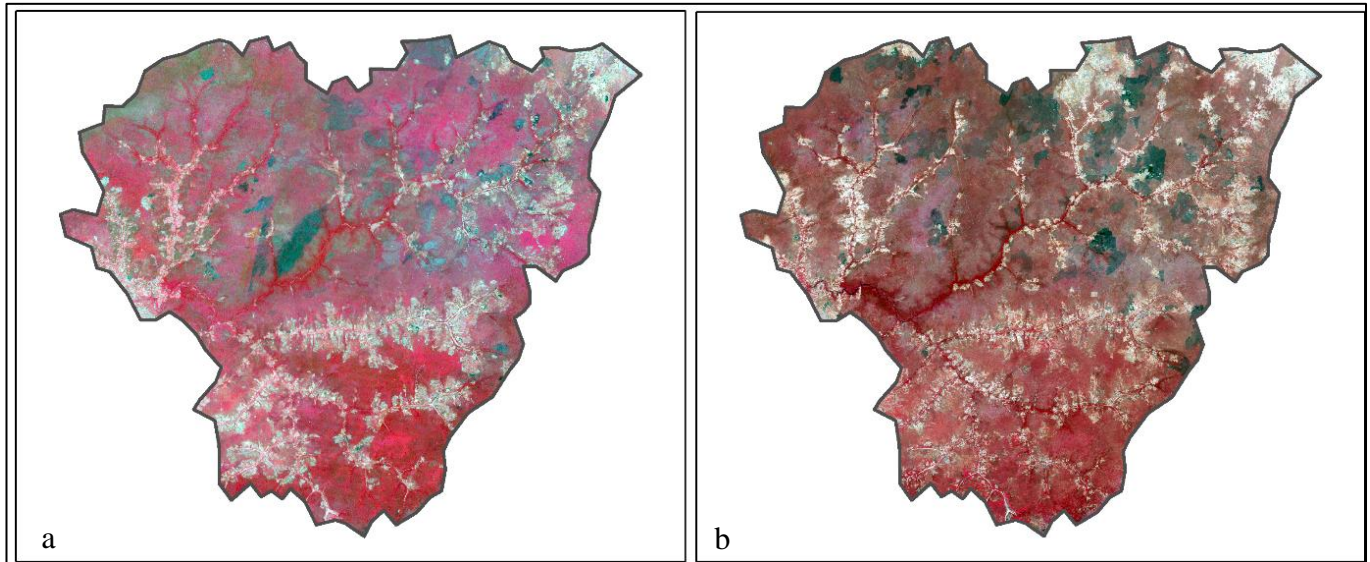

Figure 2. False infrared colour composition of Landsat images from 1987 (a) and 2018 (b) in the Casamance basin upstream of Kolda

2.3.2. Hydroclimatic approach

To characterize hydroclimatic variability and drought in the Casamance River catchment upstream of Kolda, the Standardized Precipitation Index (SPI) and the Standardized Flow Index (SFI) are used as probability distributions of long-term precipitation time series (Forootan et al., 2016). The SPI and SFI were calculated on 12-month scales. Estimated SPI values above -3 are considered extreme drought events, while values between -1 and -2 are considered moderate extreme events.

3. RESULTS AND DISCUSSION

3.1. Land use dynamics in 1987 and 2018

Generally speaking, the results indicate deforestation, either through savannah or agricultural land development (Figure 3). Indeed, the forest that was the dominant cover in 1987 with 215,271.9 ha or 58.6% of the basin's surface area has strongly decreased in favour of savannah and agricultural areas in 2018 (Table 2). These increased by 88,376.5 ha and 59,802.1 ha respectively.

In 2018, the forest represents only 16.5% of the basin's surface area. The increase in agricultural areas has been accompanied by an increase in habitats, which rose from 28.3 ha in 1987 to 461 ha in 2018. There are also plantations, consisting mainly of *Anacardium Occidentale,* especially in the southern part of the basin located in Guinea Bissau. As for the surface water area, it increased from 13.2 ha in 1987 to 231.7 ha in 2018. However, it should be pointed out that despite this increase in the surface area occupied by surface waters, a large part of the river in the basin is now dry and rainwater inputs are no longer sufficient to supply the basin's hydrographic network all year round.

3.2. Dynamics of the Normalized Vegetation Index (NDVI)

NDVI values generally indicate higher chlorophyll activity in 1987 and 2018 (Figure 4). The hue and colour of NDVI are dependent on the average signal level in the red, yellow, green range (Gond et al., 1997). Here, green indicates high intensity (abundant phytomass) and red indicates low intensity (little or no vegetation). For example, in 1987,

the maximum value of NDVI was 0.70; the minimum value was -0.40. The positive values (those above 0.1) occupy most of the basin, indicating the importance of vegetation during this period.
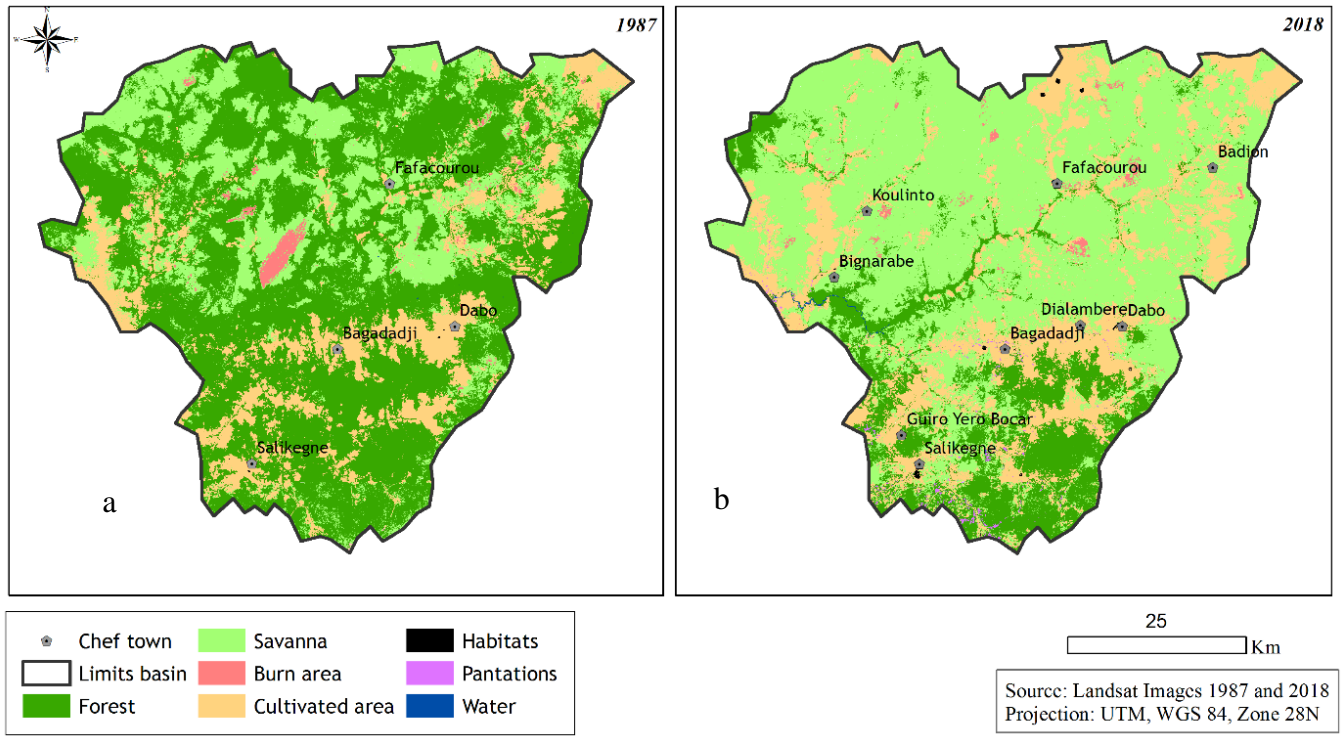

Figure 3. Mapping of land use in the basin in 1987 (a) and 2018 (b) in the Casamance basin upstream of Kolda

Table 2. Evolution and balance of land use in the basin between 1987 and 2018 in the Casamance basin upstream of Kolda

Class	*1987*		*2018*		*1987-2018*
	Ha	%	Ha	%	Balance sheet in ha
Forest	215271.9	58.6	60520.5	16.5	-154751.4
Savanna	88376.5	24.1	216159.8	58.8	127783.2
Burn area	3837.2	1	2151.4	0.6	-1685.8
Cultivated area	59802.1	16.3	86342.8	23.5	26540.7
Habitats	28.3	0.0	461	0.1	432.7
Plantations	8.1	0.0	1470.1	0.4	1461.9
Water	13.2	0.0	231.7	0.1	218.6
Total	367337.3	100	367337.3	100	0

In contrast to 1987, chlorophyll activity is relatively low in 2018. The maximum value of NDVI is +0.34. The decrease of the maximum value in 2018 is partly explained by the degradation of vegetation (decrease in density) although an increase in precipitation is noted in the recent period. In fact, it is noted that the year 1987 is in the middle of drought (Sagna, 2005). However, it should be noted that the maximum value of chlorophyll activity (+0.70) during the year 1987 could be influenced by the date of the image. Indeed, it should be noted that the vegetation index may be at its maximum at the time of lowest precipitation, although there is a strong correlation between NDVI and rainfall (Dessay, 2006; Solly et al., 2020).

In addition, the significant role of anthropogenic factors in the dynamics of the environment through land clearing, bush fires, habitat, etc. must be stressed. The latter are expressed here by a significant increase in the areas occupied by habitats, plantations and burned areas (Figure 5). Thus, although a return to normal rainfall has been noted since the end of the 1990s, the maximum value of NDVI in 2018 barely reaches +0.34, especially in the southern part of the basin.
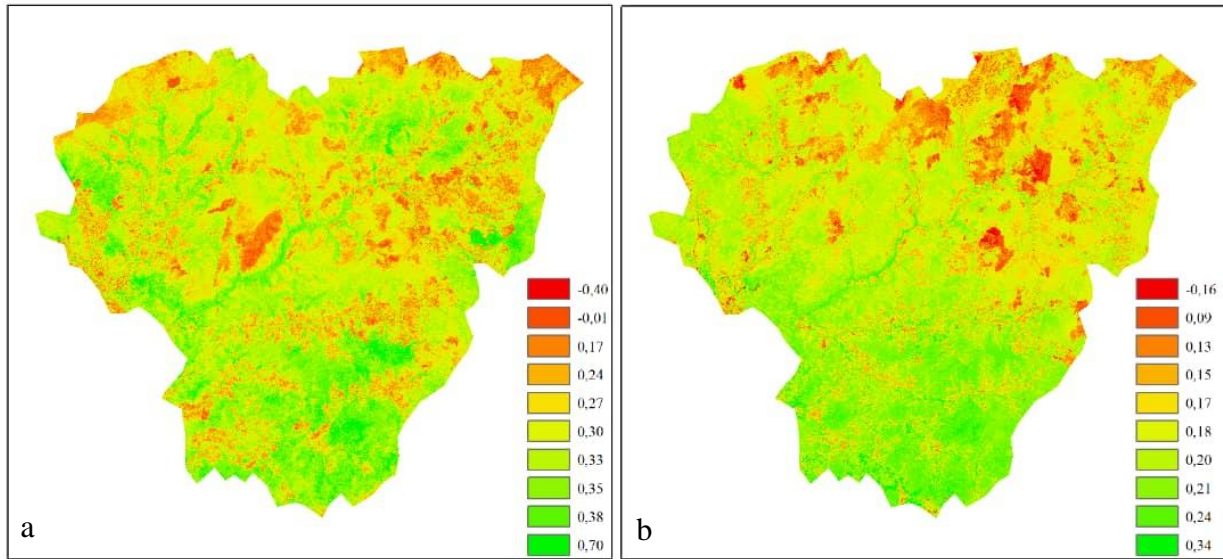
Figure 4. Status of NDVI in 1987 (a) and 2018 (b) in the Casamance basin upstream of Kolda
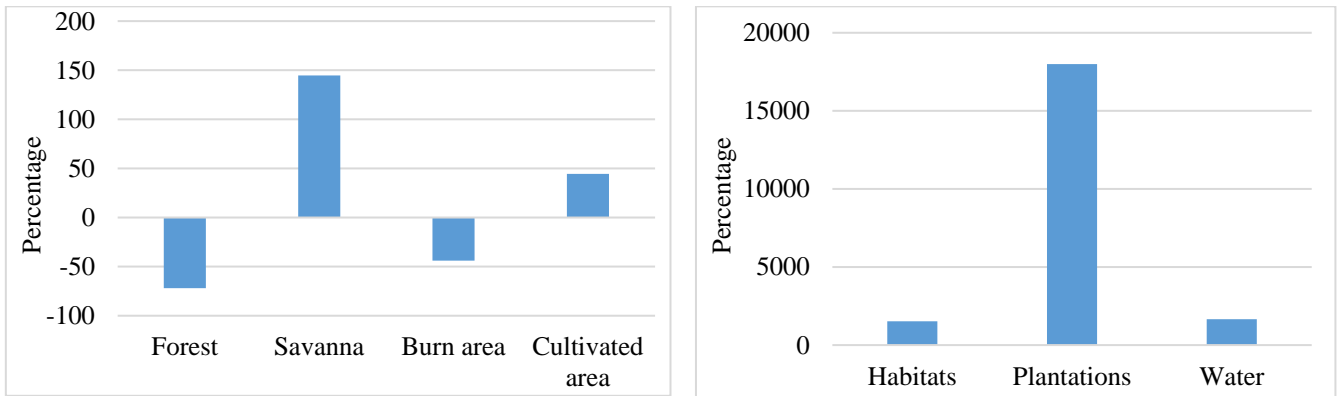

Figure 5. Percentage change in different land use units between 1987 and 2018

3.3. Rainfall and hydrological dynamics

The analysis of the rainfall (Pmm) series (Figure 6) of the four stations studied in the Casamance basin upstream of Kolda clearly shows the interannual variability of rainfall, in addition to an increasing dispersion over time, which has its origin in the great irregularity of surplus and deficit episodes. In the Casamance basin upstream of Kolda, droughts are generally light with frequencies of occurrence of 34.3% in Kolda, 36.1% in Velingara, 45.7% in Dabo and 47.2% in Kounkané. They are followed by sequences of moderate droughts (5.71% in Dabo, 8.33% in Kounkané, 11.11% in Vélingara and 11.43% in Kolda). On the other hand, sequences of severe droughts (only one case in Dabo and Kounkané and 2 in Vélingara in Kolda) and especially extreme droughts (only one case in Dabo) have the lowest frequency of occurrence in the basin.
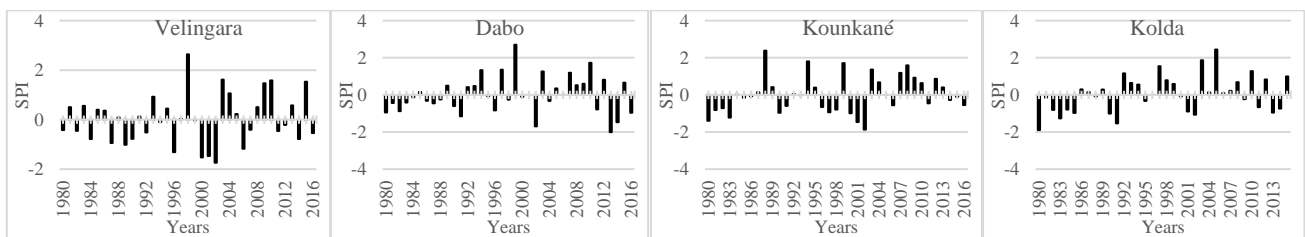

Figure 6. Evolution of standardized rainfall indices in the Casamance basin upstream of Kolda from 1980 to 2016

The years 1980, 1992, 2001, 2012 and 2013 are identified as severe drought years. The 1980s in Kolda (with a SPI of -1.89) and 2012 in Dabo (with a SPI of -2) are characterized by extreme drought (Figure 7). However, regardless of its degree of severity in the basin, the drought that occurred frequently in the past (1980s), has increasingly subsided since the 2000s, despite its persistence in some years such as 2012 and 2013. For several years now, work carried out in Senegal by various researchers has been confirming this upward trend (Dione, 1996; Sow,

2007; Bodian, 2011; Faye, 2013; Faye et al., 2015; Faye et al., 2017). Rainfall analyses carried out by the various authors on this zone show the progressive nature of the rainfall towards the end of this period. Indices such as the arithmetic mean and the comparison with the drought years of the period 1980-1999 (average of 936 mm) show a slight increase in rainfall between 2000-2016 (average of 977 mm). This indicates a relatively wet climate context and a trend towards a clear excess of rainfall (41 mm increase). However, the amount of water precipitated during this 2000-2016 period, although wet, does not equal that of the very wet 1950-1970 period.
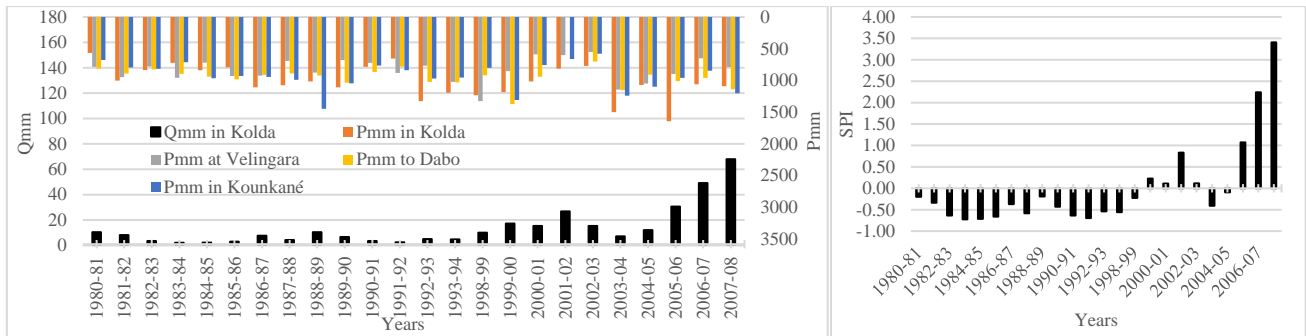

Figure 7. Precipitation and runoff in the Casamance basin upstream of Kolda from 1964-65 to 2007-08

Thus, as a consequence of the meteorological drought, the hydrological drought has resulted in the reduction of surface runoff in rivers. It manifested itself in the Casamance basin upstream of Kolda over the period from 1980 to 1999 and is manifested in the basin by a decrease in the volumes of fresh water flowing, the upward movement of salt water along the river and the drop in the level of water tables. In addition, the flows (Qmm) used make it possible to identify and characterize the recurrence and severity of drought in terms of period of occurrence, deficit and intensity. Thus, the analysis of the water flow and the standardised index of flow from 1970-71 to 2007-08), shows that 70.8% (i.e. 17 years out of 24) of the years were dry at the Kolda hydrometric station (with a standardised index of flow below 0). Only seven (07) years were considered wet (Figure 7). A long drought sequence from 1980-81 to 1999-00 is also noted. The lowest value was recorded in the year 1983-84 (lowest index year), corresponding to a flow of 0.24 $^{m3/s}$) and the highest value in the year 1967-68 with a flow of 7.84 m^3/s$^)$. However, in the mid-2000s, there was an increasing increase in flow in the basin, as evidenced by the indices generally above 1 from 1999-00 (0.23) to 2007-08 (3.41).

In the Casamance basin upstream of Kolda, the least rainy years generally correspond to the lowest flows (Figure 7). Thus, the year 1983-84, which has the lowest hydraulicity with a flow of 0.24 m3/s, coincides with the rainfall deficit with reference to the average of -6.44% at Dabo, -25.8% at Kounkané and -30.2% at Kolda. As for the year 2007-08 (year of highest hydraulicity) with a flow of 7.84 m^3/s, it coincides with a rainfall surplus of about 5.25% in Kolda, 18.9% in Dabo and 25% in Kounkané. Parallel to the rainfall, the flow has experienced the same evolution with an upward trend. The high variability (deficits and surpluses) of annual rainfall was reflected in the flows of the Casamance basin upstream of Kolda and the deficits and surpluses of flow seem to have increased.

3.4. Discussion

Comparing the 1987 and 2018 land use maps (Figure 3 and Table 2), significant changes in the distribution of land use are noted, in particular the increase in degraded land. Beyond the classification of the Casamance catchment area upstream of Kolda into seven main land categories (forest, savannah, burnt land, cultivated areas, habitat, plantations and water), the results of the analyses show a significant regression of forest cover in the basin. This study confirms that of Solly et al. (2020) who mentioned the combination of several factors such as clearings for agricultural needs, bush fires, population increase, uncontrolled wood cutting, changes in rainfall conditions, among others, as factors responsible for the regression of vegetation cover. Like rainfall, runoff flows alternately decreased during the 1980s and increased from the 2000s onwards, although the trend is not significant. These results confirm those of Ali et al (2008), Hountondji et al. (2009), Faye (2013). Faye (2019), Faye et al. (2015) and Ouoba (2013) which predict an improvement in the hydrological regime in Africa from the 1990s onwards. However, the rainfall surplus of the 2000s does not fully explain the increasing trend of runoff, as between 2000-01 and 2007-08, inflows (referring to the years 1970-71 and 1989-90) increased sharply by 108% while rainfall only slightly increased by 7.93%. These changes led to significant modifications in surface characteristics and soil hydrodynamic behaviour (Amogu et al., 2015).

Based on previous field experiments worldwide on the hydrological effect of vegetation decline (Albergel, 1987; Karambiri et al., 2003; Descroix et al., 2009; Amogu et al., 2015), it is reasonable to attribute part of the increase in

river flows in the Casamance basin upstream of Kolda to land cover decline. While many studies have investigated the relationship between land cover and hydrological yield in River Basins, most of them indicate that a reduction (increase) in land cover increases (reduces) runoff yield (Brown et al., 2005; Moran-Tejeda et al., 2012). This is a consequence of changes in evapotranspiration and infiltration processes in affected River Basins (Moran-Tejeda et al., 2012). Studies conducted in an experimental catchment south of the Duero River basin confirmed the role of the forest as a regulator of runoff yield, through interception and evapotranspiration (Martinez-Fernandez et al., 2005; Hernandez-Santana et al., 2008). These studies have highlighted the seasonal variability of forest hydrological activity as a function of soil water availability and plant water requirements.

This impact of vegetation cover modification on flow noted in the Casamance basin upstream of Kolda is similar to the studies by Zhang et al. (2001) and Cosandey et al. (2005) according to which, at local and global scales, vegetation cover is involved in the processes of infiltration, interception and evapotranspiration. Indeed, according to Bent (2001) and Gallart and Llorens (2003), any change in land use leading to an increase in vegetation cover generally causes a decrease in runoff, while the removal of vegetation tends to increase river flow in basins. This leads Descroix et al. (2009) to refer to the "Sahel hydrological paradox" to characterize the very strong modification (natural or anthropogenic) of land use in the Sahel with the decrease in vegetation cover, the increase in cultivated areas and the densification of the drainage network) having led to a more rapid concentration of water, aggravating floods and reducing base flow, despite the decrease in rainfall in the Sahel. This is attributed to soil crusting leading to an increase in the flow coefficients in the Sahelian zone from the onset of drought (Descroix et al., 2012). This "hydrological paradox of the Sahel" is attributed to an anthropogenic signal (changes in land use) much more important than the climatic signal (the decrease in rainfall) (Mahé et al., 2003; Seguis et al., 2003; Descroix et al., 2013).

However, several studies have pointed out the difficulty of establishing the hydrological effect of changes in vegetation cover. For example, Cosandey et al. (2005) found that the effects of forest thinning/reforestation or fire on river flooding and mean runoff in experimental basins in southeastern France were evident in some cases but not in others. Andréassian et al (1999) studied a set of 14 catchments in the French Massif Central and showed that expansion of the forest area had minimal effects on the evolution of annual runoff, and that if an effect was present it was completely masked by climate variability. Ashagrie et al. (2006) concluded that uncertainty in the data sets made it very difficult to detect the impact of land use changes on the floodplain of the Meuse River. Guo et al. (2008) showed that climate variability was the dominant factor in the evolution of annual runoff in a catchment in south-eastern China, and that land-use changes had little effect outside of seasonal trends. To explain the heterogeneity of results obtained at different locations, various authors (Andréassian 2004; Cosandey et al. 2005) have suggested the importance of differences between study sites in characteristics, including surface area, soils and lithology, climate and vegetation type or forest structure. It is also important to consider the scale of analysis and methodology used (Moran-Tejeda et al., 2012). For this reason, the analysis of hydrological and climate series did not provide clear evidence of the role of vegetation degradation in increasing flows in the basin. Although the hypothesis of forest decline that could affect runoff was well noted during the analysis of the series, uncertainties emerged in determining its actual impact on the evolution of runoff in the basin.

4. CONCLUSION

Land use and land-use change are dynamic phenomena that take place on fairly complex spatial and temporal scales. Environmental studies have repeatedly revealed the role of natural factors and human activities in ecosystem dynamics. This is the case of this study, which has shown the capacity of remote sensing technologies and GIS in the study of natural and anthropogenic phenomena by demonstrating the valuable contribution of information acquired through satellite images at increasingly precise and constantly improved resolutions between 1986 and 2018. The use of NDVI has provided quality information that has been of great use in determining trends in land cover dynamics, while the analysis of land cover data reinforces the indicators provided by rainfall data. Moreover, this paper also enabled an assessment of water resources in the Casamance catchment upstream of Kolda based on rainfall and flow indices in a context of climate change, while highlighting the complexity of the relations between climate and the water cycle. Indeed, it is demonstrated, among other things, that any climate change simultaneously affects different components of the hydrological systems: the quantity of rainfall, its intensity and frequency, runoffs, etc. This coupled evolution of land use and the hydrological cycle is common in the Sahel, and the increase in runoff, in particular, has also been observed at point, meso and regional scales.

Land use/land cover in the Casamance catchment upstream of Kolda underwent a radical change during the period 1987-2018. The results showed that there is a decrease in the area of vegetation cover, especially forests (-61.37%). The forest area in the Casamance River Basin upstream of Kolda has shrunk due to clearing for agricultural needs,

bush fires, population increase, uncontrolled wood cutting, and changes in rainfall conditions.... This situation is undoubtedly dependent on the climatic context, the exploitation of both water resources (hydro-agricultural development) and wood cutting (economy of extraction), etc. within the Casamance River Basin upstream of Kolda. Indeed, these already fragile and unpredictable resources could be even more so in a context of climate change due to its unpredictable nature, which would lead either to a decrease in rainfall or an increase in temperature. Also, serious threats could seriously affect the life of a population that is growing in number and strongly dependent on the exploitation of the environment.

From a hydrological point of view, the trend in recent years has been characterized by an excess of rainfall, even if the overall pattern of flows does not necessarily indicate the trend of increasing runoff. In the Sahel, this increase in flows could be partly explained by the decrease in vegetation cover, which leads to a faster concentration of water, an increase in floods and a reduction in base flow, despite the decrease in rainfall. On the other hand, there are uncertainties regarding the specific role of land cover decline on the evolution of runoff at the basin scale. This deforestation calls for the implementation of sustainable, integrated and participatory natural resource management strategies at the level of the Casamance catchment upstream of Kolda, with the involvement of various stakeholders (State, NGOs, local populations, etc.). It will therefore be a question of anticipating possible crises that could result from the misuse of an environment that is both fragile and presenting multiple stakes.

Conflict of Interest: We declare that there is no conflict of interest.

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