Journal of Geoscience and Environment Protection, 2021, 9, 225-243
https://www.scirp.org/journal/gep
ISSN Online: 2327-4344
ISSN Print: 2327-4336

Evolution of Dam Lakes in the Kayanga/Geba Basin: Contribution of Remote Sensing and GIS

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How to cite this paper: Sambou, S., Diouf, R.N., Cisse, B., Diouf, I., Sarr, J., & Dacosta, H. (2021). Evolution of Dam Lakes in the Kayanga/Geba Basin: Contribution of Remote Sensing and GIS. *Journal of Geoscience and Environment Protection, 9,* 225-243.
https://doi.org/10.4236/gep.2021.912014

Received: July 9, 2021
Accepted: December 28, 2021
Published: December 31, 2021

Abstract

The Confluent and Niandouba dams were built in 1984 and 1997 respectively to better control water resources, increase agricultural production and promote local development. This article studies their evolution on the Kayanga/Geba River, a transboundary river between Guinea, Senegal and Guinea-Bissau, from its impoundment to the present day. The topographic characteristics analysed through the DTMs (Digital Terrain Models) show a flat shape for the Confluent Dam Lake and long plateaus for the Niandouba Dam Lake. The cross-sections present a variety of morphologies ranging from wide U-shaped valleys with sinuous bottoms to deep V-shaped valleys. The homogenisation and reconstruction of missing values were carried out using the regional vector method. The application of Pettitt's statistical test on annual rainfall (1932-2019) indicates breaks of stationarity in 1967 or 1969. The post-breakage deficits range from 11.4% to 19.4%. The segmentation method corroborates the results of the Pettitt test. The variations of the surface area of the Confluent and Niandouba water bodies are linked to rainfall, evaporation and withdrawals for different uses. Their monitoring would allow for better management of available water resources but also for good planning of off-season crops.

Keywords

Dam Lakes, Remote Sensing, GIS, Watershed, Kayanga/Geba

1. Introduction

The decrease of rainfall in the 1960s and 1970s has caused a considerable reduction of water resources in the Kayanga/Geba river catchment. This reduction impacted agricultural production. In response to this situation, the State of Senegal has adopted policies for the development and management of water resources in order to improve water control, boost socio-economic activities by increasing agricultural productivity, both in the rainy and dry seasons, and promote local development. It is in this context that the Agricultural and Industrial Development Company of Senegal (SODAGRI in French, i.e., (Société de Développement Agricole et Industriel) was entrusted, in the early 1980s, with the management of the three phases of the development of the Anambe basin, a tributary of the Kayanga/Geba, the central part of which is a vast flood basin of almost 16,000 ha (Dacosta & Gomez, 1998). In the first phase, the Confluent Dam (1984) was built downstream of the confluence between the Kayanga/Geba and the Anambe. It allows the flow of the river to be diverted to fill the Anambe basin. In the dry season, the water is blocked by the Kounkane weir. After more than ten years of exploitation, it was found that the additional water provided by this dam did not allow the double cropping objective to be reached, due to the rainfall deficit, to which is added important water leakage downstream from the system, estimated at more than 50% of the runoff (Dacosta et al., 2002). So, in 1997, the Niandouba dam was built 10 km upstream to supplement the Confluent reservoir. In 2012, the Support Project for Small-scale Local Irrigation (PAPIL in French) set up the Velingara-Pakane dam upstream of the Niandouba dam to irrigate the areas developed on the right bank of the river. With a cumulative storage volume of more than 150 million cubic meters, an improvement in hydrological conditions has been noted, allowing relative control of water in the Anambe-Kayanga/Geba system. These hydro-agricultural and pastoral infrastructures, with integration of agriculture, livestock and continental fishing, have created water bodies that extend the wetlands. From 1987 to 2010, the area of wetlands in the Anambe basin increased from 2600 ha to about 17,000 ha (IUCN & IIED, 2010; IUCN & IIED, 2013). Thus, tributaries such as the Kakofowol, Kondjiwol and Thiangol Yoba Boiro, which were drying up in the non-rainy season, now have permanent water. Also, recent works of Sambou et al. (2018a) and Sambou (2019) have shown a return of improved rainfall conditions in the 1990s and 2000s. This situation is likely to further expand the wetlands.

The objective of this study is to analyze the evolution of the dam lakes on the Kayanga/Geba River, from their impoundment to the present day, using multi-date satellite images and a Geographic Information System (GIS). It is a contribution to the knowledge of the basin's water resources, particularly those mobilised in the Confluent and Niandouba reservoirs, because the rainfall and the runoff have been studied (Sambou et al., 2018a; Sambou et al., 2018b; Sambou 2019).

2. Data and Methods

2.1. Presentation of the Study Area

Straddling Guinea, Senegal and Guinea-Bissau, the Kayanga/Geba basin covers an area of 12,440 km^2 (Sambou et al., 2018a; Sambou, 2019). The river has its source in Guinea, at the west of the Badiar plateau. After 14.43 km, it enters in Senegal where it is named Kayanga, then it flows towards the South-West and returns in Guinea-Bissau and takes the name Geba, hence the name Kayanga/Geba. Finally, it forms a confluence with the Koliba/Corubal River and flows into the Geba estuary (**Figure 1**). The main tributaries, in terms of controlled area, are: the Anambe, the Gambiel, the Campossa and the Mayol Djaobe/Bidigor (**Figure 1**).

The Sudanese climate is characterized by a rainy season from May to October and a dry season for the rest of the year. The rainfall decreases from the south to the north, depending on the monsoon flow. Average monthly temperatures reach their maximum in May with 31.9˚C in Kolda (1951-2016) and 32.6˚C in Velingara (1986-2016) respectively, while the minimums are recorded in December in Kolda (23.9˚C) and January in Velingara (25.5˚C) for the same periods. The dams are not equipped with evaporation tanks. In 1992, EWI (1992) (in French, i.e. Études ElectroWatt Ingénieurs-Conseils) estimated the evaporation and the infiltration at the Confluent Dam from the observed decline in the water level between 1984 and 1991 and the daily evaporation values calculated at Basse (the nearest Gambian station). The savannah and the open forest areas cover most of the basin with open forest predominating in the east of the basin. The dense perennial or semi-deciduous forests that were once widespread downstream are now limited to patches in the middle of shrub savannah and cultivated areas (STUDI

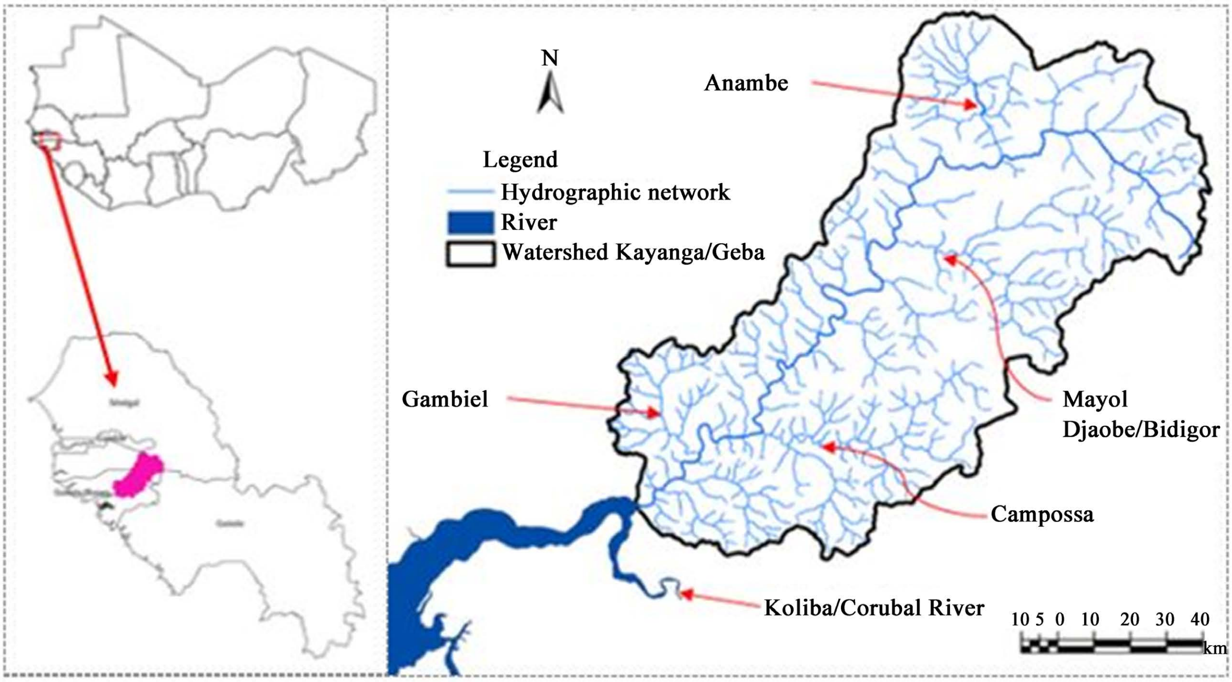


Figure 1. Geographical location of the Kayanga/Geba river basin (Adapted from (Sambou, 2019)).

International, 2011). The north of the basin (Senegalese part) seems to be more agriculturally exploited (Anambe basin and its surroundings) than the south, where agricultural areas are not very extensive despite the potential for agricultural development (Sambou, 2019).

2.2. Data

2.2.1. Physiographic Data

In the absence of recent digital topographic maps, the 30 m resolution Shuttle Radar Topography Mission (SRTM) data from the National Aeronautics and Space Administration (NASA) were used in this study to determine local elevation parameters and some cross-sectional profiles of the reservoir dams.

2.2.2. Rainfall Data

The rainfall data are provided by the National Agency for Civil Aviation and Meteorology of Senegal (ANACIM in French i.e., Agence Nationale de l'Aviation Civile et de la Météorologie). Due to their proximity to the dam lakes, 10 rainfall stations (**Table 1**) were selected for the rainfall analysis. Except Buruntuma and Koundara, which are in Guinea-Bissau and Guinean territory respectively, all the other stations are in the Senegalese part of the basin. The length of the timeseries varies from station to another. Only the results of a few stations will be presented. The choice will be based on the geographical position in relation to the reservoirs, the length of the sample and the data quality (no or few gaps).

2.2.3. Water Level Data

The Confluent and Niandouba dams are equipped with two Thalimede gauges (electronic parameterisable encoders) attached to water level scales. The first,

Table 1. List of rainfall stations selected for this study.

Country	Station	Latitude (North)	Longitude (West)	Elevation (m)	Periods covered by the data		% Gaps	Average annual rainfall (mm)
					Start	End		
Guinea	Koundara	12˚29'00"	−13˚18'00"	76	1928	2015	*	1197.9
Guinea-Bissau	Buruntuma	12˚28'00"	−13˚40'00"	100	1950	1992	*	1266.0
Senegal	Bonconto	12˚58'00"	−13˚57'00"	42	1975	2019	2,2	950.6
	Dabo	12˚48'00"	−14˚29'00"	43	1975	2019	*	961.8
	Fafacourou	13˚06'00"	−14˚56'00"	27	1962	1998	2.7	938.1
	Kolda	12˚53'00"	−14˚58'00"	8	1922	2019	*	1121.6
	Kounkane	12˚56'00"	−14˚05'00"	33	1963	2019	3.5	936.5
	Linkering	12˚58'00"	−13˚44'00"	56	1945	2008	48.4	974.7
	Pakour	12˚43'2"	−13˚59'4"	65	1980	2014	*	1143.4
	Velingara	13˚09'00"	−14˚06'00"	38	1932	2019	*	945.3

*: Complete rainfall timeseries.

placed upstream, records the variations in the water level of the reservoir. While the second, downstream, monitors the water level downstream of the dam for the safety of the dam and the surrounding villages. The one in Velingara-Pakane has a mini-Orpheus with a pressure sensor, a temperature sensor and a set of scales from 0 to 3 m. Only data from Confluent (1986-2009) and Niandouba (1997-2009) are available. They come from SODAGRI.

2.2.4. Acquisition of the Image Data

The resources used in this study are Landsat satellite images from the platform https://earthexplorer.usgs.gov/. These images provide a dataset which, through their spectral resolution, gives an account of the land use units present in the study area. They combine good spatial and spectral resolution: 30 m pixel with 7 bands. The satellite has the particularity of being oriented towards land use and vegetation work. The archival Landsat scenes and scenes from the TM (Thematic Mapper) 4 and 5, 7 ETM+ (Enhanced Thematic Mapper Plus) and 8 OLI-TIRS (Operational Land Imager-Thermal Infrared Sensor) missions (**Table 2**) covering the study area were downloaded for diachronic analysis of water bodies. Thus, starting from the years of impoundment, a time step of 10 years was adopted, which gave the following years: 1986, 1996, 2006, and 2016. Taking into account the year 2019 gives the current situation of the reservoirs.

2.3. Methodology

2.3.1. Topography Analysis

With the Shuttle Radar Topography Mission data (**Figure 2**), a contour extraction was performed with the Global Mapper 13.2 software choosing an equidistance of 1 m for more precision. Based on the local density of contour lines, three-dimensional Digital Terrain Models (DTMs) were produced using the Surfer 11 software. Then, transects designating the crossing of a geographical space were carried out in order to analyse the morphological components of the valleys. They are drawn perpendicular to the talweg of the dam lakes (**Figure 2**), from the right bank to the left bank, and then the data are exported in Excel for the elaboration of cross-sections. Their width is determined so as to include the minor and major beds.

2.3.2. Homogenisation of Annual Rainfall and Gap Filling

Due to the fact that it is based on all the stations selected without a priori and the

Table 2. Characteristics of the Landsat data used.

Satellite	Sensor	Date of acquisition	Spatial resolution
Landsat 4	TM	15/03/1986	30 m
Landsat 5	TM	22/01/1996	30 m
Landsat 7	ETM+	19/12/2006 et 20/10/2016	30 m
Landsat 8	OLI-TIRS	28/03/2020	30 m

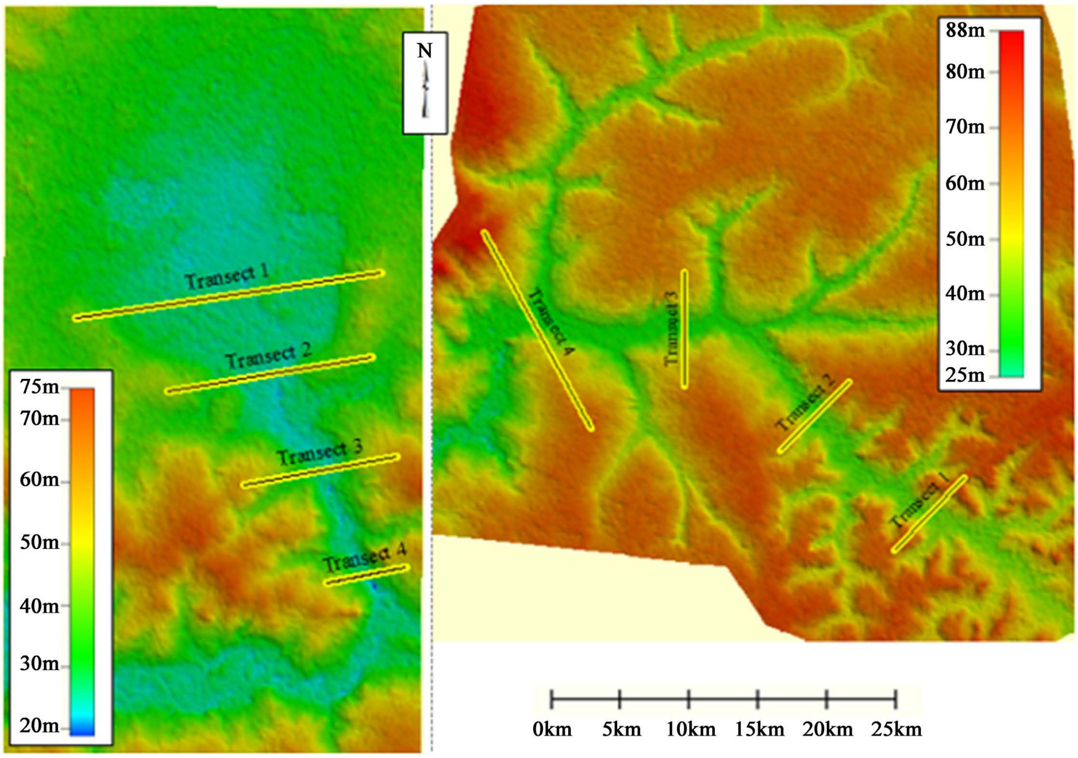


Figure 2. Location of transects in the Confluent (left) and Niandouba (right) dam lakes.

deviations calculation from the regional average, the Regional Vector Method (Brunet-Moret, 1977, 1979) was used for the homogenisation of the annual rainfall. It is a method that allows to represent the rainfall information of a region by a sequence of annual indices, representative of rainfall in that region, and by coefficients characteristic of each observation station (Hiez et al., 1992). It is based on the pseudo-proportionality of rainfall data from neighboring stations, which assumes that they all vary in the same direction and in similar proportions (Duclaux, 2009). For each station, a timeseries of annual indices is calculated and forms the regional vector. An index greater or equal to 1 indicates a wet year while an index less than 1 indicates a dry year (**Figure 3**). Thus, the timeseries are homogenized over the period 1932-2019 and the calculated rainfall was used to fill the gaps.

2.3.3. Homogeneity Tests on Annual Rainfall

Statistical tests integrated into the KhronoStat software (Boyer, 1998) were used to detect possible stationarity breaks in the annual rainfall timeseries. A break can be assimilated to a change in the law of probability of the timeseries at a given moment, most often unknown (Lubès et al., 1994). Among the existing tests, two are selected for analysis because of their sensitivity to a change in mean (if the null hypothesis of homogeneity of the timeseries is rejected) and their robustness. They are widely used in the analysis of climate variability in non-Sahelian West and Central Africa. Mann Whitney's test, modified by Pettitt (1979), consists of dividing the main timeseries into two sub-timeseries with

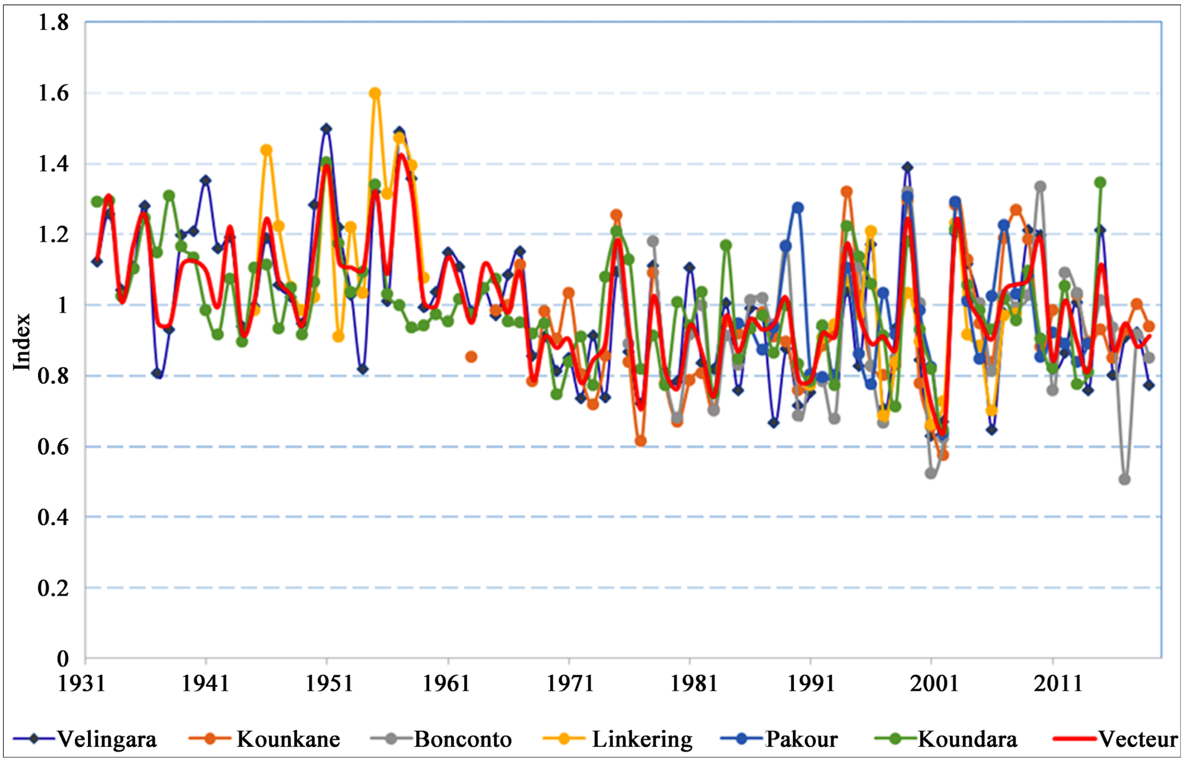


Figure 3. Vector of the annual rainfall indices over the period 1932-2019 and indices of the stations of Velingara, Kounkane, Bonconto, Linkering, Pakour and Koundara.

different statistical distributions, separated by a break at time t. The segmentation method (Hubert & Carbonnel, 1987; Hubert et al., 1989) is based on the principle of dividing the timeseries into several segments whose averages are significantly different.

2.3.4. Image Analysis Methods

The satellite images were explored using remote sensing and digital processing to extract part of the hydrographic network and the water bodies of the Confluent and Niandouba. For all selected scenes, bands 4, 5 and 6 were extracted for digital processing to highlight the water. From these bands, a composite image was created using ArcMap, a software that allows to perform a wide range of GIS tasks. It was then used in an unsupervised classification with 6 land use unit classes, where water is well highlighted. Based on this result, a second classification was carried out to group the remaining units into a single class. All water surfaces that were not part of the study sites were eliminated. Finally, the water body files were converted to a shapefile and mapped. The areas have been calculated to facilitate the comparative analysis of the figures from 1986 to 2019.

3. Results and Discussion

Topographical Characteristics

1) Digital Terrain Model (DTM)

The DTM of the Confluent dam lake (Figure 4) shows a flat shape with, however, several depressions along the Anambe tributary. Its basin forms an ovoid bowl around which large irrigated areas managed by SODAGRI are developed. The average altitude of the plateaus is around 40m. The reservoir that extends from the dam to Lake Waïma is 23.6 km long with a width that varies greatly from one place to another, for a volume of 59 million cubic meters at normal water level.

The DTM of the Niandouba dam lake (Figure 5) shows a relief characterized

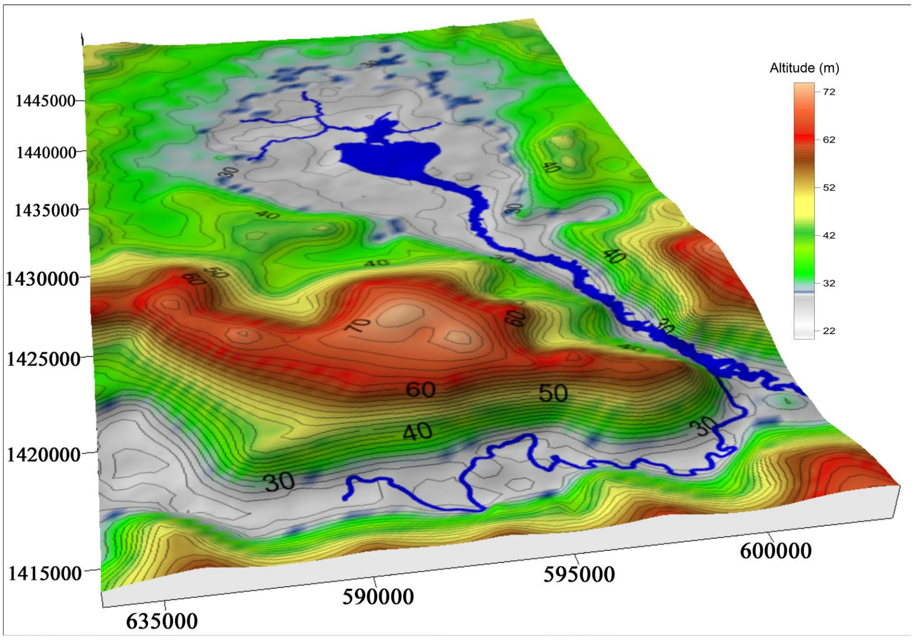


Figure 4. Three-dimensional digital terrain model of the confluent dam lake.

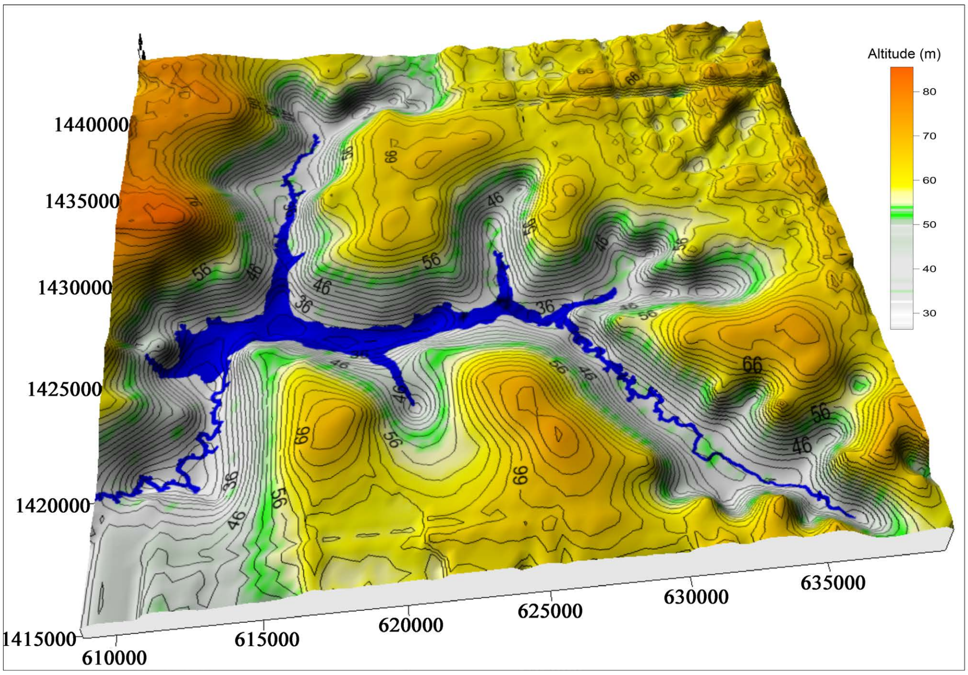


Figure 5. Three-dimensional digital terrain model of the Niandouba dam lake.

by long plateaus separating the valleys. The maximum altitude exceeds 85 m while the minimum altitude is less than 30 m. The reservoir, from the dam to the Velingara-Pakane dam, is 24.6 km long. When it is full and the water level reaches 30.9 m, the energy dissipation basin of the Velingara-Pakane weir will be drowned as well as the bottom drain. This situation will have the effect to facilitate the dissipation of energy downstream of the weir and slowing down the passage of the flood, but will in no way affect the stability of the structure (Experco International et Setico Ingénieurs-Conseils, 2007).

2) Cross-sections profile

For each reservoir, four profiles with varying morphologies were elaborated. The profile of transect 1 of the Confluent dam lake shows a wide U-shaped valley with a very sinuous bottom. As one moves towards the structure, the valley becomes more or less incised, the width (transects 2, 3 and 4) decreases and the slopes become less irregular (**Figure 6**). For the Niandouba dam lake, the profiles (**Figure 7**) show a V-shaped valley, less wide and deepened, compared to the Confluent.

4. Homogenisation of Annual Rainfall

The use of the Regional Vector Method has provided calculated rainfall data that are used to reconstruct missing values with maximum likelihood. The correlation coefficients range from 0.60 (Pakour) to 0.84 (Kounkane). "**Figure 8**"

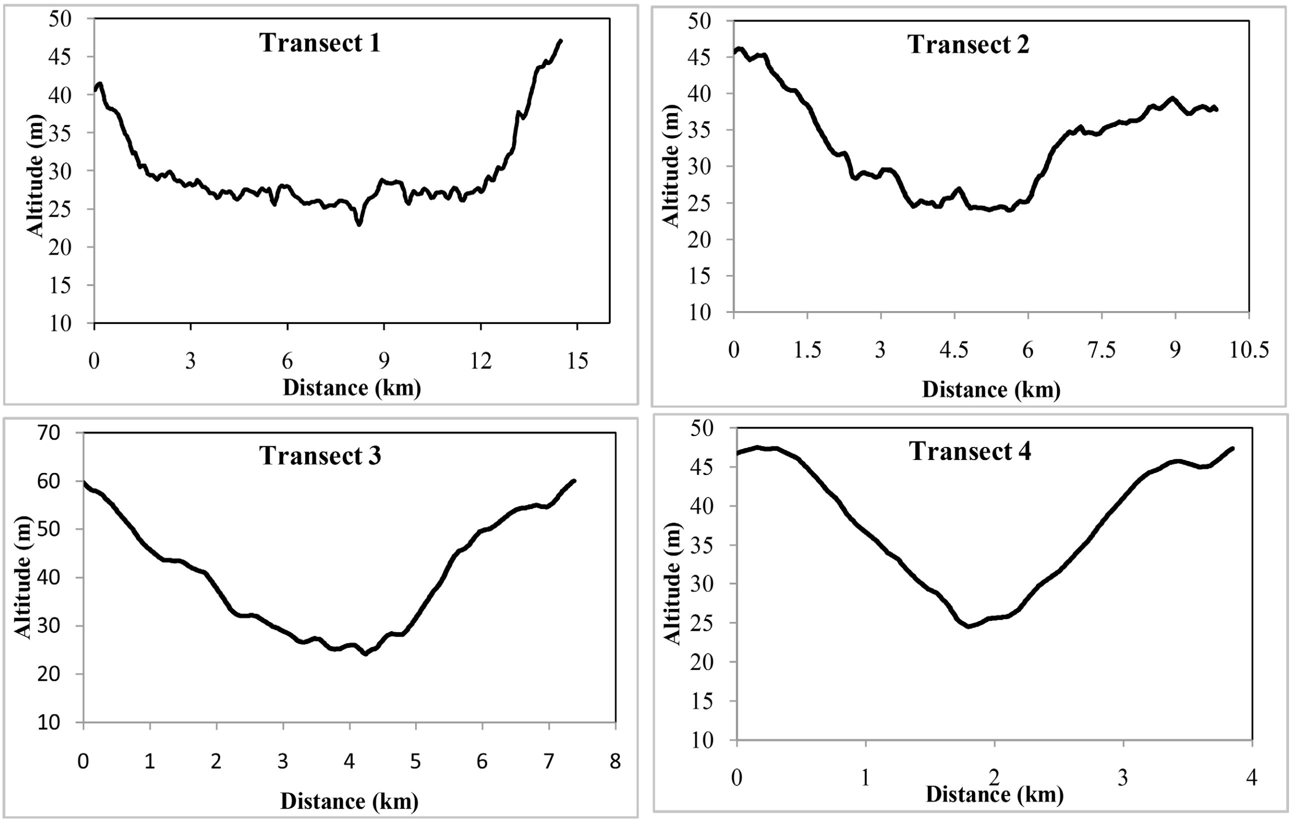


Figure 6. Cross-sectional profiles of the Confluent Dam Lake.

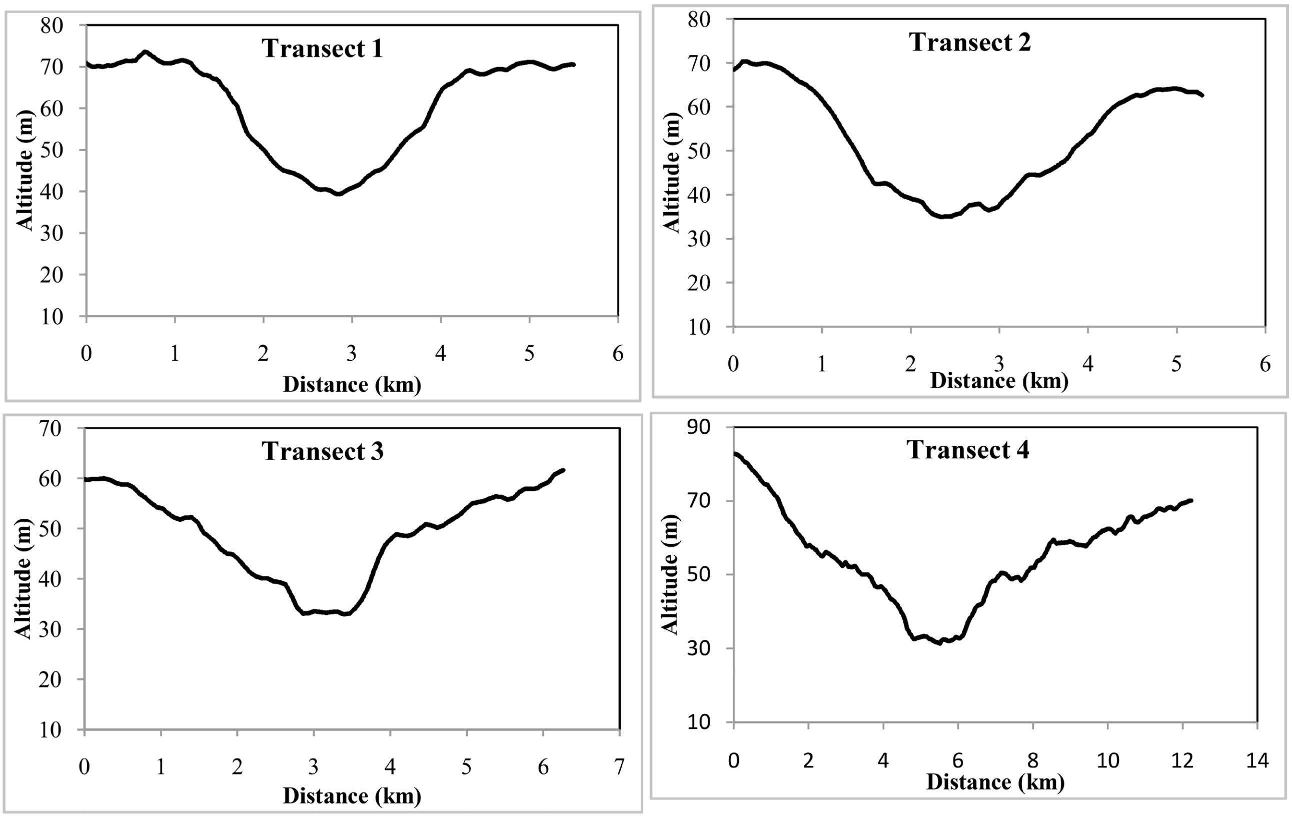


Figure 7. Cross-sectional profiles of the Niandouba Dam Lake.

shows the observed and calculated rainfall over the period 1932-2019.

5. Annual Rainfall Variation

1) Results of the Pettitt test

The results of the Pettitt test indicate that the null hypothesis of no change is rejected at the 99%, 95% and 90% confidence levels at all selected stations. This shows a decrease in rainfall. For most of the stations, the break occurred in 1967 (Table 3). Only the Koundara timeseries presents a break in 1969. The rainfall deficit after the break is between 11.4% (Koundara) and 19.4 (Velingara). In Koundara, the work of Sambou et al. (2020) on the neighbouring Koliba/Corubal basin indicated a deficit of 12.4% over the period 1924-2015. This reflects a reduction in the deficit which is closely linked to the improvement in rainfall conditions.

2) Segmentation results

The results of the segmentation, presented graphically, corroborate those of the Pettitt test at the Bonconto, Kounkane, Pakour and Velingara stations (Figure 9). However, at Koundara, the break occurred in 1955 instead of 1969 (Pettitt test). Only the Linkering station shows three (3) dates of rupture which highlight four (4) unevenly distributed periods. The first occurred in 1954, the second in 1957, marking the end of a short wet period, and the third in 1967, resulting in a succession of two phases of low rainfall (Figure 9). Whatever the

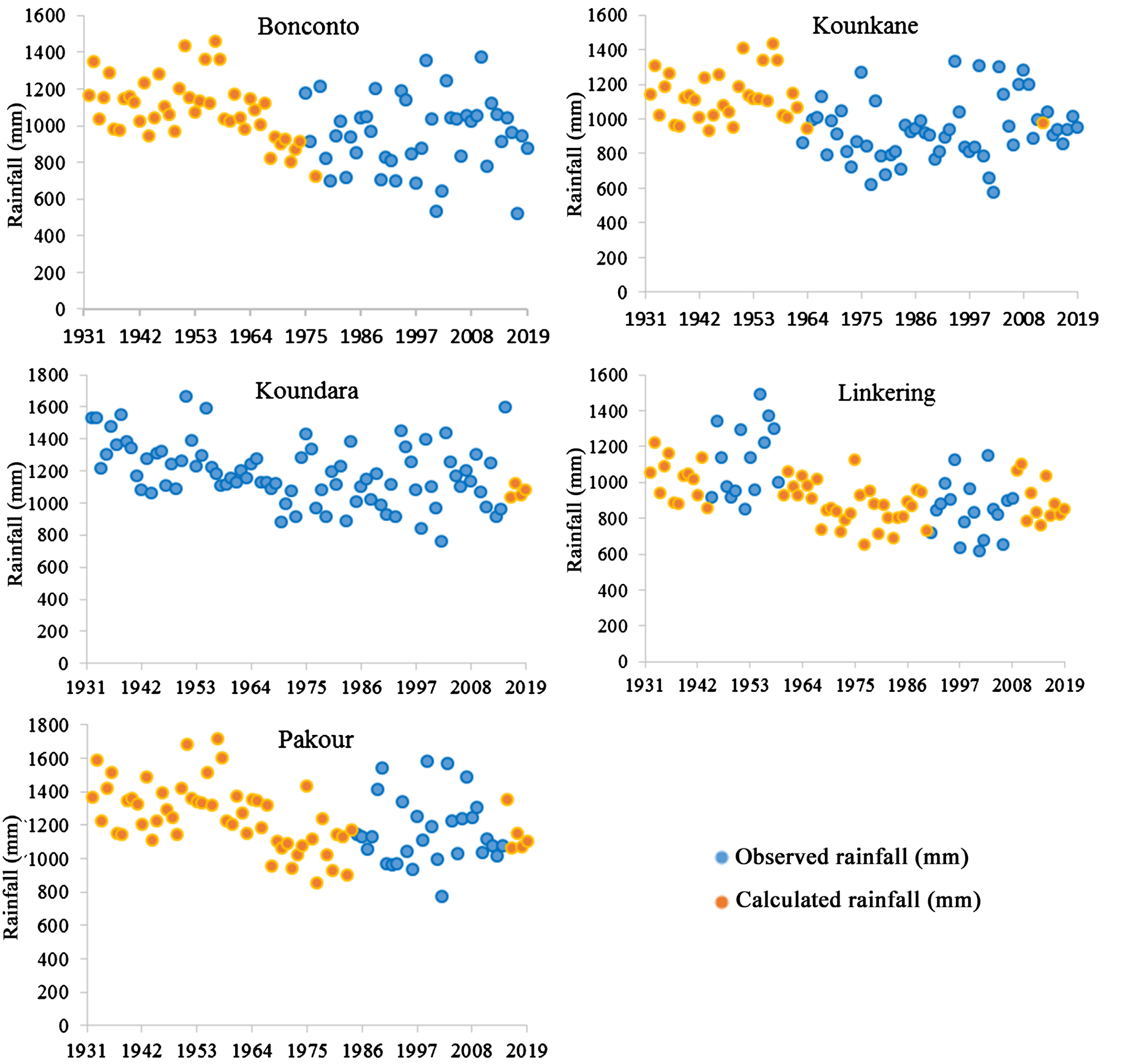


Figure 8. Observed and calculated annual rainfall at the stations of Bonconto, Kounkane, Koundara, Linkering and Pakour over the period 1932-2019.

Table 3. Years of break according to the Pettitt test.

Station	Year of break	Average (mm)		Standard deviation (mm)		Deficit (mm)	Deficit (%)
		Before	After	Before	After		
Bonconto	1967	1138.3	937.2	134.7	188.7	201.1	17.7
Kounkane	1967	1114.8	932.4	140.1	177.9	182.4	16.4
Koundara	1969	1266.5	1121.9	158.4	181.9	144.6	11.4
Linkering	1967	1056.2	855.5	158.7	127.2	200.7	19.0
Pakour	1967	1342.7	1133.6	152.1	179.8	209.1	15.6
Velingara	1967	1067.6	860.7	157.4	163.5	206.9	19.4

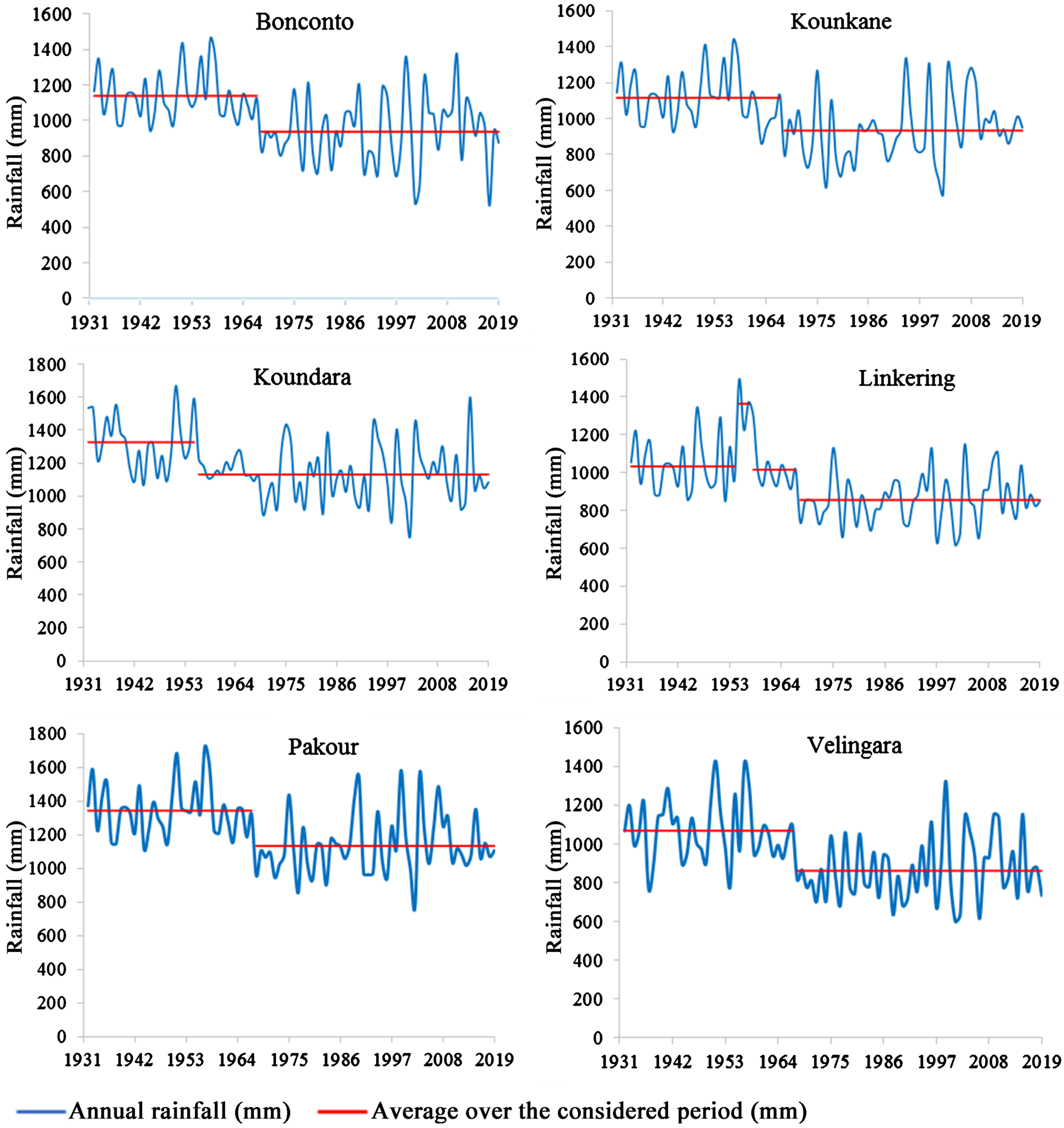


Figure 9. Variability and segmentation of annual rainfall at Bonconto, Kounkane, Koundara, Linkering, Pakour and Velingara from 1932 to 2019.

result, the downward trend continues for these stations with high interannual variability. Nevertheless, the work of Sambou et al. (2018a) and Sambou (2019) showed a resumption of rainfall in 1992 or 2002 for stations (Bafata, Sonaco and Pirada) located further south in the Kayanga/Geba basin. The neighboring Koliba/Corubal basin showed the same trend in 1987 in Gaoual and Mali or in 2002 in Gabu (Sambou et al., 2020). This recovery is also observed in many studies in West Africa (Sène & Ozer, 2002; Niang, 2008; Lebel & Ali, 2009; Sarr & Lona, 2009; Panthou, 2013; Descroix et al., 2013; Bodian, 2014; Descroix et al., 2015).

6. Evolution of the Average Annual Water Level of the Water Bodies

Figure 10 shows the variation in mean annual water level at the Confluent and Niandouba dams. Their correlation with the average rainfall in the basin (calculated by the inverse square of the distance method using Hydraccess software) shows that the variation of the water level reflects the rainfall. The Confluent dam's water level is more sensitive to variations than Niandouba's (Figure 10). According to Mballo et al. (2019), a proposed dam at the confluence of the Niokolo-Koba and Koulountou rivers (tributaries of the Gambia River) will divert their waters via a connecting channel to reinforce existing reservoirs in order to expand the area planted and increase production. This water transfer will undoubtedly distort the mean rainfall-range relationship of the water body.

7. Variation of the Surface Area of the Confluent and Niandouba Water Bodies between 1986 and 2020

The mapping of the water body between 1986 and 2020 of the Confluent Dam shows a variation in the occupied area (Figure 11). The light blue color represents the water bodies while the dark blue indicates the boundaries of the water bodies and the river network. The water body, which covered 2815.19 ha in 1986, two years after impoundment, has risen to 4311.41 ha in 1996, resulting in an increase of 1496.22 ha in the occupied area (Figure 12). In 2006, this area was reduced to 1885 ha, while in 2016 it increased to 3206.44 ha. Finally, in 2020, the water body experienced a drastic reduction in area (1451.16 ha), a decrease of 54.74% in only three years. This is the smallest area since 1986 (Figure 11 and Figure 12).

At the Niandouba dam, the area of the water body has risen from 2414.04 ha in 2006 to 2803.3 ha in 2016 (Figure 13), either an increase of 389.26 ha. In 2020, like the Confluent water body, the Niandouba water body has seen a reduction in its surface area to 2378.04 ha (Figure 13 and Figure 14). The figure

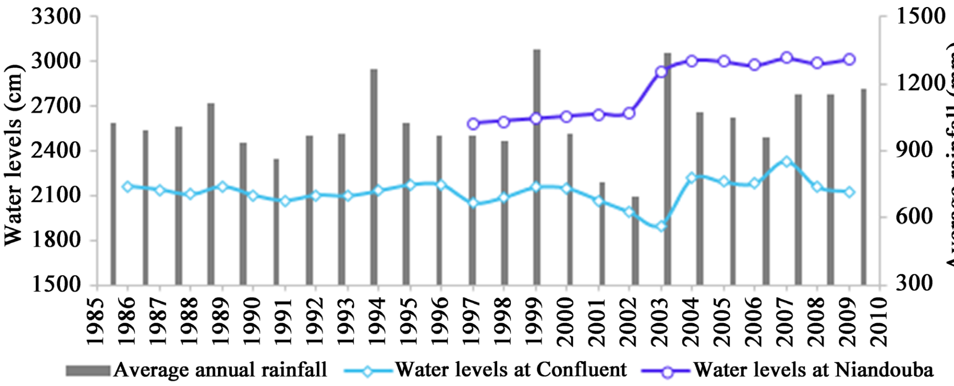
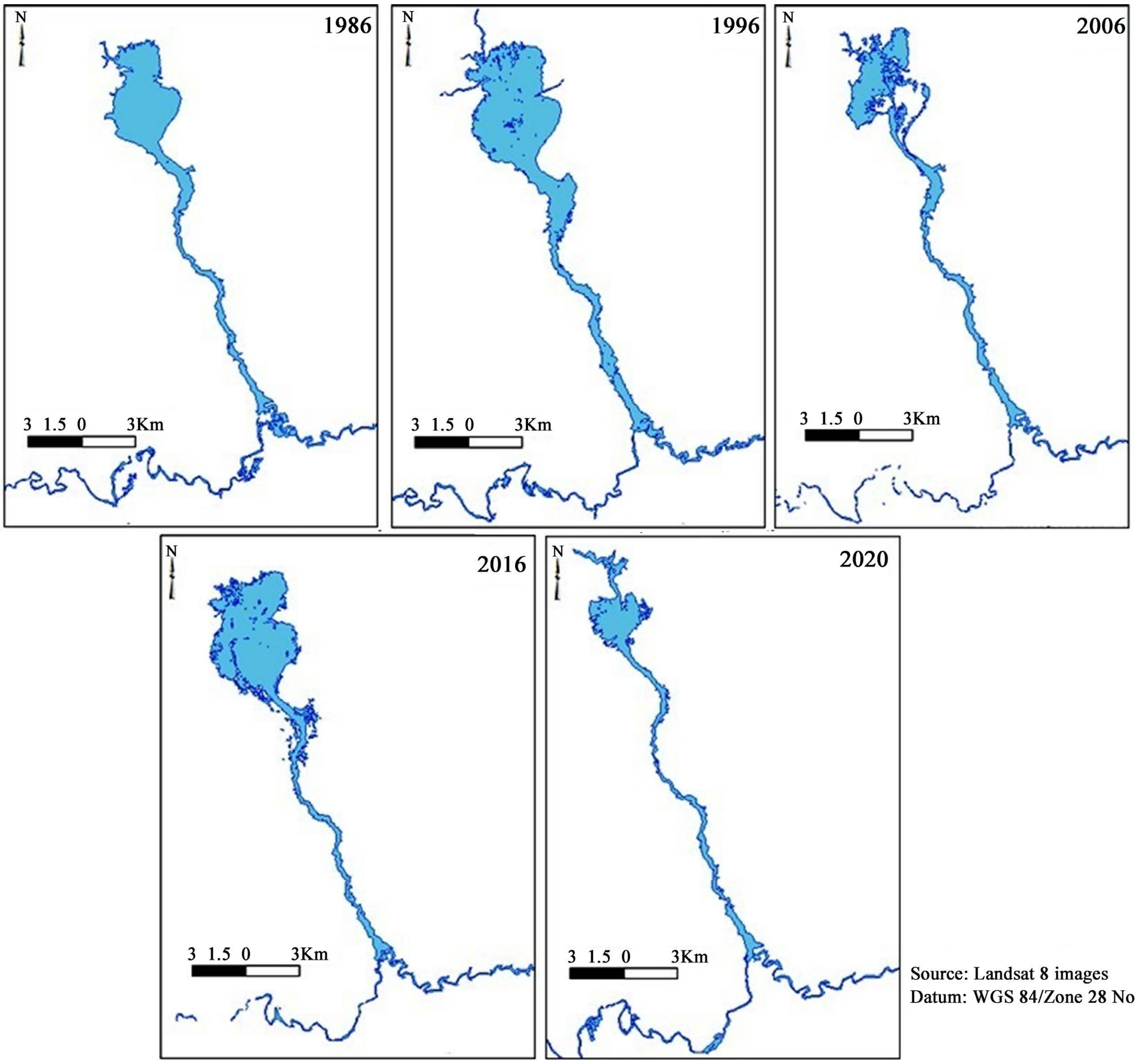


Figure 10. Average annual water levels variations at Confluent (1986-2009) and Niandouba (1997-2009) dams in relation to mean rainfall in the basin.



Source: Landsat 8 images
Datum: WGS 84/Zone 28 North

Figure 11. Water level dynamics of the Confluent Dam Lake between 1986 and 2020.

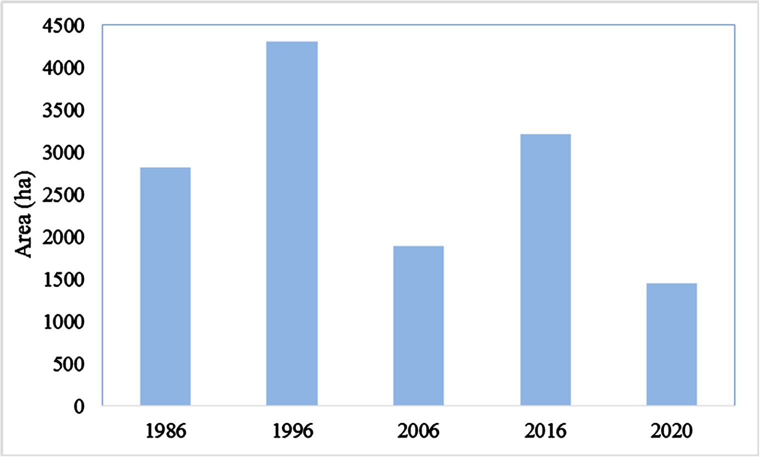


Figure 12. Variations of the water surface area of the Confluent Dam Lake between 1986 and 2020.

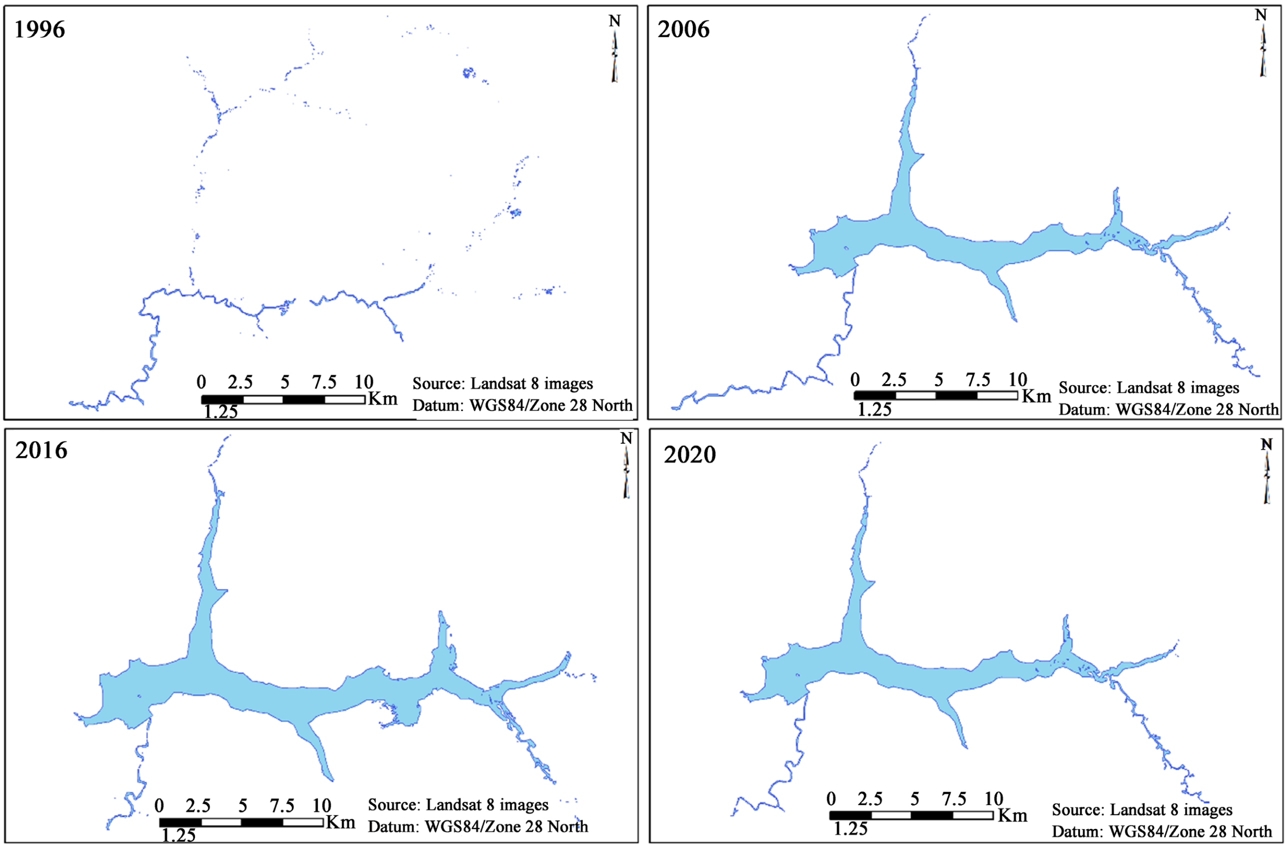


Figure 13. Water level dynamics of the Niandouba Dam Lake between 2006 and 2020.

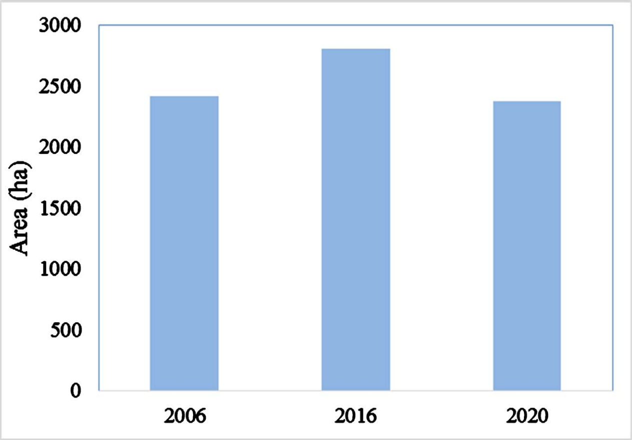


Figure 14. Variations of the water surface area of the Niandouba Dam Lake between 2006 and 2020.

for the year 1996 was chosen to show the reference situation before the dam was impounded (Figure 13). The variations in the surface area of the water bodies are closely correlated with the rainfall. Indeed, the period 1986-2019 is characterized by strong variability with rainfall that is sometimes in deficit and sometimes in surplus. Also, evaporation, infiltration and the quantities of water withdrawn for irrigation and other uses (market gardening, livestock, etc.) play a significant role in the reduction of the surface area of water bodies. Unfortunately, the relevant data are not available.

The analysis of the evolution of the Confluent and Niandouba dam lakes on the Kayanga/Geba River, using multi-date satellite images and GIS, showed an increase in water bodies since impoundment, creating new wetlands. This is in conformity with the conclusions of the work carried out in the basin by IUCN and IIED in 2010 and 2013, on the state of play around the Niandouba and Confluence dams and the capitalisation of good practices in terms of governance around these dams. In 2020, the work of Solly et al. (2020) on the spatio-temporal dynamics of forest landscapes in the department of Velingara also showed an increase in the area occupied by water between 1987 and 2018. However, variations in water levels are noted in this study, over the periods 1986-2020 (Confluence dam) and 2006-2020 (Niandouba dam). These variations are linked not only to rainfall, which fluctuates over time, but also to evaporation, infiltration and withdrawals for different uses.

8. Conclusion

The use of SRTM data was allowed to determine the topographic characteristics of the Confluent and Niandouba dam lakes through digital terrain models and cross-sections profiles.

After the homogenization of the data using the Regional Vector Method and reconstructing the missing values, the Pettitt test and the segmentation method were used to detect breaks in stationarity on the annual rainfall time series for the period 1932-2019. For the Pettitt test, the break occurred in 1967 (Bonconto, Kounkane, Linkering, Pakour and Velingara) or in 1969 (Koundara) causing a deficit that varies from 11.4% (Koundara) to 19.4% (Velingara). The segmentation method confirms Pettitt's results at the stations of Bonconto, Kounkane, Pakour and Velingara, with the exception of Koundara, where the break occurred earlier (i.e., 1955) and Linkering, which presents four different periods separated by three break dates.

The analysis of the average annual water levels of the water bodies indicated that their variations are linked to those of the average annual rainfall. The diachronic analysis of the Confluent and Niandouba dam lakes showed variations in the surface occupied areas. At the Confluent, the water body varied from 2815.19 ha in 1986 to 1451.16 ha in 2020, passing through 4311.41 ha in 1996, 1885 ha in 2006 and 3206.44 ha in 2016. In Niandouba, it has evolved from 2414.04 ha in 2006 to 2378.04 ha in 2020, passing through 2803.3 ha in 2016. These variations are linked to rainfall, evaporation and infiltration losses and withdrawals for irrigation, market gardening, livestock, etc., although the related data are not available. The monitoring of these variations would allow for better management of available water resources but also for good planning of off-season crops.

In the end, the construction of these dams has made it possible to improve water control for dual irrigation and to increase agricultural production. Moreover, the practice of off-season campaigns for rice cultivation depends to a large extent on the water resources mobilized in the two reservoirs, the financial capacity of the farmers, the functionality of pumping stations and the irrigation network. However, the high rainfall variability and dry spells mean that off-season campaigns remain uncertain and problematic in the basin. To overcome this and increase the sown areas to the existing great agricultural potential, a dam project at the confluence of the Niokolo-Koba and Koulountou rivers has been initiated. It will consist of diverting, via a connecting canal, the waters of these two tributaries of the Gambia to meet the water needs of the Anambe basin.

The installation of such a dam will artificialize the Kayanga/Geba basin even more, increase flows and distort the rain-flow relationship. Already, apart from their impact on the riverbed, the Confluent and Niandouba dams have led to changes upstream such as waterlogging of soils due to irrigation, asphyxiation of plant species due to permanent submergence, cases of flooding, etc. Downstream, low flow, the proliferation of plants and animals, and a lack of access to water have been noted. Downstream, low flow, the proliferation of invasive aquatic plants, siltation, etc. have been observed. In future research, it would be interesting to study these changes related to the dams.

Conflicts of Interest

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

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