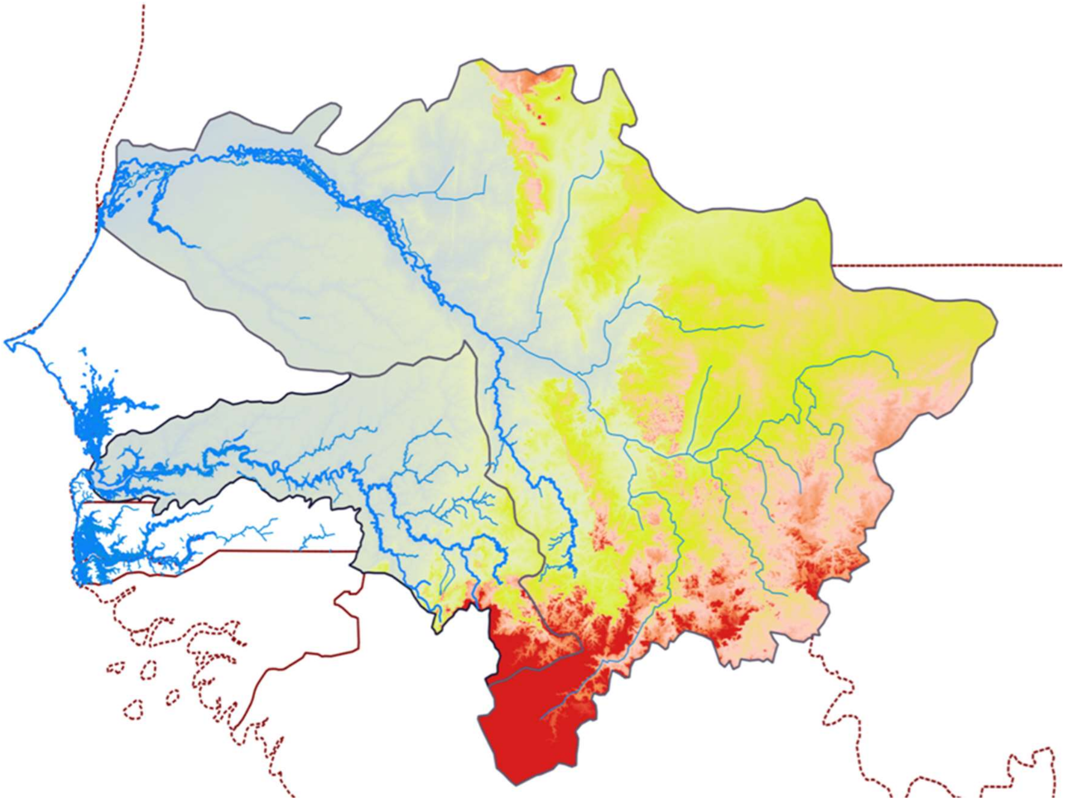
CLIMATE VULNERABILITY AND WATER RESOURCES VARIABILITY IN WEST AFRICA

SENEGAL AND GAMBIA RIVER BASIN CASES STUDIES



FINAL REPORT

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Special thanks to data providers at national and basin scale. The data sources are, among others:

- ANACIM[1] and DGPRE[2] for Senegal national level,
- National Meteorological Services of The Gambia, Guinea, Mali and Mauritania,
- Basins agencies (OMVS and OMVG) for Water Level and Discharge data,
- National IHP focal points[3],
- IRD archives like SIEREM or AMMA database (www.ird.fr).

At country level (Senegal), climatic parameters have been collected for the 24 synoptic and climatologic stations from the beginning of operations to 2016-2017. The collected parameters are:

- Temperature (maximum and minimum),
- Percentage of relative moisture,
- Rainfall (millimeters),
- Evaporation (millimeters).

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[1] Agence Nationale de l'Aviation Civile et de la Météorologie

[2] Direction de la Gestion et de la Planification des Ressources en Eau

[3] International Hydrological Programme

LIST OF ACRONYMS AND ABBREVIATIONS

2ie	International Institute for Water and Environment Engineering
ABN	Agence du Bassin du Niger
AGRHYMET	Agriculture, Hydrology, Meteorology
AMCOST	African Minister's Council for Sciences and Technology
AMCOW	African Minister's Council on Water
AMMA	Multidisciplinary Analysis of African Monson
ANACIM	Agence Nationale de l'Aviation Civile et de la Météorologie du Sénégal
ANSD	National Agency for Statistic and Demography
AUC	African Union Commission
CNLS	Comité National de Lutte contre le Sida
CT	Continental Terminal
DGPRE	Water Resources Management and Planning Directorate
DNH	National Directorate of Hydraulics
ECOWAS	Economic Community of West African States
EDEQUE	Doctoral School on "Water, Water Quality and Uses"
FRIEND-AOC	Flow Regimes from International Experimental and Network Data – Western and Central Africa
GRB	Gambia River Basin
IHP	International Hydrological Program
IRD	Institut de Recherche pour le Développement
IWRM	Integrated Water Resources Management
JRC	Joint Research Centre/European Commission
KNUST	Kwame Nkrumah University of Sciences and Technology (Ghana)
NEPAD	New Partnership for Africa's Development
NWRI	National Water Resources Institute (Nigeria)
OMVG	Organisation pour la Mise en Valeur du fleuve Gambie
OMVS	Organisation pour la Mise en Valeur du fleuve Sénégal
PNLS	Plan National de Lutte Contre le Sida
RWESCK	Regional Water and Environmental Sanitation Centre Kumasi (Ghana)
SAM	Society of Aeroports of Mauritania
SDAGE	Schéma Directeur d'Aménagement et de Gestion des Eaux
SIEREM	Environmental Information System on Water Resources and their Modelling
SODEFITEX	Cotton Fiber Development Company
SRB	Senegal River Basin
SWAT	Soil and Water Assessment Tool
UCAD	Cheikh Anta Diop University of Dakar, Senegal)
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNIBEN	University of Benin (Nigeria)
WANWATCE	Western African Network of Water Centers of Excellence
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use
WEAP	Water Evaluation and Planning System
COSEC	Conseil Sénégalais des Chargeurs
ICARM	Integrated Coastal Area and River Basin Management
GILIF	Gestion intégrée du littoral et des bassins fluviaux

ANALYTICAL ABSTRACT

West Africa, particularly the Sudano-Sahelian zone, has experienced unprecedented climate variability in recent decades. Despite some periods of respite, the statistics do not really plead for a return to better climatic conditions, precisely rainfall. Beyond the structural aspect of this climate variability, many effects have been observed on socio-economic activities and also on socio-cultural practices. This situation has a dramatic impact on water resources and in particular on the hydrology of West African transboundary basins such as those of Senegal and Gambia.

The overall objective of this study is to contribute to a better understanding of climate variability and risks and their impacts on the water resources availability in transboundary watersheds in West Africa. It aims to create up-to-date knowledge bases for climate variability analysis and risk assessment as well as the search for sustainable solutions to overcome the environmental and societal vulnerability. In this perspective, the updating of the West African climate database and its extension to shared basins (Senegal and Gambia) should make it possible to carry out relevant analyses of climate variability and its impact on the environment and more particularly on the water resources availability.

The Senegal and Gambia River basins are selected as sites for this study, which focuses on analyzing the climate vulnerability and its effects on water resource variability in West Africa. These two transboundary tropical basins cover respectively an area of about 300,000 km^2 and 77,054 km^2. The Senegal River is 1,800 km long and its basin is shared between Guinea (7%), Senegal (8%), Mali (35%) and Mauritania (50%). About 3.5 million people live in this basin, 85% of whom live near watercourses. The Gambia River basin is divided between Senegal (70.9%), Guinea (15.4%), Gambia (13.7%) and Guinea Bissau (0.021%). The Gambia River is 1,150 km long, 205 km of which are in Guinea, 485 km in Senegal and 490 km in Gambia. The project's objectives include the following:

- To update the climate database and cover all the two basins of Senegal and Gambia;
- To analyze the climate variability and trends across West Africa with a focus on the Senegal and Gambia river basins;
- To identify climate impacts on hydrology in West Africa based on data from monitoring stations, metadata, existing modelling tools and assessments and even climate re-analyses if necessary;
- To build materials for tailor-made training sessions.

Precipitation remains the main conditional factor in the hydrological regime in West Africa and constitutes the largest part of the climate data collected from these different sources. Other climatic factors (temperature, sunshine, humidity, wind regime) that have a much less direct influence and are less likely to have changed the regime were also collected. In general, the available data range from the origin of the measures until 2016. However, it must be considered that time series are rarely continuous; this can sometimes be a limitation for the implementation of analyses.

These two basins (Senegal and Gambia) straddle very contrasting climatic zones: the well-watered Guinean and Sudanese areas and the semi-arid and arid Sahelian areas. The average

rainfall of the Senegal River Basin is 550 mm.yr^{-1}, varying between more than 1500 mm.yr^{-1} at the source in Fouta Djalon Mountain, to less than 200 mm.yr^{-1} in the most northern part of Senegal. In the Gambia River Basin, the rain measurement varies considerably in each riverside country: from 1200 to 4500 mm in Guinea; from 1200 mm in the north to 2400 mm in the south in Bissau Guinea and about 500 to 1000 mm in Senegal and in Gambia.

The rainfall regime as well as the hydrological regime of these two rivers are historically marked by strong interannual and seasonal variability. From the early 1970s to the end of the 1990s, the basins had suffered from chronic rainfall and water deficits. Over the past two decades, significant improvements in rainfall and average river water conditions have been observed. But on a scale of 50 to 100 years, we are still in a generally dry sequence, marked by a strong temporal and spatial variability. The dams built on the Senegal River, particularly the Manantali dam, reduce the seasonal variability of flows but do not eliminate the very marked unimodal nature of the river regime, with most of the flows concentrated over a short period of the year (from August to October). The region is therefore facing major hydro-climatic challenges, with strong repercussions on the biophysical environment but also on the social and economic activities of these basins.

Concerning of the environment, the landscapes of the Senegal and Gambia River Basins remain highly contrasted and closely linked to climate zoning. The upper basins of Senegal and Gambia, the Fouta Djalon area, have a relatively dense vegetation cover and are home to most of the wildlife of these basins. There is here a high value protected area, the Niokolo-Koba Park, a UNESCO World Heritage Site. In the Sahel region, semi-desert landscapes are sparser, with gallery forests and wetlands containing relatively high concentrations of flora and fauna species. Overall, the physical environment of the two basins is in a fairly advanced state of degradation despite the fact that areas of rich biodiversity remain in various places. These are the Fouta Djalon Massif, the Bafing Fauna Reserve, the Boucle du Baoule Biosphere Reserve, the floodplain in the middle valley of Senegal, natural lakes such as Lake Guiers and Lake r'kiz, wetlands classified as Ramsar sites (2 in Guinea, 1 in Mali, 2 in Mauritania and 4 in Senegal), and several classified forests. To this must be added the dam reservoirs: the Manantali and Diama dams on the Senegal River, which has been in operation for some thirty years; the Felou reservoir, which dates from 2013. These reservoirs increasingly play ecological functions similar to those of natural wetlands. However, their ecosystem potential remains undervalued. In general, the environment of the basin -including the areas of high biodiversity value mentioned above- is subject to various pressures and threats resulting from a combination of factors such as deteriorating hydro-climatic conditions and very high population growth.

In view of this, the challenges of water and environmental management in these basins are therefore enormous, despite the existence of two basin organizations (OMVS for the Senegal River Basin and OMVG for the Gambia) responsible for establishing coordinated and concerted management of water resources and ensuring social peace and an institutional climate favorable to the development of riparian States.

The first results of this study confirmed the knowledge previously acquired on the main fluctuations in rainfall and hydrological regime in the Senegal and Gambia river basins. The use of hydrological indices makes it possible to visualize and subdivide the chronicles studied

into several intervals according to dry or wet conditions and thus to characterize the extent of dry periods as well as their intensity. Examination of the rain-flow relationship confirmed their synchronization throughout the study period. Hydrological drought indices indicate that the most severe droughts have occurred since the 1970s in the two basins.

Hydrological modelling with SWAT applied to the Bafing catchment area has given encouraging results on the applicability of the model with a good level of satisfaction. Given the nature of the project, it will be advisable to collaborate with JRC experts to apply to the entire Senegal River basin or even the Gambia basin.

Keywords: *climate variability; transboundary basins; hydro-rainfall data; drought; hydrological modelling*

INTRODUCTION

The West African region is subject to a very high climate vulnerability for several decades (Oyebande et al., 2008). Recent studies on rainfall variability do not really argue in favor of improving surface water capital, especially considering the high dependence between rainfall and water regime at these latitudes (Paturel et al., 1996). Climate deterioration is pushing more and more towards the use of surface water, the renewal of which could be compromised in the more or less long term. Socio-economic impacts are particularly complex, particularly in transboundary watersheds such as Senegal and the Gambia.

The Senegal (SRB) and Gambia (GRB) River Basins are transboundary watershed located in West Africa, between Gambia, Guinea, Guinea Bissau, Mali, Mauritania and Senegal (Figure 1). The two basins have been impacted by the recent drought experienced in the West African region from 1970 to early 2000. Under the aegis of OMVS (Senegal River Basin Organization) and OMVG (Gambia River Basin Organization), IWRM is currently implemented for hydraulic infrastructures operation, water management, sharing and cooperation.

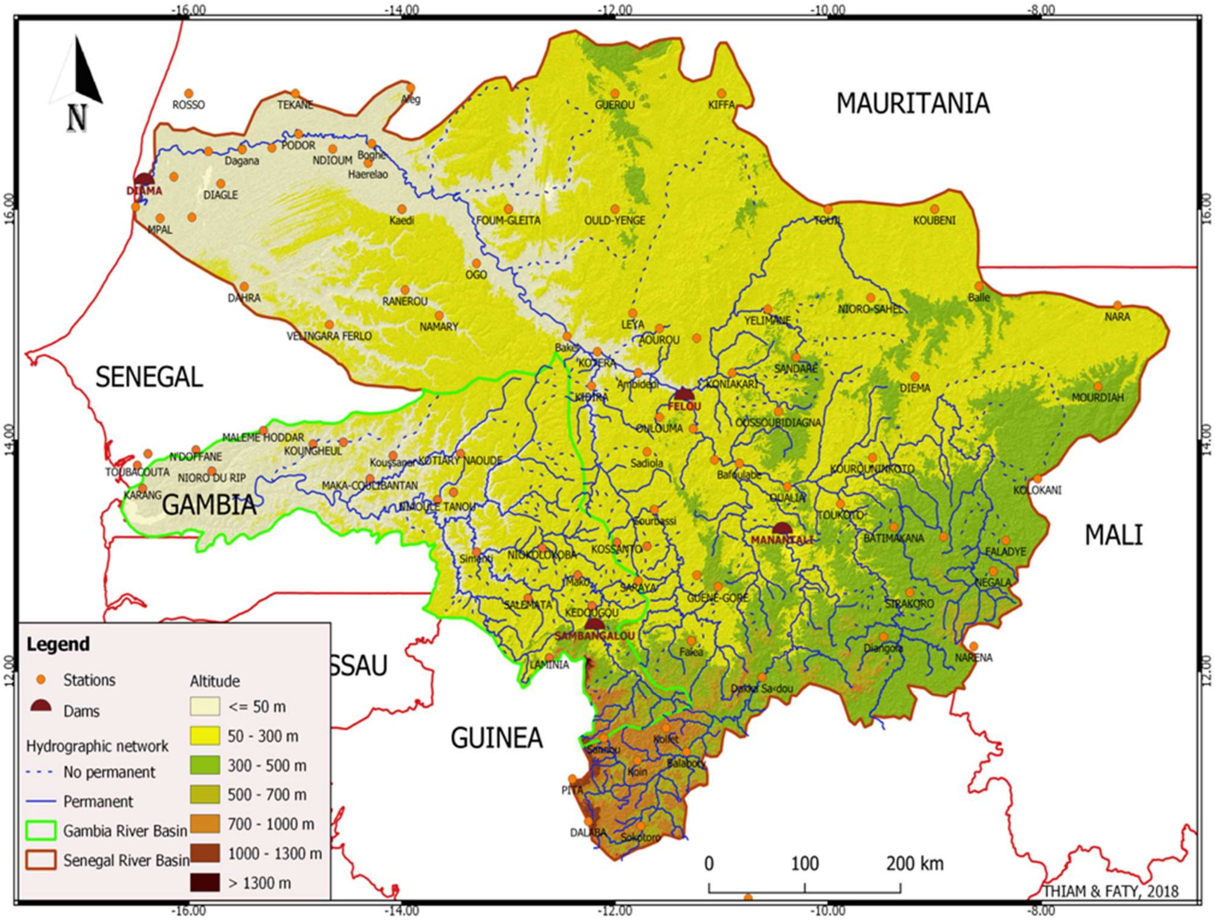


Figure 1: Presentation of studied area: Senegal River Basin and Gambia River Basin (Thiam, 2018)

However, in sub-Saharan Africa, climate variability is a reality that has been observed through several studies and research conducted for nearly a century (EQUESEN, 1993). Understanding recent climate change and, above all, medium- and long-term trends is an important development issue.

The current study named “Climate vulnerability and water resources variability in West Africa. Senegal and Gambia river basin cases studies” have four main objectives:

- Update the climate database and covering the entire Senegal Country and the two basins (SRB and GRB);
- Analyze the climate variability and trends analysis across West Africa focusing on Senegal and Gambia River Basins;
- Identify impact of climate on hydrology in Western Africa (including data from gauging stations, metadata and existing modelling tools and assessments);
- Build material for tailored training sessions.

This study contributes to the development of the regional Atlas on Water Cooperation; it focuses mainly on the challenges of water security and management. The report focuses on climate database update, climate variability and trends analysis, impact assessment of climate on hydrology in Western Africa (Senegal and Gambia River Basins).

PRESENTATION OF THE STUDY AREA

The geographical scale generally concerns the West African sub-region, which includes no less than twenty-five catchment areas. However, the area we are studied is limited to the transboundary watersheds of Senegal and Gambia, which polarize six countries in the sub-region (Gambia, Guinea, Guinea Bissau, Mali, Mauritania and Senegal). The main objective is to assess water resources availability for socio-economic activities and also the needs of the environment, with a view to maximizing cooperation and avoiding potential conflicts.

The Senegal River Basin and Gambia originate in the highlands of Fouta Djallon in Guinea, the Senegal River Basin crosses Mali before forming the border between Mauritania and Senegal, then flows into its estuary on the Atlantic Ocean. The Senegal River basin, which covers an area of 300,000 km^2, is divided into three distinct parts: (I) the upper basin, which is mountainous, (ii) the valley and delta, which are sources of biological diversity and (iii) wetlands. The average annual rainfall in the basin is 550 mm, with the South Guinean zone recording nearly 1500 mm/year compared to the northern part of the basin recording 200 to 250 mm/year. Thus, each year, the river transfers billions of cubic meters of water from the regions of the upper basin to the dry Sahelian regions of the valley and delta. While the Gambia basin covers an area of 77,000 km^2. The basin is shared by Guinea Conackry - Guinea Bissau - Senegal and Gambia.

The eight countries bordering the Senegal River Basin and the Gambia are among the poorest countries in the world, with 42-53% of the population living below the poverty line and a low per capita GNP of only $430 in Guinea. The total riverside population is estimated at 35 million people, 12 million of whom live in the basin. Most of them are subsistence or smallholder farmers and are therefore among the most vulnerable groups in the region. The population growth rate is estimated at 2.7 per cent and the population is expected to double every 25 years.

Water resources play a major role in the ecosystem of the Senegal River and the Gambia and in the economic development of the region in both basins. The livelihoods of about 85% of the basin's population depend on hydrosystems, and about 700,000 people in communities along the middle valley depend on the estuarine environment. The main economic functions of the river are power generation, navigation, irrigation, fishing, drinking water production and social functions.

1. PHYSICAL DETERMINANTS OF THE BASIN

The studied area constitutes a part of West Africa, defined here as the region partially covering the Sahel and the Economic Community of West African States (ECOWAS) area. It is a region of high topographical and rainfall contrasts, with a clear difference between well-watered areas (south and southwest) and semi-arid and arid areas (north and northeast).

The main rivers in the region originate in the Fouta Djalon Massif region before crossing the Sahel areas where rainfall deficits have been chronic since the early 1970s. These rivers allow an interzonal transfer of fresh water from wetlands to arid regions, thus creating a strong interdependence of West African countries in the use and management of freshwater resources (Niasse, 2004). The Gambia River basin is located on the Atlantic coast and borders the Senegal River basin to the south and southwest. Both rivers originate in the same region of the Fouta-

Djalon central region. The Gambia River basin, which is smaller, extends less in latitude and longitude than its neighbor (Lamagat et al., 1990).

The Republic of Senegal is located at the western end of the African continent and covers an area of 196,720 km² sharing borders with Mauritania to the north, Mali to the east, southeast with Guinea and south with Guinea Bissau. To the west of the country is the Atlantic Ocean. The Republic of Gambia forms an enclave of 11,295 km².

The Senegal River is 1,800 km long and its basin covers an area of about 300,000 km2 shared by Guinea (7%), Mali (35%), Mauritania (50%) and Senegal (8%). About 3.5 million people, 85% of whom live near watercourses, currently live within the basin. The Diama, Manantali and Felou dams satisfy part of the electricity needs of the four riparian countries of the basin as well as a significant agricultural production (INBO, 2014). The main tributaries of the Senegal River are the Bafing (760 km) and Bakoye (560 km) which meet in Bafoulabe, the Kolombine, Karakoro and Gorgol on the right river, and the Faleme on the left bank. Smaller tributaries and rivers include Lake Guiers in Senegal, Lake R'Kiz in Mauritania, Ferlo, Gorgol and Doue. The Senegal River flows into the Atlantic Ocean through a mouth located south of the city of Saint-Louis.

The average flow of the Senegal River at Bakel station is 700 $m^3.s^{-1}$ for the period 1903-1970 and 400 $m^3.s^{-1}$ for the period 1970-1990. Since then, Senegal's average flow at Bakel has remained stable between 300 and 400 $m^3.s^{-1}$.

The Senegal estuary is a highly vulnerable area in terms of environmental, social and economic conditions, given the events that took place there in 2003. In October 2003, the opening of a breach on the Langue de Barbarie Sandy spit and the moving northward of the river mouth have caused an increasing vulnerability to the environment and social and economic activities. This estuary is one of the hotspots that will be presented in this report.

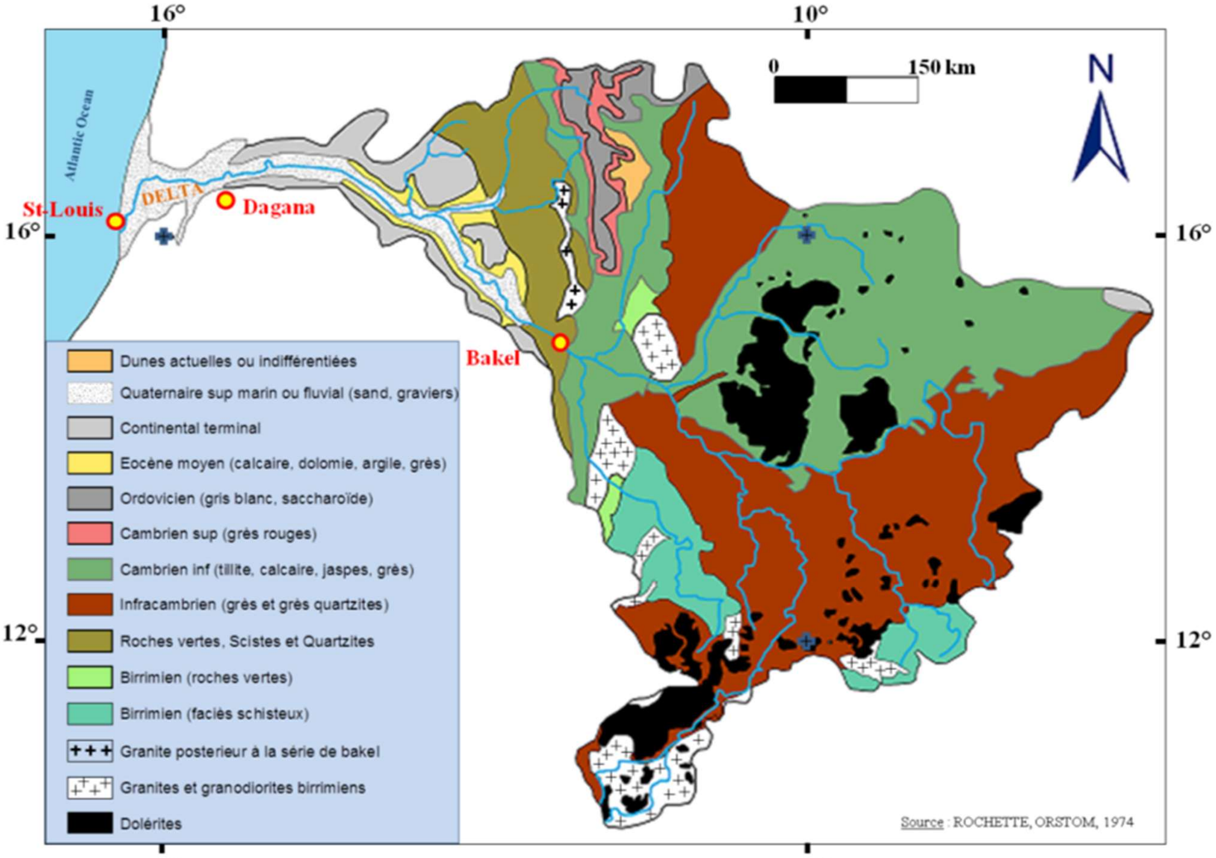
The Gambia River Basin has an area of 77 054 km² divided between Senegal (70.9%), Guinea (15.4%), Gambia (13.7%) and Guinea Bissau (0.021%). The long river is 1150 km long, 205 km of which are in Guinea, 485 km in Senegal and 490 km in Gambia. Its main tributaries are Koulountou, Sandougou, Nieriko, Thiokoye, Sili, Diaguiri and Niaoule.

Senegal's internal renewable surface water resources are estimated at 23.8 km^3 per year and renewable groundwater resources are in the order of 3.5 km^3 per year. The common part between surface water and groundwater is estimated at 1.5 km^3 per year, while inland renewable water resources are estimated at 25.8 km^3 per year (FAO, 2016). According to the same source, the renewable water resources of the Republic of The Gambia are estimated at 8 km^3 per year, of which 3 km^3 are produced in the interior of the country and 5 km^3 represent the influx of Gambia from Senegal. It estimates that the country's groundwater amounts to about 0.5 km^3 per year, is drained by the Gambia and becomes the base flow of the river. Groundwater is available in all regions of The Gambia. The basin is located in one of Africa's main sedimentary basins and is often referred to as the Mauritania and Senegal basin. It is characterized by two main aquifer systems with groundwater depths ranging from 10 m to 450 m.

The flow of the Gambia River varies in the year from 4.5 $m^3.s^{-1}$ at the peak of the dry season to +1,500 $m^3.s^{-1}$ or more at the end of the rainy season at the Gouloumbo station in Senegal according to Frenken (2005).

The level of renewable water resources abstraction in sub-Saharan West Africa in 2000 (most recent figures, Gleick and Cohen 2009) was 26.1 billion m^3 per year. Estimations of the available potential vary between 330 billion m^3 and around 450 billion m^3, resulting in tax levels of between 2% and 5.8%, which is very low. Among the States in the West African region, Mali (6.55 billion m^3 of levies in 2000), Nigeria (13.1 billion m^3 in 2005), Senegal (2.22 billion m^3 in 2002) and Côte d'Ivoire (1.55 billion m^3 in 2005) are the largest users (AQUASTAT, 2012).

Several well-known groundwater aquifers exist in the Senegal River Basin and the Gambia Basin. They correspond to different geological formations (Figure 2) that have been established in the Primary, at the end of the Secondary, Tertiary and Quaternary periods respectively (Rochette, 1974).



Source : ROCHETTE, ORSTOM, 1974

Figure 2: Geological Map of Senegal River Basin

Mainly, in the two basins, we found the following aquifers: the deep Maestrichtian aquifer, the Eocene aquifer, the Continental Terminal, the alluvial or quaternary aquifer and the basement aquifer.

The deep Maestrichtian aquifer (100 to 350 meters deep) is present throughout the Senegalo-Mauritanian sedimentary basin. The Eocene aquifer is also represented over the entire senegalo-mauritanian sedimentary basin, except for the Maastricht outcrop or subcrop zone where it has been eroded. The supply of this groundwater is dependent on rainwater, river water (infiltration following floods) or water from the Maestrichtian aquifer by vertical drainage. The Continental Terminal (CT), also known as the "Trarza groundwater", is the most important and regular groundwater in the entire coastal sedimentary basin of Mauritania. The continuity of the groundwater is linked to the general permeability of the TC formations made up, as in Senegal, of sands, sandstone with lenticular intercalations of variegated clays. Quaternary formations are made up of a portion of clays and fine sands that correspond to Post-Nouakchottian deposits and on the other hand coarse or gravelly alluvial deposits, clayey sands corresponding to the formations of the Ogolian and ancient and middle Quaternary periods. The alluvial groundwater (located between 2 and 15 meters deep) covers the major bed of the river. The flow of this water table is reversed between the flood and the low water level of the river. This slick is related to the underlying slicks due to the variability of the formations and their lenticular arrangement. Piezometric studies show that alluvial groundwater is alternately fed and drained by the river.

Basement aquifers have been identified in Eastern Senegal, Mali and Guinea (Upper basin of Senegal and Gambia also). These aquifers have the common characteristic of having low flows (often less than 1 liter/second) and being located at shallow depths (1 to 10 meters). Water availability in these aquifers often depends on local annual rainfall.

The results of the hydrogeological work carried out to date do not allow the knowledge of the country's groundwater resources in terms of precise location of groundwater resources aquifers. As for the available exploitable volumes, they are only indicative. Thus, the groundwater potential is estimated at 13 billion m^3, i.e. Higher than the volume stored in the Manantali dam (Lamagat et al., 2015. Deep confined or semi-captive aquifers (40 to 60 meters) are also found in the Upper Basin in Guinea and Mali. They are aquifers of any lithological nature protected by a thick or not very permeable covering: granite, schist, dolerite, gneiss, sandstone... The basement aquifers in the Senegal River basin are located in the high valley, mainly south of Semme. They contain scarce water resources, are important and located in the alteration fringe of Precambrian crystalline rocks. Hydraulic parameters, which are generally poor, generally only allow very limited drainage of flows to a few $m^3.h^{-1}$.

For groundwater in the SRB, we based ourselves on the recommendations and conclusions of the diagnostic study for the establishment and rehabilitation of the piezometric network in the Senegal River basin, led by the OMVS High Commission, but also the piezometer location map produced in Phase 1 and the SDAGE (Schema Directeur d'Aménagement et de Gestion des Eaux) water abstraction map.

The above-mentioned diagnostic study is a synthesis of the work carried out on groundwater issues, in particular at the end of the workshop to launch the process of setting up the groundwater monitoring network in the Senegal River basin, organized by the OMVS High Commission in January 2007. The results show that:

- Many of the piezometers installed are no longer functional. Piezometers damaged or destroyed by agricultural activities,
- Blocked or more or less dry piezometers (filling...),
- Destruction of ancillary buildings (coping stones, etc.),
- Piezometers inaccessible due to vegetation development,
- Absence of protection from water contamination (defective closing system, fence...).

In the Senegal River Delta, out of 30 piezometers visited in Senegal, operators noted 16 out of 39 on the Mauritanian shore, 22 are also out of order, representing a proportion of about 50%. This value is a constant since the same can be observed in Mali, 8 piezometers in good condition out of 20 visited.

2. CLIMATE, HYDROGEOLOGY AND HYDROLOGY

The atmospheric circulation in West Africa distinguishes between trade winds in the dry season and monsoon flows in the rainy season. All these atmospheric processes are governed by the Azores, Saint Helena high, the Saharan depression and the inter-tropical convergence zone. In the dry season, the Azores high and the Maghreb (or Saharan) seasonal cell generate trade winds that predominate in the region. On the other hand, the southwest to west flows that prevail during the rainy season originate from the St Helena High in the Atlantic. These monsoon winds are one of the necessary conditions for rainfall input. However, the influence of oceanic and orographic factors are two elements to be considered in the evolution of temperatures, winds and precipitation.

Overall, the analysis of annual average temperature observations since 1960, conducted at four stations throughout the Senegal River Basin, shows a very real increase in temperatures for all four stations. From 1960 to 2016, the analysis of temperature anomalies shows an increase of +1°C. This increase could contribute to the amplification of the effects of drought (Funk et al., 2012). Unlike temperatures, precipitation increases as we move southward.

Rainfall varies from 600 to 800 mm (in the Kaolack-Tambacounda axis: 610 mm in Kaolack, 763 mm in Tambacounda) and increases southwards to over 1,000 mm in Casamance in the Kolda region (1,015 mm) and towards Kedougou (1,192 mm), according to CSE (2000).

In the Senegal River basin, the following climatic conditions can be distinguished:

- The Guinean domain, which encompasses almost the entire Fouta Djalon to Daka-Saidou (in the upper river basin) with high rainfall and an eight-month rainy season
- (from April to November);
- The southern Sudanese domain of the northern foothills of Fouta Djallon and the western part of the Mandingo plateaus with an average rainfall and a rainy season of 6 to 8 months (from April to November);
- The northern Sudanese domain extending into the remaining part of the upper basin to the Bakel station, with lower rainfall and a rainy season of 4 to 6 months (May to October); The Sahel region with very low rainfall and a rainy season lasts 3 months.

Overall, water resources are still under-exploited. The level of renewable water resources abstraction in sub-Saharan West Africa in 2000 (most recent figures from Gleick, 2009) was 26.1 billion m³ per year. Estimates of the available potential vary: between 1 330 billion m³ and around 450 billion m³, resulting in very low harvest levels of between 2% and 5.8%. Among the States in the region, Mali (6.55 billion m³ of levies in 2000), Nigeria (13.1 billion m³ in 2005), Senegal (2.22 billion m³ in 2002) and Côte d'Ivoire (1.55 billion m³ in 2005) are the largest users (Aquastat, 2012).

According to FAO 2012, the renewable water resources of the Republic of The Gambia are estimated at 8 km^3 per year, of which 3 km^3 are produced in the interior of the country and 5 km^3 represent the Gambia's inflow from Senegal. Both basins are characterized by aquifer systems with depths ranging from 10 m to 450 m.

The Fouta Djallon massif is a mountain range and a succession of plateaus, source of many transboundary rivers including Senegal and Gambia (CIWA, 2017).

The Senegal River is 1,800 km long. Its basin covers an area of about 300,000 km2 and is shared between Guinea (10%), Mali (38%), Mauritania (30%) and Senegal (22%). It originates from the confluence of the waters of the Bafing (Guinea) and Bakoye (Mali) rivers that meet in Bafoulabé (Mali). Its tributaries are mainly the Falémé and incidentally the Kolombiné, Karakoro and Gorgol... The Guiers lake (Senegal) and the R' Kiz lake (Mauritania) form among others the river's tributaries. They are potential sources of fresh water for the supply of water to populations. It also supplies the basins of Ndiaël, Khant, Nguine, Ndiasséou, Djoudj and rivers, marigots, ponds of Djoudj, Gorom-Lampsar, Ngalam, Djeuss (Niang, 2013).

The average flow of the river at Bakel station is 700 m^3.s^{-1} for the period 1903-1970 and 400 m^3.s^{-1} for the period 1970-1990. Since then, Senegal's average flow at Bakel has remained stable at between 300 and 400 m^3.s^{-1}.

From Saint Louis, its vast delta is formed and further downstream, its lower estuary. The Senegal estuary, given the major developments on the river (the Manantali and Felou hydroelectric dams...), is a particularly vulnerable area from an environmental, social and economic point of view. Especially in October 2003, the opening of a breach in the language of Barbary and the northward movement of the river mouth aggregated this vulnerability. Among other things, the urban sprawl of the city of Saint Louis only aggravates this situation (Niang, 2013). This estuary is one of the hot spots that will be presented in this report. The Senegal River is the second largest river in West Africa, after the Niger River. What about his neighbor?

The Gambia is a river that rises at 1,225 m and then stretches for 1,150 km. Its basin covers an area of 77,054 km^2 (Lamagat et al., 1987), the third largest in the region (CIWA, 2017). This basin is shared between four riparian States (COTECO, 2004): Senegal (70.9 %), Gambia (13.7 %), Guinea (15.4%) and to a lesser extent Guinea Bissau (less than 1 %). The Gambia River Basin is generally divided in two parts (Michel, 1973; Chaperon et al., 1974; UNDP, 1982; Lo, 1984). On the one hand, the so-called "continental" upstream part (from the source in the Republic of Guinea to the Gouloumbou station in Senegal) is marked by a dense network of tributaries, the main ones being respectively Tiokoye, Diarha, Koulountou, on the left, and on the right, Diaguéri, Niokolo koba, Nièriko and Niaoulé. These tributaries form the bulk of the river's fresh water inflows. On the other hand, a downstream part known as the "estuary" (from Gouloumbou in Senegal to the mouth at Banjul) where the river is at sea level and is subject to the tide (Lamagat.et al, 1987). Indeed, this Gambia estuary ranks among the largest in the world: it covers nearly 36,000 km^2 (Dione, 1996). Thus, the weakness of river dynamics facilitates the progression of tidal waves reaching Gouloumbou (Senegal), which is more than 400 km from the mouth (Michel, 1973). This suggests the problem of salinity and vulnerability of the estuary's water resources, which can be very detrimental to the activities of basin societies. As with the Senegal River, here too, the Sambangalou hydroelectric development project, although offering interesting electrical advantages, also presents environmental and social risks (OMVG, 2014), particularly in its estuary.

3. SOCIO-ECONOMIC AND CULTURAL ACTIVITIES

The standard of living in Senegal and Gambia River basin reflects the living conditions which prevail in the riverside states. According to the Human Development Index of the United Nations, the riverside countries of Senegal and Gambia River basin are very poor and very low classified. The population of the Gambia River Basin was estimated at about 19.9 million inhabitants in 2001 with an annual growth rate of about 2.7%. The demographical density of the sub-region varies from 53 in Guinea, 68 in Guinea-Bissau to 214 in Gambia (Table 1). In Senegal, the rate ranges from 10.6 inhabitants per km² in Kedougou to 19.2 inhabitants per km² in Tambacounda (ANSD, 2018).

In Guinea, poverty would relate to some 55 % of the population according to the World Bank (2012). In Senegal, the percentage of the poor decreased between 1994 and 2002: it passed from 67.9 % to 57.1 %. Nowadays, the poverty rate is near 47 %. Poverty is very marked in the department of Kedougou, strongly wedged with respect to the remainder of the country, 80 % of households and 89 % of the individuals live below the poverty line. The poverty of the department is the strongest of Senegal despite the hydrographic, agricultural, pastoral and mining potentialities.

Table 1: Socio-demographic data for the Senegal and Gambia riverside states

Country	Population 2018	Density (inhkm²)	Fertility Rate	Medium Age	Urban Population	IDH 2017
Gambia	**2 163 765**	214	5.6	17	59%	0.460
Guinea	**13 052 608**	53	5.1	18	38%	0.469
Guinea Bissau	**1 907 268**	68	4.9	19	50%	0.455
Mauritania	**4 540 068**	4	4.9	20	57%	0.520
Mali	**19 107 706**	16	6.4	16	38%	0.427
Senegal	**16 294 270**	85	5.0	18	43%	0.505

Source: www.worldometers.info

The socio-economic developments along the Senegal and Gambia River mainly rely on the opportunities arising from the hydraulic infrastructures. The main focus of development strategies within the two basins is on agricultural activities and drinking water.

Traditionally, along Senegal River, flood recession has been the most important agricultural system and supports a relatively large population. The size of the inundated area and the duration of the inundation determine the potential for flood-recession agriculture in any given year. Details of the effects of river flow dynamics on flood-recession agriculture in the area are given in Rasmussen et al. (1999). The crops grown are mainly millet, sorghum and corn, and average yields are in the order of 400 $kg.ha^{-1}$ for cereal (Gibb et al, 1987a). Crop production through pump-based irrigation has increased since the 1970s and it is supported by national subsidies in Senegal. A Senegalese institution named Société Nationale d'Aménagement et d'Exploitation des Terres du Delta du Fleuve Sénégal (SAED) has been responsible for the establishment of irrigation schemes on the Senegalese side of the river. Here, rice is the main crop and yield levels are 1 to 6 tons/ha, with the higher yields only obtained in newly established or rehabilitated and well-functioning schemes. Approximately, the Senegal River Valley produces 750,800 tons of rice in 2017, according to the National Statistics Agency. The importance of rain-fed agriculture is decreasing since the droughts of the 1970s, especially in the lower valley.

After the construction of the Manantali Dam, water availability was no longer the critical factor for irrigated agriculture in the region. Economic profitability, management difficulties and in particular the maintenance and replacement of pumps appeared to be the controlling factors. The construction of the Manantali Dam was also meant to generate hydroelectric power (800 $gwh.yr^{-1}$) and to secure adequate flow for navigation on the Senegal River all the way up to Kayes.

For flood-recession agriculture, yields may be limited by water availability, plant nutrient availability, plant diseases, and/or attacks by insects or birds. The effect of limited water or nutrient availability is a low plant density. Nutrient availability may have been influenced by changing patterns of inundation and the reduced deposition of sediments on the floodplain following the construction of the Manantali Dam. The inundated area has been considerably reduced since the early 1970s and this, in combination with a considerable increase in the valley's population, has meant that the flood-recession agriculture can no longer ensure sustainable food production for the local market. Regarding irrigated agriculture, rice cultivation is based on large inputs of mineral fertilizers, and thus reductions in fertilizer input immediately lead to decreasing yields.

Waters of Gambia River lend themselves to several uses with primarily the agriculture. Other activities like, rearing, fishing are presents in the basin. The potentialities in irrigable lands in the basin are 93,000 ha. In Senegal, 4,100 hectares were recognized as having a good capacity in the irrigation. We have several agricultural speculations in the basin; the main ones are rice, groundnuts and cotton. Rice stays the base of alimentation in the region; that explain rural's problems when drought occurs. Cotton was introduced in 1963-64 by the Cotton Fiber Company, which will be relieved in 1974 by the Cotton Fiber Development Company (SODEFITEX). The production of cotton that was formerly very prosperous suffered a slight fall and later stabilized at 18,000 tons in 1988. In 2003-2004, a record production was registered with more than 50,000 tons; the production would have even reached 52,000 tons in 2006-2007. There are major differences between the two basins: in terms of hydro-agricultural infrastructure, morphology, etc. The two basins are very different despite their great climatic similarity.

4. MANAGEMENT AND PLANNING (OMVS AND OMVG)

Proper river basin management requires a hierarchy of institutions at different levels. In the case of the Senegal River Basin, these include institutions at the village, national and transboundary levels. The interests of institutions at different levels are likely to be in conflict (Rasmussen et al., 1999). The management of the water resources of the Senegal River has caused controversy between the countries involved and between the various stakeholder groups. Conflicts of interests have been associated with hydroelectric power production, allocation of and access to water for irrigation and domestic supplies, modern and traditional agricultural water requirements, and the conservation of wetland ecosystems and the wider environment (Kipping, 2005; Ndiaye et al., 2007; Richter et al., 2010; Auclair, 2013; Bruckman, 2017). Conflicts regularly occur between herders and farmers following the divagation of animals due to the absence of grazing areas or simply due to the occupation of pastoral corridors by farmers; in addition, there is a lack of grazing land and the uncontrolled occupation of the banks of the river by agriculture, which constitutes serious damage for agropastoralists.

In the Bafoulabe circle, this type of conflict sometimes also pits fishermen against the inhabitants of the surrounding villages. Fishing is under serious threat in the Kayes Circle - who expect more fodder from its structures.

The land issue: land management remains in the domain of the State; land is difficult to access and is subject to strong pressures: this access is all the more difficult with the conversion of some stakeholders to market gardening activities.

Since 2011, a water resource allocation model, funded by the European Union, has been developed at OMVS to address priority environmental issues. However, we do not have enough information on this allocation model developed by OMVS given the administrative difficulties of the central body

To overcome these conflicting interests, a supra-national authority, Senegal River Basin Development Organization (OMVS), was established to decide on water allocation and dam management principles within the river basin. Mali, Mauritania and Senegal are members of the OMVS, whereas Guinea, where most of the discharge originates, is not. The members have developed a legislative and institutional framework for the management of water resources in the basin. The institutional framework for each riparian country comprises:

- A representative of the OMVS;
- The ministry in charge of water resources;
- A national institution (e.g. SAED in Senegal, SONADER in Mauritania and Niger Office in Mali);
- Institutions for water partnership (ngos, donor agencies);
- Associations (farmers, fishermen, women’s associations, etc.).

As part of the water resources management program of the Senegal River Basin, OMVS has planned to carry out new hydraulic infrastructures in a more or less distant horizon. This is to realize the second generation of dams as part of a regional master plan for energy transmission and interconnection. In the long term, the objectives as expressed by the interstate organization are:

- To have more than 66 % of the total hydroelectric power of the basin, more than 3000 gwh.year-1;
- To control more than 97 % of flows in the Senegal River with a storage of 23 billion m3 of water;
- To save about 240 billion CFA francs a year on the oil bill of the riparian states of the basin;
- And finally, to facilitate interconnections and exchanges of electrical energy.

The Diama Dam was built in the delta to limit the intrusion of seawater during periods of low discharge and to protect the river ecosystem. The social, economic and environmental gains and losses associated with the dam are not well known. According to Gibb et al. (1987), the total sediment transport over the period 1908-1934 in Bakel and in Saint-Louis was ~4 million tons. Only 30 % of this quantity was deposited on the floodplains, whereas 70 % reached the sea. Although data of sediment transport are available for several stations in the basin (Orange, 1990; Kane, 1997), a wider range of factors need to be considered when assessing the impact of the dam. In alluvial rivers such as Senegal, it is common to recognize that solid matter transport takes two forms: suspended solids (SS) and solid transport.

Solid transport involves the transport of the materials that make up the bottom of the bed. Its quantitative assessment, based on in situ measurements, is very difficult. Its evaluation by applying theoretical and semi-empirical transport formulas is very imprecise. In addition to the choice of the best formula, there is the problem of choosing the representative calculation parameters (flow rate, average diameter, average height, average slope, etc.). These estimates generally yield very scattered results that are not very useful.

On the Senegal River upstream of Gouina, the many sills that block the river severely limit the possibilities of solid transport in the upper part of Senegal. The Manantali dam, which is an obstacle to water transport on the Bafing, can only further reduce the possibilities for solid transport upstream from Senegal. Transport in the upper basin would therefore mainly come from the tributaries between Kayes and Gouina.

The measurement of suspended solids (SS) is easier than that of solid transport. Measurements were carried out by Senegal-Consult in 1968 and 1969. The average diameter of the suspended particles is 0.002 mm. The concentration of suspended solids (SS) varies from 25 to 250 $mg.l^{-1}$ when the flow rate varies from 800 to 2,500 $m^3.s^{-1}$. By integration, the average annual quantities transported in suspension were estimated at 2.9 million t/year at Bakel. Measurements carried out in 1971 by Surveyer, Nenninger and Chevenert for OMVS, gave an average value of 900,000 tons/year, or an average of about 2500 t/day, with a maximum flood of 14,000 tons/day. These measurements were made at 30 cm from the bottom for flow rates of 0.1 to 0.2 $m.s^{-1}$ on materials with an average diameter between 0.005 and 0.007 mm. The concentrations obtained ranged from more than 1000 $mg.l^{-1}$ during the flood to less than 30 mg.l^{-1} during the recession. This disparity between the results clearly shows the difficulty of estimating sediment transport.

Since the early years of operation of large dams on the Senegal River, many research studies have been devoted to the consequences of these structures on the hydrological cycle, water quality and environmental changes on the local to regional scale (Diakhate, 1988; Orange 1990; Gac, 1993; Kane, 1997). A near unanimity has emerged about their appropriateness and their effects, some of which are considered highly beneficial.

The Manantali Dam on the Bafing tributary in Mali was built for hydroelectric power production and regulation of the river flow. The dam controls approximately 50 % of the total flow. Ideally, operation of the dam should allow for both artificial flooding of the river valley (100,000 ha) and for secure navigation on the Senegal River. Inundations, however, have been much less effective than were planned for.

The Felou hydroelectric dam is a run-of-river project commissioned in December 2013. It is located on the Senegal River in Mali, 15 km upstream from Kayes. With a cost of 125.7 million Euros, it produces 431 gwh for an installed capacity of 60 MW. Energy is transported approximately 4 km by connection to the Kayes substation on the 225-kv grid.

Several other dams are planned to complete the management scheme of the Senegal River Basin: Gouina, Koukoutamba, Boureya and Gourbassi. The dam projects of Bindougou, Badoumbe and Boudofora are not sufficiently advanced. With these second-generation infrastructures, the OMVS member states will be able to mobilize a good part of the electrical potential of the Senegal River and its main tributaries. Interconnection and sharing of electrical energy will reduce the energy deficit of some member states such as Guinea where this issue remains crucial.

In order to support decision-making, hydrological models of the Senegal River Basin have been developed by OMVS in collaboration with IRD (French Institute of Research for Development), mainly to manage propagation of flows from upstream to downstream (Lamagat et al., 1999 & 2000). The first model was COREDIAM, dedicated to evaluate the expected level at the various stations influenced by the Diama dam and to calculate the backwater curve of the Diama dam. SIMULSEN was designed to evaluate the effects of the different management rules of the Manantali dam and the degree of satisfaction of the following requests:

- Hydropower generation;
- Flow passing through Bakel station, corresponding to irrigation needs, city consumption and other possible needs like navigation and annual flooding necessary for flood recession crops in the Senegal River Valley;
- Flood rolling at the outlet of the Manantali reservoir.

It should, however, be emphasized that decision-making in water resources management, e.g. That associated with the operations of the Manantali and Diama dams, as well as the Felou dam, cannot be solely based on hydrological reasoning. Obviously, agronomic, economic, social and environmental issues also need to be considered.

Consequently, these hydrological models are limited; they do not allow the analysis of the consequences of climate change and climate variability on the basin, of dam operations and land-use changes. For these reasons, WEAP software should be used on Senegal River basin. WEAP has been specially designed to model and illustrate forms of water resource management, planning and allocation.

In March 1972, the ultimate institutional framework, OMVS was born. Its creation comes in the context of serious climatic deterioration, marked by a persistent and severe drought that devastates the entire valley. Drought cycles, degradation of natural resources, rainy crops and flood recession lead to the impoverishment of the population and a high emigration of young people. Added to this is the rise of the salt tongue over nearly 250 km, making the land unfit for cultivation.

Mali, Mauritania and Senegal then decided to join forces to master the availability of water and seek ways for a rational and coordinated exploitation of the basin's resources. The new Organization for the Development of the Senegal River has assigned itself as missions:

- Achieve food self-sufficiency for the populations of the basin and the sub-region,
- Secure and improve the incomes of the populations,
- Preserve the balance of ecosystems in the basin.
- To reduce the vulnerability of the economies of the Member States of the Organization to weather and external factors.
- Accelerate the economic development of the member states.

This common will of the member states is cemented by the ideals of solidarity, sharing, equity and culture of peace.

5. IWRM RECENT PERSPECTIVES

Concerning the hydroelectricity production, a study on the integration of production investments and electrical energy transport in the four countries members of OMVG was conducted from 1994 to 1996 (ADF, 2008). The OMVG Energy Project includes the Sambangalou hydroelectric dam located on the Gambia River near Kedougou (Senegal) and the creation of an electricity interconnection line linking the four OMVG member countries, work on which has already begun. The Sambangalou dam project includes four turbines of 32 MW for a total capacity of 128 MW and a water reservoir with a capacity of 3.795 Billion m^3. The OMVG Energy Project is 85 % funded by the Chinese Group EPC; the rest is supported by all OMVG countries.

The Gambia River Basin Development Organization (OMVG) was created in 1978 by the Republics of The Gambia and Senegal. The Republics of Guinea and Guinea-Bissau joined the Organization respectively in 1981 and 1983. The OMVG, whose mission is to emphasize the Gambia, Kayanga/Geba, Koliba/Corubal and Konkoure river basins, aims at the socio-economic integration of Member States through the achievement of the Organization's common programs and projects for the four countries. Master plans' studies of the hydrological basins carried out within the framework of the OMVG's various programs have been based on a vision and a global development approach which consider the river basin as action unit. OMVG is also responsible for creating and managing the hydrological and cartographical database of the basin. The organization is in charge of the coordination of the different national policies and define the criteria that permit the harmonization of data collection network and data processing systems. OMVG also ensures training, exchange of information & experiences among the hydrologists from different riverside states.

The Member States of OMVG are bound by four conventions: those relating to the statute of the Gambia River, the legal statute of the common works and the methods of financing of the common works like that bearing creation of the OMVG. The origans of OMVG are the following:

- The Conference of the Heads of State and Government;
- The Council of Ministers; the Executive Secretary;
- Steering Committee of Water;
- And the Consultative Committee.

Diama dam Salt barrier (Senegal)

Manantali Regulatory dam (Mali)

Regulatory Felou dam

Figure 3: Dams on Senegal River Basin (© OMVS)

DESCRIPTION OF THE METHODOLOGY

Generally, climate variability refers to the intra and inter annual natural variation of the climate, whereas climate change refers to a change in climate directly or indirectly attributed to human activities that alter the composition of the global atmosphere and added to natural climatic variability observed over comparable time periods (UNFCCC, 1992).

Climate change is considered one of the most serious threats to development, with significant impacts on economies of developing countries. Given the difficulty of disentangling variability and climate change, particularly in the West African context, the notion of "variability and climate change" is often used to better reflect the issue and avoid complex and endless debates.

Thus, the notion of “variability and climate change” refers to the significant modification or variation of the climate, whether natural or due to anthropogenic factors (Niasse et al., 2004). Such a definition has the advantage of simplifying that given by the Climate Convention and also considering that of the IPCC, which considers climate change as a long-term variation of the climate, whether anthropogenic or natural.

The dry areas are the arid, semi-arid and sub-wet regions in which the relationship between annual precipitations and the potential evapotranspiration range in a fork going from 0.05 to 0.65 (UNCCD, 1994); 10 to 20% of these zones are already turned into a desert.

In West Africa, these zones essentially cover the Sahelo-Saharan region. Last decades, these areas are characterized by an important climatic variability, testify to the decrease of the rainfall and the rise of the temperatures, with negative consequences on ecosystems and production systems. That makes this part of the world one of the zones most vulnerable to the climate changes (IPCC, 2007) and thus, the most exposed to the climatic risks.

In an attempt to address climate change in the Senegal River basin, we examined a (fairly representative) part of the extensive work on climate change at global (IPCC assessment reports, including the 5th Assessment Report of 2014), regional (on West Africa and the Sahel Region), and river basin and riparian country levels, including the National Adaptation Reports on Climate Change (napas) and the expected contributions, determined at the national level (SSC) developed under the UNFCCC.

We also reviewed the climate change scenarios examined in these documents typically rely on hydrological and regional climate models using global climate model outputs, and in particular those used in IPCC assessment reports. Global models often lead to imprecise and contradictory results from one model to another. The shift from global to regional models (by spatial disaggregation) amplifies uncertainties.

An additional challenge is to use the results of regional models to predict climate change at the sub-regional level, as is the case in the Senegal River basin. In addition, unlike river basins such as the Volta or Congo, the Senegal River has not been systematically analysed for climate change scenarios, despite the fact that such an exercise is less risky since the Senegal River basin has more complete hydrological data. In the absence of a systematic study on climate change in the Senegal River basin, the scenarios discussed below remain highly indicative of possible futures.

The conclusions of the studies consulted thus indicate considerable uncertainty with regard to most of the characteristics of the future climate in West Africa and in particular in the Senegal River basin. The only area where there is a convergence of climate predictions for the river basin is temperature. The various studies agree that the average temperature of the basin will be higher than the average observed at present. It is even expected that the level of temperature increase in the Senegal River Basin and West Africa will be higher than the global temperature increase (ARTELIA, 2013 ; TRACTEBEL et al. 2012; Gaye & Ndiaye, 2015; and NAPA and CPDN of Guinea, Mali Senegal and Mauritania).

The consequence which results from this is that knowledge on the impacts of climate changes in certain sectors are contradictory. Whereas the forecasts of the IPCC (2007) estimate between 2 and 4% losses of GDP related to the agricultural sector by 2100. Case studies realized in Senegal, Mali, Burkina Faso and Niger present contrasted results (CEDEAO, CSAO, OECD, 2008). Other studies estimate that the average output of millet and sorghum cultures, would decrease between 15 and 25% in Burkina Faso and Niger by 2100; while the output of rice culture (rain or irrigated) would increase by 10 to 25% for irrigated rice and by 2 to 10% for rain rice; and this even in case of rise of the concentration of CO2 in the atmosphere (CEDEAO, SAO, OECD, 2008).

The West African climate is currently subject of in-depth studies, notably under the AMMA 2020 Program, with the hope of removing uncertainties about the monsoon-climate link on a global scale, but also about impacts of climate variability on local communities.

To sensitize decision-makers on the climate challenges facing the region, and to undertake necessary preparatory actions to address the predictable impacts of climate variability, change and events extreme, a West African Regional Preparedness and Adaptation Strategy was developed, on the initiative of CILSS and its partners. However, the implementation of this strategy raises important financial and institutional issues. Also, the issue of the complementarity of this strategy with National Action Plans for Adaptation (NAPA) deserves to be studied.

1. ANALYSE OF RECENT BIBLIOGRAPHY AND STATE OF THE ART ON CLIMATE VARIABILITY, CLIMATE CHANGE AND RISKS, EXTREME EVENTS AND CLIMATE MODELING IN WEST AFRICA

To carry out the necessary additional analyses to inform the assessment of the climate regime, the basic data listed below have been compiled from sources that have already carried out significant collection work from the institutions responsible for the measurements.

Precipitation is the main conditional factor in the hydrological regime, and constitutes the largest part of the climate data collected from different sources (see table below). The homogenization and analysis effort is therefore focused mainly on precipitation.

Other climatic factors (temperature, sunshine, humidity, wind regime) have a much less direct influence, and the regimes described in the 1974 monograph are less likely to have changed since then (Rochette, 1974; Bader, 2015). To complement the analyses available in the existing studies, we have compiled the weather data collected from the IRD collections, 1986 and updated until 2016.

It remains to establish reference series of precipitation from the different sources by choosing the most reliable source (the same station can appear several times for different periods and under different versions, including raw or homogenized). It will be necessary to aggregate and correct or complete them.

Indeed, the series are rarely continuous (see attached chronogram of rainfall data archived in the Hydraccess database, which have a median gap rate of 15% to 60%). In addition, we have already noticed that the data stored in Hydraccess are raw data with some erroneous values, the quantity of which we do not know at this stage.

It is specified that the complete series of homogenized annual rains are not present in the Hydraccess database and are therefore not yet available.

The following database have also been investigated:

- **AMMA CATCH database:** The project was carried out in 2007 for UNESCO and concerns the updating of the hydro-pluviometry network of West Africa, which is the origin of this database. It contains raw precipitation values up to 2006 (for the most recent) for many stations in or near the Senegal River basin.
- **OMVS database: i**n addition to hydro-rainfall data, OMVS has set up a database of daily gross rainfall readings at 8 stations followed by daily radio shifts. These statements are updated to cover the period from 2001 to July 2012.
- **SIEREM database:** The SIEREM database (Environmental Information System on Water Resources and their Modelling) database was developed by HSM (hydrosciences Montpellier). The hydro-climatological data contained in SIEREM are data from the hydro-pluviometry database of the former ORSTOM Laboratory of Hydrology. These data have been enriched and updated by the various research programs developed by HSM or by the many doctoral students hosted at the Hydrological Antenna in Abidjan (1987 -1998) and in Montpellier in a second phase (1999 to date).

Table 2: Climatic and meteorogical data collected

Data types	Source
Some daily precipitation records over 5 to 8 years for 10 stations (updated by OMVS at the same time as the hydrometric measurements for dam's management): Bafing Makana, Bakel, Dakka Saïdou, Diama, Gourbassi, Kayes, Kidira, Manantali, Oualia (2001-2012), Diangola (2004-2012).	Hydraccess OMVS
Daily and / or monthly raw rainfall archived in Hydraccess for 139 stations: very variable histories depending on the station, from 1 to 87 years (median age 29 years) starting between 1900 and 1971 and ending between 1912 and 2016, with a median rate of deficiencies from 15% to 60%.	Hydraccess OMVS
Instant rainfall over 6 to 10 years archived in Hydraccess by OMVS for the following 3 stations: Labe, Mamou (70-80), Ranerou (90-97)	
Weather data archived in Hydraccess for the following 9 stations: Labe, Mamou, Siguiri (16 to 35 years from 1971 with a median	Hydraccess OMVS

Data types	Source
rate of gaps of 6%), Bamako, Kayes, Kenieba, Kita, Nioro and Yelimane (less than 3 years) See detailed table attached for step, history and type of humidity measurements, sunshine, temperature, and wind speed	
Monthly rains collected in the SIEREM database: 46 stations with a history varying from 17 to 152 years (median age 56 years) starting between 1848 and 1970 and ending between 1980 and 2003	SIEREM (IRD-Hydrosciences Montpellier)
Daily rains collected in the SIEREM database: 12 stations with a variable history of 4 to 23 years (median duration 11 years) starting between 1980 and 1999 and ending between 1996 and 2003	SIEREM (IRD-Hydrosciences, Montpellier)
Monthly rainfall collected by the US National Climatic Data Center (NCDC): 19 stations in the medium and upstream catchment, with a variable history between 1895 and 2000 (mainly 66 years from 1931 to 1997)	NCDC (US National Climatic Data Center)

The description of the climatic factors makes it possible to determine the influence of these factors on the flow and water level regimes, in addition to other conditional factors such as physical and anthropogenic factors (dams).

The updating of the data is largely based on the numerous synthesis studies carried out since 1974. The most recent studies are the theses of Dione (1996), Ardouin-Bardin (2004) and Bodian (2011); the article by Faty et al. (2017); two reports: the SDAGE of Senegal (2009) and the cross-border diagnosis of the environmental problems of the Senegal River Basin (2017). From these data, a synthesis of the climatic conditions was carried out, referring to the important synthetic data which they contain (maps of the isohyets, compass of wind, statistical adjustments, etc...).

Data from existing studies were supplemented by additional analyses needed to inform the chapters on the water level regime and flow rates (rainfall / discharge correlations, regional rainfall vector, etc.).

Precipitation data are the main conditional factor of the regime of heights and flows, and the effort of updating, homogenization. Climate analysis will therefore focus mainly on precipitation.

The other climatic factors (temperature, insolation, relative humidity, wind regime) have a much less direct influence, and the regimes described in the first monograph of the Senegal River (Rochette, 1974) are less likely to have changed.

Table 3: Summary of bibliography on Climatic Factors

Subject	**Type**	**Year**	**Author(s)**
Hydro-climatic variability and impact on the water resources of the major watersheds in the Sudano-Sahelian zone	Thesis	2004	Ardouin-Bardin S., 2004
Recent climatic evolution and fluvial dynamics in the high basins of Senegal and Gambia rivers	Thesis	1996	Dione O., 1996
The lowlands in the Gambia River system: mapping, hydrological regime, agricultural valorization and typology	Thesis	1998	Konate L., 1998
Influence of the climatic event on seasonal rainfall patterns in Senegal's high watershed. Journal of Water Sciences,	Article	2017	Faty, A., Kane, A. & Ndiaye, A., 2017
Senegal River SDAGE (Phase 1)	Study	2009	CSE-CG- GINGER-SCP, 2009
Monographic update of the Senegal River	Study	2012	J. Albergel
Cross-border diagnostic analysis of the environmental problems of the Senegal River Basin	Study	2017	Niasse M., Kane C., Faty A., 2016

In the Senegal River basin, particularly in its Sahelian part, climate remains one of the determinants of environmental evolution and has been since geological times. The awareness of the importance of climate data since the beginning of the 20th century has led to the availability of high-value time series for the management of the Senegal River basin. The Saint-Louis rainfall station has been in existence since 1848, while the Bakel hydrological station has been in operation since 1903. This large amount of data makes it possible to characterize the recent spatial and temporal evolution of the climate of the River basin. It also allows for very detailed analyses of the past and current climate, in a context where the issue of climate change and especially its impacts is being debated everywhere (IPCC, 2004 and 2007).

The basin is divided into three main climate domains (Figure 4):

- The Guinean domain located in the upper basin between Fouta Djalon and Dakka Saidou station is the wettest part of the basin with an average annual rainfall of more than 1500 mm.yr^{-1} and a rainy season that lasts more than eight months.
- The Sudanese domain, which is divided into southern Sudanese and northern Sudanese, is moderately rainy. The average annual rainfall range between 1500 and 500 mm.yr^{-1}; the duration of the rainy season varies from eight to six months from south to north.
- -The Sahelian domain occupies nearly 50% of the basin's surface area from the north of Bakel to the mouth in Saint-Louis. With a rainfall generally less than 500 mm.yr^{-} 1, this is a dry area where humidity is very low and the rainy season reduced to three months. During the severe drought of the 1970s, with low rainfall, sometimes less than 200 mm.yr^{-1}, some authors likened it to the Saharan arid domain (CARN, 1993; KANE, 1997).

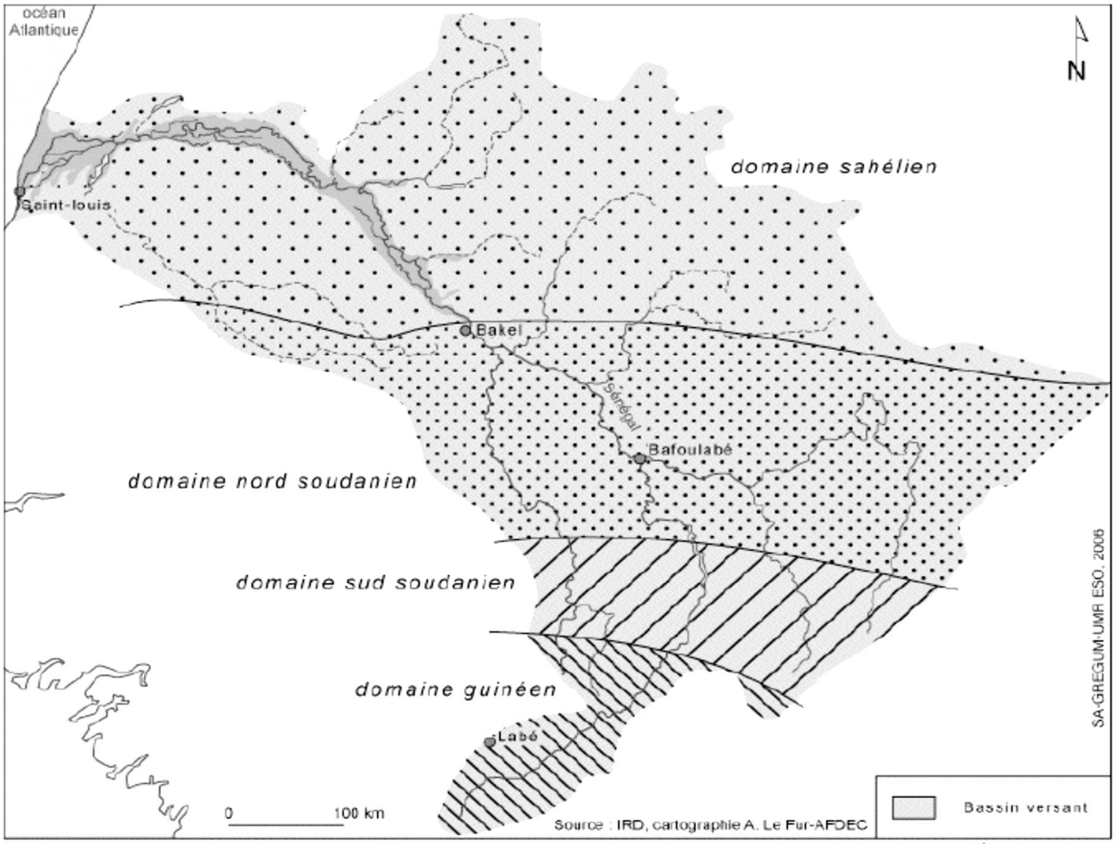


Figure 4: Climate domains of the Senegal River Basin
(modified by SALL (2006) from SOW (1984))

2. DATA AND TOOLS

2.1. IDENTIFICATION OF DATA NEEDS

The monitoring of climate parameters and the collection of the resulting data are the responsibility of the meteorological departments of the various countries over which the Senegal catchment area extends. These are the National Meteorological Departments (mnds) of Guinea, Mali and Senegal and the Society of Aeroports of Mauritania (SAM), which houses the meteorological service and some development and research organizations.

The quality and duration of the available data varies from country to country. The data archiving methods are also different.

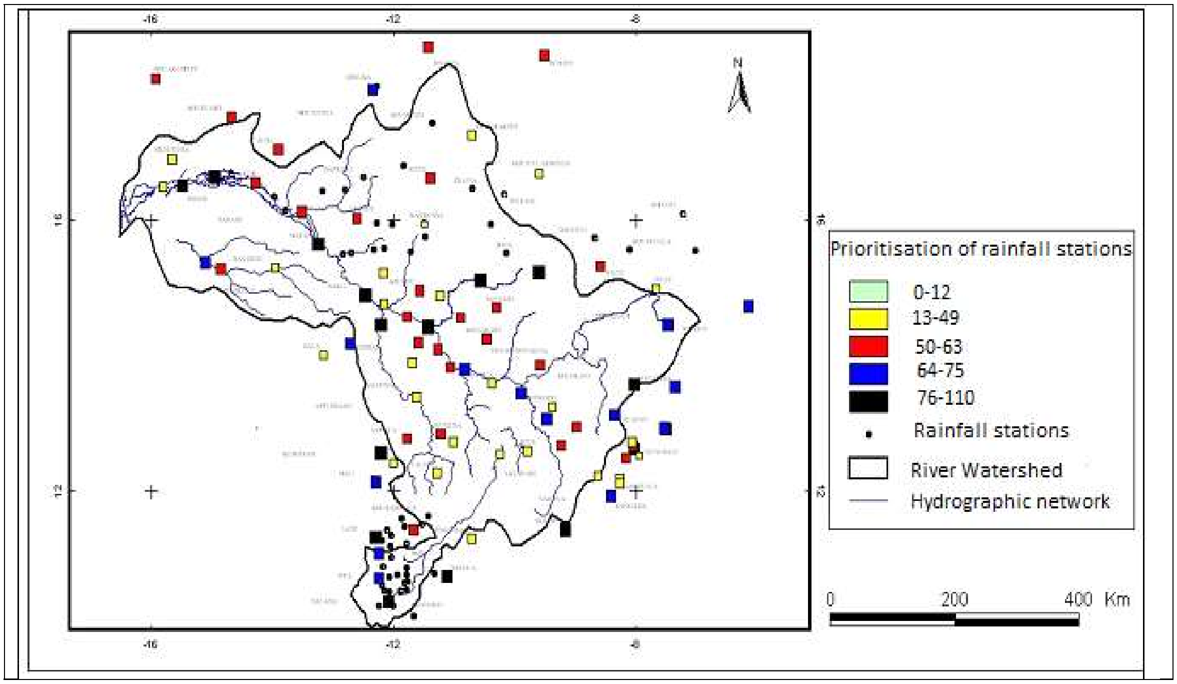
2.2. DATA ACQUISITION

The climatic data network of the Senegal River basin includes 20 synoptic stations and 19 climatological stations in the four countries. The data are of variable quality and duration. The Table 4 presents the data available at some reference stations.

Table 4: Status of available data at some stations in the SRB

Station	Average temperature (°C)	Relative humidity (%)	Insolation (hours)	Wind speed (meters)	Evaporation (mm)	Rainfall (mm)
Bakel	1979-2016	1982-2016	1984-2016	2012-2016	1981-2016	1918-2016
Labe	1971-2016	1971-2016	1971-2016	1971-2016	1971-2016	1923-2016
Siguiri	1971-2016	1971-2016	1971-2016	1971-2016	1971-2016	1923-2016
Kedougou	1970-2016	1970-2016	1982-2016	1980-2016	1970-2016	1918-2016
Saint-Louis	1980-2015	1980-2015	1981-2015	1981-2015	1981-2015	1848-2016
Matam	1960-2016	1960-2016	1960-2016	1969-2016	1960-2016	1918-2016
Mamou	1971-2016	1971-2016	1971-2016	1971-2016	1971-2016	1923-2016

The rainfall observations in the Senegal River basin are quite old. They date back to 1848 in Saint-Louis and at the beginning of the 19th Century for the main stations in the basin like Bakel (1918), Labé (1923), and Kayes (1895). The basin's rainfall network includes 262 stations with an observation period ranging from one year to one hundred and ten years (Kayes). The list of stations is provided in the annex. Figure 5 shows the distribution of hydro-climatic stations and the duration of observations of these stations in the Senegal River basin.



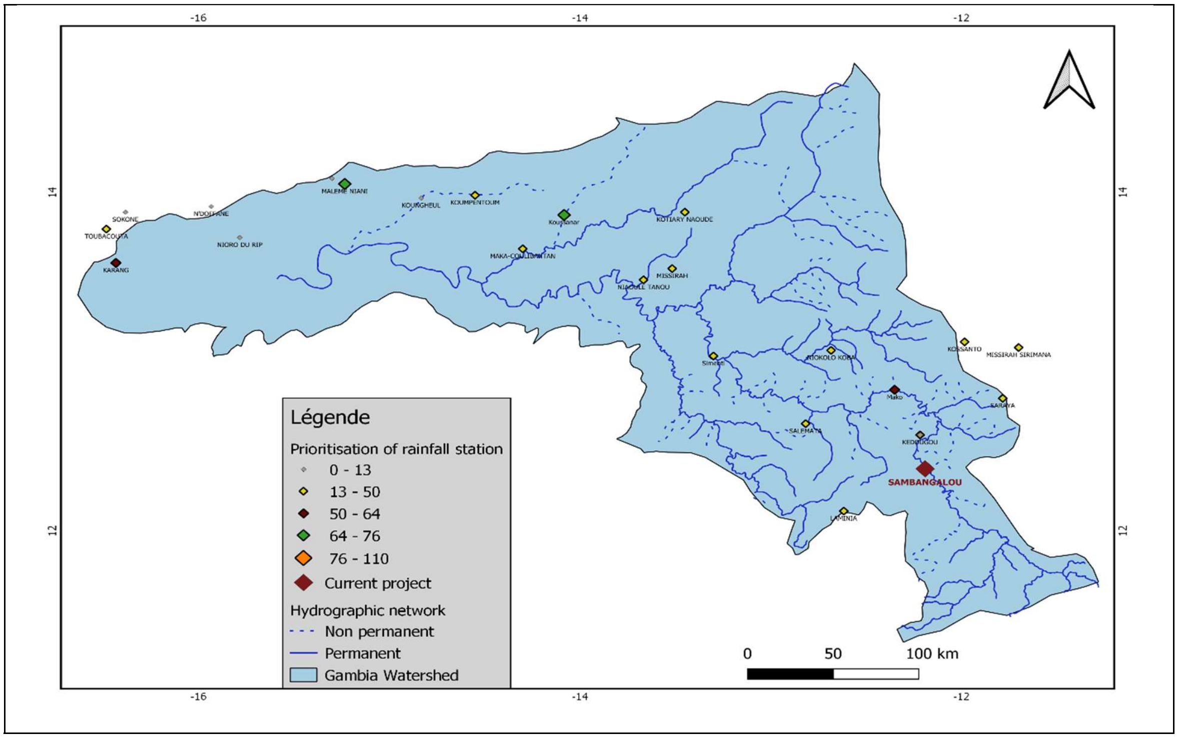


Figure 5: Maps of the rainfall network of the Senegal and Gambia Rivers basins

2.3. TOOLS

Several tools have been identified for processing hydro-climatic data from the Senegal River and Gambia basins. After an evaluation of all these tools, we made our choice according to their relevance in the area - their information production capacities according to the objective of the study and the expected results: Khronostat, Xlstat and Hydraccess were used in this study.

The Khronostat software combines different statistical tests that are specific to a change in the behavior of the variable in the time series. The most widely used, best argued in the literature and, the most robust tests were chosen. The first category of test concerns the randomness of the series (rank correlation test and autocorrelogram); they concern the constancy of the mean of the series throughout its observation period; in the event that the series is declared non-random, tests are proposed (Pettitt test, Buishand statistic and control ellipse, Bayesian procedure and Hubert segmentation procedure) to try to characterize the "non-random" nature present in the series. They are particularly suitable for detecting breaks in a time series. Thus, the use of Khronostat will be decisive in the detection of climatic breaks over time series to be analyzed.

Xlstat is described as an intuitive statistical software allows the computation of hydro-climatic time series. Xlstat is easy to use, works under Excel environment and offer over 200 features. In this project, Xlstat is mainly used to compute primary statistics.

Hydraccess is a hydrology software developed by IRD researchers. It allows to manage hydrological databases and to easily carry out a set of current treatments on hydrological and rainfall data. Hydraccess requires a 2010 or later version of Microsoft Office, including Microsoft Access, installed on an XP 7, 8 or 10 version of Windows, in 32-bit or 64-bit format.

Climate change influences water reserves in Sudano-Sahelian Africa; therefore, it is essential to develop geospatial tools to determine the impacts of climate on Senegal and Gambia River Basins. Thus, the combination of hydro-climatic analysis and remote sensing results can be used to assess the level of climate change. Modis-Terra images are used to determine land cover types for better classification. Remote sensing is one of the preferred tools for strengthening hydro-climatic data analysis. These images can also be used to monitor environmental conditions at the regional scale and therefore for the two studied basins: Senegal and Gambia.

However, the REFRAN-CV (Regional Frequency Analysis of Climate Variability) software was used during the first phase of the ACEWATER1 project to process ground station time series (rainfall data) and to generate spatially explicit products (return period maps) from the statistics of moments L. For the moment, the idea is to do the same exercise and extend it to other climate parameters such as temperature, evaporation and humidity from the 24 national synoptic stations in Senegal.

REFRAN-CV is a web-based or standalone tool for calculating L-moments and return periods of extreme climate events (temperature or rainfall); it was developed using open source R statistical software.

R statistical software is both a computer language and a working environment. The commands are executed via instructions coded in a relatively simple language, the results are displayed in text form and the Graphics viewed directly in a window of their own.

3. DETAILLED METHODOLOGY FOR CLIMATE VARIABILITY ASSESSMENT

3.1. DESCRIPTIVES ANALYSES

The inventory and evaluation of existing data and information as well as additional data to be collected for updating were the first step in this study. Indeed, after Sow (1984 and 2007), Lo (1984), Kane (1985 and 1997), Descroix (1986), Diakhate (1988), Orange (1990), Dione (1995), Konate (1996), Ardouin (2004), Bodian (2011), Faty et al. (2017) and numerous reports of OMVS and OMVG, there is a clear need to update the hydrological and rainfall information of the Senegal and Gambia River Basins.

The initial rainfall database developed during the first phase of ACEWATER project has been extended to Senegal and Gambia River Basins. That means a covered territory of near 400.000 km2 between five (05) States: Senegal, Mali, Mauritania, Gambia, Guinea Bissau and Guinea.

In the SRB, 262 ground stations have been identified and 158 with data available and already collected. The dataset extends from 1850 to nowadays for Saint-Louis and Kayes (1895) and from the beginning of 20th Century for the other major stations like Bakel (1918) and Labe (1923).

In the GRB, the number of ground stations is 157 but the level of data collection is very low (near 35-45%). In this watershed, the first observations date back to 1958.

3.2. SEGMENTATION AND HOMOGENIZATION PROCEDURES

The segmentation procedure provides, by means of a specific algorithm, one or more break dates (possibly none) that separate contiguous segments with significantly different means (Hubert et al., 1998). If the procedure does not produce an acceptable segmentation of order greater than or equal to two, the assumption of stationarity of the series is accepted. The results obtained are defined in terms of the number of segments. Segmentation is retained when the quadratic difference between it and the series is minimal. This condition is necessary, but not sufficient for determining the optimal segmentation. We define: ik, k =1, 2,...,..., m, the rank in the initial series of the terminal end of the kth segment, the mean of the Kth segment, Dm the quadratic difference between the series and the considered segmentation. The quadratic deviation under these conditions is expressed by equation 2:

$$Dm = \sum_{k=1}^{k=m} \mathrm{Dk}$$

$$dk \ = \sum_{i=ik-1-1}^{i=ik} \left(Xi - Xk \right) 2$$

This method has the advantage of being able to search for multiple mean changes in a hydrometeorological series.

4. METHODOLOGY FOR CHANGE AND TRENDS DETECTION

As part of this work, basic geospatial data such as the 250 m resolution MODIS-Terra satellite imagery were also collected. Given the size of the Senegal River Basin (about 300000 km^2) and the Gambia Basin (77,000 km^2), the choice is focused on the MODIS sensor because it allows to cover large areas compared to other sensors as Landsat or Spot. The idea is to work with the Landsat or Spot data in order to get better classification of land use indicators of the two basins. Landsat products have been previously used to carry out studies in Senegal River estuary (Niang, 2014; Niang & Kane, 2014).

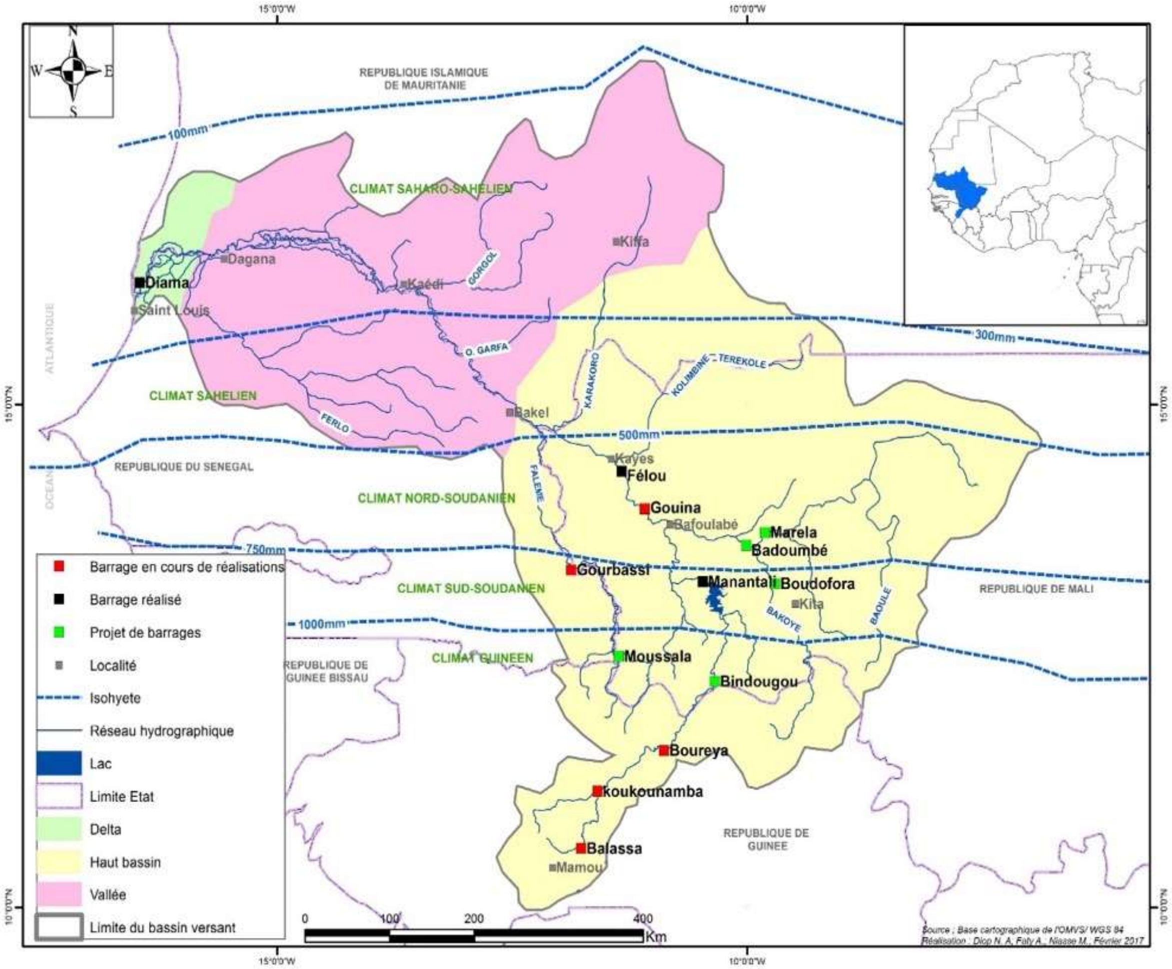
Landsat or Spot will also be used to highlight evolution of some hotspots like Fouta Djalon area (deforestation), Senegal River estuary (the breaching of Langue de Barbarie sandy spit) and Gambia estuary.

Indeed, rain is the most important climatic parameter and is therefore used to define climate regimes (Rodier, 1964). The Senegal River watershed has four (04) climatic regimes:

- The **Guinean regime**: climate characterized by a rainy season of 6 to 8 months with an average annual rainfall > 1200 mm and average annual temperatures ranging between 25°C and 27°C.
- The **sub-Sudanese regime** is tropical in nature. This regime is characterized by two seasons, a rainy season from May to October (06 months) and a dry season from November to April (06 months). This climate corresponds to the sub-Sudanese climate. August and September are the rainiest months. The regime is characterized by average annual precipitation > 1000 mm.
- The **North Sudanese regime**, unimodal with a rainy season of 3-5 months and a more marked non-rainy season. This regime is also called "transition", a transition from the

sub-Sudanese regime in the south to the Sahelian regime further north. This regime is characterized by average annual rainfall between 1000 mm and 620 mm.

- The **Sahelian regime**, single modal with a rainy season ranging from a few days to 2 months and a non-rainy season that lasts the rest of the year. The average annual rainfall is less than 600 mm.



Source : Base cartographique de l'OMVS/ WGS 84
Réalisation : Diop N. A, Faty A., Niasse M., Février 2017

Figure 6: Map of the subset of the SRB and the variation of the isohyets

In conclusion, the average annual rainfall in the basin decreases from the south of the basin to the north. The annual average values accurately reflect the succession of regions and climate domains. Apart from the spatial and temporal variation of annual rainfall patterns, the main consequences of the distribution of rainfall patterns from the South of the basin to the North are:

- The decrease in average rainfall from South Guinea to North Sahel;
- The decrease in the number of days and months of rain linked to the monsoon wind flow dynamics in the Fouta Djalon massif.

In the Senegal River basin, the hydrological regime is highly dependent on rainfall (Figure 7).

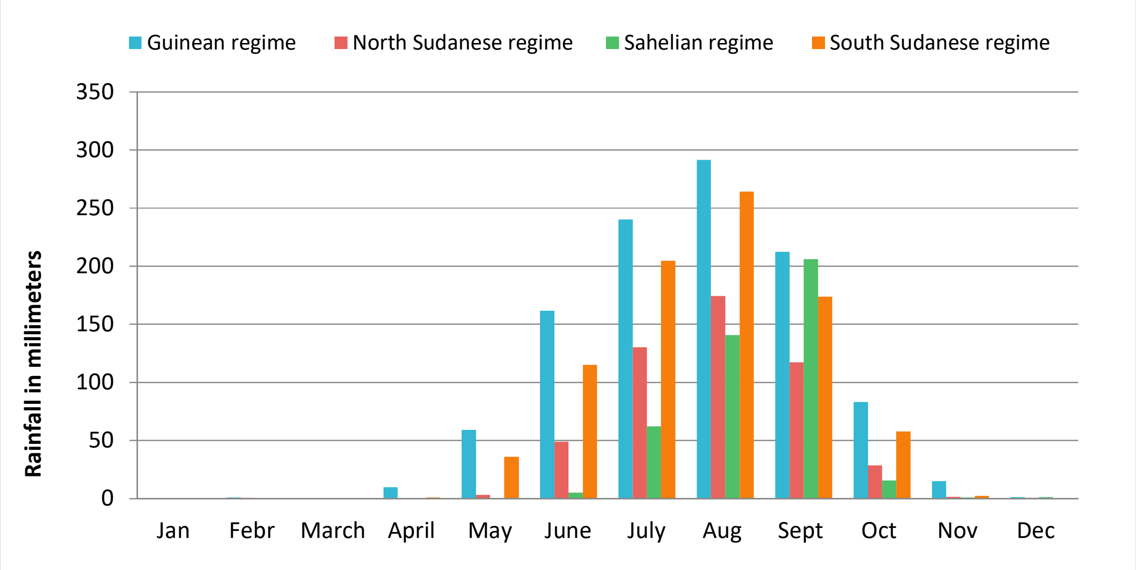


Figure 7: Average monthly rainfall by climatic zone

The monthly distribution of rainfall is characterized by the alternation of a rainy and a dry season, with only the duration of the seasons changing from one climatic domain to another. The monthly rainfall averages calculated over the period 1923-2016 show a seasonal distribution of precipitation that is in deficit.

Figure 7 shows the monthly rainfall averages of all reference stations. The maximum monthly rainfall is everywhere in August (the Guinean domain - southern Sudan and northern Sudan), with the exception of the Sahel domain where September records the maximum rainfall. By climate domain (Orange, 1990), August accounts for about 40% of annual rainfall in the Sahel region, 31% in the North Sudan region, 29% in the South Sudan region and 22% in Guinea (Faty et al., 2017).

CLIMATE VARIABILITY, CLIMATE CHANGE AND TRENDS ANALYSIS AND MODELLING ON SENEGAL AND GAMBIA RIVER BASINS

1. RECENT CLIMATE VARIABILITY, CLIMATE CHANGE AND TRENDS

The climate of the Senegal River basin is governed by the circulation of the atmosphere induced by the Azores (Atlantic Ocean) and Libyan high-pressure systems in the boreal hemisphere and the St Helena high pressure system in the South Atlantic Ocean.

The Senegal basin, by its latitudinal extension from Guinea to Mauritania, has a great climatic diversity. The climatic factors and the resulting climate are explained by the movements of the ITD, which separates the wind flows (maritime and continental), emitted by the Azores high-pressure systems and the Libyan cell, and the monsoon flow from the St Helena high-pressure system. These two flows differ in their humidity, which allows the year to be divided into two very distinct seasons:

- The dry season: it varies in length from the south of the basin (Guinea) to the north in Mauritania. It runs from November to May and is characterized by the absence of precipitation. The circulation is dominated by continental sea trade winds, with the ITD located south of latitude 12° N.
- The wet season: it lasts from June to October with decreasing rainfall from the south to north of the basin. These rains are brought by the monsoon flow, from south to southwest, from the St Helena high. Its arrival is due to the rise of the ITD, attracted by the Saharan depression, very hollow, towards the north.

The Senegal River basin is divided into four climatic domains, from south to north: the Guinean climate - south Sudanese south - north Sudanese and Sahelian with their variants and transition zones.

Climate parameters are observed from the synoptic and climatological stations located in the basin. These stations are distributed in the basin as follows:

- In Guinea: Mamou, Labe and Siguiri stations
- In Mali: Kita, Kenieba, Kayes, Yelimane and Nioro du Sahel
- In Senegal: Kedougou, Bakel and Saint-Louis.

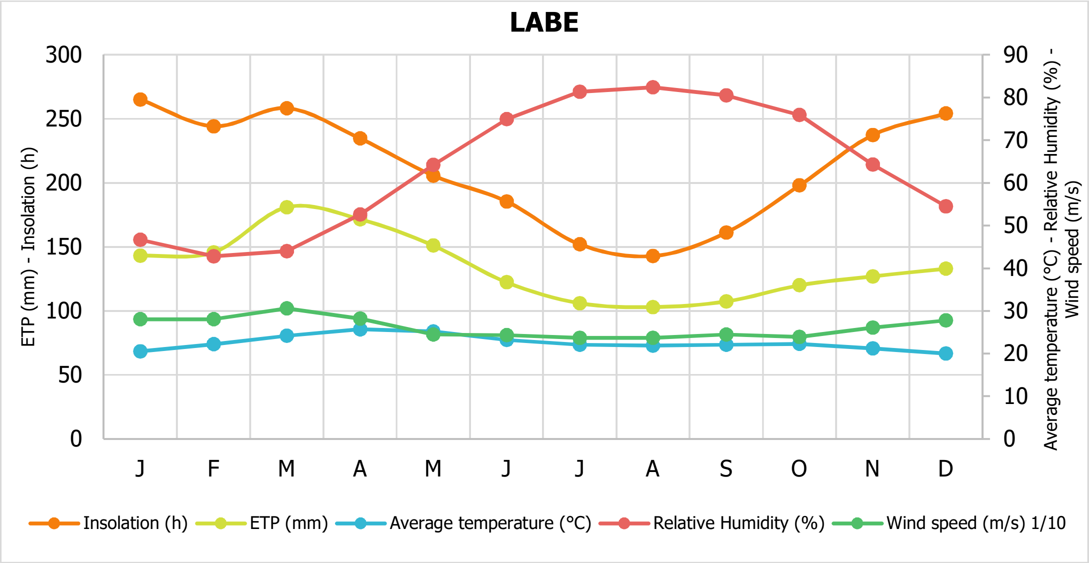
For Guinean stations, monthly data from 1971 to 2016 were provided by the Direction de la Météorologie Nationale. For Malian stations, the data are provided by the OMVS Observatory and cover the period 2002 to 2016. The Kedougou dataset range from 1968 to 2016 and Bakel from 1981 to 2016. The Table 5 and Figure 8 show the variations in climate parameters at the study stations. They show the division of the year into two parts:

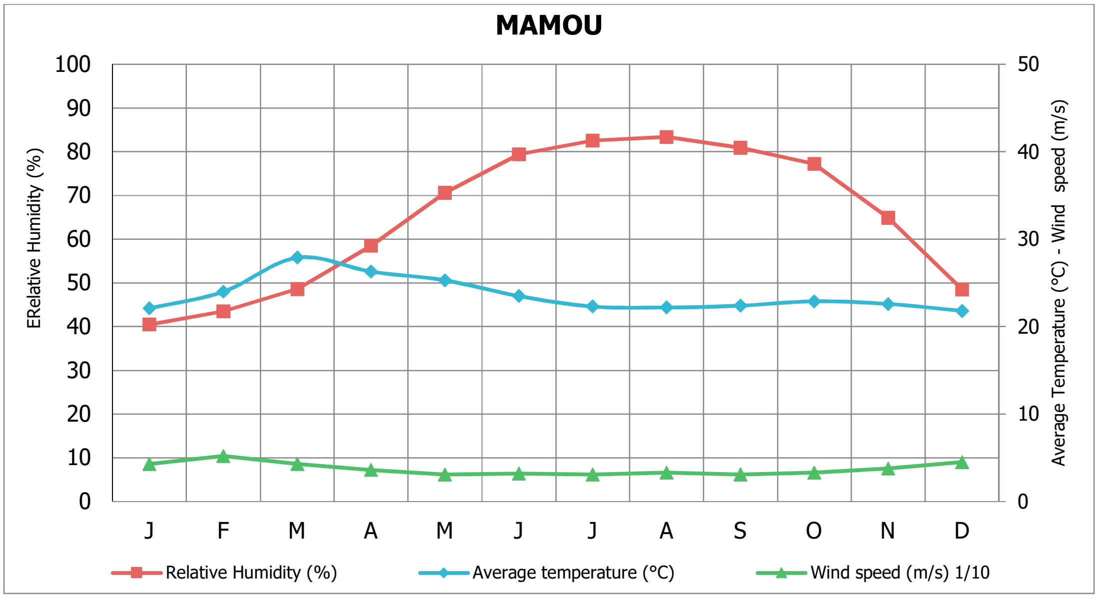
- From November to April: the dry season with the increase in the annual average temperature, potential evapotranspiration and sunstroke
- May to October: the rainy season with a sudden drop in sunstroke, potential evapotranspiration and a sharp increase in relative humidity due to the increase in cloud cover.

In Labe, the average monthly temperatures do not exceed 26°C (maximum 25.7°C in April). In Mamou, the maximum is 27.9°C in March while in Siguiri it reaches 31°C. The minimum temperature in Labé is 20°C (December); 21.8°C in Mamou (December) and 25°C in Siguiri (January). Temperatures rise from the foothills of Fouta Djalon in the south towards the Sudanian and Sahelian zone in the north. The same is true for all climatic parameters, especially the evaporative demand, whether it is the Piche evaporation or the Penman evapotranspiration.

Table 5: Climatic parameters in the upper basin

LABE												
Month	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Average temperature (°C)	20.5	22.2	24.2	25.7	25.2	23.2	22.1	21.9	22.1	22.3	21.2	20.0
Relative Humidity (%)	46.7	42.8	44.0	52.6	64.2	74.9	81.3	82.4	80.5	75.9	64.3	54.5
Wind speed (m/s) 1/10	28.09	28.1	30.6	28.2	24.7	24.3	23.7	23.7	24.5	23.9	26.1	27.8
Insolation (h)	265	244.2	258.3	234.6	205.7	185.5	152.0	142.9	161.2	198.0	237.3	254.1
ETP (mm)	143.1	145.8	181.0	171.6	151.0	122.4	106.0	103.0	107.4	120.0	127.0	133.0
MAMOU												
Average temperature (°C)	22.1	24.0	27.9	26.3	25.3	23.5	22.3	22.2	22.4	22.9	22.6	21.8
Relative Humidity (%)	40.5	43.5	48.6	58.5	70.6	79.4	82.6	83.4	80.9	77.2	64.9	48.5
Wind speed (m/s) 1/10	4.3	5.2	4.3	3.6	3.1	3.2	3.1	3.3	3.1	3.3	3.8	4.5
SIGUIRI												
Average temperature (°C)	25.0	27.7	29.3	31.0	29.6	26.8	28.3	25.1	25.4	26.7	26.3	25.1
Relative Humidity (%)	34.3	30.9	34.4	46.5	58.3	71.1	77.1	79.0	76.6	68.9	52.9	39.5
Wind speed (m/s) 1/10	29.2	28.8	26.9	26.8	27.5	25.4	25.1	22.8	22.7	19.7	25.1	27.3
Insolation (h)	257.0	236.4	241.2	218.3	227.8	219.1	190.6	184.0	208.2	242.1	250.2	233.1
ETP (mm)	180.2	183.4	207.8	197.9	186.7	144.9	138.9	124.7	129.5	146.3	159.6	169.4
KEDOUGOU												
Average temperature (°C)	26.2	28.8	31.1	33.1	32.5	29.1	26.8	26.5	26.6	27.3	27	25.5
Relative Humidity (%)	29.3	29.1	29.5	34.4	46.7	67.1	78	81	79.2	72.9	55.5	39
Insolation (h)	231	212	247	273	256	229	207	193	209	240	246	251
Evaporation (mm)	251.8	250.8	285.6	292	240.9	112.1	60.6	49.4	51.5	76.5	138.8	211.1
ETP (mm)	180.1	187.8	230.3	244.2	244.0	172	142.3	134.9	134	142.9	146.1	165
Wind speed (m/s) 1/10	2	2.1	2.2	2.5	2.9	2.4	2	1.8	1.5	1.6	1.6	1.9
BAKEL												
Average temperature (°C)	25.2	28.7	30.1	33.2	34.6	33.2	30.4	28.6	29.3	30.6	27.8	26.1
Relative Humidity (%)	35.6	33.6	32.6	31.6	42.6	54.8	63.0	70	68.6	55.9	46.9	39.8
Tension Vapeur	285.2	252	310	372	527	693	843.2	923.8	888	765.7	450	310
ETP (mm)	821.5	876.4	1076	1008	967.2	750	678.9	579.7	588	607.6	705	734.7
Evap.(mm)	359.6	355.6	427.8	450	455.7	375	241.8	145.7	189	198.4	273	313.1
Insolation (h)	242.5	227.2	267.8	268.8	268.98	244.6	247	239.9	229.8	269.9	253.6	241.8


LABE
300
250
200
150
100
50
0
ETP (mm) - Insolation (h)
90
80
70
60
50
40
30
20
10
0
Average temperature (°C) - Relative Humidity (%) - Wind speed (m/s)
J F M A M J J A S O N D
Insolation (h)
ETP (mm)
Average temperature (°C)
Relative Humidity (%)
Wind speed (m/s) 1/10


MAMOU
100
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ERelative Humidity (%)
50
40
30
20
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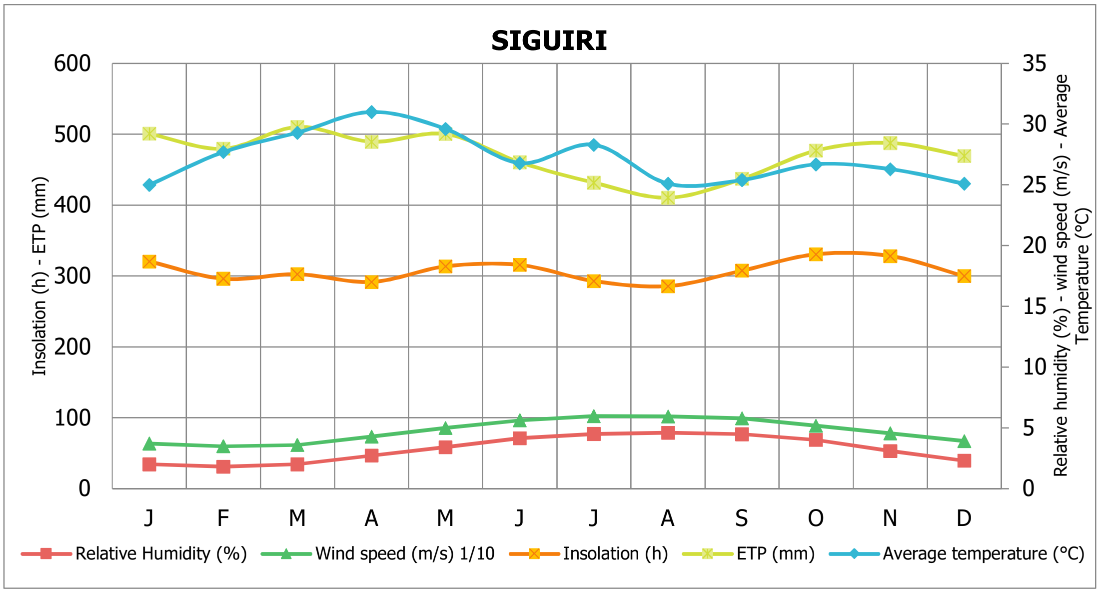
Average Temperature (°C) - Wind speed (m/s)
J F M A M J J A S O N D
Relative Humidity (%)
Average temperature (°C)
Wind speed (m/s) 1/10


SIGUIRI
600
500
400
300
200
100
0
Insolation (h) - ETP (mm)
35
30
25
20
15
10
5
0
Relative humidity (%) - wind speed (m/s) - Average Temperature (°C)
J F M A M J J A S O N D
Relative Humidity (%)
Wind speed (m/s) 1/10
Insolation (h)
ETP (mm)
Average temperature (°C)

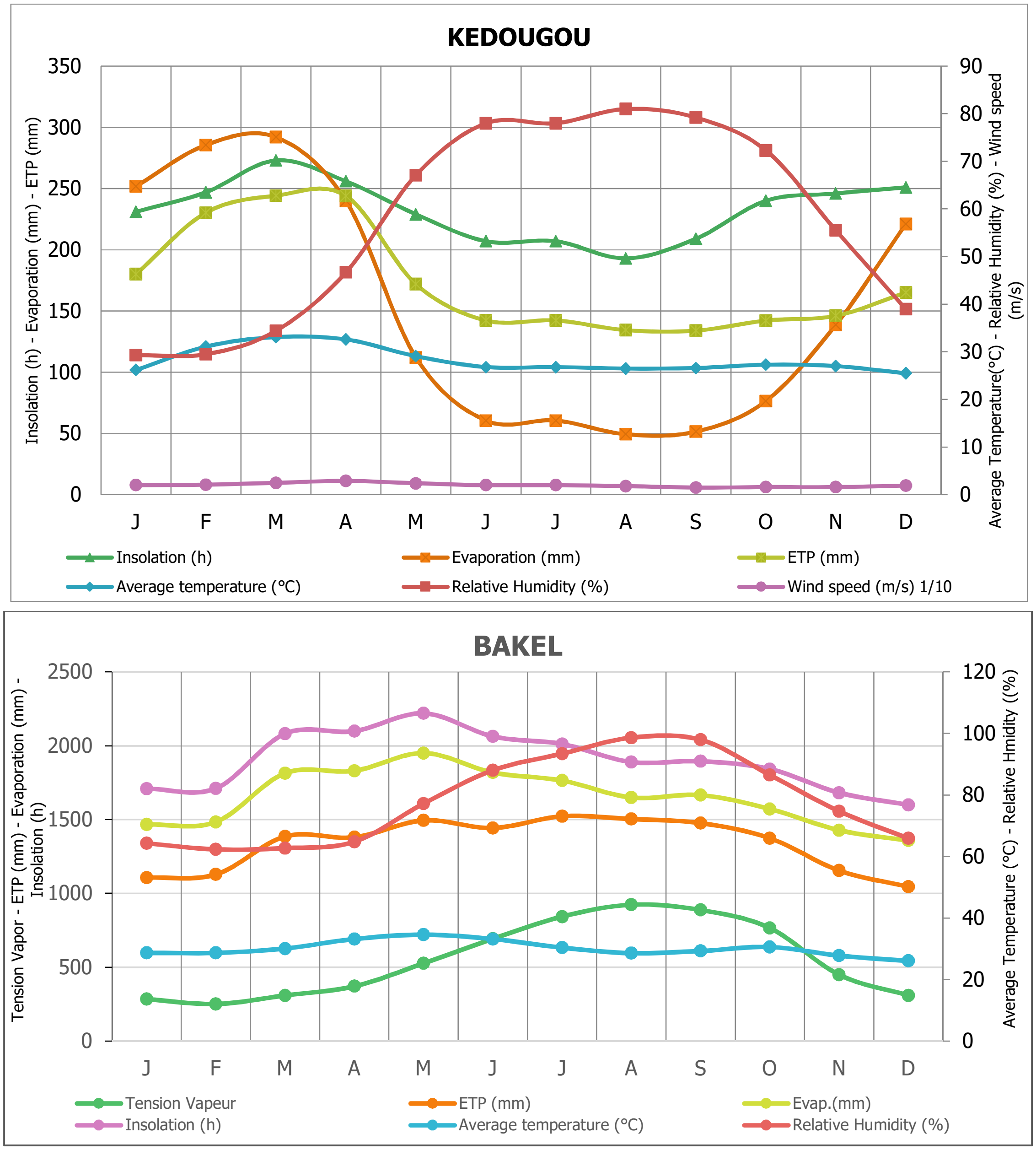


Figure 8: Monthly variation of climatic parameters

As an illustration, the wind rose at Labé station (Figure 9) gives a clear division of the year into two seasons: from January to April, the circulation is eastward, controlled by the Libyan high. From May onwards, the West circulation appears and asserts itself more and more during the whole rainy season, especially in July and August. In September, it reversed when it returned to the East.

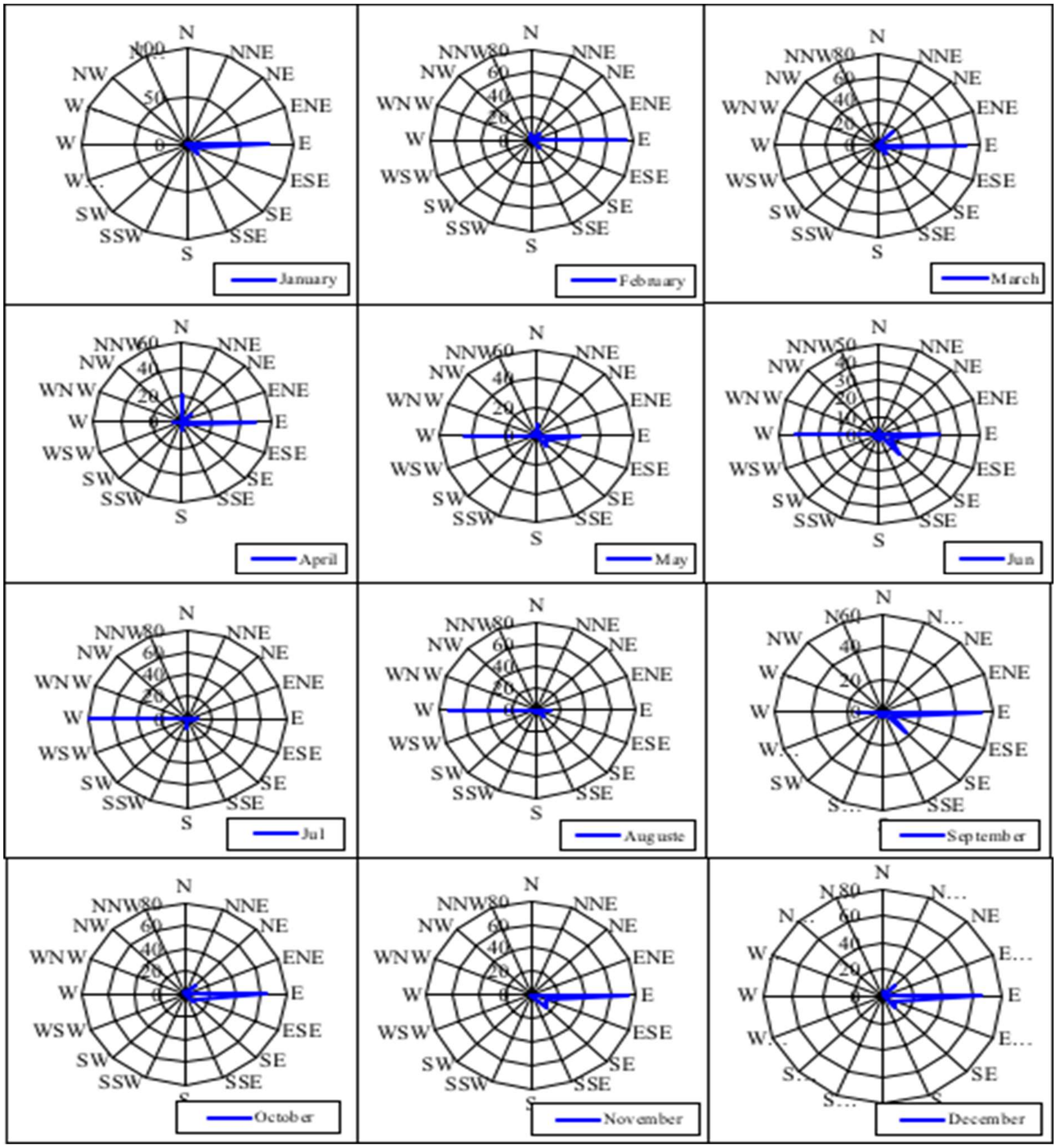


Figure 9:Wind rose at Labe Station

2. CLIMATE CHANGE, EXTREMES HYDROLOGIC EVENTS AND CONSEQUENCES ON HYDROLOGIC REGIMES

Given the disparity in observation periods between rainfall stations, the homogeneity of the data was controlled by the regional vector method (Brunet-Moret, 1971 & 1977; Hiez, 1977 & 1986).

The Regional Vector is defined as a time series of rainfall indices, derived from the extraction of the most "probable" - in the most frequent sense - information contained in the data of a set of observation stations grouped in a homogeneous climatic region".

It is therefore a chronological series of annual precipitation indices considering the effects of persistence, trend and pseudo-cycles of the climate zone, but homogeneous over time. The basin has been divided into three areas:

- The upper basin: it concerns Guinean rainfall stations
- The intermediate basin: it includes the Malian, Mauritanian and Senegalese stations up to the latitude of Bakel
- The middle and low valley: the Mauritanian and Senegalese stations concerning this area

This criticism made it possible to detect "outliers" and homogenize the annual rainfall samples. In general, the data are of good quality despite the importance of the gaps for some stations.

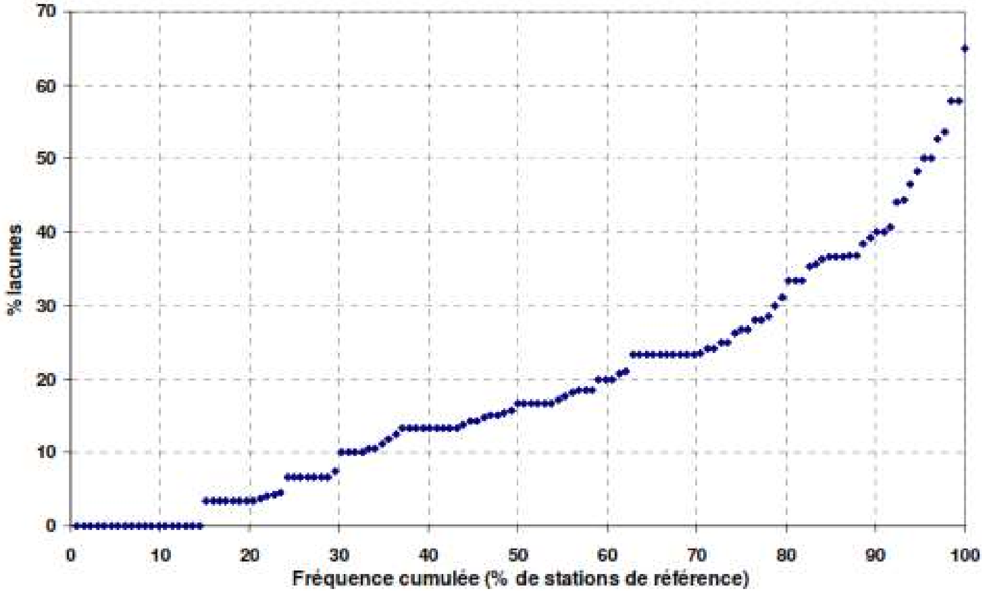


Figure 10: Percentage of gaps in extreme events

2.1. VARIATIONS IN RAINFALL

Changes in rainfall can be assessed through fluctuations in the indices of the regional vector. Figure 11 shows the variation in the indices of the four vectors constituted. The value 1 of the vector indicates the regional average rainfall in the area of application of the vector; values greater than 1, years in excess and values less than one, years in deficit. The vector reproduces well the general trend of rainfall in the basin:

- An increase in annual variations from south to north, from Guinea to Mauritania
- From 1923 to 1967: a period of overall excess rainfall despite the deficits of 1941-1942. In the Guinean basin, this period has an average to excess rainfall except in 1947 with very low fluctuations. The annual contrasts are more pronounced in Mauritania.
- From 1968 to 2016: drought affects the entire basin with strong nuances: in Guinea, small deficits not exceeding 20%; larger fluctuations in the Malian basin of up to 35% (1983); in Mauritania, deficits exceed 60% in some years.

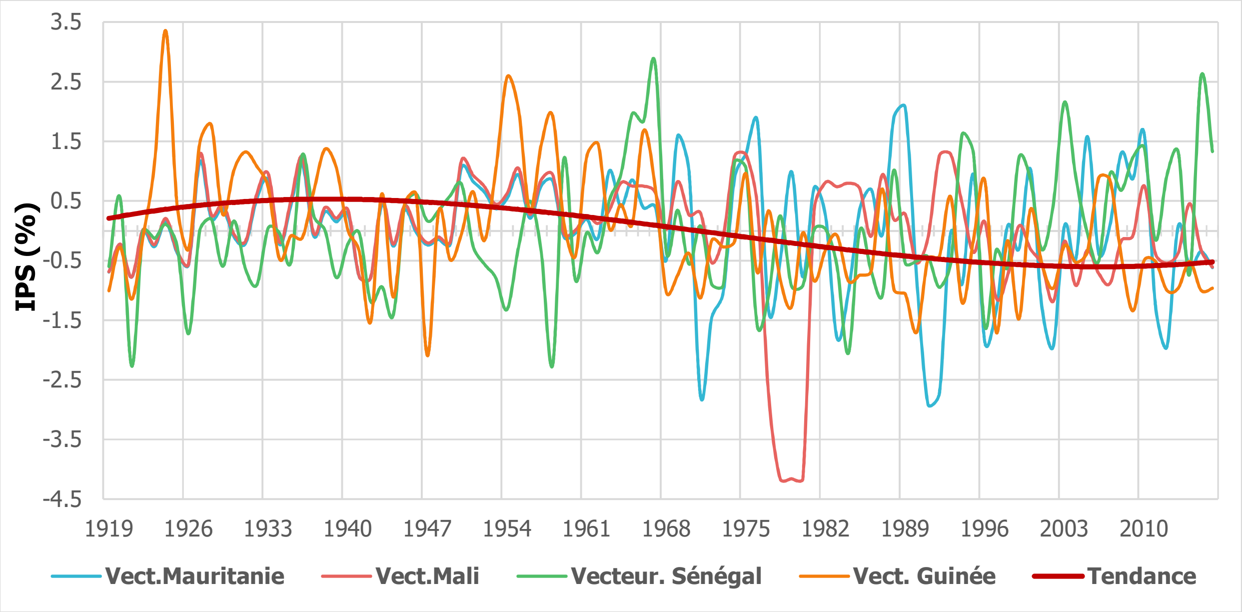


Figure 11: Changes in the indices of the three regional vectors from 1919 to 2016

By classifying the interannual averages in decreasing order, there is a gradual decrease in the annual averages from Mamou to Saint-Louis. It is possible to divide the Senegal basin in five homogeneous rainfall zones which are based on a Latitudinal gradient and are materialized by successive 200 mm steps.

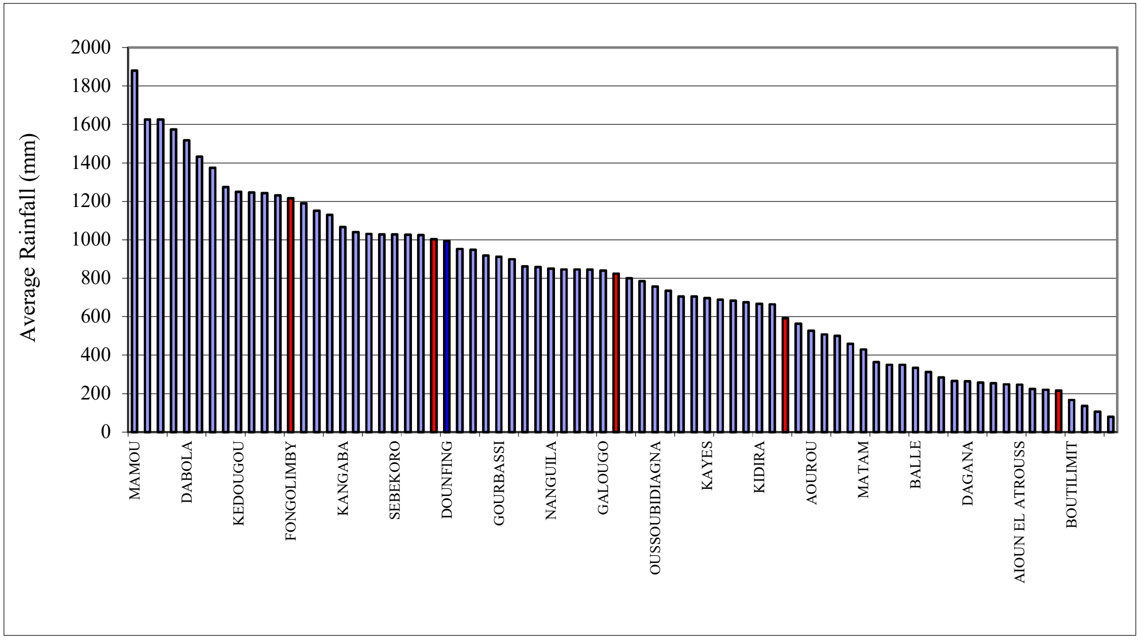


Figure 12 : Average rainfall per station over the period 1919-2016)

The decrease in annual rainfall is gradual with latitude. A correlation latitude - average rainfall shows a functional relationship between the two parameters. Figure 11 shows the adjustment and the resulting relationship with a correlation coefficient of 0.96, or 92% of the explained variance. On the basis of latitude, we could deduce with good accuracy the average rainfall, on a given point defined by its latitude, over the basin. For example, the Bakel station, with a latitude of 14.9 degrees, has an average rainfall of 507 mm.

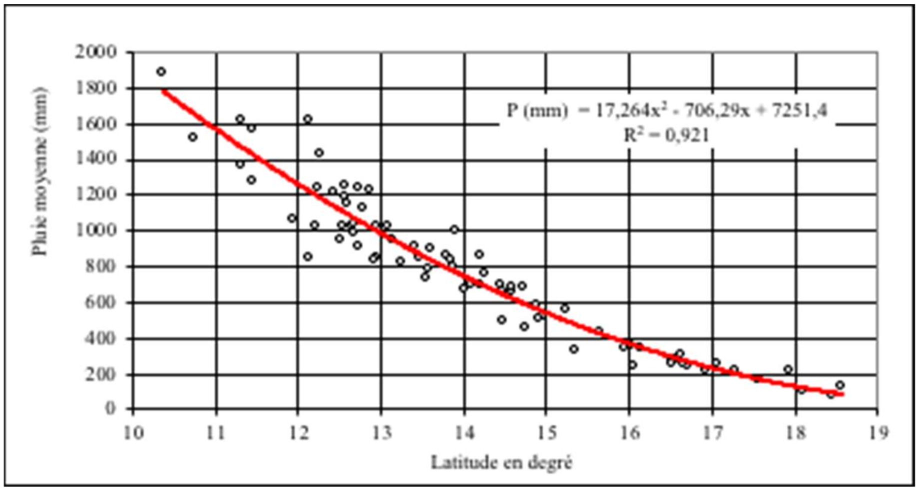


Figure 13: Correlation between precipitation and latitude (in degrees)

On the basis of this relationship, the average rainfall patterns can be deduced as a function of latitude as shown in the table below (Table 6). Analysis of the annual chronicles and their statistical characteristics shows that rainfall variability increases along a south-north gradient. Up to the latitude of Bafoulabe, the coefficients of variation are less than 20%.

Table 6: Lower limit of rainfall average (millimeters) in the Senegal River basin.

Latitude (Degrees)	Rainfall average (mm)
11	1571
12	1262
13	987
14	747
15	541
16	370
17	234
18	132

While the regional vector gives the general trends in rainfall, the variations show the local fluctuations in annual rainfall. Figure 13 shows these variations for the synoptic stations of Mamou, Siguiri, Kita, Bakel and Kayes. We note the same sequences already mentioned above. The amplitudes of variations increase from south to north with the decrease in annual inputs. The result is a greater fluctuation in annual totals from upstream to downstream in the basin.

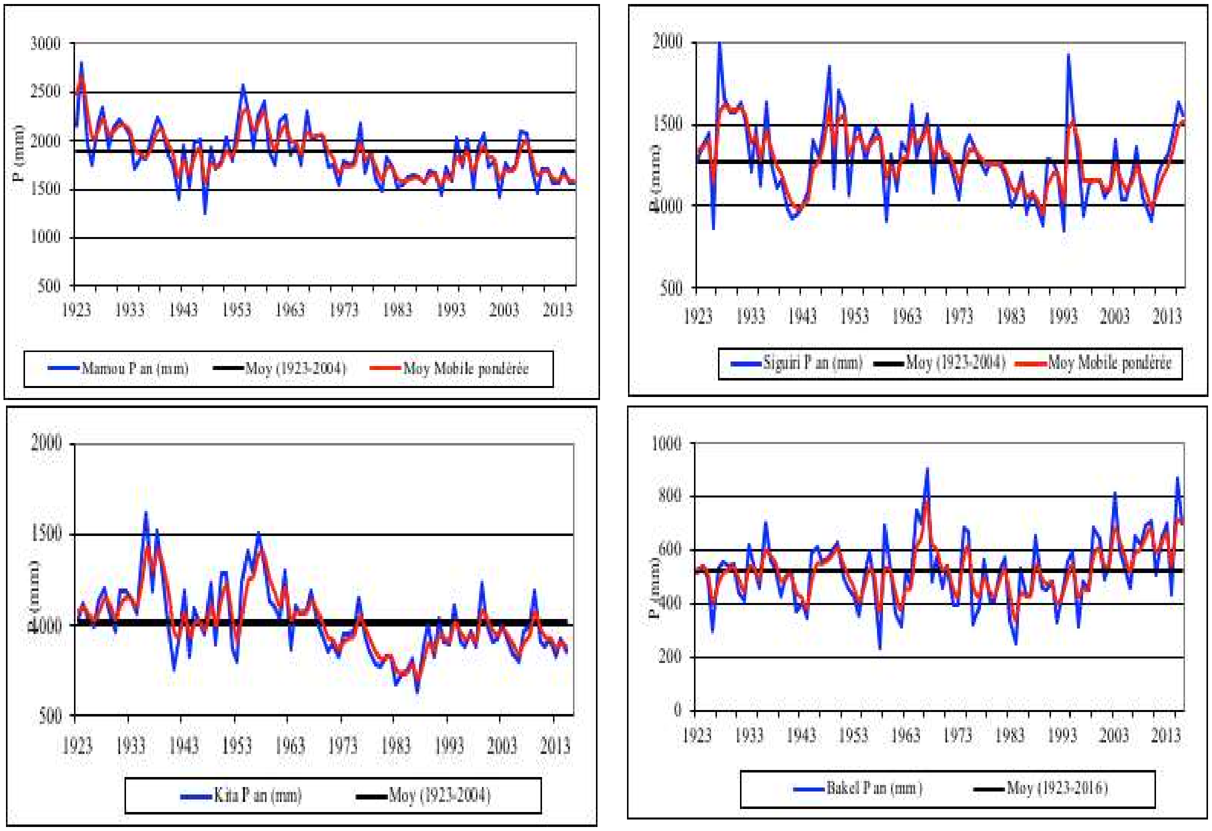


Figure 14 : Annual rainfall variations (in millimeter) in Mamou, Siguiri, Kita, Bakel and Kayes

2.1.1. Rainfall distribution

The distribution of Precipitation follows a south-north gradient from Guinea to the Sahel in the lower Senegal River valley. This distribution has been studied at the interannual (climate normal), decennial, monthly and daily scales.

2.1.2. Interannual rainfall

After homogenization of the annual rains, chronicles were obtained from 1923 to 2016. Rainfall normal 1941-1970, 1951-1980, 1961-1990, 1971-2000 and 1981-2010 were calculated (

Table 7 and Figure 15). For the whole basin, there is a clear decrease in rainfall with the exception of the Bakel station where there is some stability in rainfall despite the drought. For some (Mamou, Siguiri and Kedougou) the decrease in rainfall was insensitive between 1941-70 and 1951-80.

For the Guinean stations, the decrease in rainfall ranges from 10% to 13% between 1941 and 2010, while for the Sahel stations (Kayes, Nioro du Sahel, Yélimané) the deficit varies from 23 to 32%.

Table 7: Thirty-year average rainfall (mm) at synoptic stations in the basin.

Station	Country	1941-1970	1951-1980	1961-1990	1971-2000	1981-2010
LABE	Guinea	1693,0	1677,8	1649,8	1530,1	1475,0
MAMOU	Guinea	1948,3	1954,2	1958,1	1802,3	1721,7
SIGUIRI	Guinea	1299,8	1326,1	1319,2	1230,5	1174,4
BAMAKO - SENOU	Mali	1127,7	1112,2	1062,7	949,9	910,6
KAYES	Mali	799,7	768,5	695,4	630,9	615,5
KENIEBA	Mali	1340,0	1335,4	1291,5	1153,1	1083,6
KITA	Mali	1159,9	1091,3	1055,8	920,3	898,8
NIORO DU SAHEL	Mali	626,1	603,9	563,5	454,7	427,7
YELIMANE	Mali	616,8	604,8	564,2	477,8	445,3
BAKEL	Senegal	505,9	518,0	503,2	499,1	481,0
KEDOUGOU	Senegal	1264,0	1266,9	1282,1	1178,8	1153,2

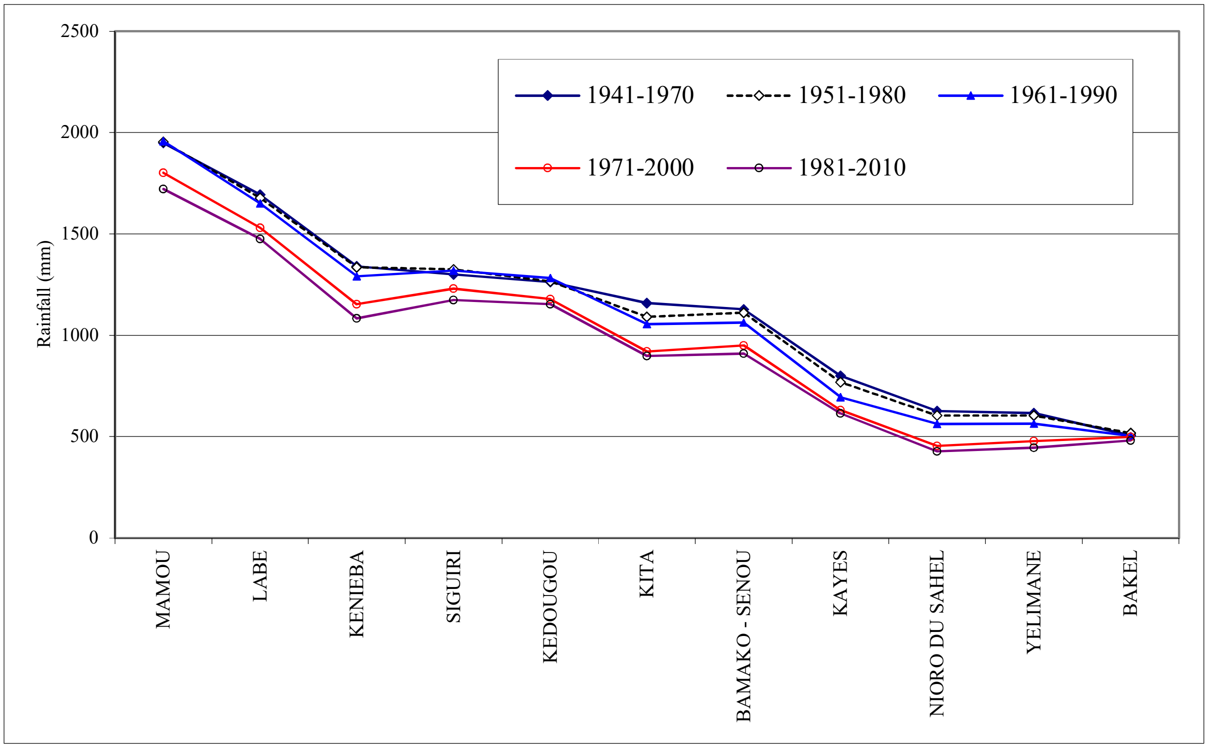
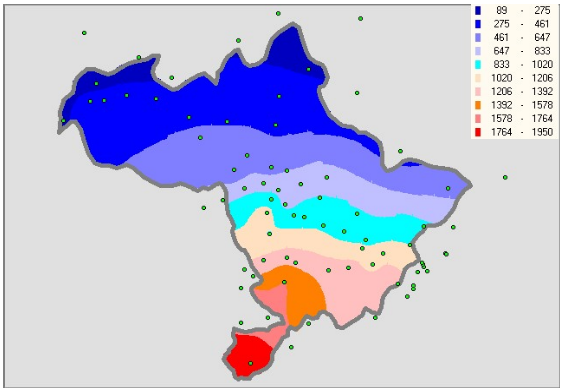


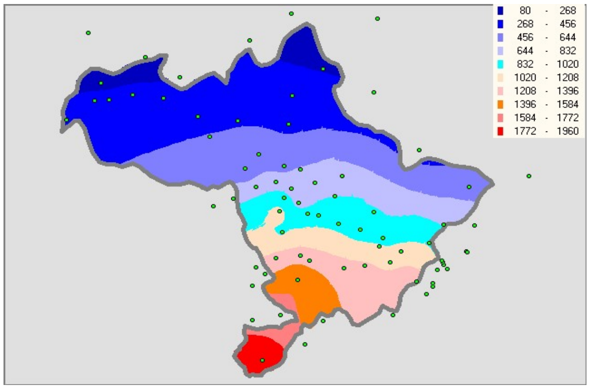
Figure 15 : Variations of the thirty-year rainfall averages at the synoptic stations

For all the stations in the basin, the 30-year averages were calculated and presented in the form of maps. The Krigeage tool was applied in this study. It assumes that the distance or direction between the sampling points reflects a spatial correlation that can explain surface variations. The Kriging tool applies a mathematical function to all points, or certain specified points, located within a specific radius. It determines the output value of each storage bin. Kriging is a multiple process; it includes exploratory statistical data analysis, variogram modelling, surface creation and possibly exploration of the variance surface. The Kriging tool is particularly suitable for cases where it is known that there is a spatial correlation of distance or directional deviation in the data.

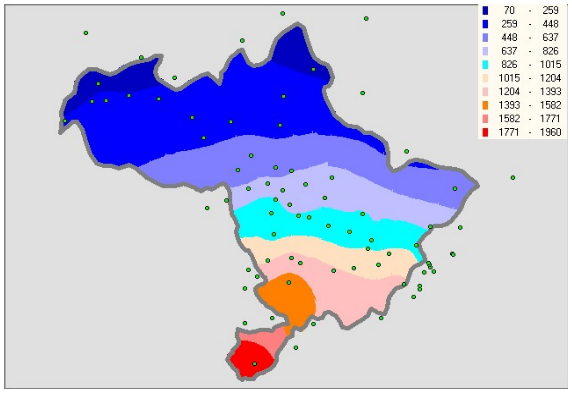
The fairly zonal distribution of precipitation is noted in accordance with the decreasing south-north rainfall gradient. In the north of the basin, the average rainfall fell from 90 mm (1941-1970) to 50 mm in 2010, representing a 45% decrease in rainfall. In areas with low rainfall, such a decrease has more significant consequences.



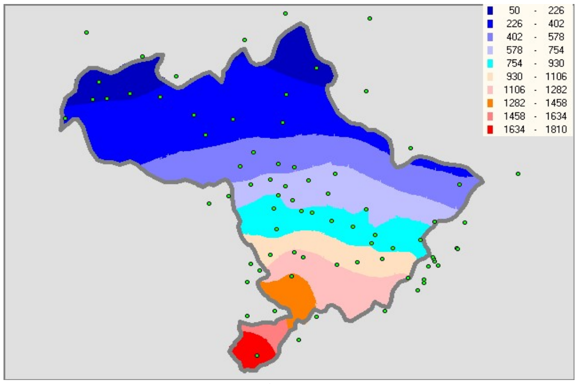
Normale 1941-1970



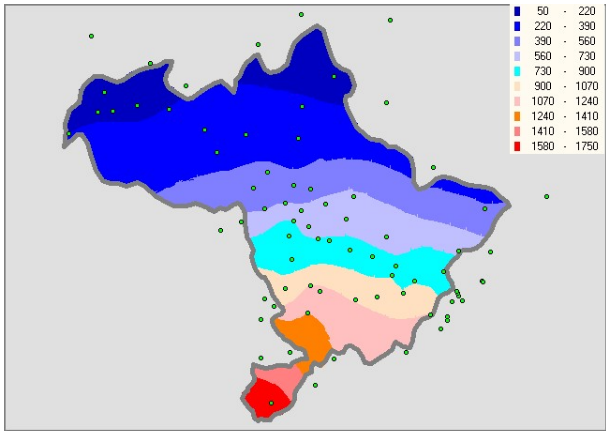
Normale 1951-1980



Normale 1961-1990



Normale 1971-2000



Normale 1981-2000

Figure 16 : Spatial distribution of precipitation (30-year average) over the basin (in millimeters)

Source: Senegal River Monograph, 2011

2.1.3. Statistical distribution of annual rainfall

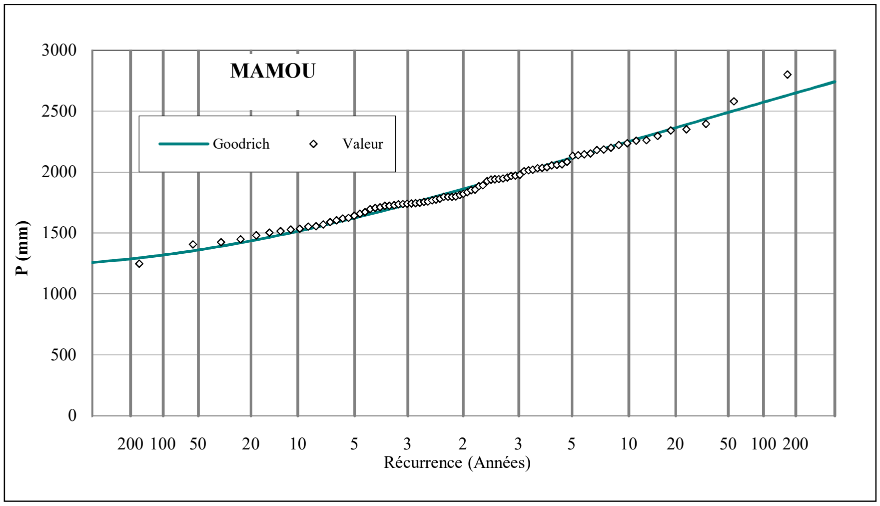
The homogenized annual rainfall chronicles were subjected to statistical treatment. About ten statistical laws (Brunet-Moret, 1969) were adjusted to these annual rainfall samples. The results are recorded in the table below (Table 8). Goodrich's law provides the best fit for all stations.

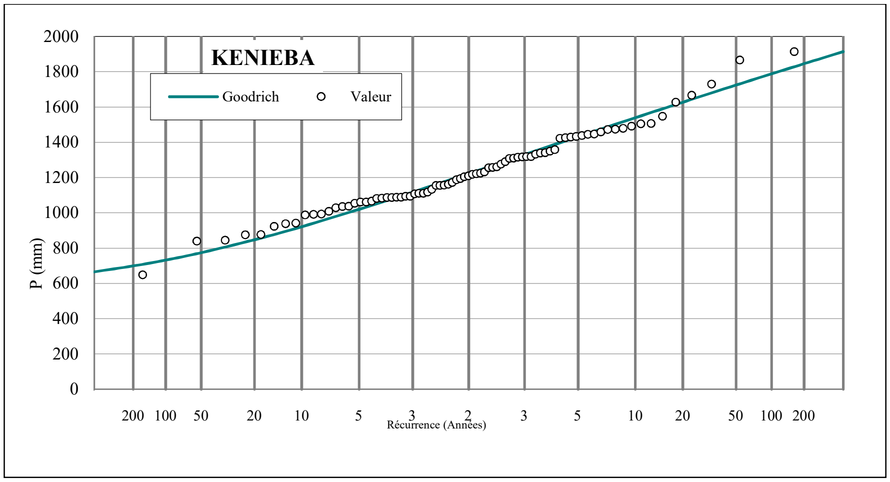
In the median year, rainfall of more than 1500 mm can be expected. At Bakel station, the median frequency of rainfall is 500 mm, a third of what is expected in the upper basin. Rodier's K3 ratio (ratio between wet and dry decadal years) is illustrative of the variation in recurrent rainfall. In the basin, it is in the range of 1.4 to 1.5; in the Sudanian zone, it has 1.6 - 1.7 and in the Sahel zone, it exceeds 2 (2.7 in Matam). In dry recurrences, such as the dry centennial, if for the high basin the rainfall contributions are still significant (above 1000 mm), they become very low, even random, in Bakel and Matam.

Table 8: Frequent annual rains for the main stations in the basin (1941-2016)

	Dry Recurrences					**Mediane**	**Wet Recurrences**					
Frequencies	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99	
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100	K3
Mamou	1319,5	1360,6	1435,7	1514,9	1624,0	1860,8	2116,0	2251,8	2364,0	2489,8	2573,3	1,5
Labe	1316,7	1323,6	1341,2	1366,7	1413,8	1564,2	1801,3	1959,6	2107,4	2291,5	2424,3	1,4
Mali	1257,1	1275,1	1312,3	1356,6	1424,7	1595,5	1808,0	1931,3	2037,9	2162,3	2247,5	1,4
Tougue	1082,5	1118,0	1184,2	1255,9	1356,9	1582,6	1833,3	1969,0	2082,3	2210,4	2295,9	1,6
Dinguiraye	1010,0	1033,2	1077,5	1126,4	1196,7	1357,9	1541,3	1642,1	1726,9	1823,5	1888,3	1,5
Siguiri	872,5	892,6	933,8	982,6	1057,4	1243,8	1474,5	1607,9	1723,1	1857,3	1949,0	1,6
Kédougou	808,4	836,6	890,2	949,2	1033,7	1226,2	1444,2	1563,7	1664,0	1778,1	1854,6	1,6
Narena	758,4	810,2	893,8	971,8	1068,3	1249,7	1418,9	1501,4	1566,6	1636,8	1681,9	1,5
Kenieba	732,4	774,3	847,6	921,7	1020,1	1223,4	1432,1	1539,9	1627,6	1724,7	1788,3	1,7
Kita	664,0	686,5	729,7	778,0	847,9	1009,9	1196,3	1299,5	1386,6	1486,0	1552,9	1,7
Kayes	402,0	420,5	455,9	495,2	551,9	682,6	832,3	914,8	984,4	1063,7	1117,0	1,8
Yelimane	316,3	325,6	345,7	370,8	411,1	517,7	658,0	742,1	816,2	904,0	964,8	2,0
Nioro du Sahel	261,4	276,3	306,3	341,0	393,0	519,1	671,0	757,3	831,2	916,7	974,8	2,2
Bakel	256,1	275,7	310,8	347,3	396,8	502,2	613,6	672,1	720,2	773,9	809,4	1,9
Matam	165,2	179,2	207,5	240,4	289,9	410,3	556,0	639,1	710,4	792,8	848,9	2,7

The 30-year adjustment of the series (normal precipitation) shows a significant decrease in the frequency of precipitation, particularly for the last two normal years: 1961-1990 and 1971-2000 (Figure 17).





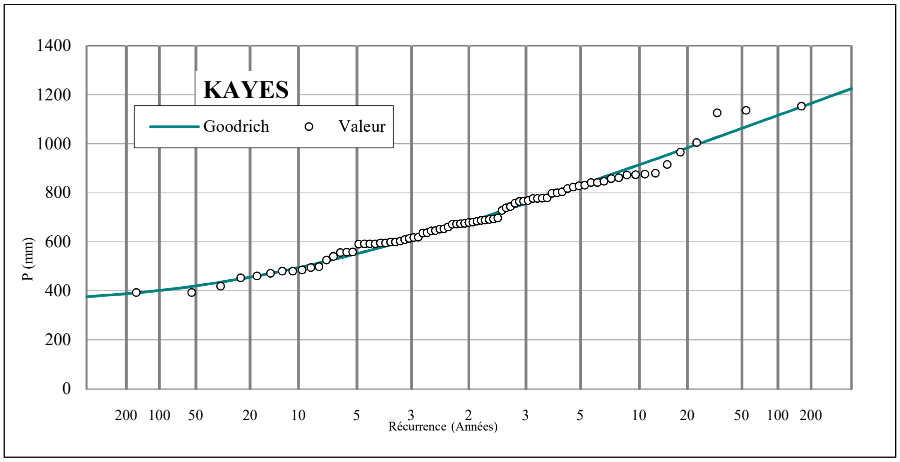


Figure 17 : Statistical adjustment of annual rainfall in Mamou, Kenieba and Kayes (1923-2016)

Table 9: Recurring annual rainfall (mm) from Mamou, Labé, Kenieba, Kayes and Bakel for different normal rainfall patterns

1941-70											
Frequencies	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100
Mamou	1264,9	1335,7	1450,4	1558,3	1692,3	1946,2	2184,8	2301,7	2394,1	2494,0	2558,3
Labe	1322,1	1335,2	1364,7	1402,9	1466,2	1641,5	1882,2	2030,3	2162,5	2320,9	2431,8
Kenieba	992,3	1005,8	1035,5	1072,9	1133,8	1297,6	1516,5	1648,9	1766,1	1905,5	2002,4
Kayes	506,4	528,7	568,9	610,9	668,4	791,8	923,3	992,9	1050,2	1114,3	1156,6
Bakel	234,5	269,2	321,7	367,9	421,9	516,4	598,3	636,5	665,9	697,1	716,7
1951-80											
Frequencies	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100
Mamou	1252,9	1333,1	1459,7	1575,6	1716,3	1974,7	2210,0	2323,2	2411,8	2506,7	2567,3
Labe	1322,9	1333,4	1358,1	1391,9	1450,7	1624,2	1878,0	2039,9	2187,5	2367,5	2495,2
Kenieba	939,6	958,9	998,9	1046,9	1121,4	1309,8	1546,7	1684,8	1804,8	1945,1	2041,3
Kayes	491,4	515,8	558,2	601,0	657,7	774,5	893,8	955,4	1005,4	1060,7	1096,9
Bakel	243,2	263,0	299,3	338,0	391,6	509,2	637,2	705,7	762,5	826,4	868,9
1961-90											
Frequencies	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100
Mamou	1479,8	1507,3	1561,3	1622,7	1713,3	1928,1	2181,1	2323,1	2443,8	2582,5	2676,2
Labe	1333,7	1337,6	1348,9	1367,5	1406,2	1551,1	1817,3	2011,6	2202,3	2450,1	2635,1
Kenieba	818,1	847,5	903,4	964,8	1052,5	1252,0	1477,5	1600,9	1704,5	1822,2	1901,0
Kayes	441,3	462,9	500,2	537,7	587,2	688,5	791,5	844,4	887,3	934,7	965,7
Bakel	242,7	258,1	288,3	322,3	372,1	489,1	625,7	701,9	766,5	840,5	890,5
1971-2000											
Frequencies	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100
Mamou	1484,5	1493,3	1514,4	1543,1	1593,1	1741,0	1957,5	2095,8	2221,8	2375,6	2484,6
Labe	1309,2	1311,4	1318,1	1329,7	1355,0	1455,9	1652,7	1801,6	1950,5	2147,4	2296,3
Kenieba	662,8	699,2	765,3	834,7	930,0	1135,6	1356,1	1473,1	1569,7	1677,7	1749,3
Kayes	416,7	429,2	453,6	481,3	522,0	618,0	730,5	793,4	846,8	908,1	949,5
Bakel	256,6	270,2	297,4	328,7	375,5	487,8	622,2	698,3	763,2	838,2	889,1
1981-2010											
Frequencies	0,01	0,02	0,05	0,1	0,2	0,5	0,8	0,9	0,95	0,98	0,99
Recurrences (years)	100	50	20	10	5	2	5	10	20	50	100
Mamou	1452,2	1461,1	1481,7	1508,7	1554,5	1684,4	1867,0	1980,8	2083,3	2207,0	2294,0
Kenieba	1312,0	1315,5	1324,4	1337,5	1362,1	1441,8	1569,7	1655,9	1736,8	1838,1	1911,4
Kenieba	673,8	712,2	776,6	838,9	918,5	1074,7	1226,9	1303,2	1364,2	1430,7	1473,8
Kayes	397,1	405,3	423,5	446,8	485,1	590,0	732,4	819,4	896,9	989,4	1054,0
Bakel	251,4	267,9	298,2	330,3	374,9	472,6	578,8	635,6	682,7	735,6	770,8

2.1.4. Decennal rainfall

The ten-year rainfall averages were calculated for all stations in the basin. The downward trend, observed at the level of normal rainfall, is confirmed with two particularities:

- At the basin level: the decrease in rainfall began in the late 1960s. The 1941-1943 drought affected the average for the 1941-50 decade.

- For Sahelian stations, such as Kayes, the variation in the ten-year averages indicates a continuous decrease in rainfall over the years. The defect of the average values is to smooth out the fluctuations of the phenomena studied. The Bakel station is an exception to rainfall stability in the Senegal basin.

We can observe a slight improvement in annual rainfall over the period 2000-2016. In reality, this decade includes years of excess or even very excess rainfall; a situation similar to that observed in 1961-70, decade. This has a positive influence on the average rainfall over the period.

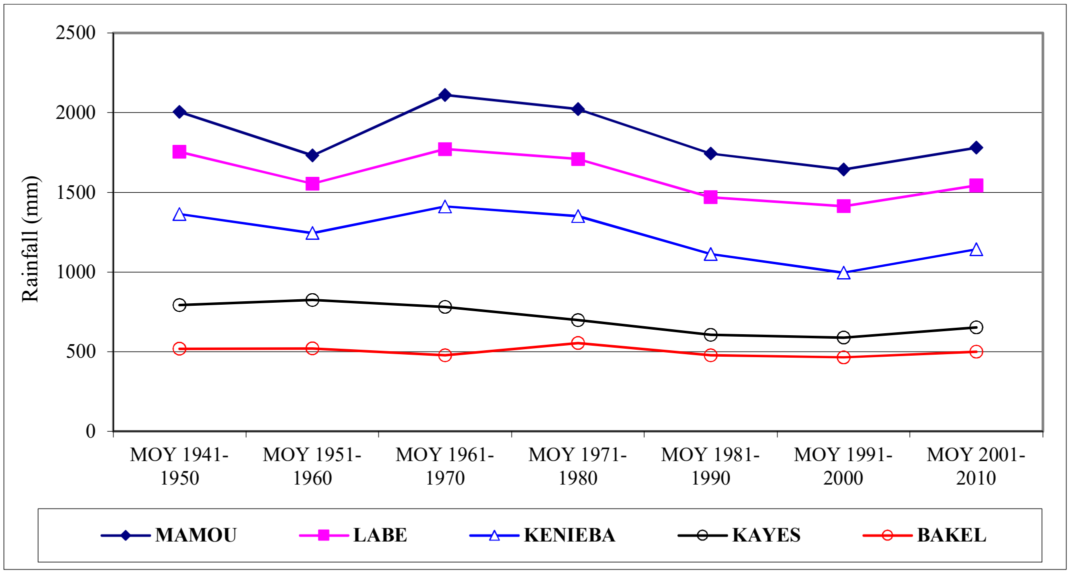


Figure 18 : Variations in ten-year average rainfall at a few stations in the basin

2.1.5. Monthly rainfall

The monthly rainfall assessment focused on synoptic stations with long chronicles; incomplete years were removed from the sample. It is used to characterize rainfall patterns in the basin. Table 10 gives the statistical characteristics of monthly rainfall at the main stations in the basin. The length of the rainy season varies from south to north. Considering the median situations, the rainy season:

- In Mamou, it lasts 9 months, from March to November. December, January and February are not without precipitation every year;
- In Labe, it goes from April to November, i.e. 8 months. The rains from December to March are insignificant;
- In Kenieba, the rainy season from May to October, i.e. 6 months. The dry season covering the rest of the year;
- The stations of Kayes and Bakel correspond to the South Sahelian climate with a rainy season lasting 5 months, from July to October.

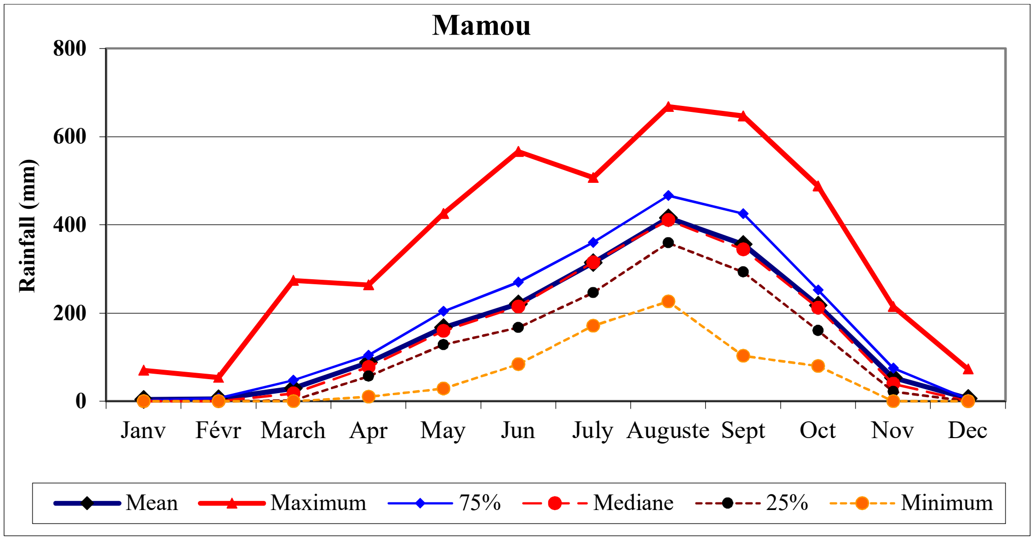
The length of the rainy season in the basin allows a permanent supply to the hydrographic network, which contributes to the sustainability of the river's flows and the recharge of groundwater.

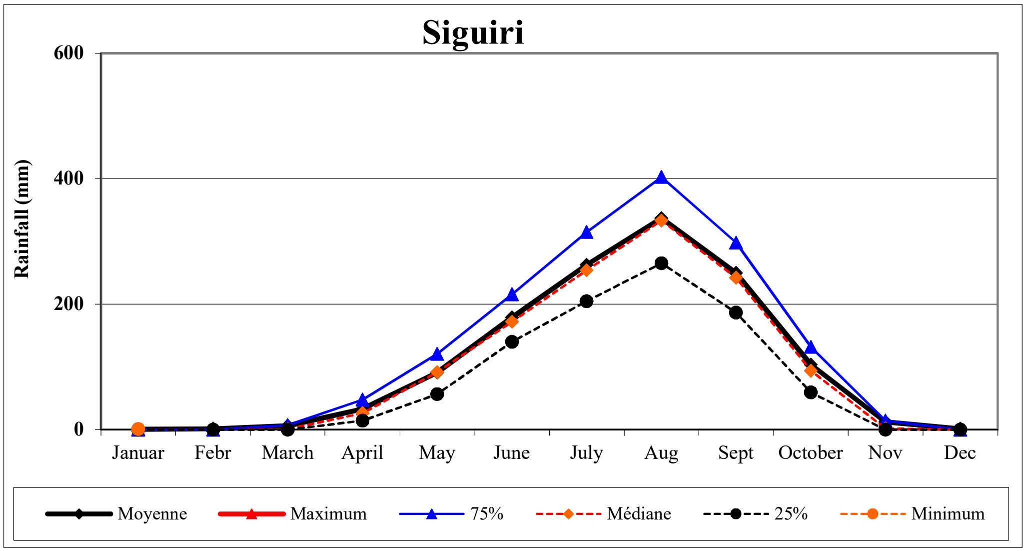
Generally speaking, the maximum rainfall is always in August (with possible shifts in July or September), with July, August and September being the main months of the season. The August maximum varies from 175 mm in Mamou to 41 mm in Bakel. Table 10 shows the monthly rainfall profiles of Mamou, Siguiri, Kenieba and Kayes. They show the interval of variation of monthly rainfall which can reach 600 mm in Mamou and 931 mm in Kenieba.

Table 10: Statistical characteristics of monthly rainfall in Mamou, Labe, Kenieba, Bakel and Kayes

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mamou													
Average (mm)	4,22	5,32	29,49	88,2	167	221	314	415,8	356	217	53,1	6,32	1867
Ecart-type	10,5	9,89	38,56	51,6	69,8	76,8	78,2	87,98	101	76,8	45,3	14,6	285,3
Maximum (mm)	70,5	54	274	264	425	566	507	668	647	488	215	73	2801
75%	1,8	7	48,1	105	204	270	360	466,2	425	252	75	5	2039
Mediane (mm)	0	0	18	78	160	215	315	410,9	344	212	39,7	0	1820
25%	0	0	2,425	56,9	128	167	246	359,2	293	160	22	0	1677
Minimum (mm)	0	0	0	10	29	84	171	226,3	103	79,8	0	0	1248
Coeff. Variation	2,49	1,86	1,308	0,58	0,42	0,35	0,25	0,212	0,28	0,35	0,85	2,3	0,153
Labé													
Average (mm)	2,0	2,8	9,4	42,7	143,2	241,8	324,1	362,3	292,4	161,0	38,7	7,0	1612,2
Ecart-type	5,2	7,0	19,9	38,6	60,9	62,2	86,0	82,1	78,6	76,9	45,8	18,4	261,0
Maximum (mm)	29,0	34,6	115,0	177,3	281,0	372,7	591,0	573,0	527,0	430,0	246,0	108,0	2159,0
75%	0,9	1,0	7,1	63,0	182,0	285,4	370,9	423,5	331,6	191,5	55,8	1,0	1792,5
Mediane (mm)	0,0	0,0	1,0	31,0	147,0	242,0	312,0	363,0	278,9	151,0	24,2	0,0	1561,5
25%	0,0	0,0	0,0	11,5	104,2	197,5	275,3	307,2	242,5	108,0	4,0	0,0	1445,1
Minimum (mm)	0,0	0,0	0,0	0,0	12,0	93,0	147,0	207,5	125,9	37,5	0,0	0,0	628,5
Coeff. Variation	2,6	2,5	2,1	0,9	0,4	0,3	0,3	0,2	0,3	0,5	1,2	2,6	0,2
Kéniéba													
Average (mm)	0,2	0,2	0,6	5,6	51,0	165,3	256,4	374,9	264,9	94,8	7,6	0,8	1199,0
Ecart-type	0,9	1,0	2,9	7,4	36,8	57,7	83,2	153,8	93,8	83,3	12,3	3,5	298,0
Maximum (mm)	5,0	6,3	19,6	32,6	165,0	300,0	446,0	931,1	500,9	508,5	49,9	22,2	1913,7
75%	0,0	0,0	0,0	9,0	71,7	206,7	294,0	434,7	330,8	128,8	10,3	0,0	1341,0
Mediane (mm)	0,0	0,0	0,0	2,9	47,1	155,8	236,0	370,7	241,4	69,6	1,5	0,0	1178,6
25%	0,0	0,0	0,0	0,0	24,3	121,9	192,5	261,5	208,1	47,5	0,0	0,0	1014,4
Minimum (mm)	0,0	0,0	0,0	0,0	0,0	54,4	128,1	161,4	94,8	0,0	0,0	0,0	275,5
Coeff. Variation	4,5	5,0	4,6	1,3	0,7	0,3	0,3	0,4	0,4	0,9	1,6	4,4	0,2
Bakel													
Average (mm)	0,7	0,3	0,4	0,2	5,5	46,5	122,0	175,8	124,5	26,4	2,4	1,3	505,6
Ecart-type	3,2	1,7	3,3	0,9	10,0	29,3	58,8	77,1	67,6	28,0	7,3	5,9	123,7
Maximum (mm)	24,5	11,0	29,4	7,0	60,4	149,9	349,7	384,8	358,2	131,3	49,9	48,0	902,5
75%	0,0	0,0	0,0	0,0	6,3	61,5	154,3	222,6	169,5	37,8	0,0	0,0	574,4
Mediane (mm)	0,0	0,0	0,0	0,0	1,4	40,3	113,6	161,8	114,0	19,9	0,0	0,0	500,5
25%	0,0	0,0	0,0	0,0	0,0	25,4	84,3	129,3	67,1	5,9	0,0	0,0	426,9
Minimum (mm)	0,0	0,0	0,0	0,0	0,0	1,7	23,5	33,3	5,0	0,0	0,0	0,0	234,6
Coeff. Variation	4,8	5,3	8,2	5,1	1,8	0,6	0,5	0,4	0,5	1,1	3,0	4,5	0,2
Kayes													
Average (mm)	0,26	0,47	0,303	1,17	15,7	84,7	167	223,3	147	39,7	2,13	0,56	670,3
Ecart-type	1,94	2,48	1,54	4,77	21,6	43,6	69,8	94,5	63,1	36,5	10,2	2,55	174,4

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mamou													
Maximum (mm)	17	16,6	10,2	30	122	224	344	588,1	370	203	82,9	19,8	1154
75%	0	0	0	0	22,1	112	212	273,4	186	56,3	0,05	0	777,6
Mediane (mm)	0	0	0	0	8,5	77,8	154	210,6	135	29,7	0	0	655,3
25%	0	0	0	0	2	51,9	123	161,2	95	11	0	0	544,1
Minimum (mm)	0	0	0	0	0	0	32,2	54,5	57,2	0	0	0	361,2
Coeff. Variation	7,37	5,27	5,09	4,06	1,38	0,52	0,42	0,423	0,43	0,92	4,78	4,58	0,26





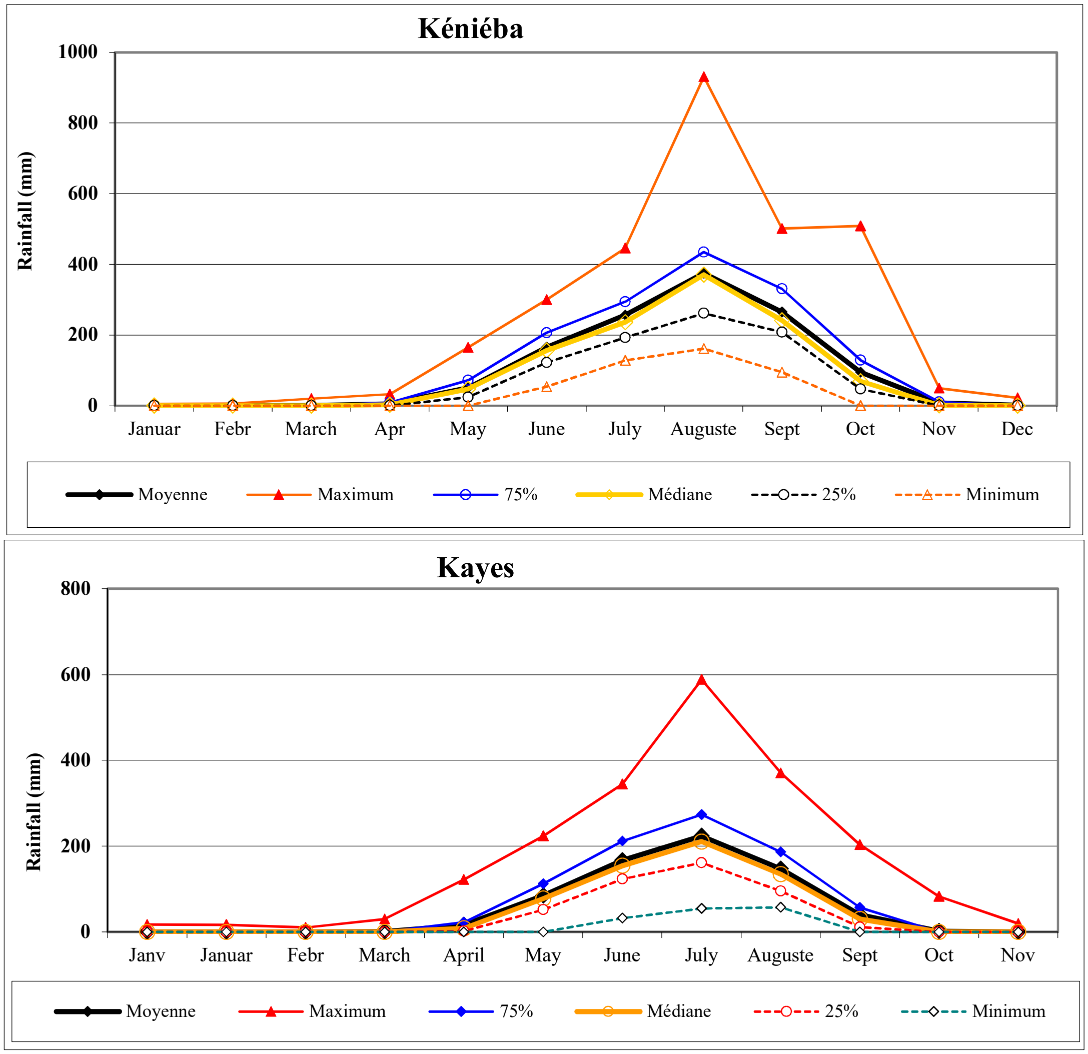


Figure 19 : Monthly rainfall profiles of Mamou, Siguiri, Kéniéba and Kayes

2.1.6. Daily rainfall

The first daily precipitation studies carried out in the Senegal River basin concerned Senegal (Brunet-Moret, 1963), Mali (Brunet-Moret, 1963) and Mauritania (Brunet-Moret, 1964). This study did not cover Guinea. We resume the analysis by considering the new data acquired from the rainfall network of the Senegal River basin. With regard to the data used:

- Through OMVS, we obtained daily rainfall data from the stations of Dabola, Mamou, Labe, Mali, Dinguiraye, Siguiri and Tougue over the period 1971-2016. Some stations such as Dinguiraye have significant gaps. Dabola's data are short (1996-2001) and are excluded from processing. The rainfall data provided to us are too short (less than 5 full years) and incomplete.
- Data from Malian stations are from before 1995. Recent data have not been provided by Mali's MND (despite OMVS request) except for synoptic stations (2002-2004).
- Mauritanian data are from before 1980. We have not had more recent data;
- Data from Senegalese stations have been updated until 2016.

The daily time step is the basis of the available rainfall chronicles. The river's floods are the result of an accumulation of precipitation. But the rain received in 24 hours (which can be the sum of one or more showers falling during a day) is a determining parameter in the study and calculation of floods on small basins that react with a low response time to rain impulses.

A critical analysis of the daily data leads to the elimination from the station sample of observation years for which some basic data are incomplete at the daily scale, either because several consecutive rains of days have accumulated or because gaps in observations are noted. As a result, the sample studied here is significantly shorter than the sample considered in the monthly or annual precipitation study.

Moreover, the observation periods are extremely variable from one station to another; the longer the observation period, the greater the significance of the results obtained. Counted according to the sample size, the stations are distributed as follows:

- Information obtained from samples covering more than 30 years of observations is considered good. This implies that additional measures would bring relatively small variations in the statistical analysis. The analysis of short samples, covering less than 10 years of observations, obviously leads to much less reliable results, as these samples may not be representative of the general local precipitation regime. However, it seemed interesting to give the results which, with a few exceptions, are part of a coherent context.
- The frequential study of daily precipitation amounts consisted, after classifying the daily showers, in seeking for each station the adjustment of a distribution law. Three truncated laws, Pearson III (incomplete Gamma), Goodrich (generalized exponential) and Galton (Gausso-logarithmic) were adjusted to the daily rain samples. The truncated Pearson III law is best suited to all stations. It's distribution function is as follows:

$$F_1(x) = F_1(0)\frac{1}{\Gamma\gamma}\int_x^\infty \left(\frac{x}{s}\right)^{\gamma-1} e^{-x/s}\frac{dx}{s}$$

Where **F_1 (x)** is the probability that the value of the variable is greater than or equal to x

$F_1(0)$ is the probability that the value of the variable is not zero, truncation parameter

Γ, shape parameter, positive, dimensionless

S, scale parameter, positive, expressed in the same unit as x, here as precipitation in mm.

$\Gamma\gamma$ is the complete gamma function (Eulerian of the second species).

All daily precipitations are considered, hence the treatment n values **xi,** ($x_i n_{xi} = N * M$), N being the number of years of observations and M the average annual number of rainy days. $F_1(o)$ is theoretically equal to $\frac{M}{365.25}$, ratio of the average number of rainy days per year to the number of days in the year, but it is preferred to calculate $F_1(o)$ with M', the theoretical average number of rainy days in the year obtained by the moment method (which excludes the imprecision of the number of uncounted rainy days below 0.1 mm).

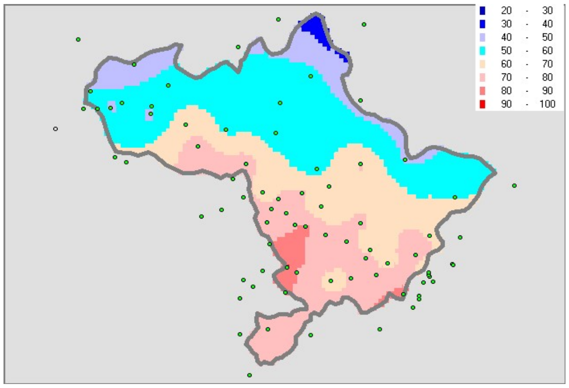
The results of the adjustment of the truncated Pearson III law to daily rainfall are recorded in the table below.

Table 11: Quantiles of recurrent daily rainfall analysed from Hydraccess

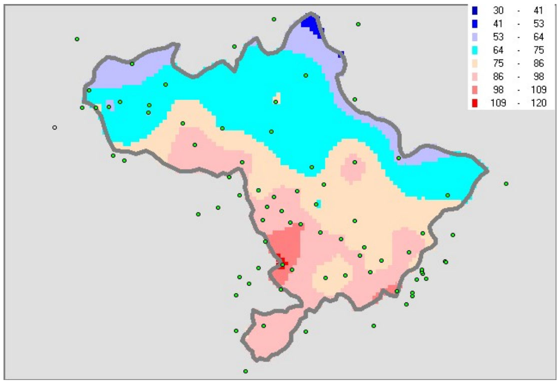
Frequency **Recurrence (year)**	**0,5000** **2,0**	**0,2000** **5,0**	**0,1000** **10,0**	**0,0500** **20,0**	**0,0200** **50,0**	**0,0100** **100,0**
Dinguiraye	74,8	92,6	106,3	120,1	138,7	153,0
Labe	71,8	82,8	91,8	100,9	113,0	122,5
Mali	77,2	92,9	105,2	117,4	134,0	145,7
Mamou	76,3	88,8	98,5	108,3	121,2	130,9
Siguiri	83,3	100,0	112,8	126,4	143,1	156,3
Tougue	75,8	91,8	104,3	117,0	134,1	147,2
Bamako Ancien Aero	80,3	97,6	110,3	123,0	140,1	152,8
Ambidedi	59,0	71,6	81,0	90,3	102,6	111,8
Bafoulabe	81,1	99,7	113,3	127,8	146,5	160,9
Bamako Senou Aero	65,1	77,5	86,5	96,1	108,4	117,4
Faladye	77,9	96,9	111,8	127,4	147,7	164,2
Falea	81,7	96,8	108,8	120,6	136,1	147,4
Gourbassi	80,2	100,7	117,7	133,9	156,1	173,4
Kayes	73,9	94,7	111,2	128,4	151,9	170,4
Kenieba	92,2	113,7	130,5	147,7	171,1	189,1
Kita	75,0	90,1	101,2	112,4	127,3	138,3
Nioro du Sahel	70,9	92,0	109,1	126,9	151,5	170,9
Sadiola	76,3	92,2	104,2	115,5	132,1	143,6
Toukoto	71,9	86,8	97,3	108,8	123,4	134,2
Yelimane	54,8	66,7	76,3	84,7	96,3	105,1
Aleg	55,3	70,8	83,3	95,3	111,6	123,6
Adel Bagrou	35,3	43,6	50,5	56,8	65,0	71,7
Aioun el Atrouss	45,1	55,9	64,7	73,7	84,3	93,5
Nouakchott	36,7	53,9	68,6	84,7	108,1	127,3
Akloujt	31,6	44,6	55,8	66,2	80,4	91,6
Bir Moghrein	15,1	25,7	35,3	44,6	56,9	66,4
Boutilimit	41,4	53,4	63,3	73,2	86,0	95,7
Kaedi1	66,7	85,2	99,6	114,3	134,3	149,6
Kankossa	54,3	67,0	77,2	86,7	100,7	110,5
Kiffa	58,9	76,1	89,7	103,7	122,9	137,7
Moudjeria	48,4	63,9	75,7	87,9	103,4	116,0
Rosso	51,9	65,3	76,1	86,3	99,5	110,3
Tidjikja	41,1	55,8	67,9	79,9	96,4	109,5
Bala	72,7	90,3	103,8	117,3	134,7	148,3
Bakel	70,3	87,9	101,4	115,3	133,5	147,4
Goudiry	74,6	91,6	104,3	116,7	133,9	146,7
Kédougou	86,5	102,5	115,2	127,2	143,7	155,8
Kidira	81,5	101,0	115,6	130,4	150,5	165,5
Matam	74,2	96,0	113,3	131,2	155,8	175,1
Dagana	60,5	81,7	98,9	116,3	139,5	157,5
Diamou	68,8	84,5	95,8	107,3	122,9	134,5
Faraye dieri	46,3	58,9	68,3	78,3	90,5	100,0
Ferentoumou	67,7	81,9	92,2	103,3	117,1	127,4
Fongolomby	79,9	95,6	107,5	119,5	135,3	147,3
Galougo	78,5	95,8	109,0	122,2	139,8	154,0
Guene-gore	78,3	94,6	106,5	118,8	135,7	147,5

Frequency **Recurrence (year)**	**0,5000** **2,0**	**0,2000** **5,0**	**0,1000** **10,0**	**0,0500** **20,0**	**0,0200** **50,0**	**0,0100** **100,0**
Haere lao	46,5	62,7	74,9	87,4	104,3	116,9
Kangaba	86,4	107,5	123,6	140,2	162,2	179,6
Kati-haut	54,7	66,1	75,3	83,7	95,6	104,3
Kiffa	57,9	74,0	86,5	98,6	116,0	128,6
Kolokani	69,2	84,0	96,3	107,7	123,6	135,3
Koniokary	70,8	87,2	100,2	113,0	130,0	142,8
Kourouninkoto	71,2	86,0	97,8	109,9	125,8	137,1
Linguere	63,7	78,6	90,4	102,5	117,7	129,7
M'bout	56,8	71,5	82,9	94,7	109,5	121,0
Mederdra	50,2	64,0	74,0	85,2	98,8	108,6
Mourdiah	59,9	73,7	83,8	94,6	108,6	118,9
Nanguila	75,2	90,7	102,1	114,0	128,7	140,5
Narena	83,9	104,7	119,5	135,4	156,5	172,6
Nienebale	67,7	81,2	92,3	102,7	116,7	127,4
Oualia	72,5	86,7	98,2	109,8	124,7	136,4
Oulouma	74,2	91,8	104,5	118,2	135,5	148,7
Oussoubidiagna	60,4	72,5	81,6	90,8	102,4	110,5
Podor	54,9	70,1	82,2	94,6	110,0	122,4
Ranerou	57,0	74,5	87,2	100,9	118,6	132,4
Sagabari	70,8	84,2	94,9	104,9	118,9	129,7
Sandare	66,0	81,1	91,5	102,7	116,9	127,5
Saraya	86,8	105,3	119,7	134,4	153,9	168,9
Sebekoro	67,1	80,7	90,9	101,0	114,3	124,2
Selibaby	76,3	94,5	109,1	123,1	142,1	157,0
Sirakoro	71,3	85,3	95,8	106,4	120,5	131,1
Sokolo	59,4	72,6	82,5	92,5	106,5	115,8
Tamchackett	53,1	72,8	88,8	105,3	126,8	144,0
Tichitt	23,1	33,6	41,4	49,7	60,8	69,2

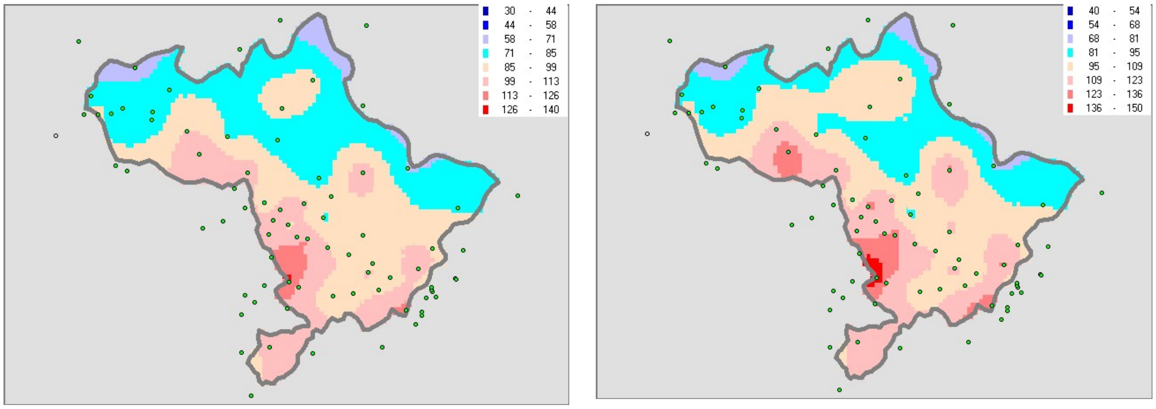
Maps of daily precipitation quantiles over the entire basin have been prepared. Figure 2019 shows the spatial distribution of daily rainfall quantiles according to their recurrence. Because, for the same return time, the quantiles increase from Sahelian stations to stations in the Sudanese domain (active zone of grain lines) before decreasing at stations in the Senegal River basin. Indeed, in the basin, the spreading of the rainy season is accompanied by a decrease in rainfall intensity (Rochette, 1974).



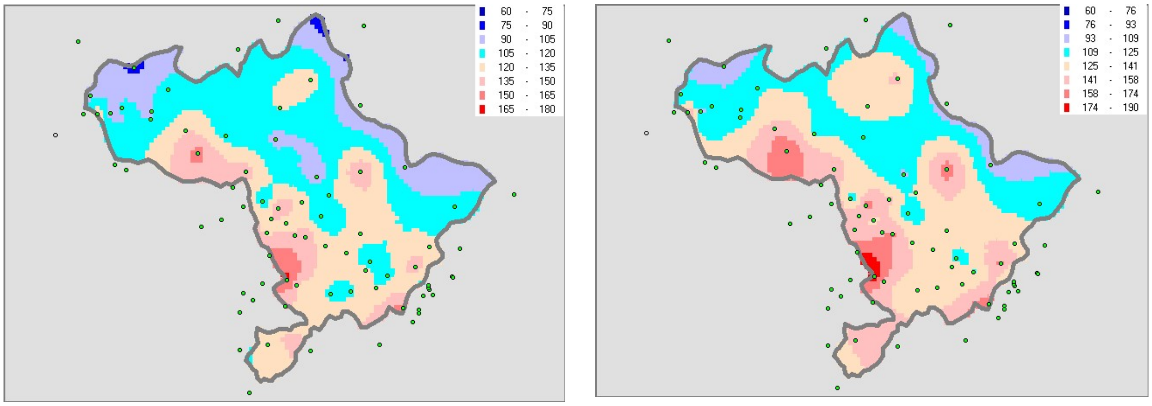
Median frequency rainfall



Five-year frequency rainfall (1/5 years)



Ten-year frequency rainfall (1/10 years) *Perennial frequency rainfall (1/20 years)*



50-year frequency rainfall (1/50 years) *Centenial frequency rainfall (1/100 years)*

Figure 20 : Spatial distribution map of daily frequency rainfall (mm) over the Senegal basin (Source: Hydrological monograph of the Senegal River, 2011)

2.2. SURFACE RUNOFFS

Flow in tropical areas is a direct response to rainfall pulses, the transfer of which can be subject to various modalities depending on the size, configuration, relief, geology and soils of the basin. First, the available data and their quality will be considered, followed by the statistical quantiles of the annual and monthly modules, the characteristic flows and low flows.

2.2.1. The available data and their qualities

Data on the Senegal River Basin are managed by the Hydrology Division of OMVS. Data reception is daily at OMVS level by radio communication. They come from the different brigades in the member countries:

- Saint-Louis Brigade for the DGPRE (Water Resources Management and Planning Directorate) of Senegal with the relay constituted by Bakel
- Kayes Brigade for the DNH (National Directorate of Hydraulics) of Mali
- Labe and Mamou Brigades for the DNH (National Directorate of Hydraulics) of Guinea

The hydrological monitoring of the river dates back to 1903 at the Bakel station. This monitoring concerned high water levels during flood periods until 1950. From 1951 onwards, the coastal surveys of the plan were daily. The main stations have complete data until March

2010. In reality, the OMVS database only manages data from hydrometric stations that are considered important to have a global view of the resources in the basin. The flow chronicles of the stations in the upper basin (Guinea) are quite brief; observations began in 1969 and are described below.

Table 12: Hydrometric network of the upper Bafing/Senegal River basin in Guinea

N°	Stations	Watershed	Commissioning year	Existing Equipment
1	Balabori	Bafing	1969	Limnimeter
2	Boureya	Bafing	1969	Limnimeter
3	Pont km 17	Bafing	1967	Limnimeter
4	Sokotoro 2	Bafing	1972	Limnimeter
5	Ley-Kioma	Kioma	1969	Limnimeter
6	Salouma	Kioma	1969	Limnimeter
7	Teliko	Kioma	1955	Limnimeter
8	Trokoto	Kioma	1969	Limnimeter
9	Bebele	Téne	1970	Limnimeter
10	Pont Fatako	Dombele	1986	Limnimeter

- Balabori, a key resort since it is located downstream of all the tributaries of the Bafing in Guinea. Tracked since 1969, it has only 16 years of complete data (58% of gaps)
- Boureya: 1969 -2016, no full year (54% deficiencies)
- Sokotoro 2: 1969-2007, has 22 complete hydrological years (18% of gaps)
- Teliko: 1969-1991, 9 full years
- Trokoto: 1969-1990, 7 full years
- Bebele: 1970-1991, 2 full years

The quality of the basin data, in particular the length of the series, is likely to reduce the scope of the conclusion that can be inferred from it. Given the geology of the region, which gives stability to the course bed, all calibrations are bi-unique.

The other stations in the basin have much more consistent data allowing a detailed analysis of the variability of inputs at the annual, monthly and daily scales as well as the characteristic flows.

Table 13: Inventory of flows at the main stations in the basin

Name	Sensor	Description	Value number	Start date	End date	% lacunes
BALABORI	I1	Main Flow	3315	10/07/1969	01/08/2010	58.2
BOUREYA	J1	Main Flow	796	19/04/1969	31/12/1973	54.2
SOKOTORO 2	I1	Main Flow	12058	01/01/1970	31/01/2007	17.5
TELIKO	I1	Main Flow	8943	01/11/1969	31/10/1991	14.6
TROKOTO	I1	Main Flow	7881	01/11/1969	30/06/1990	29.6
BEBELE	J1	Main Flow	2806	08/07/1970	30/11/1991	64.3
BAFING MAKANA	I1	Main Flow	24871	01/01/1961	23/02/2016	0.0
BAKEL	I1	Main Flow	40883	02/01/1904	05/03/2016	22.0

Name	Sensor	Description	Value number	Start date	End date	% lacunes
BAKEL	Iuniq	JPL Single Calibration Flow Rates	40592	02/01/1904	28/11/2016	22.1
BAKEL	J1	Main Flow	30449	03/01/1904	04/03/2016	24.8
DAKA SAIDOU	I1	Main flow	26777	27/05/1952	05/03/2016	1.1
DIANGOLA	I1	Main Flow	397	01/12/1999	16/06/2000	0.0
DIBIA	JH	Homogenized flows	33468	16/06/1903	31/01/1995	0.0
FADOUGOU DRAGUE	JH	Homogenized flows	33606	14/06/1903	16/06/1995	0.0
GALOUGO	JH	Homogenized flows	33468	16/06/1903	31/01/1995	0.0
GOURBASSI	I1	Main Flow	28943	01/01/1954	05/03/2016	0.0
KAYES	I1	Main Flow	35350	01/07/1903	05/03/2016	27.9
KIDIRA	I1	Main Flow	25332	01/06/1930	05/03/2016	33.5
MANANTALI AMONT	IS	Area	6985	19/07/1987	28/02/2016	0.0
MANANTALI AMONT	IV	Volume	6985	19/07/1987	28/02/2016	0.0
MANANTALI AMONT	JS	Area	7163	20/07/1987	27/02/2016	0.0
MANANTALI AMONT	JV	Volume	7163	20/07/1987	27/02/2016	0.0
MANANTALI AVAL	Jlach	Discharged flows of the dam	7166	18/07/1987	28/02/2016	0.0
OUALIA	I1	Main Flow	24270	01/06/1954	05/03/2016	2.2
OUALIA	J1	Main Flow	18845	01/06/1954	04/03/2016	2.2
OUALIA	JH	Homogenized flows	33605	15/06/1903	16/06/2016	0.0
SIRAMAKANA	JH	Homogenized flows	33605	15/06/1903	16/06/1995	0.0
SOUKOUTALI	JH	Homogenized flows	33470	15/06/1903	01/02/1995	0.0
TOUKOTO	JH	Homogenized flows	33620	15/06/1903	01/07/1995	0.0

2.2.2. Flow statistics

The flow analysis makes it possible to determine the natural flood and low water regime in the Senegal River catchment area - the Affluent component (Faleme - Bafing -Bakoye/Baoule).

Senegal's flood regime is that of an annual flood, linked to the rainy season in the upper basin. Peak floods, which vary greatly depending on the rainfall of the year, between 3,000 and 12,000 $m^3.s^{-1}$, can occur in Bakel from July to October. The peak flow at Bakel is most often in the early days of September.

Downstream from Bakel, the contributions of Mauritanian tributaries to Senegal are negligible. On the other hand, the damping of the flood by flooding of the major bed and by evaporation is very important. Thus, the centennial flood peak of 8,300 $m^3.s^{-1}$ in Bakel, is only 6,500 $m3.s^{-1}$ in Matam and 3,200 $m^3.s^{-1}$ in Dagana.

In low water, Senegal's natural flow is about 10 $m^3.s^{-1}$ at Bakel. It can practically cancel each other out in some dry years. The river module (average flow) is about 750 $m^3.s^{-1}$.

Given the very low slope of the river, flow rates remain moderate, even during floods. They vary from 0.1 to 0.6 $m.s^{-1}$ during low water periods (flows less than 500 $m^3.s^{-1}$). They vary from 1 to 1.4 $m.s^{-1}$ during the rise of the flood and from 0.4 to 0.8 $m.s^{-1}$ only during the flood.

This large asymmetry between the rise of the flood and the decline, due to the low slopes and water storage in the major bed, explains the absence of a clear height/flow (flood) law in the river downstream of Bakel. For this reason, Bakel is Senegal's reference scale.

2.2.3 Analysis of annual and monthly modules

The series of annual and monthly average modules in the Bafing basin are of variable quality due to the length of the samples due to numerous gaps. The following is a summary of these. Only the Sokotoro station has monthly flows covering 36 hydrological years, 21 of which are complete. Balabori has only 5 complete and Bebele 2, the other resorts such as Teliko and Trokoto being respectively 12 and 10 years old. For some stations, they have only one missing month during the hydrological year. The average monthly flows calculated on the basis of such samples are therefore of relative importance.

The stations of Daka-Saidou and Bafing Makana have longer data from nearly 55 years of hydrometric monitoring. Only observed flows were included in this study. Given the brevity of the modules of the Guinean stations, the Figure 21 shows the variations of the annual modules of Daka-Saidou, Bafing Makana and Sokotoro. The data from this last station are very incomplete, which explains the discontinuity of the curve. It should be noted that the fluctuations in the flow rates of the other two stations are similar.

Table 14: Number of years of hydrological monitoring of stations in the Upper Basin

Station	Number of records	Number of complete records
Balabori	13	5
Sokotoro	38	21
Téliko	23	12
Bébélé	13	2
Trokoto	21	10
Daka-Saidou	55	53
Bafing Makana	55	52

The Figure 21 shows a clear gap between the pre- and post-drought periods:

- 1954 to 1967: annual modules greater than 250 $m^3.s^{-1}$;
- 1968 to 1977: modules fluctuating between 250 and 200 $m^3.s^{-1}$;
- 1978 to 1993: modules less than 200 $m^3.s^{-1}$;
- 1994 to today: slight increase in modules which are greater than 200 m3/s despite a continuation from 2013.

The increase in the number of modules in recent years is due to the improvement in rainfall, which nevertheless remains highly fluctuating from one year to another, so that the trend towards replenishing resources remains very uncertain and makes it more difficult to forecast availability.

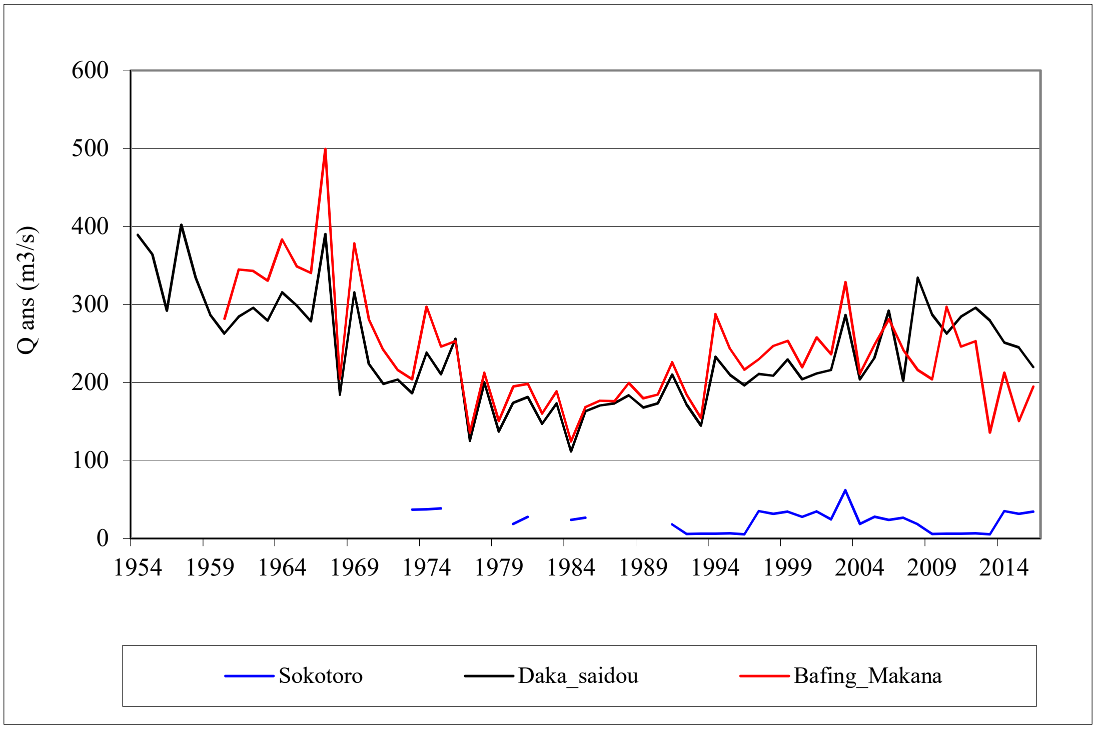


Figure 21 : Variations of the annual modules of Bafing in Sokotoro, Daka-Saidou and Bafing Makana

3. CHARACTERIZATION OF HYDROLOGICAL DROUGHT IN THE SENEGAL AND GAMBIA CATCHMENT AREA

Drought is a natural phenomenon that occurs in all regions of the world and particularly in West Africa (Mirabbasia et al., 2013). It is one of the extreme weather conditions affecting more people than any other form of natural disaster (Faty et al., 2017). In recent decades, the occurrence of major droughts occupying large territories on all continents has underlined the importance of this phenomenon (Wilhite and al, 2000). Both developing and industrialized countries are affected. In underdeveloped countries, the effects can be disastrous (Beaudin, 2007). Drought is related to a lack or decrease in rainfall in a given region. This results in water shortage problems at certain times of the year and particularly in the Gambia's hydrosystem, which is an area with high agricultural activity. Like other hydrosystems, the Gambia Basin is experiencing climate disruptions caused by deteriorating climate parameters such as precipitation, which makes it difficult to manage water resources in river systems. Our purpose is therefore to analyze the hydrological dynamics of the hydrosystem through the evolution of Gambia's daily flows at the Bansang and Oundou Bac hydrometric stations in order to highlight the effects of drought on the hydrological regime of the rivers in the study area. These data were made available through the Organization for the Development of the Gambia River basin (OMVG).

3.1. METHODOLOGICAL APPROACH

3.1.1. Methods for analyzing the effects of drought on surface water

The assessment of drought risk in the study area led to the analysis of its impact on surface water resources. This analysis consisted in studying the fluctuations in daily flows from the Gambia basin to the Gouloumbou station and from the Senegal basin to the Bakel station and (1982-2016). The flow regime was studied to determine the level of dryness in the basins. A study of the variation in the drying coefficients and the volume of water used was also carried out. The analysis was done using hydrological drought detection indices such as the Normalized Hydrological Index (NHI), the Drought Flow Index (DFI) and the Logarithmic Decimal Index of Hydrological Deviations (LDIHD).

3.1.2. Calculation of the drying coefficient

The risk of drought on water resources is assessed by calculating drying coefficients using the dichotomous method and by quantifying the volumes of water mobilized by aquifers (Soro et al., 2011). Tapping is defined as the decrease in groundwater flow to surface water during periods of no recharge, due to the decrease in groundwater supply and expressed by the drying curve. In other words, it is the period during which groundwater recharge is the only contribution to the flow of a basin's watercourses.

According to Doumouya et al. (2009), the drying coefficient makes it possible to assess the state of the water "inputs" that would contribute to the apparent modification of the rain-flow relationships observed in the river basins. It thus makes it possible to compare the evolution of surface water and the storage of the aquifer in order to better understand the behavior of the discharge reservoir. The drying coefficient (k) depends on the physical and geometric characteristics of the aquifer. It is determined by the Maillet method, improved by dichotomous resolution (Irie et al., 2015).

The main drying up, by the volumes it implies and its representativeness of all the aquifers in the basin, is an important feature of the tropical hydrological regime (Briquet et al., 1995). The calculation of the drying coefficient is based on the Maillet model that has already been used by other authors (El-Ouafi, 1993; Savané et al., 2001; Saley, 2003; Vissin, 2007; Amoussou, 2010). These authors have shown the relevance of this model in the study of drying up.

The mathematical expression of the drying up is given by the equation: $Q_t = Q_0 e^{-kt}$

Hence:

Qt= flow at the given time t;
Q0= initial flow rate (flow rate at the beginning of drying);
T = time in day;
K = mallet drying coefficient.

It can be obtained by solving equation 2 by dichotomy:

$$\frac{e^{-kt}}{k} + \frac{V}{Q_0} - \frac{1}{k} = 0$$

With:

V = the volume of water flowing at each instant (m3).
The expression of the drying time T (in days) can be formulated by this equation $T = \frac{1}{k}$ (Faty et al., 2017):

To construct the drying curves, the flow rates are plotted in ordinates and the time in abscissa. The highest daily flow of the year is considered as the initial flow noted (Q_0). From Q_0 onwards, a series of flows is constituted by reading the flows (Qi) in a ten (10) day time step, until they rise significantly (Saley, 2003; Savane et al., 2003). The drying curves will correspond to the periods during which the flow decreases more or less evenly (uninfluenced regime), i.e. In the absence of any precipitation.

3.1.3. Calculation of the volume of water mobilized by aquifers

The volume of water mobilized by all aquifers is thus obtained by integrating the formula of the equation below over the $V_{\text{mobilisé}} = \int_0^t Q_0 e^{-kt} dt = \frac{86400 * Q_0}{k}$ range 0 to +∞:

With:

Q0= initial flow rate (flow rate at the beginning of drying), expressed in $m^3.s^{-1}$;
K= Maillet dryness coefficient, expressed in days-1.

The volumes of water mobilized by the calculated aquifers were graphically represented at the annual time step from the Excel spreadsheet.

3.1.4. Hydrological drought index method

3.1.4.1. NORMALIZED HYDROLOGIC INDEX (HLI)

The normalized hydrological index (HLI) is similar to the standardized precipitation index (mckee et al., 1993; Hayes et al., 1996). Thus, it has been developed to quantify the hydrological deficit for multiple time scales that will reflect the impact of drought on the availability of different types of water resources for a given period (Mirabbasia et al., 2013). It is expressed mathematically by the following equation:

$$IHN = \frac{(D_i - D_m}{S}$$

With:

Di: the flow of the month or year i;
Dm: the average flow of the series on the time scale considered;
S: the standard deviation of the series on the time scale considered.

Studying this index also makes it possible to distinguish between dry months and years (deficit) and wet months and years (surplus). A drought occurs when the HLI is consecutively negative and its value reaches an intensity of -1 or less and ends when the HLI becomes positive. A drought classification is performed according to the HLI values (Table 15).

Table 15: Classification of drought sequences according to the HLB

HLB value	Drought	HLB value	Wet sequence
0.00< IHN <-0,99	Slightly dry	0.00< IHN	Slightly wet
-1.00< IHN <-	Moderately dry	1.00< IHN	Moderately wet
-1.50<IHN<-1.99	Severely dry	1.50< IHN	Severely wet
IHN < -2.00	Extremely dry	2.00< IHN	Extremely wet

3.1.4.2. FLOW DROUGHT INDEX (DFI)

The dry flow index (DFI) is similar to the Bhalme and Mooley index (Bhalme and Mooley, 1979) which represents the percentage difference between rainfall and the long-term average. The DFI, also called the mean flow deviation (MDF), is used to determine the river's response to the rainfall deficit (Nalbantis and Tsakiris, 2009) and to determine flow deficits and variations (Mahe and Olivry, 1997). It is calculated according to this equation:

$$\mathbf{ISD} = \left(\frac{D_i}{D_m}\right) - 1$$

With:

Di: the flow of the month or year i;
Dm: the average flow of the series on the time scale considered.

This method consists in highlighting the periods during which the basin's inflows are significantly lower than the average monthly inflow. Compared to the classification of this index: if the ISD is greater than 1, the period is wet; if the ISD is 0, the period is moderately normal; if the ISD is less than 0, the period is dry.

3.1.4.3. LOGARITHMIC DECIMAL INDEX OF HYDROLOGICAL DEVIATIONS (LDIHD)

The percentage of flows may represent the simplest method used to express the hydrological deficit of a period by the ratio between the actual flows and the multi-year average for that period [15]. Since the graphical expression of the ratio is not sufficiently suggestive to qualify the maximum deviations, the logarithmic decimal index of hydrological deviations (LDIHD) is calculated from the equation below:

$$\mathbf{ILDH = \log\,(Di\,/Dm)}$$

With:

Di: the flow rate of the month or year i;
Dm: the average flow rate of the series on the time scale considered.

The LDIHD much better highlights the hydrological surplus or deficit, with a good tendency to highlight positive or negative extremes. A classification of the drought according to LDIHD values (Table 16**Error! Reference source not found.**).

Table 16: Classification of drought sequences according to the ILDH

ILDH value	Drought	HLB value	Wet sequence
0.00< ILDH <-	Moderately dry	0.00< ILDH	Moderately wet
-1.00<ILDH<-	Heavily dry	1.00< ILDH	Heavily wet
ILDH < -2.00	Extremely dry	2.00< ILDH	Extremely wet

3.2. ANALYSIS OF THE WATERCOURSE REGIME

The interannual evolution of Gambia's average daily flows, illustrated in Figure 22 and Figure 23, can be broken down into a single short-term flood phase and a long-term recession (low-water level) phase. At the Bansang and Oundou Bac stations respectively (Figure 22 and Figure 23), the flood phase runs from April 30 to September 30. It is marked by an optimum average daily flow or peak flow of 244.26 $m^3.s^{-1}$ and 240.2 $m^3.s^{-1}$. The recession phase, expressing a drying up, begins from 30 September after the production of the peak flood and ends on 30 April, with an average daily flow of 0.38 $m^3.s^{-1}$ and 1.56 $m^3.s^{-1}$.

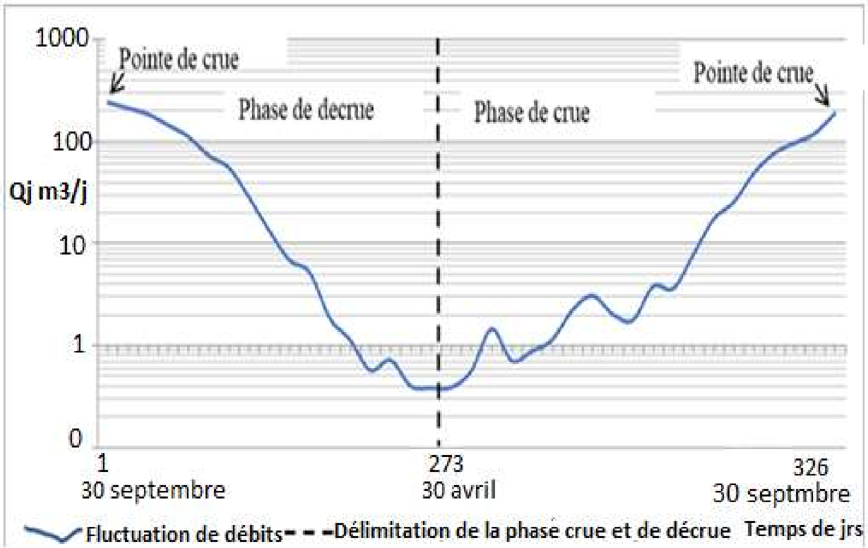


Figure 22: Fluctuation of interannual daily average flows at Bansang station (1982-2016)

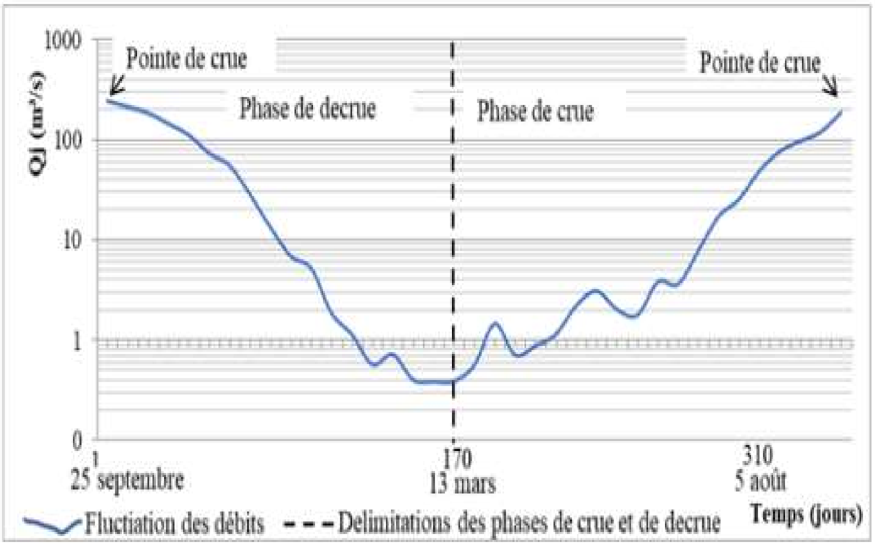
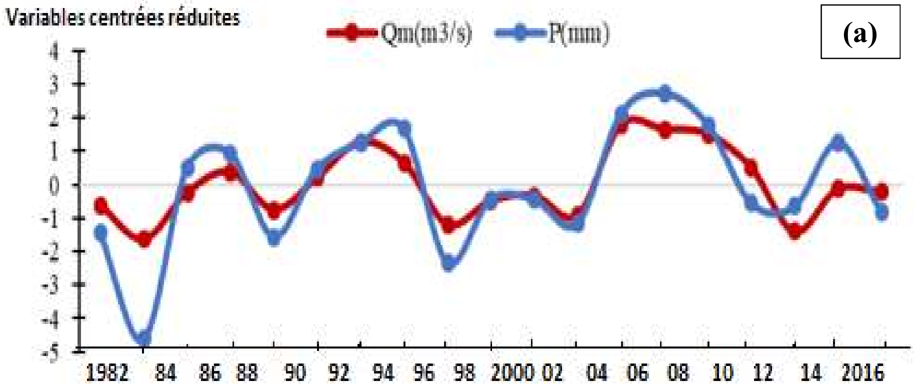


Figure 23: Fluctuation of interannual daily average flows at the Oundou Bac station (1982-2016)

3.3. ANALYSIS OF THE RAIN-FLOW RELATIONSHIP

The annual mean fluctuations in ebb and flow rates, coupled with those in mean annual precipitation on the common chronic for hydrometric and rainfall data, i.e. 1982-2016 for Bansang and Oundou Bac stations, are illustrated in Figure 24 (a-b), respectively, and at Bansang station a synchronous trend emerges from the analysis of rainfall fluctuations (precipitated water wave) and flows (ebb) over the entire chronic. This synchronous trend in the rain-flow relationship is expressed by the increase in flows during periods of excess rainfall and by the decrease in flows during periods of rainfall deficit. This trend was also observed throughout the study chronicle at the Oundou Bac station (Figure 24).



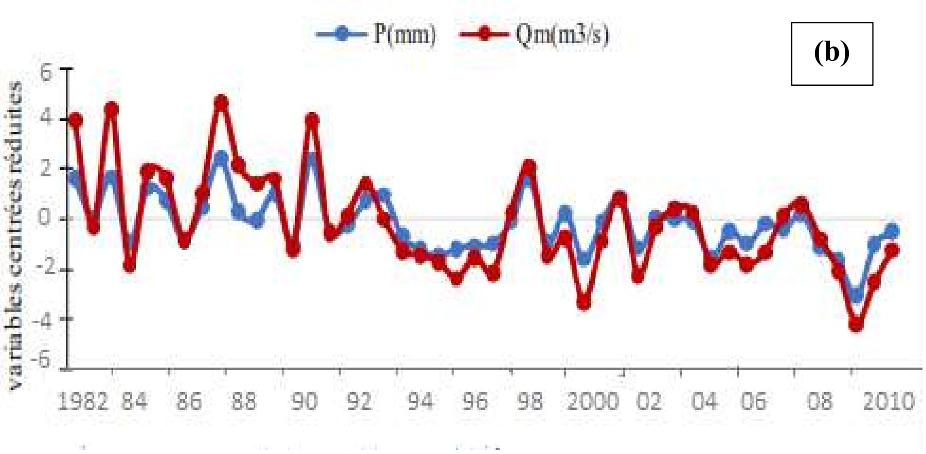


Figure 24: Variation in the drying coefficient and annual volume of water mobilized at Bansang (a) and Oundou Bac (b) stations (1982-2016)

In this approach, the annual drying curve is the expression of the emptying of the tank underground. The Mallet model admits that in an uninfluenced regime, i. E. In the absence of any precipitation, the drying up corresponds to the exponential decrease in the flow rate as a function of of time. Indeed, drying is defined as the decrease in groundwater flow rate going to surface water during periods of no water supply, due to the decrease in the reserve of groundwater and expressed by the drying curve. In other words, it is the period during which groundwater discharge is the only contribution to flow of the watercourses of a basin. According to Olivry et al (1998) cited by Amoussou (2010), the coefficient of drying-up makes it possible to assess the state of the "inlets" of water that would contribute to the modification of rain-flow relationships observed over river basins. It thus makes it possible to compare surface water evolution and aquifer storage to better understand the behaviour of the drain tank. The drying coefficient (k) depends on the physical characteristics and of the aquifer.

Drying coefficients and water volumes mobilized at the Bansang station in Gambia, the drying coefficients (k) vary between $1.37.10^{-2}.d^{-1}$ and $3.69.10^{-2}.d^{-1}$, with an average value of $2.31.10^{-2}.d^{-1}$ (*Cf. Methodology: the Maillet coefficient*). The volumes of water mobilized vary between 0.08 and 2.67 km^3, with an average of 1.33 km^3. A decrease in the drying coefficient is recorded in Bansang, which has led to an increase in the volumes of water mobilized since 1992 (Figure 24a and 24b).

At the Oundou station, the drying coefficients (k) fluctuate between $3.59.10^{-2}.d^{-1}$ and $1.19.10^{-2}.d^{-1}$ with an average of $2.28.10^{-2}$ $d.^{-1}$. The volumes of water mobilized range from 4.97 km^3 to 0.09 km^3 with an average of 1.90 km^3. A gradual decrease in the volume of water mobilized is observed from 1992 onwards, which has led to a gradual increase in the drying coefficient (Figure 25).

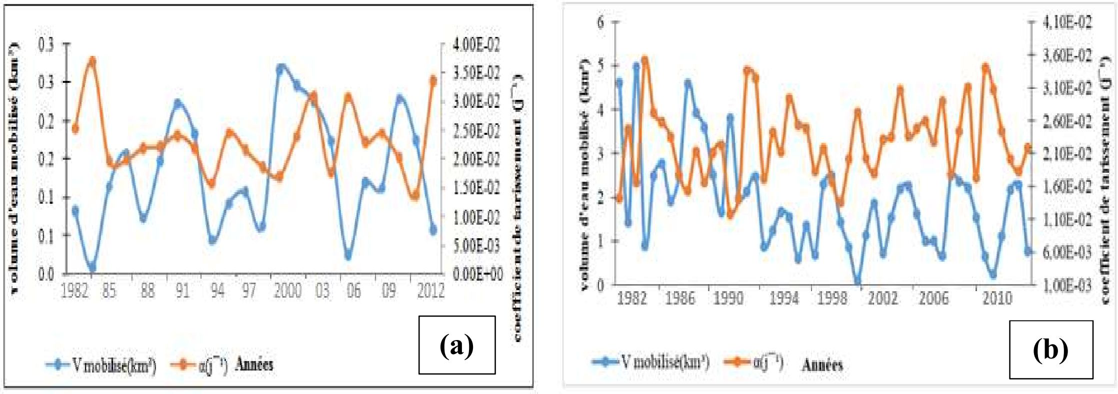


Figure 25: Variation in the drying coefficient and annual volume of water mobilized at Bansang (a) and Oundou Bac (b) stations (1982-2016)

Fluctuations in drying coefficients and mobilized water volumes are asynchronous and therefore normal over the entire flow observation period. Indeed, in periods of heavy rainfall, groundwater reserves are important so that after the rainfall stops, underground reservoirs continue to ensure the flow of the river. The drying coefficients are then low and indicate a long to very long drying time. In this case, the volumes of water mobilized by underground tanks are enormous. The opposite situation occurs in dry periods when the quantities of rainfall in the study area remain insufficient to compensate for water losses from underground reservoirs.

3.4. ANALYSIS OF THE IMPACT OF DROUGHT THROUGH SHORT TERM HYDROLOGICAL DROUGHT INDICES

The results of the short-term hydrological drought analysis at the Bansang hydrometric station are presented Figure 26. At the surface water level, the analysis of the rain-flow relationship showed that the annual yield of the watercourse in the study area is highly correlated with rainfall. ORSTOM (1986) showed a strong correlation between the annual yield of the Gambia River catchment area and the precipitated water wave. Analysis of the annual drying coefficients over the period 1982-2016 at the Bansang and Oundou Bac stations showed that they fluctuate over time. These results converge towards the evidence of a significant drying up of groundwater reserves under the effect of climate variability manifested by a decrease in precipitation and an increase in evapotranspiration following the monotonous increase in temperature since the late 1960s. The volumes of water mobilized by aquifers are declining due to the reduction in rainfall observed from the end of the 1960s onwards. The sustainable depletion of base flow inputs is linked to a reduction in the volume of water in aquifers. Indeed, a considerable depletion of underground reserves that normally feed rivers during dry periods is observed. These variations in the volume of water mobilized by aquifers suggest a considerable decline in groundwater reserves, which explains the high magnitude of the recent drought on the decline in flows.

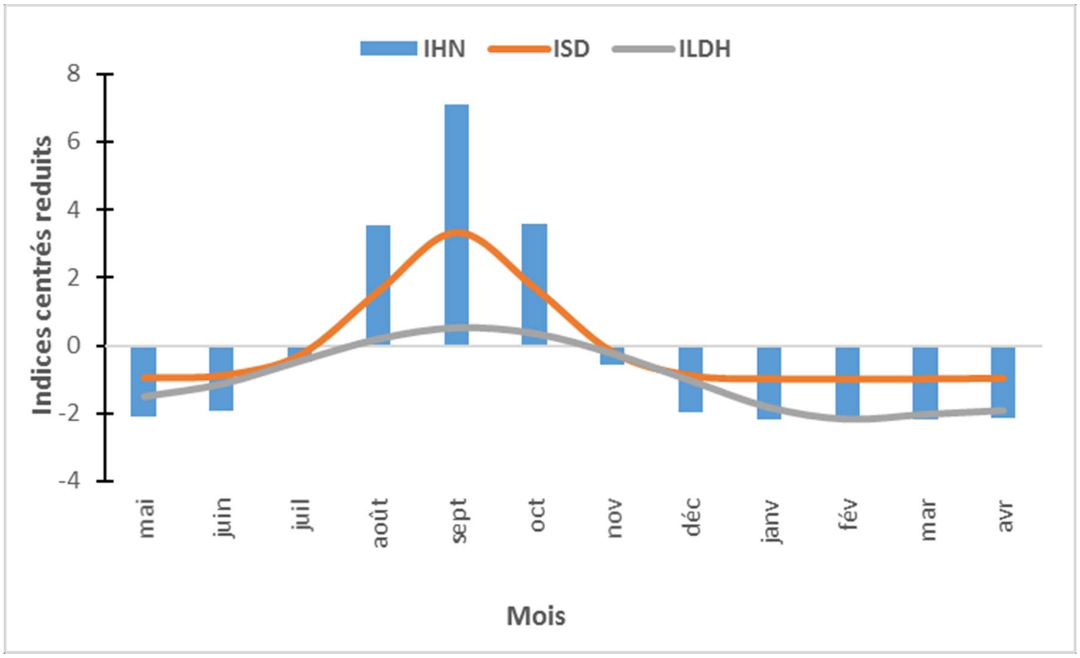


Figure 26: Evolution of hydrological drought in the short term using the HLB, ISD and ILDH (Bansang Station)

3.5. REFRAN-CV ANALYSIS OVER SENEGAL

3.5.1. Reminders on the physical context of Senegal

Senegal is located in West Africa, between 12° and 17° North latitude and 11° and 18° West longitude, over an area of 196,722 km²; it is bordered to the north by Mauritania, to the east by Mali, to the south by Guinea and Guinea Bissau, to the west by Gambia and the Atlantic Ocean on a coastline of over 700 km (Figure 27). Senegal's maritime space covers an area of 198,000 km² while its exclusive economic zone is 200 nautical miles wide for a continental shelf of 23,800 km² where most artisanal fishing takes place.

It is a flat country overall with 75% of its surface area located below 50 m. Maximum altitudes are recorded in the southeast on the foothills of Fouta Djalon, on the border with Guinea where the Bassari Mountains peak at 581 m. From a geological point of view, 4/5 of the territory is located in the large Senegal-Mauritanian sedimentary basin, with mainly secondary and tertiary age formations. The Precambrian basement outcrops in the southeast of the country (Kane and Niang Fall, 2007).

Figure 27: Location map of the Republic of Senegal

From a climatic point of view, Senegal is located in the dry tropical domain known as the Sahel domain, characterized by two seasons: a dry season from November to June and a rainy season from July to October. According to Sagna's genetic classification, Senegal has three main climatic zones: Sahelian, North Sudanese and South Sudanese (Sagna, 2007). The presence of the ocean introduces nuances that divide these three areas into six climatic domains: coastal Sahel (Dakar 541 mm and Saint-Louis 265 mm) and continental Sahel (Podor 272 mm and Linguere 446 mm); coastal North Sudanese (Mbour 639 mm) and continental Sudanese (Kaolack 707 mm); coastal South Sudanese (Ziguinchor 1408 mm) and continental South Sudanese (Kolda 1124 mm and Kedougou 1251 mm).

The climate is characterized by a high spatial and temporal variability in precipitation, which results in a relatively low annual average annual rainfall almost everywhere in the country. Rainfall varies between 300 mm in Saint-Louis in the north and 1200 mm in Ziguinchor in the south. The maximum temperatures are before the rains arrive, usually in April or May. The average temperatures are greater than or equal to 30º C with an average relative humidity of less than or equal to 40%. These climatic conditions favour the presence of three types of plant formations: the forest in the south, the savannah in the centre and the steppe in the north of the country.

Senegal's hydrographic network is mainly composed of four hydrographic systems (CSE, 2010): the Senegal River (1,790 km), the Gambia River (1,180 km), Casamance (300 km) and the upper reaches of the Kayanga River, known as Rio Gêba in Guinea Bissau. This hydrographic network is highly dependent on rainfall conditions and therefore very vulnerable to climatic conditions. Several hydrographic systems with non-perennial flows are also present in Senegal: The Sine, the Saloum and the Car-Car, which lead to hypersaline estuaries. Along the coast, on the “Petite Côte”, between Dakar and Joal, a few small coastal basins are becoming more individualized.

Like the Sahel region, Senegal has been particularly affected by rainfall deficits since the early 1970s (Figure 28). From a hydrological point of view, this has resulted in a significant reduction in flows estimated by Mahe and Olivry (1995) to about 75% between 1970 and 1990 and 50% in the 1980s alone.

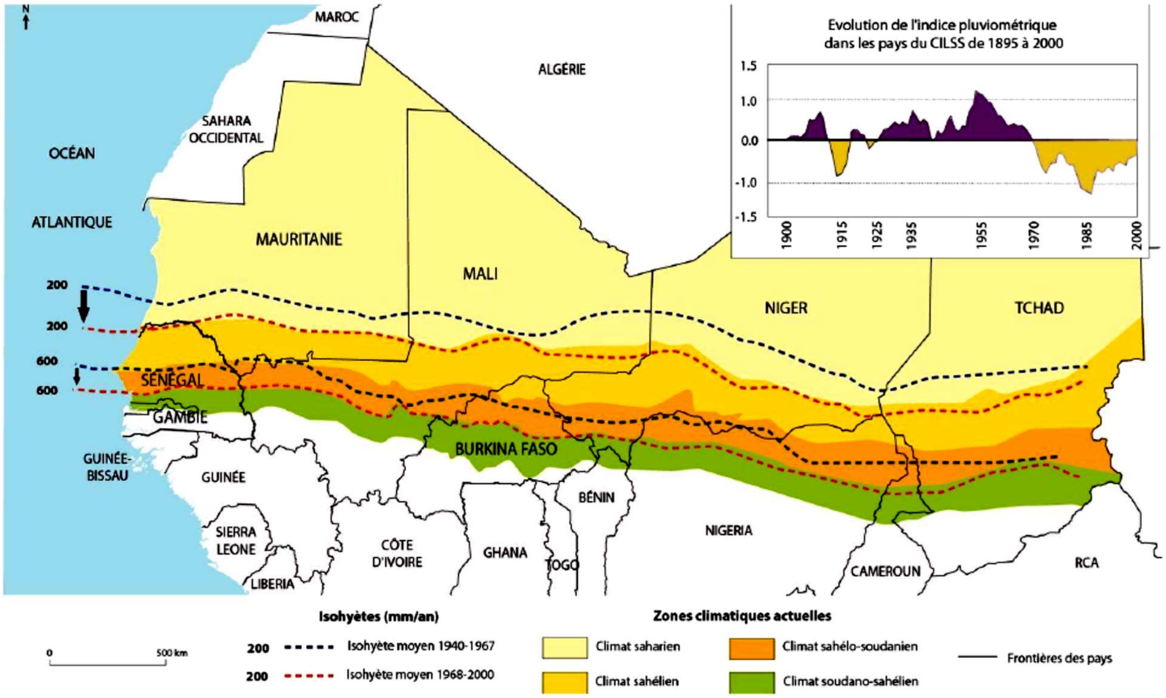


Figure 28: Rainfall and Climate Zones in West Africa
(source : Club du Sahel et de l’Afrique de l’Ouest, 2007)

3.5.2. Data and tools of the study

The Republic of Senegal has a network of meteorological stations comprising about 250 stations, the oldest are Saint-Louis and Dakar, which were installed in 1848 and 1897 respectively. The analysis of recent climate change is based on data from Senegal's twenty-four synoptic and climatological stations (Table 17). The main parameters observed are rainfall, temperatures, relative humidity and evaporation, from the origin of the measurements until 2016.

Table 17: List of studied stations and data availability

Station Name	*Lat. North*	*Long. West*	*Height (m)*	*Starting date*	*Rainfall*	*Temperature*	*Relative Moisture*	*Evaporation*
BAKEL	14°54'	12°28'	25	1918	1918-2016	1979-2016	1982-2016	1981-2016
BAMBEY	14°42'	16°28'	20	1921	1921-2016	1987-2016	1987-2016	1981-2016
CAP SKIRING	12°24'	16°45'	11	1977	1977-2016	1978-2016	1980-2016	1980-2016
DAKAR YOFF	14°44'	17°30'	24	1897	1897-2016	1960-2016	1960-2016	1960-2016

Station Name	*Lat. North*	*Long. West*	*Height (m)*	*Starting date*	*Rainfall*	*Temperature*	*Relative Moisture*	*Evaporation*
DIOURBEL	14°39'	16°14'	25	1919	1919-2016	1960-2016	1970-2016	1961-2016
FATICK	12°41'	16°25'	6	1918	1918-2016	1991-2016	1991-2016	1991-2016
GOUDIRY	14° 11'	12°43'	59	1918	1918-2016	-	-	-
KAOLACK	14°08'	16°04'	6	1960	1960-2016	1960-2016	1960-2016	1961-2016
KEDOUGOU	12°34'	12°11'	122	1918	1918-2016	1960-2016	1970-2016	1970-2016
KOLDA	12°53'	14°58'	38	1922	1922-2016	1987-2016	1987-2016	1987-2016
KOUNGHEUL	12°37'	16°21'	11	1932	1932-2016	-	-	-
LINGUERE	15° 23'	15°07'	20	1933	1933-2016	1960-2016	1978-2016	1980-2016
LOUGA	15°37'	16°13'	38	1919	1919-2016	1963-2016	1980-2016	1971-2016
MATAM	15°39'	13°15'	15	1918	1918-2016	1960-2016	1960-2016	1960-2016
MBOUR	12°36'	16°20'	10	1931	1931-2016	1980-2016	1980-2016	1980-2016
NIORO DU RIP	13°44'	15°47'	18	1980	1980-2016	1987-2016	1989-2016	1987-2016
PODOR	16°39'	14°58'	6	1918	1918-2016	1960-2016	1970-2016	1981-2016
RANEROU	15°18'	13°58'	33	1963	1963-2016	-	-	-
SAINT-LOUIS	16° 03'	16° 27'	4	1848	1960-2016	1980-2015	1980-2015	1981-2015
SIMENTI	13°03	13°18	47	1968	1968-2014	1995-2014	1995-2014	-
TAMBACOUNDA	13° 46'	13° 41'	49	1919	1919-2016	1960-2016	1960-2016	1960-2016
THIES	14°48	16°57	71	1918	1918-2016	1977-2016	1977-2016	1977-2016
VELINGARA	15° 0'	14° 41'	25	1945	1945-2016	1984-2016	1985-2016	1984-2016
ZIGUINCHOR	12°33	16°16	19	1918	1918-2016	1951-2016	1960-2016	1981-2016

The analysis is based on "approved" methodologies for the Sahelian environment (see Methodological Approach). The parameters analyzed are temperature and rainfall. The issue of climate change is addressed here, more from the point of view of questioning than from the point of view of proven facts.

Rainfall is studied more closely, using a regional frequency analysis (REFRAN-CV), an approach tested and validated in other climatic contexts (Maeda et al., 2012). A prospective study on the evolution of rainfall in Senegal, by 2020 and 2050 will be proposed, even if these results are still very preliminary and need to be refined and extended to the Senegal and Gambia River basins.

3.5.3. Recent evolution of climatic parameters in Senegal

The analysis of minimum and maximum average temperature data at the main stations in Senegal shows their high spatial and temporal irregularity as well as the existence of a West-East thermal gradient between the coastal zone and the interior of the country. The annual temperature cycle is generally bimodal with two maxima, the first in March-April and the second in September-October (Gaye and Sylla, 2008). But on the coastal zone, oceanic influence, especially during the northern winter, results in a significant drop in minimum temperatures.

During the period 1960 to 2010, there was a net increase in temperature at all stations in the country, with an average increase of 1.6°C and regional variations according to climate zones. According to the report on the state of the environment in Senegal (CSE, 2010), the temperature increase is estimated at 3°C in the Sahel zone and 0.7°C in the south-east in the south Sudanese zone. From the point of view of spatial distribution, the highest temperature values are found east of the Saint-Louis - Dakar - Ziguinchor axis (Figure 29). The eastern part of the country, including the Bakel area, recorded the highest temperature values during the period 1981-2010 (Sambou, 2012).

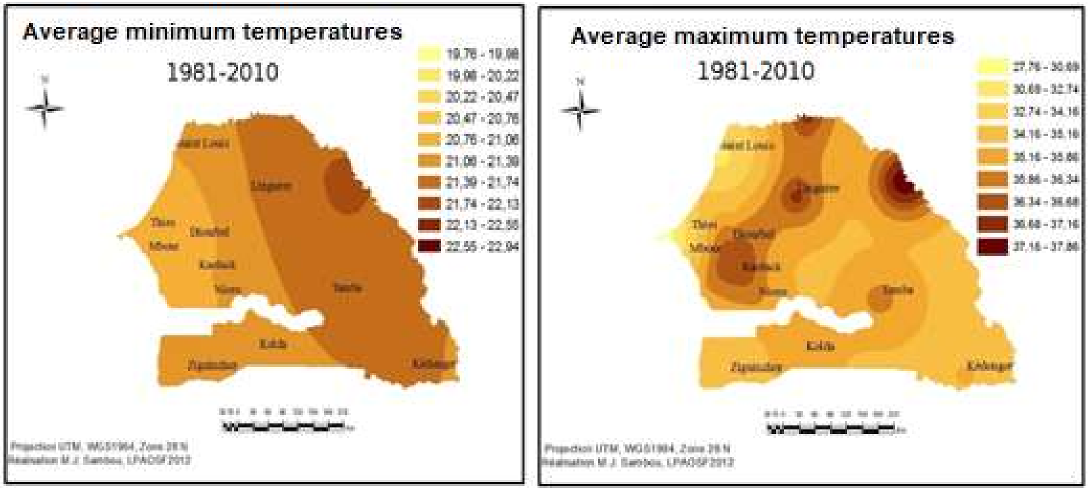


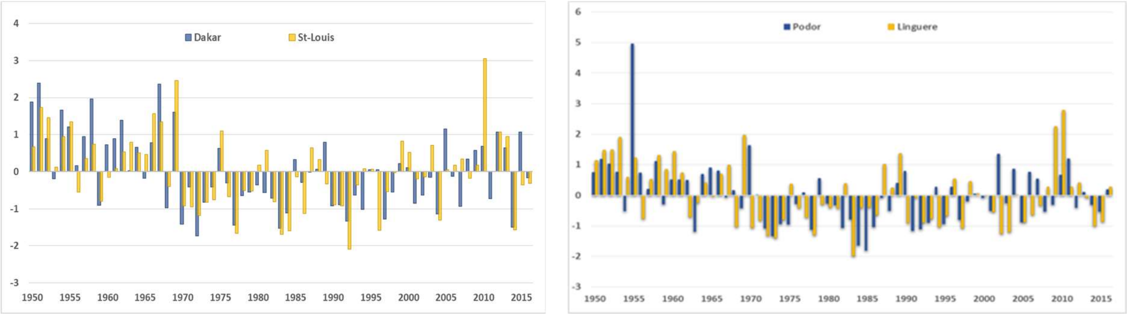
Figure 29: Spatial distribution of minimum and maximum temperature averages during the period 1981 to 2010 (Sambou, 2012)

Concerning the distribution of rainfall in Senegal, it is very heterogeneous both spatially and temporally, associated with a north-south gradient. Rainfall indices for all climatic domains show the presence of a long dry period. Since 1968, Senegal's stations have been periodically hit by droughts with dramatic consequences on production systems (Leroux and Sagna, 2000). The decade 1980-1990 was particularly dry, with minimum annual precipitation values recorded for almost all stations in the country, all climatic zones combined (Figure 30). This drought cycle of unprecedented duration is clearly materialized by the meridian translation of the isohyets drawn for the normal 1931-1960 on the one hand and 1961-90 on the other hand. Between these two normal, the 400 mm isohyet, for example, moved nearly 100 km southward, weakening rainfed crops throughout the northern part of the country.

A similarly large displacement of the 800 mm isohyet is one of the causes of the southward displacement of the groundnut basin and the retreat of cotton in northern Gambia (Oyebande and al., 2006). In northern Senegal, the calculation of the drought index for the stations of Saint-Louis, Podor and Matam for the period 1961-2010 shows a deep deterioration in climatic conditions, which places them in an increasingly arid situation (Thiam, 2013).

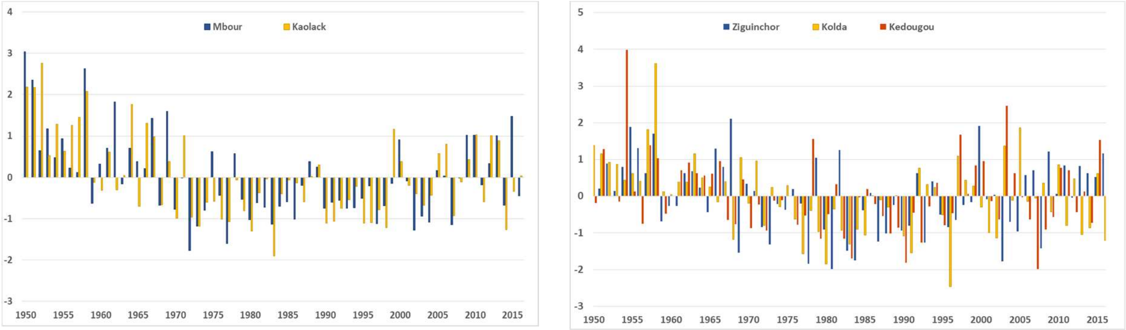
Rainfall has decreased by 30% since the 1950s and throughout the country; in Dakar, this drop reaches 50% while in the Southeast in Kedougou it is 7% (CSE, 2010). Over the past twenty years, rainfalls have remained relatively stable but are 15% below the 1920-1969 average (Funk et al., 2012).

Since 2000, there has been a slight increase in rainfall in almost all stations in the country. However, this recovery cannot be considered as a signal of the end of the drought cycle. More than rainfall amounts, it is rainfall intensities that have increased sharply, contributing to the worsening of floods in Senegal's major urban centers.



Coastal Sahel

Continental Sahel



Coastal (Mbour) and continental (Kaolack) North Sudanese

Coastal (Ziguinchor) and continental (Kolda and Kedougou) South Sudanese

Figure 30: Rainfall indices calculated for the five Senegal's climate domains

3.5.4. Results of REFRAN-CV analysis

At the sub-regional level, much thought has been given to climate dynamics in the Sahel (Sene and Ozer, 2002; ECOWAS and SWAC/OECD, 2008) because it is one of the determinants of social and economic development for these predominantly rural societies.

The high climatic variability, a major feature of the Sahel region, can be observed through time series of rainfall and temperature. The analysis of these parameters for Senegal is based on a database of stations spread over the country's 14 administrative regions (Figure 27). Rainfall data are analyzed from the origin of the stations to the current period. The desire to reflect regional climatic specificities justifies this approach in the choice of stations.

The following four return periods were selected for this study: 5 years, 10 years, 50 years and 100 years each corresponding to a rainfall amount based on a percentage probability of occurrence in a year (1/T*100). The images "T5 years", "T10 years", "T50 years" and "T100" years represent probabilities of occurrence of 20% (1/5*100), 10% (1/10*100), 2% (1/50*100) and 1% (1/100*100) respectively.

The results of the rainfall analysis with the REFRAN-CV tool are perfectly coherent with the knowledge acquired on climate variability in Senegal. The precipitation analyzed over the whole country shows the spatial distribution of average rainfall over the country (Figure 31).

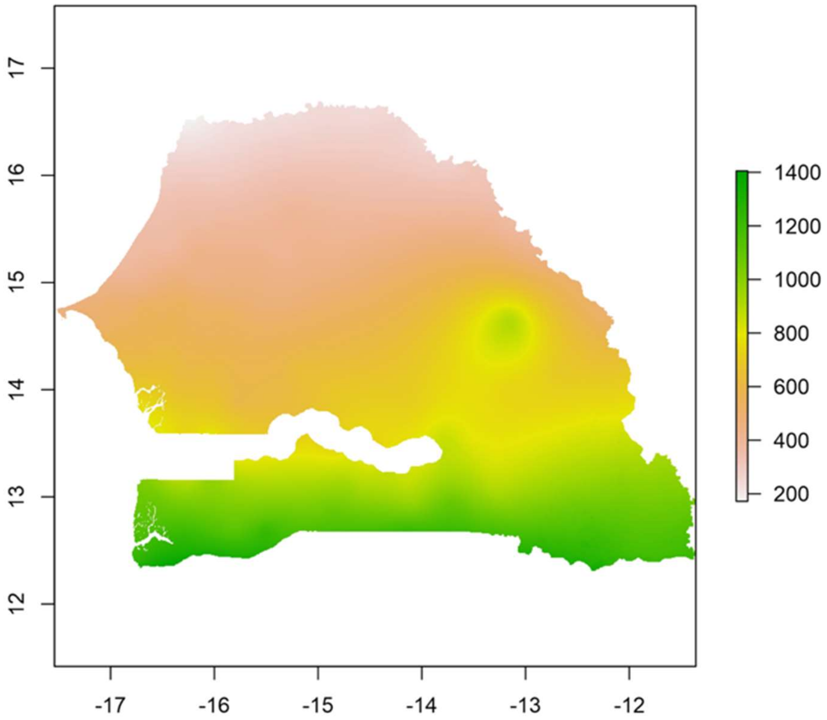
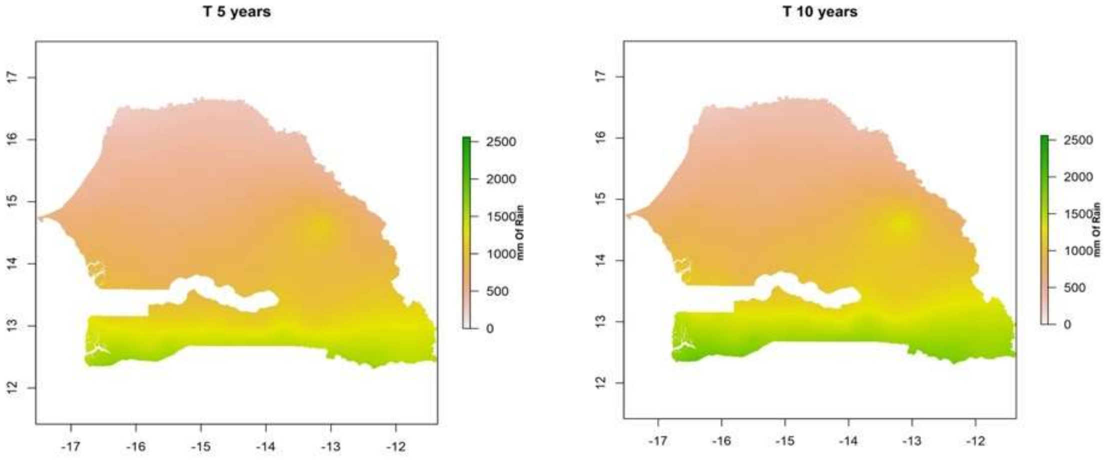
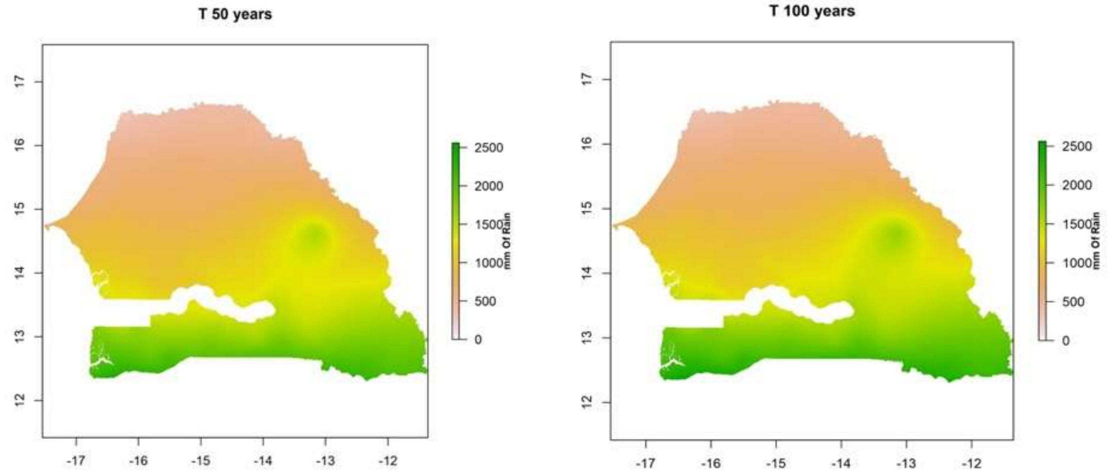


Figure 31: Spatial distribution of rainfall based on observed data

These return period maps (Figure 32) show a spatial and temporal distribution of rainfall associated with its probability of occurrence in a given time period (5, 10, 50 and 100 years). Senegal's rainfall is characterized by a very high spatial and temporal heterogeneity associated with a north-south gradient. The existence of a long period of drought between 1968 and the end of the 1990s is attested by various rainfall indices. The decade 1980-1990 is particularly dry; it was also marked by the displacement of the isohyet 400 mm southward by nearly 100 km, resulting in the displacement of the groundnut basin southward due to the displacement of the isohyet 800 mm. From 2000 onwards, there was an increase in rainfall in almost all stations in the country. However, in the North, an intensification of aridity is observed.




T 50 years

T 100 years

Figure 32: Return period maps for 5, 10, 50 et 100 years

HIGHLIGHTING ENVIRONMENTAL VULNERABILITY IN THE SENEGAL AND GAMBIA RIVER BASINS THROUGH HOTSPOTS

In West Africa and particularly in the hydrosystems of the Fouta Djalon Massif, the Senegal River Basin and the Gambia are influenced by drought and water scarcity. These manifestations result in vulnerability at all environmental, social and other levels and to varying degrees over time.

It is in this perspective that the determination of land cover is a means of knowledge on the impact of surface conditions. This occupation of the surface states adopts the method of processing satellite data from the Fouta Djalon massif, the Senegal basin and the Gambia.

The map was done according to a series of operations. The coloured composition made it possible to distinguish the different objects on the images, (Diallo et al., 2011).It is followed by the choice of training areas (representative sites of the numerical characteristics of the classes) that make it possible to define the spectral signatures of each landscape unit (Kouassi et al., 2012). These training areas serve as the basis for a supervised classification. Then the "maximum likelihood" classification algorithm was chosen in order to perform the classification. Finally, field surveys validated the classification (Kouassi et al., 2012). In short, maximum likelihood supervised classification consists in classifying pixels according to their similarity to numerical counts of reference geographical objects previously determined on the image and validated by field surveys (Kouassi et al., 2012). Based on the thematic classifications obtained, land use maps were produced. Envi 5.1. Software was used for digital processing of satellite images and arcgis 10.1 for mapping work.
- Assessment of changes in land occupancy units:

It was done according to a series of operations. The colored composition made it possible to distinguish the different objects on the images (Diello, 2007). It is followed by the choice of training areas (sites representative of the numerical characteristics of the classes) that make it possible to define the spectral signatures of each landscape unit (Diello, 2007). These training areas serve as the basis for a supervised classification. Then the "maximum likelihood" classification algorithm was chosen to perform the classification (Niang et al., 2014). Finally, field surveys validated the classification. In short, maximum likelihood supervised classification consists in classifying pixels according to their similarity to numerical counts of reference geographical objects previously determined on the image and validated by field surveys (Kouassi et al., 2012). Based on the thematic classifications obtained, land use maps were produced. Envi 5.1. Software was used for digital processing of satellite images and arcgis 10.1 for mapping work.

In the study area covering the topographic basins of the Senegal and Gambia rivers, three sites were targeted (Figure 33). These are the following:

(i) The Fouta Djalon Massif,
(ii) The lower estuary of the Senegal River and,
(iii) The Gambia River estuary.

Each of these sites is illustrative of a type of vulnerability or a combination of several types:

- The Fouta Djalon site is essentially marked by environmental vulnerability, mainly related to the effects of variability and hydro-climatic change and the related effects of community practices in response to these hydro-climatic shocks.
- In the Senegal River estuary, there is a combination of several types of vulnerability: environmental (instability of the estuary and change in the position of the mouth), social and economic as a result of attempts to adapt to environmental changes.
- The Gambia estuary is an inverse estuary (Diop, 1990) and is therefore highly vulnerable to the effects of marine dynamics and salt intrusion. It is a poorly studied site because it is not well developed with very limited uses.

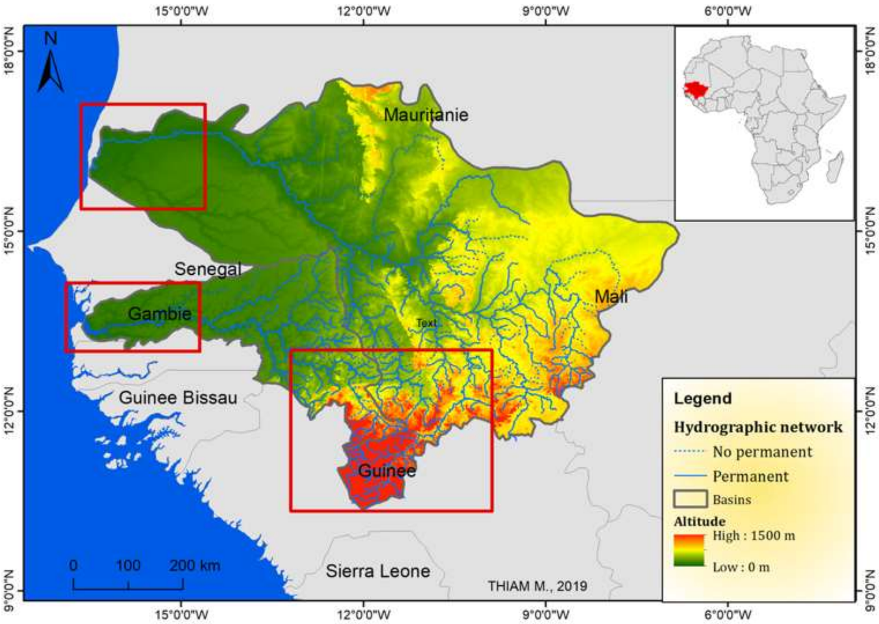


Figure 33: Location of studied hotspots in the Senegal and Gambia River Basins

1. FOUTA DJALON MOUNTAIN

1.1. PRESENTATION OF THE STUDY AREA

Fouta Djalon or Djalon and its neighbours (the Guinean coastal massif and the Guinean ridge) are the most distinguished landforms in West Africa from an altitudinal point of view. Fouta Djalon is indeed a massif made up of mountains and plateaus, located mainly in Guinea. This massif covers 47,000 km^2, 96% of which is in Guinea, 3% in Mali and less than 1% in Sierra Leone-Senegal (CIWA, 2017).

Fouta Djalon is a natural entity with a very fuzzy geographical delimitation (Orange, 1990; EQUESEN, 1995). Etymologically, Fouta Djalon or "Country of Djalonkes", Peulh farmers (World Bank, 2017), refers to an anthropological definition. This definition is all the more valid as it is linked to the history of the region with the former kingdom of Fouta Djalon, which was created around the middle of the 18th century under the influence of a Foula chief. Fouta Djalon as a unique landscape entity is therefore at the crossroads of an important ethnic, social and cultural history.

The Fouta Djalon massif is also associated with the water tower of Africa and more specifically of West Africa since several major rivers have their source there. This is the case for the Niger, Senegal, Gambia, Gêba, Corubal, Konkoure, etc. (Figure 34). There are nearly twenty rivers that originate in this Fouta Djalon region (Orange, 1992). Hence the importance of the area in the context of knowledge, optimization and integrated management of water resources at the sub-regional level. His important role in the architecture of the West African hydrographic network earned him the title of "West African Water Tower".

From a lithological point of view, the predominance of metamorphic and eruptive rocks is noted. Fouta Djalon's soil is similar to breastplates, ferralitic soils and its dense forest vegetation at the top is only savannah type in its plains (Dione, 1996).

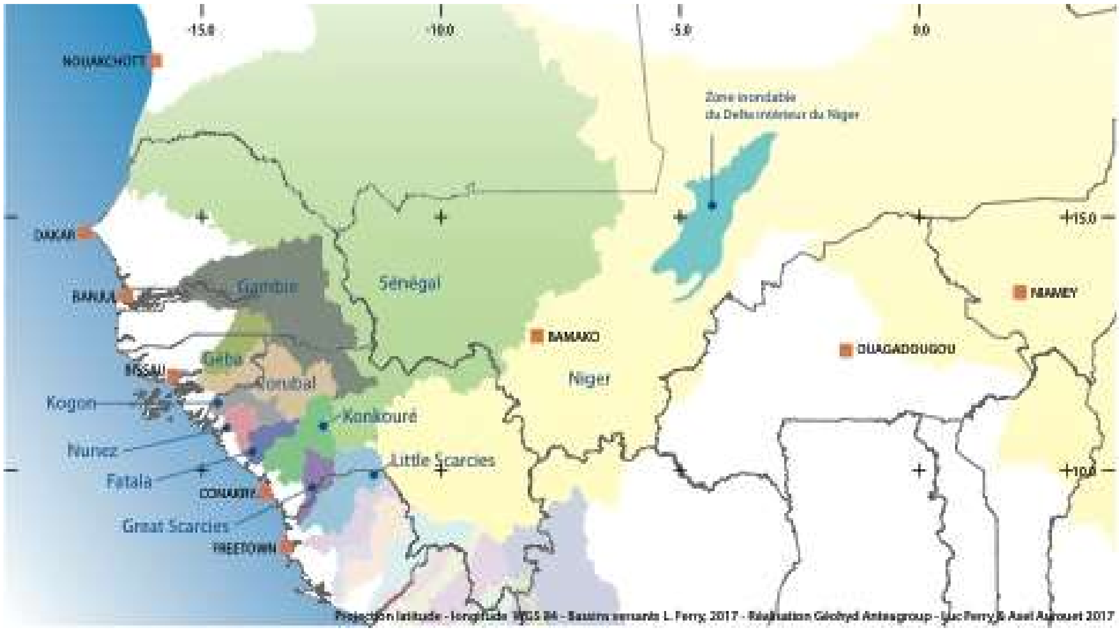


Figure 34: The main catchments of the Fouta Djalon area (World Bank, 2017)

According to FAO, the boundaries of Fouta Djalon are even wider because they include part of the Guinean Ridge, the relief of Maritime Guinea, northeastern Guinea, southern Mali and an extension area to Guinea Bissau and southern Senegal. This FAO delimitation includes topographical, climatic and hydrographic dimensions.

Within the framework of this project, the choice was made to remain on the topographical limits of Fouta Djalon and to study the area centered on the Labe climate station in Guinea Conakry (Figure 35). The interest of the site stems from several factors, including but not limited to:

- The availability of a long series of rainfall data to identify climatic breaks that can be used as benchmark dates for surface state analysis
- The existence of embryonic urbanization
- And the development of agricultural and commercial activities likely to have a significant impact on the environment.

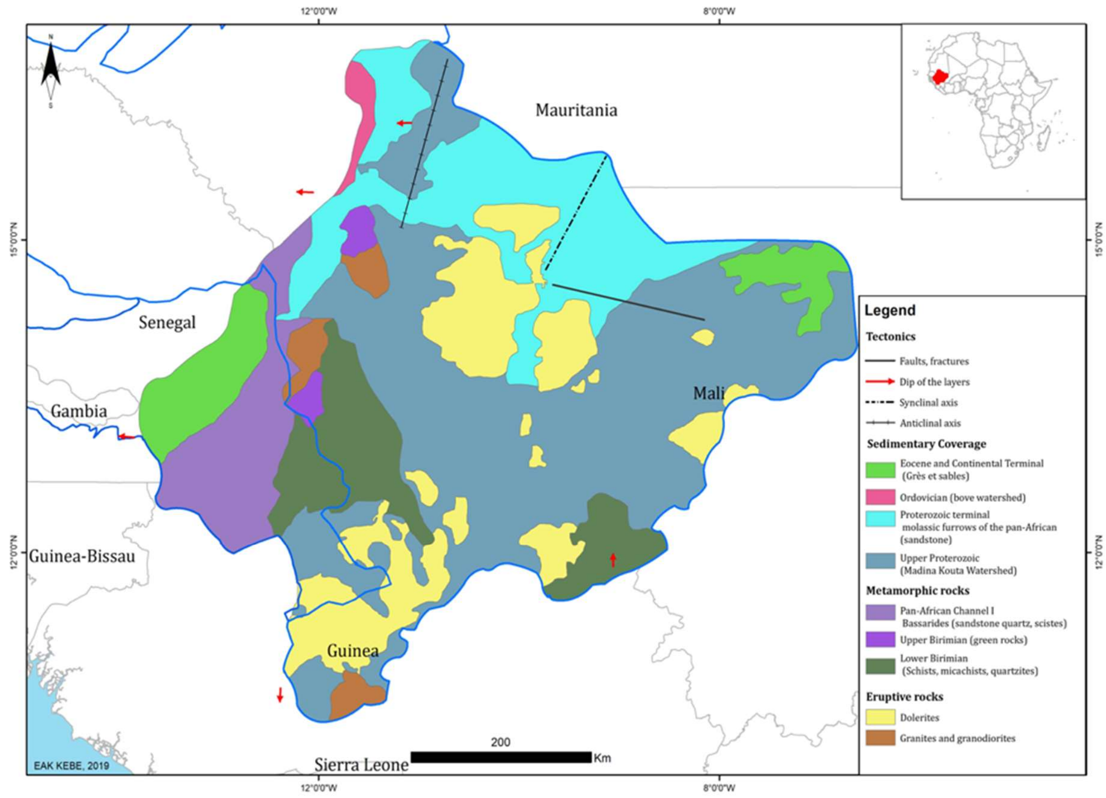


Figure 35: Location of the Fouta Djalon region

1.2. METHODOLOGY FOR LAND USE CHANGES ANALYSIS

Three stages mark the remote sensing component of hotspots:

- Photo-interpretation;
- Classification by maximum likelihood and
- Image processing.

The processing of the raster data used is a visual and/or digital interpretation of the processed image. It is then necessary to identify the entities to extract the information you want to obtain on the target. The classes are defined on the basis of the user's needs and correspond to semantic units of the image, which requires a photo-interpretation step before the actual classification.

Supervised classification consists in determining the classes by a learning process that can be carried out either on each scene treated, or for each type of application (agriculture, forestry, coastline, geology, etc.) Or for each type of sensor used (optics: Landsat). This step strongly influences the classification results.

In order to be able to process these images, they must first be acquired. The United States Geological Survey (USGS) is a U.S. government agency dedicated to earth sciences. In particular, it is responsible for monitoring seismic activity on its territory and throughout the world. Its activity is similar to that of the “Bureau de recherches géologiques et minières” in France. Its website is a real database through which satellite images can be downloaded.

1.3. THE REFORESTATION OF FOUTA DJALON MOUNTAIN, MYTH OR REALITY?

The analysis of the 2003 land use map (Figure 36 and Table 18) shows the following trends: predominance of vegetation or mangroves 52.40%, bare soils with 38.04%, bodies of water, which represent 0.15% and finally buildings occupying 0.08% of the total area of the study area.

While in 2016, the entities' areas are about 0.26% for water, the cultivated areas are about 4.18%, bare soils are estimated at 33.03%, and vegetation (62.38%), with a slight increase in built areas with 0.15% (Table 18). The table below summarizes the statistical difference in land use in the Fouta Djalon massif.

Table 18: Land use in the estuary of the Fouta Djalon Massif

Spatial units	**2003**		**2016**	
	Surface ha	***Surface %***	***Surface ha***	***Surface %***
Water	3326.09	0.15	5812.36	0.26
Vegetation	1192880.00	52.40	1420210.06	62.38
Bare soil	884213	38.84	751925	33.03
Housing areas	1893	0.08	3458.38	0.15
Cultivation area	194267.00	8.53	95176.5	4.18
Total	**2276579.09**	**100**	**2276582.3**	**100**

The re-greening of the area is due to a return of rainfall in 2005. The increase in built-up areas is also reflected in an increase in the number of active areas, resulting in an increase in cultivation areas.

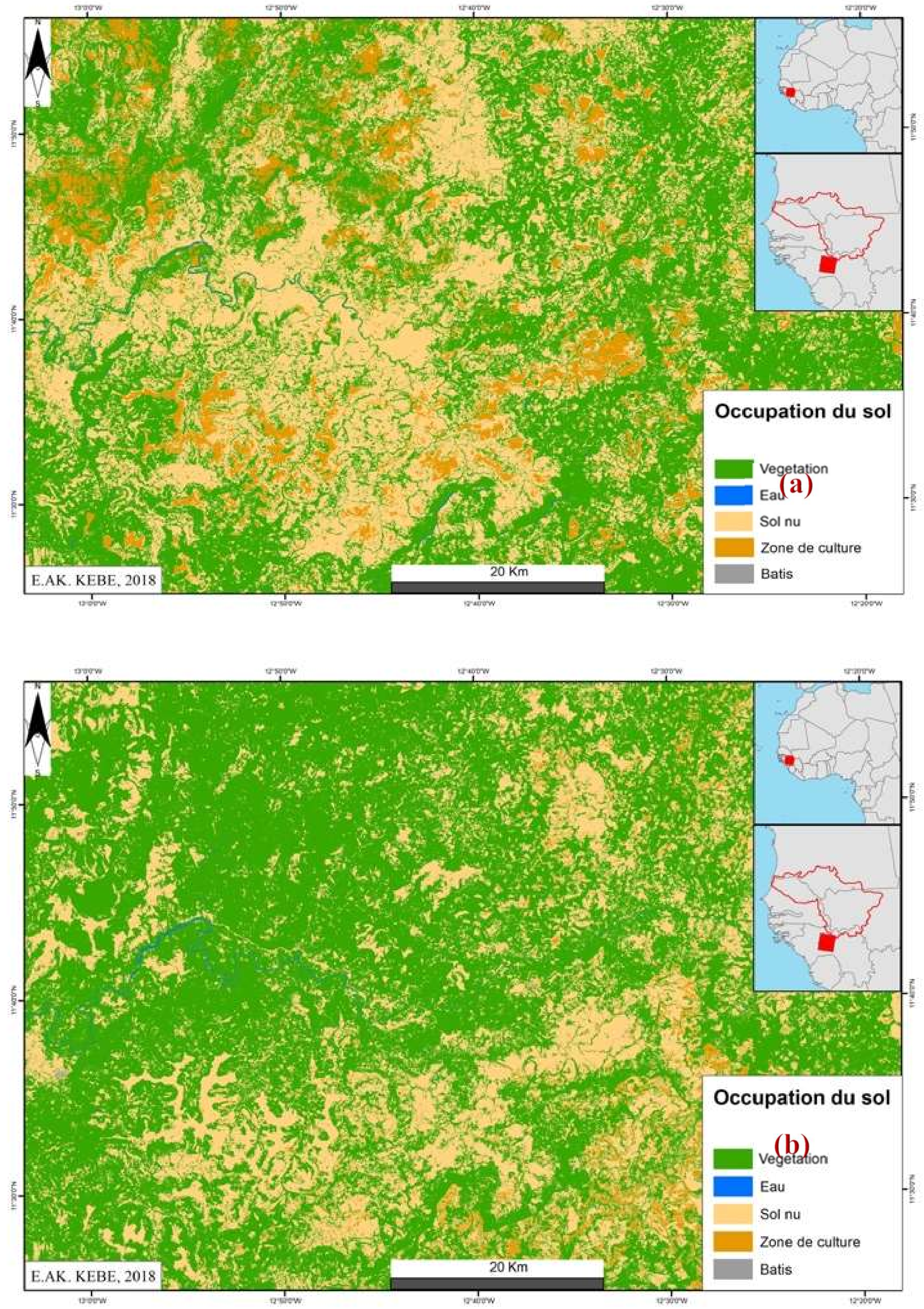


Figure 36: Land use map of the Fouta Djalon massif in 2003 (a) and 2016 (b)

2. THE SENEGAL RIVER ESTUARY: BREACHING OF THE "LANGUE DE BARBARIE" SANDY SPIT, SOCIO-ENVIRONMENTAL CHANGES AND VULNERABILITY OF COASTAL COMMUNITIES IN THE LOWER ESTUARY

The Senegal River estuary is a very complex environment characterized by the interaction of marine and fluvial dynamics. Until the 20th century, the hydrological functioning of this terminal part of the river depended on natural factors. Today, highly artificialized and very reduced, the Senegal estuary is undergoing a major change characterized by greater vulnerability to marine hazards but still dependent on the management of the Senegal River upstream of the Diama dam.

In 2003, following an early flood, the Senegalese authorities opened a breach on the Langue de Barbarie spit sand. This breach, which has become the new mouth of the Senegal River, has greatly contributed to changing the hydrological regime in the estuary. It has also caused disturbances in estuarine ecosystems and increased the vulnerability of societies in the lower estuary whose activities are mainly based on the exploitation of water resources. Gandiolais' local communities are particularly affected by this situation.

Given the lack of monitoring of this breach since 2009 and the need to understand the dynamics of this artificial breach, the choice of satellite imagery has become the only alternative for tracing the trajectory of the estuary. LANDSAT satellite imagery has indeed made it possible to reconstruct the evolution of this environment over the past fifteen years in order to understand the meaning of current and future dynamics.

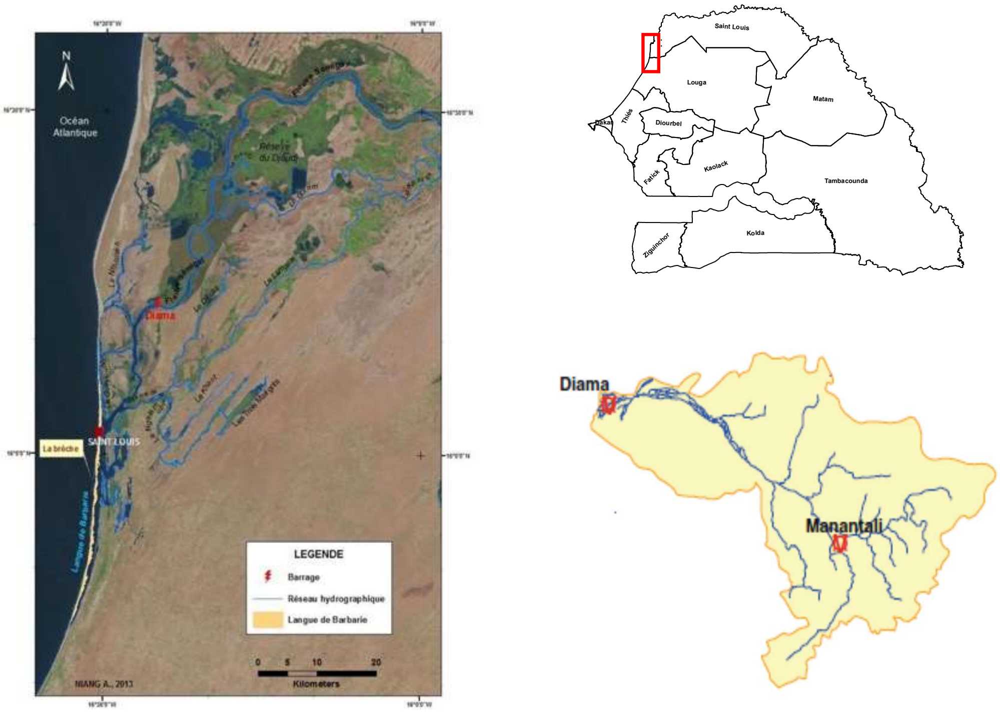


Figure 37: Location map of the Senegal River estuary (NIANG et al., 2014)

2.1. THE ESTUARY AND THE NEW MOUTH OF SENEGAL RIVER

The Senegal estuary is a very low area whose altitudes, close to sea level, favor flooding, either rain induced or riverine flooding in the city of Saint-Louis (Kane, 2010; Seck, 2010). These floods are all the more frequent as the recent urban expansion, carried out in the major riverbed, contributes to increasing the city's environmental vulnerability. In its current form, the nature of the terminal part of the Senegal River has been discussed by various authors including Monteillet (1988) and Kane (1985; 1997). As a result of these discussions, the estuary, traditionally delimited by the spread of marine waters in the Senegal River, is now limited to the downstream part of the Diama dam.

Before 1985, i.e. Before the Diama dam, in some years, the saline rise could be significant during low-water periods as far as Podor, about 300 km from the mouth. The Diama Dam introduced discontinuity into the estuarine system by modifying not only water quality, but also in water quantity and in nutrient inputs from inland waters (Cecchi, 1992). The dam therefore constitutes a rupture for the river regime and modifies certain physical and hydrodynamic characteristics of the water masses in its estuarine part.

In October 2003, the opening of the breach limited the dynamics of the river current over a distance that went from 55km (old mouth - Diama dam) to 33 km (between the new mouth and the Diama dam): the river is now more subject to tidal wave fluctuations. During flood periods, this phenomenon fades somewhat with the increase in the river's flow; these freshwater inflows have a direct influence on the salinity of the water. Dam management constraints require the periodic opening of gates to regulate the upstream coast in non-rainy periods, so the estuary can receive fresh water discharged from the dam, a situation that helps to soften the water downstream of the dam. However, with the clogging of the old mouth, exchanges between marine and river waters are reduced.

The Langue de Barbarie is a sandy, north-south facing spit of land that stretches over a length of about 25 km with a very variable width. This arrow, the result of a long alternative process of fattening and de-migrating the beach as a result of coastal drift, has not widened or risen since its origin (GAC et al., 1982). The southern end of the Barbary Tongue still determines the position of the mouth of the river, which is subject to natural southward migration. Strong marine currents cause marine sedimentation forcing the river to erode the coast and causing the lengthening of the Barbary spit sand.

From 1850 to 1973, twenty natural ruptures of unequal importance were recorded in the Barbarian Language. The most notable ones took place in 1894 and 1959, the most recent one in 1973. Since then, the boom has been stable despite many areas of weakness that could break. The failure to occur due to natural ruptures is partly linked to the artificialisation of the river regime and to the presence of the Diama and Manantali dams (Niang, 2002; Nakamura et al., 2002; Taïbi et al., 2007).

Analysis of data on the mobility of the mouth shows that from 1900 to 2002 (Figure 5), the mouth remained constantly beyond the 15th kilometre south of the island of Saint-Louis (Niang, 2014).

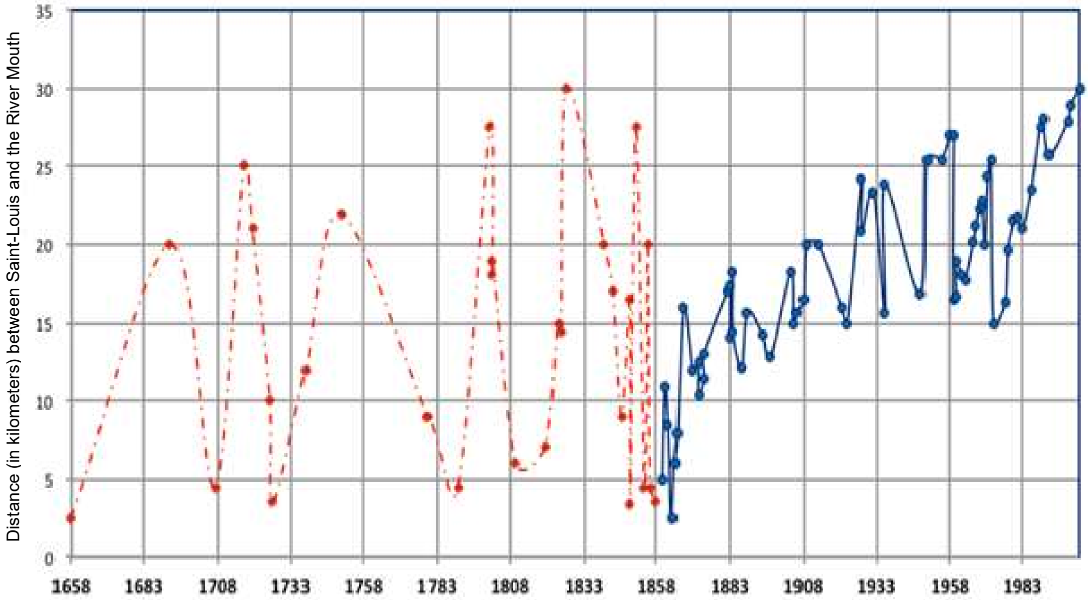


Figure 38: Mobility of the Senegal River mouth from 1658 to 2002, according to data on Langue de Barbarie spit sand migration (Niang, 2014)

The maximum limit of the extension of the Langue de Barbarie was estimated at 30km south of Saint-Louis according to Gac et al. (1982) who estimate that beyond that, it becomes vulnerable and breaks under river pressure. This limit had already been reached in 2002 according to the results of the ICARM[4] Program (PNUE/PAM/PAP, 1999; Nakamura et al., 2002); at the time the breach was opened, the mouth was 32 km south of the Faidherbe Bridge reference.

The distance of the mouth from the city of Saint-Louis leads to a low flow velocity of about 0.4 m.s-1, i.e. A duration of 24 hours for flood waters to propagate at sea (Kane, 2010). This pressure drop is the cause of river overflows at low points. Since the colonial period, the displacement of the mouth was no longer accompanied by dredging of the river channel. As a result, sediments accumulate at the ends of the mouth and floodwaters have difficulty evacuating into the sea, causing flooding.

2.2. CONTEXT OF THE OPENING OF THE BREACH

The idea of breaching the Langue de Barbarie and/or dredging the Senegal River mouth is not a new one; it has been mentioned since the 19th century, particularly with Admiral Aude's project and Bouquet de la Grie's report (Boisseau & Henry, 1927). The idea even began to be implemented in 1913-14 with the Project of the engineer Louise, which consisted in opening a channel through the Langue de Barbarie, downstream of Pointe aux Chameaux (Dieng, 2010). The studies on the navigability of the Senegal River carried out by COSEC[5] in 2002 as part of the OMVS Navigation Programme had also recommended that a channel be dug to improve navigation and make it safer to cross the bar. The ICARM Research Program (Nakamura et al.,

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[4] Integrated Coastal Arean and River Basin Management

[5] Conseil Sénégalais des Chargeurs

2002) proposed, among other solutions, the opening of a channel equipped with a valve about 5.5 km south of Saint-Louis. However, the effectiveness of this structure was to be enhanced by dredging the river channel to allow for faster water drainage. Unfortunately, none of these studies were considered when making the decision.

The main argument put forward to justify the decision to open the breach is the need to anticipate a very high flood linked to exceptional rains in the upper basin and valley of the Senegal River. From the analysis of the data from the stations concerned, it would seem that the exceptional nature of the 2003 rainfall year is questionable. Indeed, an examination of stations such as Labe, Kita, Kayes and Yelimane shows a normal rainy year even tending towards a deficit (Niang, 2014). In the valley and Delta, on the other hand, there is a year of good rainfall as shown by data from the Bakel, Matam, Podor and Saint-Louis stations (Tableau 1).

Table 19 : Comparison between 2003 rainfall, average and normal rainfall 1931-60 and 1961-1990 at some stations in the Senegal Basin

Parameters / **Stations**	**Mean of the Normal**	**Normal series 1931-1960**	**Normal 1961-1990**	**Rainfall 2003**	**Mean deviation 2003**
Bakel (1918-2010)	511.5	502.5	500.4	812.7	58.9%
Matam (1918-2010)	440.4	535.1	363.6	544.6	23.7%
Podor (1918-2010)	272.7	333.4	214.3	348.2	27.7%
Saint-Louis (1892-2011)	322	341.5	260.2	349.8	8.7%

In Saint-Louis, the daily maximum is 72.8 mm as of September 09, a value below the flood threshold of 90mm (Kane, 2010). However, by adding the rains that fell between 07 and 09 September, we obtain a height of 88.6mm, a critical value for the city of Saint-Louis, particularly for low and waterproofed areas for residential purposes.

From a hydrological point of view, the arrival of five successive flood waves at the Bakel station between August and October 2003 was also decisive. The valley and estuary recorded significant early water levels, generally above alert levels. As a reminder, the alert rating of 1.50 m in Saint-Louis was reached on August 19, 2003 (Figure 39). In mid-September, the river level remained constantly between 1.25 and 1.50 m in Saint-Louis and 1.35 m and 1.60 m in Diama.

With the rise in water levels becoming a concern for Saint-Louis and for the safety of the dam, Diama managers were forced to release water towards the lower estuary, contributing to the rise of the river coast. As of 03 October 2003, the Diama dam evacuated a flow of around 1940m3.s-1 coinciding with a river tide of 0.01m at Saint-Louis; at ocean level, this situation coincided with a low tide of 0.84 m (Kane, 2010).

a) Limnimetric scale at the Quay of Saint-Louis b) Guet Ndar Cimetery on the Langue de Barbarie

Photo 1: View of the floods in Saint-Louis in September 2003
(Photos NDAO M., September 2003)

The temporary ruptures of the Langue de Barbarie highlighted in the past were followed by more or less rapid reconstructions (Gac et al., 1982; Kane, 1985; EQUEQEN, 1995). This was not the case in 2003 since the artificially opened load shedding channel quickly gave way to a large breach (Photo 1), which is still being enlarged more than 15 years later.

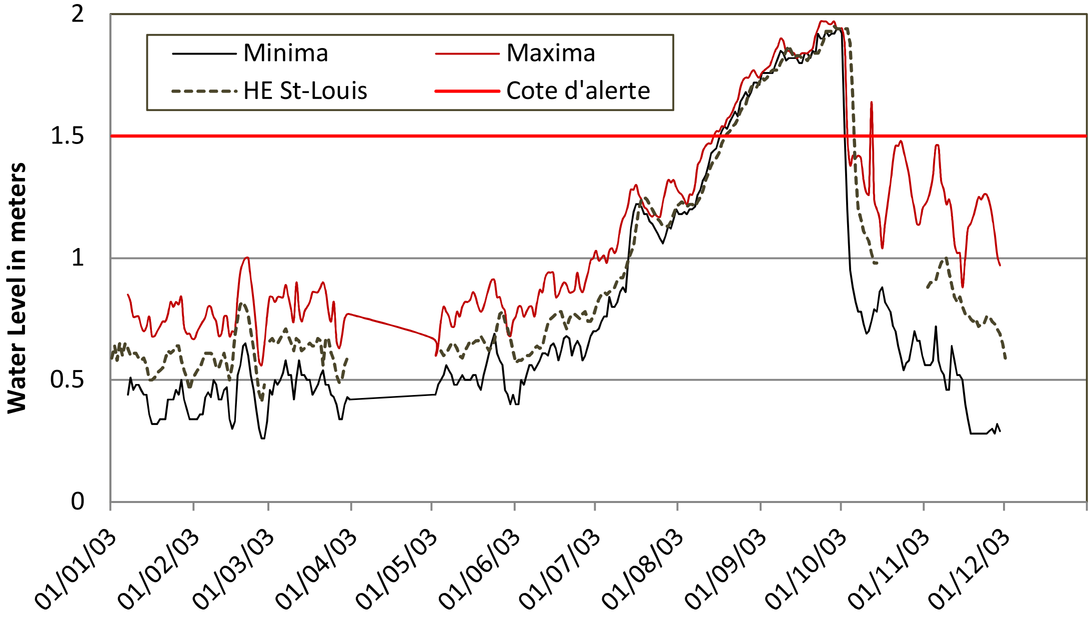

Figure 39: Variations in minimum and maximum tidal and water levels in St.-Louis during 2003

The decision to open this relief canal about 6.5 km south of the city of Saint-Louis to quickly evacuate the flood is the result of a decision by the highest authorities of the Senegalese State, which, alerted and sensitized by the local authorities and decentralized technical services in the region, took this decision, which can be described as historic. No studies or prior communications from government authorities were noted.

In total, the operation lasted less than a day; it began on the morning of 3 October 2003 with a meeting between the Governor of Saint-Louis and the heads of the regional technical services, headed by the Regional Director of Hydraulics. The arrival by military aircraft of the Moroccan engineer in charge of the operation truly marks the beginning of operations. At 10:45 p.m., the Military Engineers are already on the move to dig what will become the breach and will begin to evacuate the water on the morning of October 4, 2003.

2.3. EVOLUTION OF THE BREACH AND MORPHOLOGICAL CHANGES IN TH LOWER ESTUARY FROM 2003 TO 2018

2.3.1. Methodological approach for Determining Recent Evolution of the lower estuary of Senegal River

From the first hours of its opening, the breach of the Langue de Barbarie (lower estuary of the Senegal River) was the subject of great popular and then scientific interest (Niane and Sene, 2004; Sy, 2005 and 2006; Diakhate, 2008). The spectacular expansion at the beginning (Photo 2) gave rise to monitoring programs and projects, notably by the Hydrology Laboratory of IRD[6], the Laboratory of Morphology and Hydrology of UCAD in collaboration with the Saint-Louis Regional Directorate of Hydraulics until June 2008. A monitoring system had been set up, through measuring stations identified by a system of geo-referenced markers. On the basis of these data, mapping reports of the different positions of the breach between 2003 and 2009 were carried out by Kane (2010). Other measurements were also carried out by researchers from the Gaston Berger University of Saint-Louis (Diatta, 2004; Dieng, 2010; Faye, 2010; Sy et al., 2013).

However, the main scientific question here is whether [*the breach is an example of human action caused by climate change*] (Niang-Diop, 2011) or simply if this action (opening the breach) can be justified by scientific and/or technical arguments.

Sy (2005 and 2006) and Diakhate (2008) had even believed in the scenario of a rapid closure and had helped to defend the thesis that the breach would be soon stabilized and thus react like the mouths created following the previous ruptures of the sandy spit. These remarks were obviously made in complete ignorance of the way the mouth of the Senegal River works (Niane and Sene, 2004). On the scientific side, however, some voices of indignation were raised from the very first hours of the announcement of the breaching of the Langue de Barbarie sandy spit Thus Niang-Diop (2003) launched a real cry from the heart with a powerful title in the Daily Journal Walfadjiri; "the sorcerer's apprentices at work at the floodway[7]".

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[6] Institut de Recherche pour le Développement

[7] In French : *Les apprentis sorciers à l'œuvre au canal de dérivation*

04th October 2003 *1 week later* *After one month*

Photo 2 : Views of the breach at one day, one week and one month

2.3.1.1. METHODOLOGY CHOICE AND VALIDATION

Faced with the lack of monitoring and field data from 2009 onwards, satellite imagery becomes the only alternative to trace the evolution of the breach but also that of the sandy spit of Langue de Barbarie (Faye, 2010; Dieng, 2010). Free LANDSAT imagery is available to compensate for the lack of field monitoring (Figure 40). Indeed, the comparison between the measurements carried out in the field from 2003 to 2009 and those carried out using LANDSAT satellite imagery validated the methodology adopted. Some test classifications were performed on the acquired images and compared with other treatments previously performed on these data (Niang, 2002; Nakamura et al., 2002) as well as with other environmental characterization data (Fall, 2005; Sall, 2006). This operation made it possible to refine the processing to be carried out on the images, as well as the results.

From a methodological point of view, the choice of LANDSAT imagery is essentially justified by its accessibility. However, the resolution of the images (30 m) and their scale (approximately 1/200,000) may constitute limitations to their use, particularly in the context of fine environmental studies. However, for the purposes of this study, these data are more than sufficient to trace the evolution of the estuary, thus replacing the lack of field data.

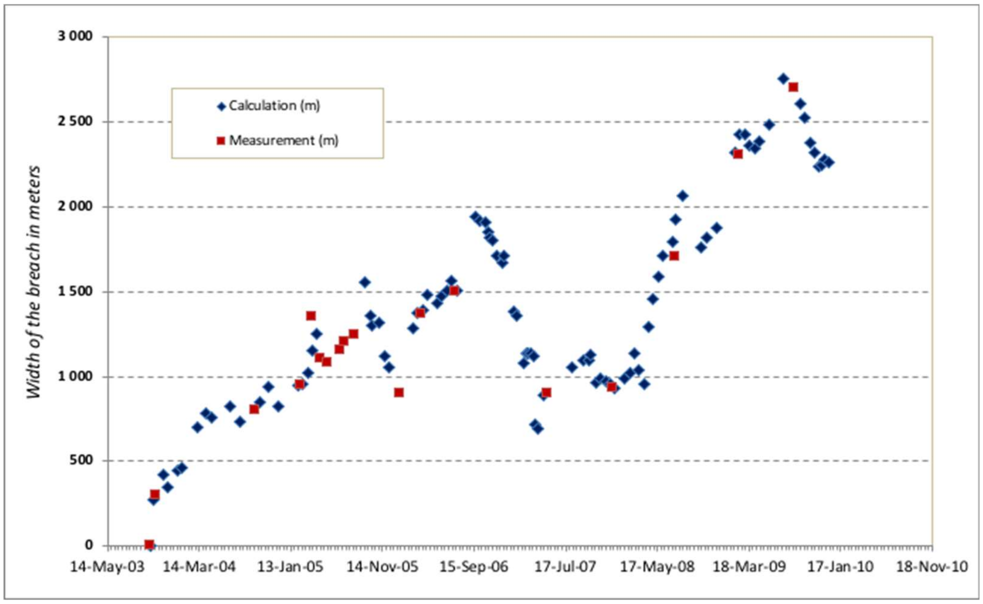


Figure 40: Comparison between the widths of the breach measured in the field and the widths measured from LANDSAT imagery

2.3.1.2. METHODS AND TOOLS

The methodological approach adopted involves several steps such as:

(i) Identification and acquisition of images;
(ii) Extraction of the lower estuary window;
(iii) Creation of vector layers;
(iv) Measuring the dimensions of the breach and the northern portion of the arrow of the Barbary Tongue;
(v) Diachronic mapping.

The study is based on a series of LANDSAT images listed on www.usgs.gov and accessible free of charge by simple download. These images are from the American ERTS program, which began in 1972 and was renamed LANDSAT in 1975. It is one of the oldest and most stable satellite imaging programs despite some failures such as the failure to launch LANDSAT 6 and LANDSAT 7 resolution problems (Nicolas, 2012).

The main objective is to have a general overview of the evolution of the limits of the lower estuary between October 2003 and October 2018, i.e. Over a period of fifteen (15) years. As a reminder, the measurement of the length of the Barbary Language is based on a reference point located at the Faidherbe Bridge and named PK0; it is the same reference as that used in the historical documents (Gac et al., 1982; Kane, 1997; Dia, 2000).

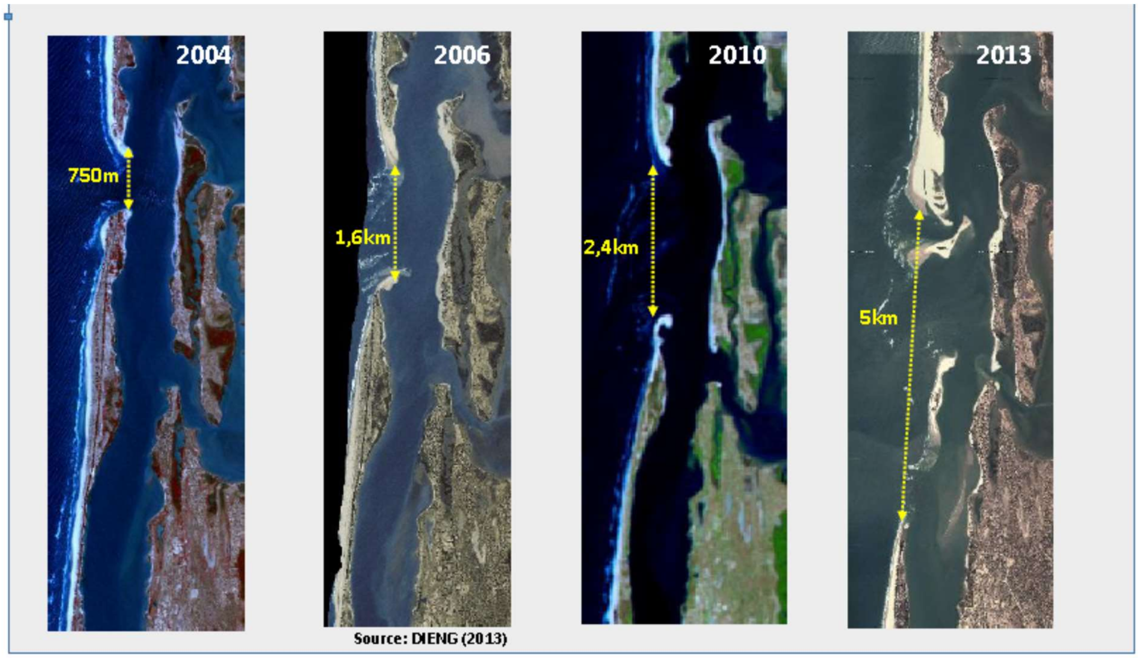
A total of two hundred and seventy-one (271) images, dated between October 14, 2003 and December 18, 2018 (see annexes) were acquired and analyzed to reconstruct the spatial and temporal evolution of the new mouth of Senegal as well as that of the northern portion of the spit of the Langue de Barbarie. The average time step of the measurements is monthly, even bi-monthly or even tri-monthly when LANDSAT 7 and LANDSAT 8 images are available. Several data from the period 2003 to 2004-2005 have been eliminated due to image quality (noise problems).

The mapping of the limits of the Langue de Barbarie sand spit is based on the use of the instantaneous shoreline as a reference line for all the studied years. This methodological choice can be discussed, given the heterogeneity of the images in terms of shooting dates, tidal conditions, etc. (Faye et al., 2008). The extraction of the shoreline is carried out automatically by the arcgis 10.2 vectorization module. The use of this process is justified by the large number of images that make up the work base (271 LANDSAT images).

The approach consists of constructing vectors of the lower estuary, then measuring the width of the breach and the length of the northern portion of the Langue de Barbarie using tools such as arcgis 10.2 and Quantum GIS 2.6.1. The choice of images meets both date criteria (at least one image for each month) and quality (% cloud cover). On some images of average or even poor quality, filtering and contrast enhancement was necessary to achieve the vectors.

2.3.2. Dynamics of the breach

From the opening in October 2003 to October 2018, in the absence of continuous field measurements, a comprehensive chronicle of the breach dynamics was reconstructed from a series of LANDSAT images (Figure 42 ; Figure 41). In terms of width, the breach increased from 273 m on 14 October 2003 to 5126 m on 07 October 2018, representing an average width of 3379 m and a maximum of 5859 m. With a coefficient of variation of nearly 55%, the breach shows very strong interannual and intra-seasonal variations. These variations could be related to the elements of oceanic forcings (tides, sea level pressure) and wind (zonal and southern winds at 800 PDT, winds at 10 m).



Source: DIENG (2013)

Figure 41 : Evolution of the breach on the Barbarian Language in Saint-Louis (Sy, B. A. And A. A., Sy, 2015)

However, this hypothesis remains to be confirmed with different correlations between the width of the breach and the data relating to these different elements.

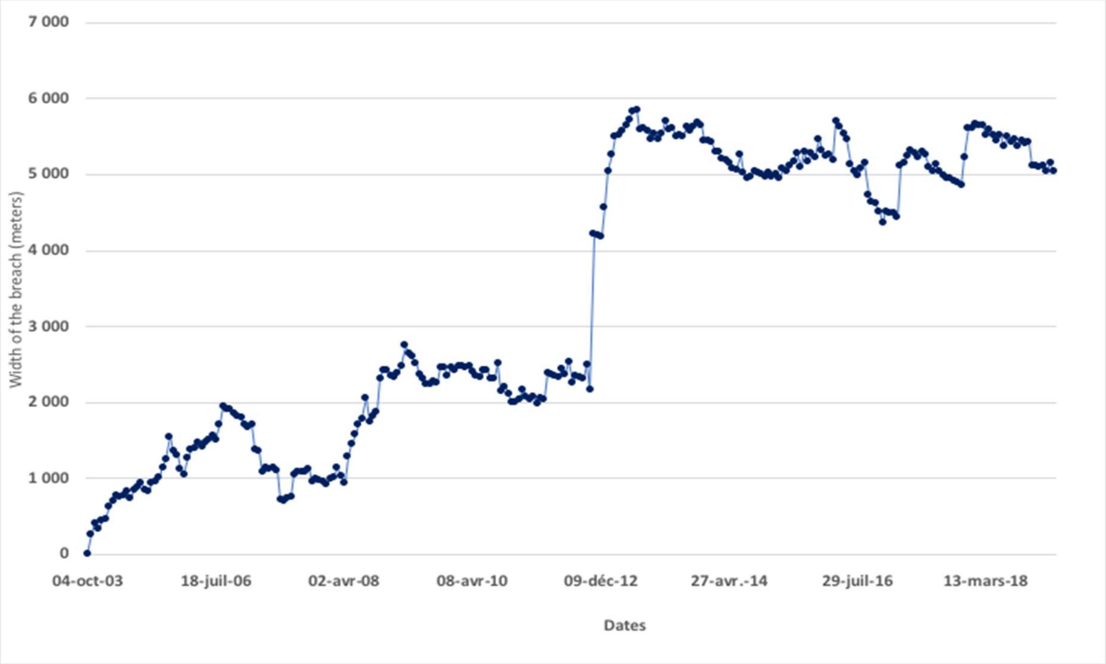


Figure 42: Reconstruction of the widths of the breach from its opening to October 2018 (data calculated from LANDSAT satellite imagery)

The progression of this breach is therefore not linear; it is subject to a very strong irregularity with phases of enlargement followed by phases of retreat where the breach has given the impression of closing up (Figure 42). After an almost exponential evolution between 2003 and 2006, when it rose from 4m to nearly 2 km in September 2006, the breach is experiencing a period of retreat that reduces it to widths ranging from 700 to 900 m. A new phase of exponential growth began again in January 2007, with increasingly large widths reaching a record 2.7 km in July 2009. From September 2010, with the appearance of an islet that materializes the creation of a second pass, the breach behaves like a real mouth that, like the old natural mouth, moves slowly but surely southward, in accordance with the acquired knowledge (Gac et al., 1982; Kane, 1985 and 1997; Dia, 2000; Lamagat, 2000).

In October 2012, a series of storms in the North Atlantic affected ocean circulation and caused the opening of two new breaches to the south of the 2003 breach. The width of the initial breach doubled to more than 4 km by 07 November 2012. Indeed, the two breaches have merged into a single one that joins the first one and doubles its width. This event constitutes one of the major disruptions in the evolution of the region, after the one that occurred in 2003 (Figure 43). This situation means that the lower estuary of the Senegal River is more vulnerable to the sea and its hazards. However, these two new breaches have revived the debate in the national press on the situation in the Senegal estuary. This has led to some attempts to stabilize the new mouth.

Since October 2013, the expansion of the new mouth has slowed down significantly, giving the impression of stabilization. However, given the current state of knowledge on this breach, there is no reason to claim a return to normal conditions prior to 2003.

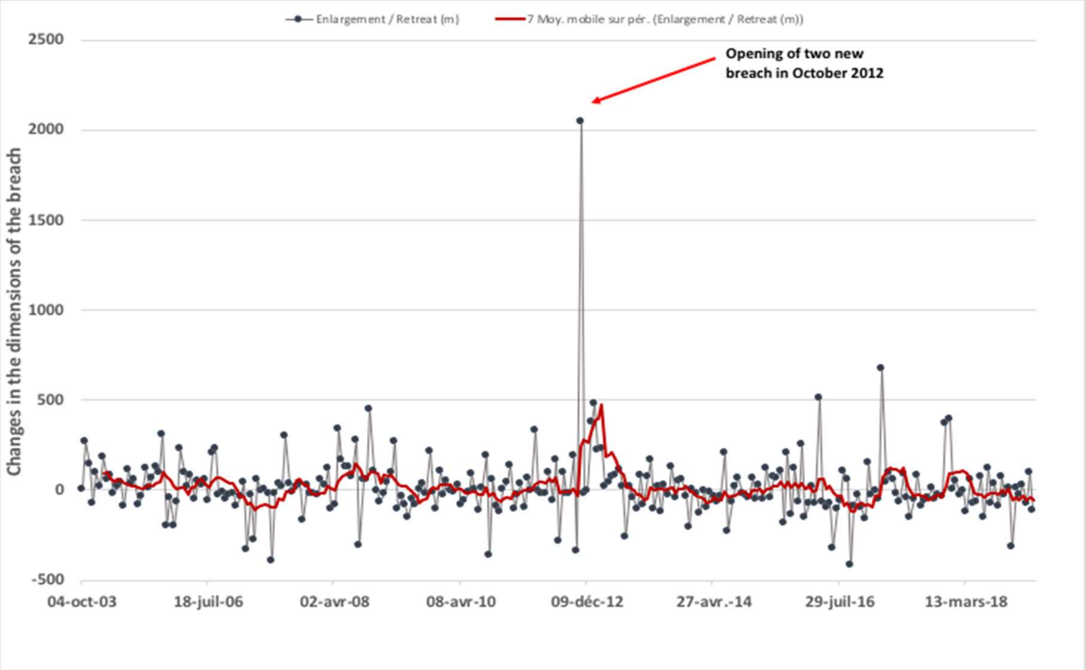


Figure 43: Dynamics of the breach on Langue de Barbarie sandy spit (enlargement = positive values ; rétrécissement = negative values)

2.3.3. Morphological changes in the lower estuary

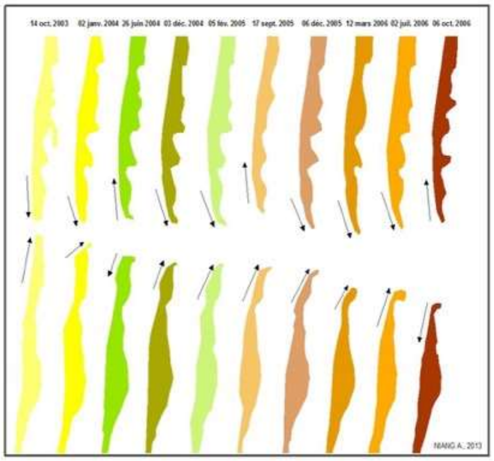
Comparison between the widths of the breach and the lengths of the northern part of the Barbary Tongue makes it possible to determine six main periods of evolution corresponding to as many phases of change in the morphology of the estuary between 2003 and 2018. During this decade, the breach widened, in absolute value by 5122 m while the northern part of the Barbary Spire gained +4564 m (Table 20).

Table 20: Annual variations in the breach width and lengths of the northern part of the Langue de Barbarie sandy spit from 2003 to 2018 (completed after Niang, 2014)

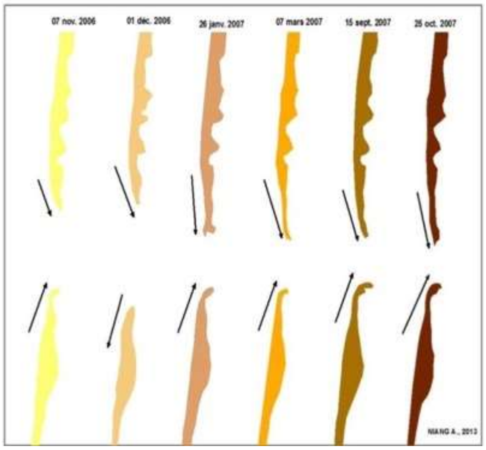
Date	**Breach**		**Langue de Barbarie Sandy Spit**	
	Width (m)	**Enlargement / Retreat (m)**	**Length (m)**	**Elongation / Recoil (m)**
04-oct-03	4.0	-	6500	-
14-oct-03	273.3	269.3	6497.6	-2.4
16-oct-04	882.0	608.7	6521.2	23.6
03-oct-05	1 360.8	478.9	6411.8	-109.4
06-oct-06	1 919.8	559.0	6470.9	59.1
01-oct-07	1 099.0	- 820.8	7109.9	639.0
11-oct-08	1 756.6	657.7	6805	-304.9
06-oct-09	2 373.8	617.1	6408.2	-396.8
25-oct-10	2 209.3	- 164.5	6656.8	248.6
04-oct-11	2 058.3	- 151.0	6768.5	111.7
06-oct-12	2 167.8	109.5	7611.8	843.3
1-oct.-13	5 543.3	3 375.5	7694.6	82.8
12-oct.-14	5 047.4	- 495.8	8936.6	1242.0
31-oct-15	5 320.4	273.0	9521.0	584.4
01-oct-16	4 734.1	- 586.3	9976.2	455.2
28-oct-17	4 914.3	180.2	10504.1	527.9
07-oct-18	5 126.4	212.1	11064.5	560.4
2003-2018	**+5 122.4**		**+4564.5**	

Statistical analysis of the breach width and length data for the northern part of the Langue de Barbarie sandy spit provides a summary of the evolution of the lower estuary between 2003 and 2018. In general, there has been significant erosion, resulting in significant land losses on the coast of the Langue de Barbarie and on the internal shores of the continental zone of Gandiolais (Figure 41; Figure 44). The most affected area seems to be the Isle of Doune Baba Dieye (Sy, 2006; Dieng et al., 2010; Sy et al., 2013) which, in a decade, lost more than three-quarters of its surface area, causing the displacement of many families and the loss of their agricultural land and therefore their sources of income.

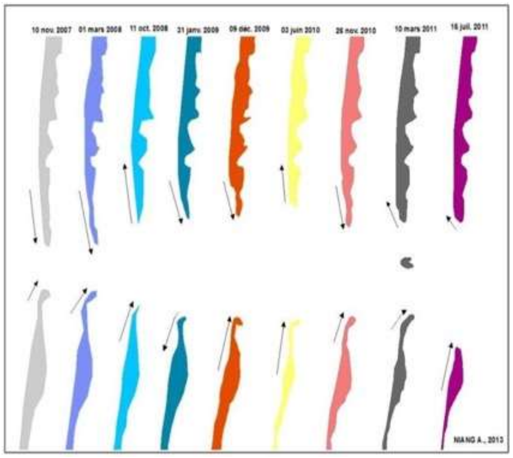
From 2003 to 2006, during the first period of evolution of the post-brick estuary, there was a steady increase in the size of the relief channel and a relative stability of the northern portion of the arrow of the Langue de Barbarie. In 2005, the closure of the old mouth, which now forms a lagoon, foreshadows major ecological problems due to the proximity of the Langue de Barbarie National Park. The same year, a significant area of weakness appeared in the southern part of the Barbary Language.



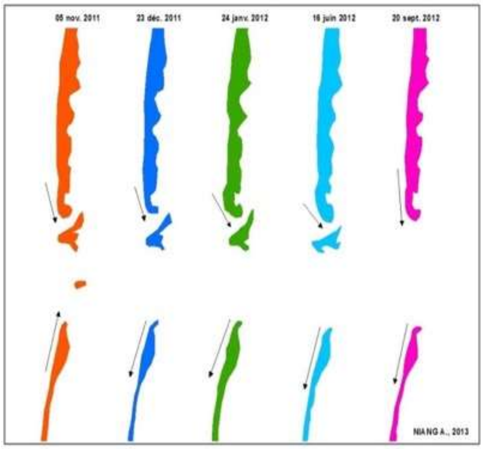
2003-2006



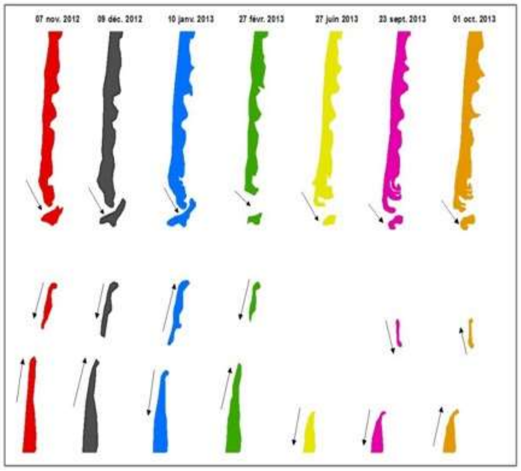
2006-2007



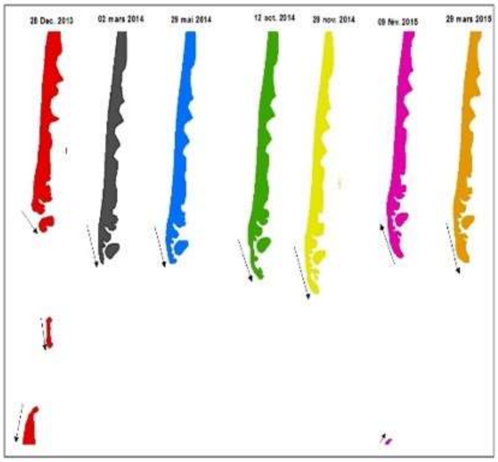
2007-2011



2011-2012



2012-2013



2013-2015

Figure 44: Morphological changes in the breach and in the Langue de Barbarie sandy between 2003 and 2015 (Niang et al., 2015)

Since October 2013, the gradual stabilization of the lower estuary has sometimes given the impression of a return to pre-2003 conditions (Figure 45). The width of the breach is steadily decreasing while the arrow is rebuilding more quickly than in previous periods. However, there is no evidence to predict a definitive return to the semi-natural conditions that prevailed in the lower estuary in the early 2000s. Nevertheless, there is still uncertainty about the future of this structurally unstable and fragile sandy spit.

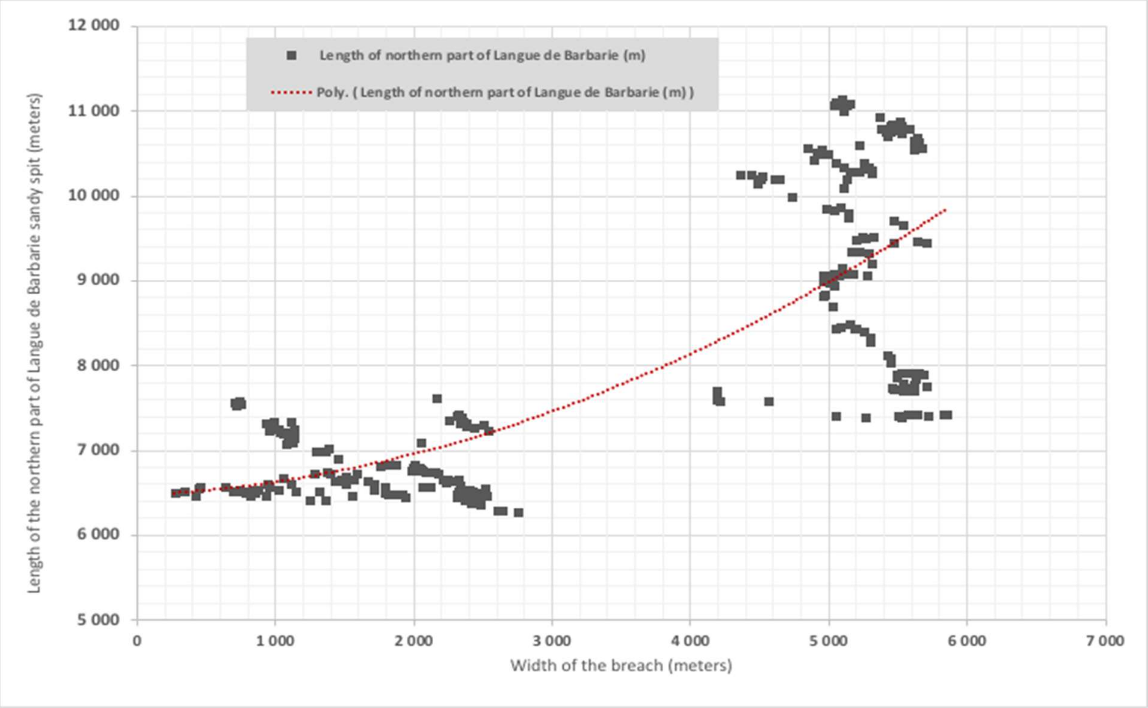


Figure 45: Evolution of the dimensions of the breach and the Langue de Barbarie sandy spit from October 2015 to December 2018

The artificial breach on the Langue de Barbarie, its functioning and dynamics are now part of the determinants of the evolution of the lower estuary of Senegal. More than fifteen years after its opening, nothing seems to be able to stop the evolution of this load-shedding channel, initially announced as a temporary structure with a very limited lifespan (Sy, 2005 and 2006; Diakhate, 2008).

Following the reconstruction of the spatio-temporal evolution of the breach from satellite imagery, Niang (2014) proposed a modelling attempt based on three scenarios of possible evolution of the lower estuary (Table 21). Generally speaking, whatever the scenario chosen, and unless an unexpected event occurs, the vulnerability of Gandiolais' coastal communities should remain substantially equal to what has already been observed in the recent past.

These scenarios are solely based on a statistical analysis of the breach data. However, it should be pointed out that these scenarios are forward-looking and have no other objective than to sound the alarm and stimulate in-depth reflection on the future of the region.

Table 21: Main characteristics of the presented scenarios (Niang, 2014)

	SCENARIO 1 Statu quo		SCENARIO 2 Accéelerated evolution		SCENARIO 3 New breaching of the sandy spit	
	Width of the breach (m)	*Length of north arrow (m)*	*Width of the breach (m)*	*Length of north arrow (m)*	*Width of the breach (m)*	*Length of north arrow (m)*
1 year	**5 760**	**7 795**	**6 047**	**7 895**	**7 543**	**7 795**
05 years	**6 625**	**8 195**	**8 061**	**8 695**	**8 409**	**8 195**
10 years	**7 707**	**8 695**	**10 579**	**9 695**	**9 491**	**8 695**

In order to develop a reliable and robust model, there is a need of additional measures to relaunch research and knowledge development on the Senegal estuary. The main focus will be to fill gaps in wave, tide and wind data as well as breach accident statistics.

2.4. SOCIAL, ECONOMICAL AND ENVIRONMENTAL CONSEQUENCES OF THE BREACH AND ADAPTATION ATTEMPTS

The opening of the breach on Langue de Barbarie spit sand have caused major changes on the hydrological Regime, Morphology of the lower estuary, hyper-salinization, flooding, change in fish population and crop production. The environmental and socioeconomic impacts of these morphological changes are of concern today, putting this socio-ecological system at a critical stage of its evolution.

The accumulation of signs of vulnerability such as hyper-salinization of water and agricultural lands upstream and the rapid morphological changes of the “Langue de Barbarie” spit sand caused by severe erosion along the coast, constitutes nowadays a major challenge for the daily activities of the local communities.

Fishing communities living along the sand spit of the “Langue de Barbarie” are threatened by sea- level variations; they are experiencing regular storm surges with serious loss of social and economic facilities including their settlements, fishing boats, and gears. The number of accidents and casualties are now more frequent than before.

Moreover, in the ecological zone of the Gandiolais, salinity levels are a standing challenge to economic development. These farmer communities, traditionally specialized in market gardening and livestock breeding, are now facing decreasing income due to salt intrusion into the aquifers and soils that impact their agricultural activities (Koulibaly, 2015). Market gardening survives with low yields (Figure 46) kept on hold by the massive use of manure, which explains the greater precariousness of local communities.

It also appears that biodiversity has been affected by both the breach and the salinization of surface and groundwater. Certain fish species have been disappearing due to their inability to adapt to the new conditions. On the other hand, fisher- men have noted the appearance of new fish species such as *Sardinella*, white carp, cheek fish, or tilapia (Kane, 2010), which has resulted in increased fish landings in Saint-Louis. According to the Regional Fisheries Service of Saint-Louis, the 60,000 tonnes mark was reached in 2008 (Figure 47), the highest catch on record since 1992 (Seck, 2014).

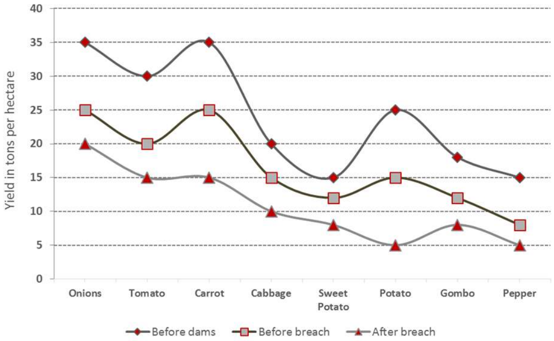


Figure 46: Yield of the main agricultural specualtion in the Gandiolais region

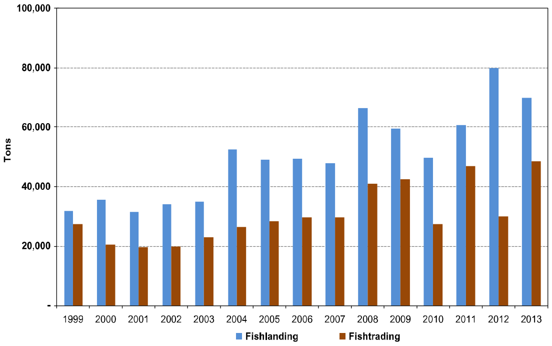


Figure 47 : Change in fish production from 1999 to 2013 (data from Regional Division of Fisheries of Saint-Louis)

Since the opening of the breach in October 2003, the consequent (hyper) salinization of the waters in the lower estuary has been paralyzing agricultural activities of local populations (Gac & Kane, 1986; Corea, 2006). Due to the salinization of soils, irrigated agriculture has become increasingly difficult in the entire delta of the river, with the total area affected amounting to ~15,000 ha (SAED, 2012; Gning, 2015). To escape such challenges, populations have started to relocate their activities, when and where possible, to areas less affected by salinization processes. Cases have been reported in particular in the lower estuary, specifically in Ndiebene Gandiole and Lahrar. One could consider this relocation a way of adapting, although on-going socioeconomic surveys will still have to show in which way this shift affects people's livelihoods.

Traditionally, salt exploitation in Gandiolais area has always been practiced by women but managed by men and placed under the exclusive authority of *Jaaraf* and its *Jambur*. The *Jaaraf* or *Diaraf* is a customary chief of Djolof and *Jambur* constitutes the Assembly of Elders of the *Djolof* Empire. In colonial times, the Gandiolais salt was under the exclusive control of the *Damel of Cayor* who then delegated the administration to his vassal, the *Montel* whose descendants are the *Jaaraf* (Faye and Sambe, 2012). At present, salt exploitation requires official authorization on the basis of a 10-years renewable contract. Each operator has the obligation to pay an annual fee to the local government. After every campaign, the harvest is divided into three parts: one for the farmer and two for the *Jaaraf* (Faye and Sambe, 2012).

Salt extraction is practiced by women in most villages of Gandiolais, particularly in Tassinere, Mouit, and Ndibene Gandiole, around the Ngaye-Ngaye basin (Photo 3), tributary of the Gueumbeul basin where the salinity level generally exceeds 35 g.l^{-1} at the beginning of winter season (Corea, 2006). The volumes of salt produced have been steadily increasing over the last 10 years, according to Gandon Local Development Plan (PLD Gandon, 2008), a fact related to the opening of the offloading canal and mainly since the closure of the old Senegal River mouth, which was transformed into a lagoon since 2005 and then evolved almost like a salt swamp. The size of the salt farms is in this respect revealing of the very increase of salt in the estuary.

Salt extraction activity can be seen as an attempt to adapt to changing environmental conditions by developing alternative economic activities. However, the income from salt is not enough to improve the livelihoods of the population, as Gandiolais salt has a low commercial value, despite efforts to improve the product quality through iodization processes.

Photo 3: Salt mining near Ndiebene Gandiole (lower estuary of the Senegal River). (From A. Niang on 3rd October 2012.)

Despite adaptation efforts of communities through the development of alternative activities such as salt extraction or transfer of agricultural activities to more favored areas, the situation is rather alarming, given the level of impoverishment. There remains, therefore, serious concern about the future of those fragile environments and their communities. Politically, moreover, the situation is complicated by regional interests from the OMVS (Senegal River Basin Management Organization) projects (river navigation, hydroelectricity, and large-scale irrigation schemes) and national policy such as one of the present major "*Plan Sénégal Emergent*" (Senegal Emerging Plan) that aims to develop national irrigation plans for food self-sufficiency, mainly from rice culture. In addition, such a fragile and changing environment is likely to be further weakened by the construction of a maritime-river harbor in Saint-Louis as part of the main Senegal River Navigation Program.

The main risk here is once again, a modification of the dynamics of the estuary and the river mouth, after the major upheaval experienced in October 2003 with the breaching of the Langue de Barbarie. The question is therefore, what will be the future of this region, especially after the construction of the maritime river harbor of Saint-Louis? How will this affect the Gandiolais communities, which have gone from a flourishing market gardening occupation to large-scale salt marshes?

The opening of the relief channel corresponds to a major and sudden upheaval in the environment of the Langue de Barbarie. After fifteen years of existence, the artificial breach of the Langue de Barbarie has strongly contributed to the modification of the estuarine environment. From a small breach of a few meters, we reached a mouth more than five (5) kilometers wide and located about ten kilometers from the city of Saint-Louis. This greater and faster penetration of marine waters into the estuary means increased concerns about hydrological functioning and salinization phenomena. The Senegal lower estuary is now a bay that is largely open to the sea, subject to its conditions and impacts such as salinization of water and land, flooding due to tidal waves, etc.

We are no longer in a breach pattern, since it is no longer conceivable that this opening, which is more than +5 km wide, could be closed in a natural way.

Satellite imagery makes it possible to compensate for the lack of a monitoring system and to trace the morphological evolution of the estuary with acceptable accuracy at monthly or even bi-monthly time steps. However, in order to model the estuarine functioning, it is necessary to set up a field monitoring system which, combined with satellite imagery, could contribute to feeding an observatory of the Langue de Barbarie. Already used in the framework of a summary modeling proposed by NIANG (2014), the results from satellite imagery processing are currently the only series of continuous chronological observations on the lower estuary of the Senegal River. They will again have to be validated using topobathymmetric field data, supplemented with sedimentological measurements and hydrodynamic data to arrive at a reliable model of the Senegal estuary. The breaches of the Langue de Barbarie sandy spit have produced real environmental shocks that provide an opportunity to revive and develop new perspectives for research in the Senegal River estuary.

3. THE GAMBIA RIVER ESTUARY

The Gambia River ends in the Atlantic Ocean with an estuary. This one extends from Gouloumbou to Banjul. Its topography: the river is at sea level. The tidal wave then travels up to Gouloumbou, 492 km upstream (Lamagat et al, 1987). The estuary covers an area of 36,000 km^2. Its salinity decreases as you move away from the mouth and Mangroves follow the river for about 220 km. The degradation of mangroves is one of the most important issues in this environment. Indeed, this mangrove is considered as one of the last reserves in West Africa.

Analysis of the 2003 land use map (Figure 48) and table shows the following trends: predominance of water bodies, which represent 22.19% of the total area of the study area, vegetation or mangroves 16.39% and bare soils, which occupy 18.06% of the area and buildings 17.01%.

While in 2016 (Figure 49), the plan areas are in the order of 16.67%; mangroves (16.67%); bare soils are estimated at 19.85%; cultivation areas are in the order of 28.12% (Table 22). The table below summarizes the statistical difference in land use in the estuary of the Gambia Basin.

Table 22: Land use in the estuary of the Gambia Estuary

Spatial units	2003		2016		Differences (%)
	Surface ha	Surface en %	Surface en ha	Surface en %	
Water	7987000,00	22,19	6000000,00	16,67	**5,52**
Vegetation	5900000,00	16,39	6000000,00	16,67	**-0,28**
Bare soil	6500000,00	18,06	7144400,00	19,85	**-1,79**
Built	6123530,00	17,01	6734156,00	18,71	**-1,70**
Cultivation area	9404267,00	26,12	10121444,00	28,12	**-1,99**
Total	**36000000,00**	**99,76**	**36000000,00**	**100,00**	

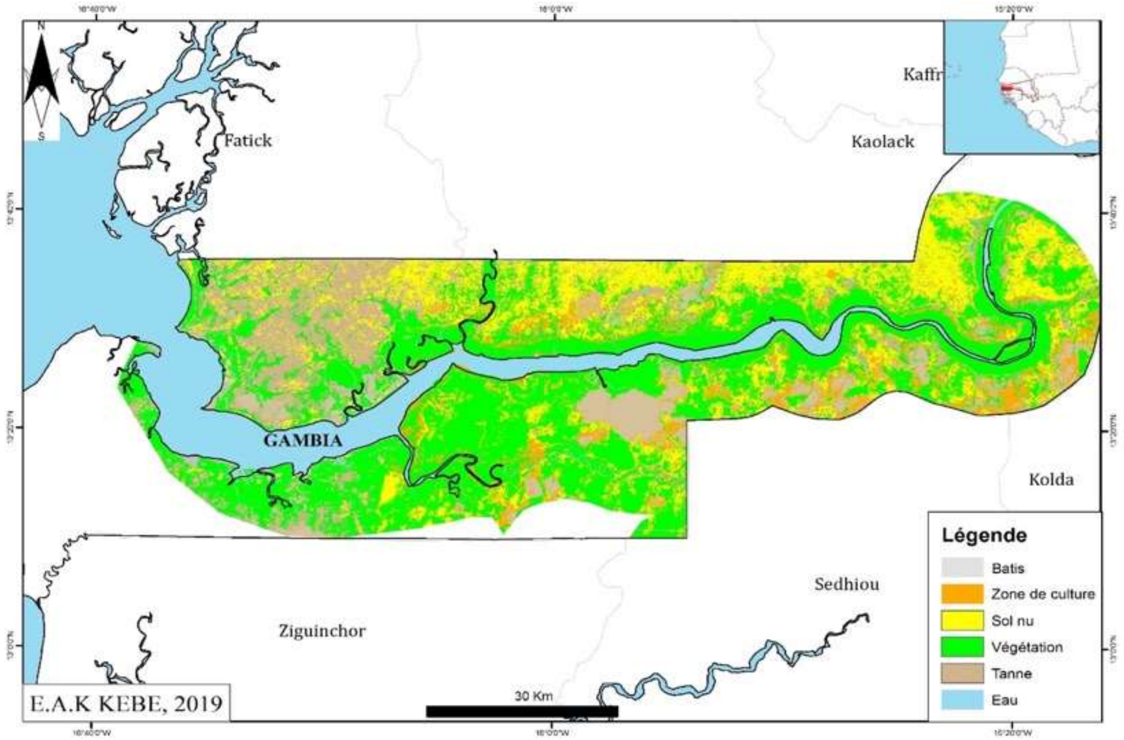


Figure 48: Land use map of the Gambia estuary in 2003

Although the use of satellite images is very appropriate for studying land use, the method is not without risk. According to Tonyé et al (2000), the assessment of land cover changes through visual comparison is limited by the risk of errors of judgment in relation to reality. To minimize these risks, we assessed the degree of land use change using the approach used by Sietchiping (2002).

To do this, we combined visual examination, automatic precision evaluation and comparison of AOIs between 2003 and 2016. Due to the low resolution of the satellite images used, it was not possible to discriminate between mangroves and vegetation in 2003. However, this does not affect the results since mangroves can be included in the vegetation class.

Land use mapping between 2003 and 20016 in the Gambia estuary revealed some changes with a decline in vegetation - mangroves. Bare soils are increasing north of the study area. Water surface classes also increase. The consequences of irregular rainfall, which has also resulted in unprecedented periods of drought, have strongly contributed to the gradual abandonment of agricultural practices but also to the movement of people to cities for the conversion of activities (rural exodus).

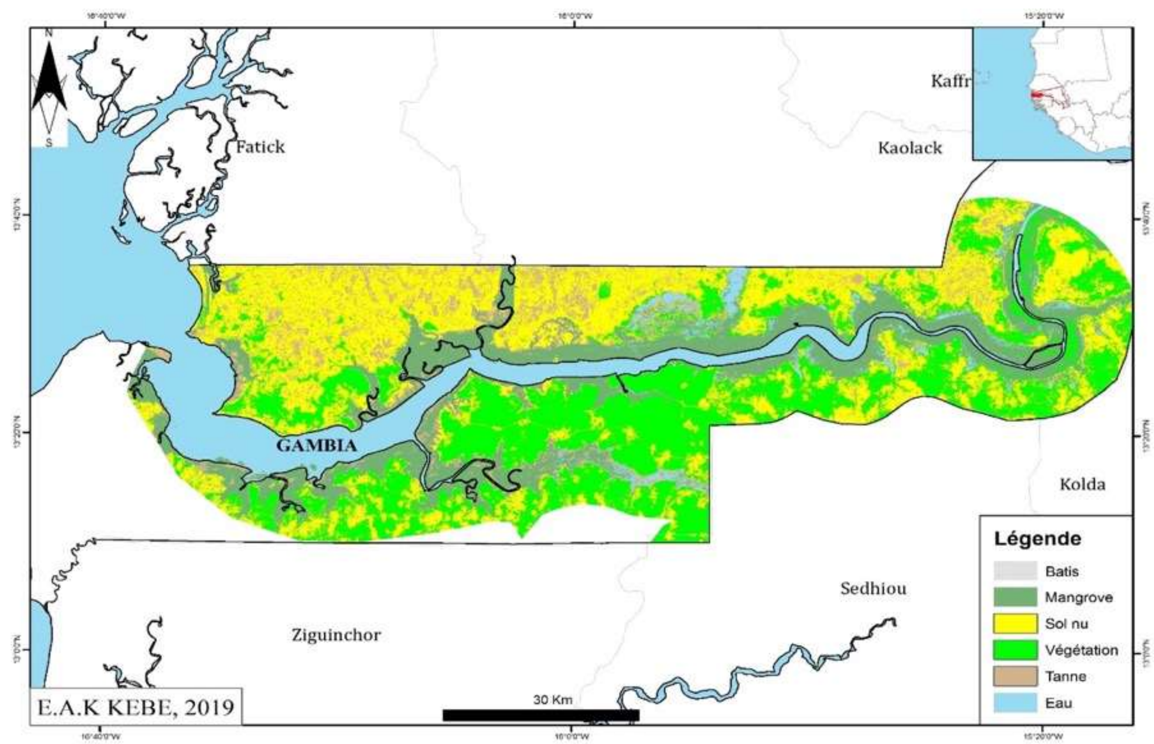


Figure 49: Land use map of the Gambia estuary in 2016

CONCLUSION AND FUTURE PROSPECTS

Given the geopolitical position of the hydrosystems of the Senegal River Basin and Gambia, the acquisition of hydro-climatic data was very complex. It took a lot of synergy of effort to obtain the data despite the presence of basin organizations such as OMVS and OMVG. Rainfall and hydrological data provide an essential knowledge base for water resources assessment and decision-making in the context of climate change and climate variability. Thus, we will have to cooperate with basin organizations (OMVS and OMVG) for a coherent synergy of action with well identified research axes and in a logic of partnership in research and development.

This report highlighted the main fluctuations in rainfall and water regime in the Gambia River Basin while highlighting land use in the Fouta Djalon hotspot, the Senegal River Delta estuary and the Gambia estuary.

The use of hydrological indices made it possible to visualize and subdivide the chronicles studied into several intervals according to dry or wet conditions and to characterize the extent of dry periods and their intensity. Hydrological indices of drought indicate that the most intense droughts have occurred since 1970.

Land use in hotspots (Fouta Djalon-Delta Estuary and Gambia Estuary) shows land use trends such that water bodies and biodiversity are declining at the expense of the expansion of bare surfaces.

The following actions have been carried out:

- Creation of a rainfall database for the Senegal River basin;
- Creation of a hydrometric database (water flow) of the Senegal River basin;
- Acquisition of Landsat Oli 8 satellite images for the hotspots of Fouta Djalon - the Senegal River estuary and Gambia for land cover and land use mapping;
- Development of an environmental database (GIS) to highlight environmental problems in selected hot spots (Senegal River Estuary, Gambia River Estuary and Fouta Djalon Mountain)
- Update of the former ACEWATER1 database of Senegal with the 24 rainfall stations for climate vulnerability

However, some problems remain:

- Some rainfall and hydrometric stations as well as data from Mauritania and Guinea are missing;
- Lack of climate data (temperature-humidity-evaporation) at the basin scale (Senegal and Gambia river basins);
- Problems related to the acquisition of rainfall, hydrometric and socio-economic data from the Gambia River Basin.

Within the framework of this project, the future prospects will essentially be to develop scientific cooperation between the UCAD team and the WEFE Senegal project to pool efforts in order to proceed to the hydrological modelling stage of the Senegal River catchment area with the SWAT software.

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ANNEXES

CLIMATIC DATABASE OF SENEGAL (METADATA)

CODE_STATION	STATION_NAME	TYPE	LAT. NORTH	LONG. WEST	Starting year	Period	Average rainfall (mm)	Temperature (Min & Max)	Moisture (Min & Max)	Evaporation
1380000400	BAKEL	P	14° 54'	12° 28'	1918	1918-2016	527,8	1979-2016	1982-2016	1981-2016
1380001000	BAMBEY	S	14° 42'	16° 28	1921	1921-2016	582,4	1987-2016	1987-2016	1981-2016
1380002700	CAP SKIRING	S	12° 24'	16° 45	1977	1977-2016	1 217,6	1978-2016	1980-2016	1980-2016
1380000100	DAKAR YOFF	S	14° 44'	17° 30	1897	1897-2016	541,7	1960-2016	1960-2016	1960-2016
1380006400	DIOURBEL	S	14° 39'	16° 14	1919	1919-2016	555,5	1960-2016	1970-2016	1961-2016
1380007600	FATICK	S	12° 41'	16° 25	1918	1918-2016	680,9	1991-2016	1991-2016	1991-2016
1380009400	GOUDIRY	P	14° 11'	12° 43'	1918	1918-2016	685,0	-	-	-
1380011800	KAOLACK	S	14° 08'	16° 04	1960	1960-2016	707,9	1960-2016	1960-2016	1961-2016
1380012400	KEDOUGOU	C	12° 34'	12° 11'	1918	1918-2016	1 251,2	1960-2016	1970-2016	1970-2016
1380013300	KOLDA	S	12° 53'	14° 58'	1922	1922-2016	1 124,5	1987-2016	1987-2016	1987-2016
1380014200	KOUNGHEUL	P	12° 37'	16° 21'	1932	1932-2016	776,8	-	-	-
1380015100	LINGUERE	S	15° 23'	15° 7'	1933	1933-2016	446,7	1960-2016	1978-2016	1980-2016
1380015400	LOUGA	C	15° 37'	16° 13'	1919	1919-2016	372,7	1963-2016	1980-2016	1971-2016
1380016300	MATAM	S	15° 39'	13° 15'	1918	1918-2016	442,0	1960-2016	1960-2016	1960-2016
1380018100	MBOUR	P	12° 36'	16° 20'	1931	1931-2016	639,4	1980-2016	1980-2016	1980-2016
1380019900	NIORO DU RIP	P	13° 44'	15° 47'	1980	1980-2016	818,6	1987-2016	1989-2016	1987-2016
1380021400	PODOR	S	16° 39'	14° 58'	1918	1918-2016	272,8	1960-2016	1970-2016	1981-2016
1380021700	RANEROU	P	15° 18'	13° 58'	1963	1963-2016	446,4	-	-	-
1380023200	SAINT-LOUIS AERO	S	16° 03'	16° 27'	1957	1960-2016	265,6	1980-2015	1980-2015	1981-2015
1380024900	SIMENTI	P	13° 03'	13° 18'	1968	1968-2014	894,7	1995-2014	1995-2014	-
1380025300	TAMBACOUNDA	S	13° 46'	13° 41'	1919	1919-2016	815,5	1960-2016	1960-2016	1960-2016
1380026500	THIES	S	14° 48'	16° 57'	1918	1918-2016	550,5	1977-2016	1977-2016	1977-2016
1380028000	VELINGARA FERLO	P	15° 0'	14° 41'	1945	1945-2016	715,3	1984-2016	1985-2016	1984-2016
1380028600	ZIGUINCHOR	S	12° 33'	16° 16'	1918	1918-2016	1 418,7	1951-2016	1960-2016	1981-2016

RAINFALL DATABASE OF SENEGAL RIVER BASIN (METADATA)

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
1170317000	DABOLA	C	Guinea	10°45'	-11°07'	438	1923	1923-1990 / 1995-2014	-
1170320000	DALABA	C	Guinea	10°42'	-12°15'	1202	1933	1933-2014	1942,82
1170335000	DINGUIRAYE	C	Guinea	11°18'	-10°43'	490	1954	1995-2014	1340,31
1170406500	FARANAH	S	Guinea	10°02'	-10°45'	467	1923	1995-2006	1587,72
1170435000	GAOUAL	C	Guinea	11°45'	-13°12'	100	1925	1926-1978	1886,29
1170524000	KANKAN	S	Guinea	10°23'	-09°18'	377	1921	1921-2015	1548,72
1170537000	KINDIA	S	Guinea	10°03'	-12°52'	458	1921	1922-1996	2023,989
1170587000	LABE	S	Guinea	11°19'	-12°18'	1050	1923	1923-1992 / 1995-2015	1619,21
1170617000	MALI	P	Guinea	12°05'	-12°18'	1464	1922	1995-2016	1564,54
1170618000	MAMOU	C	Guinea	10°22'	-12°05'	782	1921	1922-2016	1860,13
1170720000	PITA	P	Guinea	11°04'	-12°24'	965	1922	1925-1990 / 1998-2016	1658,54
1170768000	SIGUIRI	S	Guinea	11°26'	-09°10'	362	1923	1923-2015	1266,22
1170842000	TOUGUE	C	Guinea	11°26'	-11°40'	868	1930	1951-1991 / 1995-2014	1510,74
1170971500	YOUKOUNKOUN	C	Guinea	12°32'	-13°07'	83	1923	1928-1977	1313,04
1270000400	AMBIDEDI	P	Mali	14°35'	-11°47'	30	1951	1951-1986 / 1995-2015	656,543
1270001000	AOUROU	P	Mali	14°58'	-11°35'	65	1951	1951-1989	492,805
1270001600	BAFING-MAKANA	P	Mali	12°33'	-10°15'	239	1960	1960-2014	1174,05
1270001900	BAFOULABE	C	Mali	13°48'	-10°50'	104	1921	1931-2014	886,452
1270002500	BALLE	P	Mali	15°20'	-08°35'	285	1953	1951-2015	470,481
1270000100	BAMAKO-SENOU	S	Mali	12°38'	-08°02'	332	1919	1919-2014	1021,99
1270003700	BANAMBA	P	Mali	13°33'	-07°27'	380	1933	1933-1994	732,838
1270004500	BANGASSI	P	Mali	13°10'	-08°55'	320	1951	1951-1956	665,417
1270005500	BATIMAKANA	P	Mali	13°15'	-09°23'	319	1963	1963-1979	761,322
1270007600	BOUGOUNI	C	Mali	11°25'	-07°30'	353	1921	1921-1995	1147,89
1270008800	DIAMOU	P	Mali	14°06'	-11°16'	60	1950	1950-2015	708,962
1270009100	DIEMA	P	Mali	14°33'	-09°11'	252	1941	1941-2015	600,829
1270012400	FALADYE	C	Mali	13°08'	-08°20'	337	1931	1931-2014	875,739
1270012700	FALEA	P	Mali	12°16'	-11°17'	455	1950	1951-2014	1175,24

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
1270014200	GALOUGO	P	Mali	13°51'	-11°03'	91	1950	1950-2014	848,797
1270015100	GOUALALA	P	Mali	11°13'	-08°14'	350	1945	1945-2001	1211,1
1270015700	GOURBASSI	P	Mali	13°24'	-11°38'	79	1950	1950-2014	819,898
1270016300	GUENE-GORE	P	Mali	12°44'	-11°02'	240	1950	1950-2014	1251,14
1270018700	KALANA	P	Mali	10°47'	-08°12'	379	1950	1950-2000	1331,87
1270019300	KANGABA	P	Mali	11°56'	-08°25'	370	1939	1939-2002	1073,72
1270020800	KAYES	S	Mali	14°26'	-11°26'	43	1921	1895-2014	663,457
1270021700	KENIEBA	S	Mali	12°50'	-11°14'	150	1942	1942-2014	1143,74
1270022900	KITA	S	Mali	13°05'	-09°29'	332	1931	1930-2014	1001,01
1270023800	KOLOKANI	P	Mali	13°40'	-08°02'	390	1923	1923-2014	765,427
1270024700	KONIAKARI	P	Mali	14°35'	-10°54'	81	1955	1955-2014	673,353
1270026800	KOTERA	P	Mali	14°46'	-12°10'	27	1959	1959-1978	448,429
1270027700	KOUROUNINKOTO	P	Mali	13°51'	-09°35'	267	1951	1950-1990	818,341
1270028000	KOUSSANE	P	Mali	14°53'	-11°14'	96	1959	1951-1993	574,283
1270028600	LEYA	P	Mali	15°06'	-11°50'	52	1959	1968-1969	462,00
1270032200	MOURDIAH	P	Mali	14°28'	-07°28'	314	1930	1930-1988	509,829
1270032800	NARA	P	Mali	15°10'	-07°17'	265	1921	1921-2014	454,411
1270033100	NARENA	P	Mali	12°13'	-08°38'	380	1964	1968-1978	1082,2
1270033700	NEGALA	P	Mali	12°52'	-08°27'	350	1954	1954-1982	989,862
1270034900	NIENEBALE	P	Mali	12°54'	-07°30'	290	1923	1950-1980	853,214
1270035800	NIORO-SAHEL	S	Mali	15°14'	-09°36'	225	1919	1919-2014	565,326
1270036700	OUALIA	P	Mali	13°36'	-10°23'	130	1959	1954-2014	832,492
1270037600	OULOUMA	P	Mali	14°12'	-11°35'	173	1951	1951-1975	840,048
1270037900	OUSSOUBIDIAGNA	P	Mali	14°15'	-10°28'	259	1951	1951-1991	787,644
1270038500	SABOUCIRE	P	Mali	14°18'	-11°17'	50	1960	1963-1966	733,5
1270038800	SADIOLA	P	Mali	13°54'	-11°42'	120	1959	1950-2014	805,597
1270039100	SAGABARI	P	Mali	12°36'	-09°48'	322	1959	1950-2014	1084,23
1270040300	SANDARE	P	Mali	14°43'	-10°18'	281	1954	1954-1979	721,913
1270041200	SEBEKORO	P	Mali	12°58'	-08°59'	360	1951	1968-1978	752,859

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
1270042400	SIRAKORO	P	Mali	12°41'	-09°14'	369	1951	1950-1998	1029,51
1270046300	TOUKOTO	P	Mali	13°27'	-09°53'	177	1932	1932-2014	796,857
1270047200	YELIMANE	P	Mali	15°08'	-10°34'	97	1919	1919-2014	582,893
1300201000	ACHRAM SONADER	P	Mauritania	17°21'	-12°24'	-	1984	1984-1996	815,231
1300000200	ADEL BOGROU	P	Mauritania	15°35'	-07°00'	200	1978	1988-1996	823,636
1300000600	AIN-FARBA	P	Mauritania	15°56'	-10°23'	226	1978	1979-1980	278,3
1300000400	AIOUN-EL ATROUSS	S	Mauritania	16°44'	-09°38'	223	1946	1946-1998	835,695
1300001000	ALEG	C	Mauritania	17°03'	-13°55'	45	1920	1921-2014	263,367
1300001100	AMOURJ	P	Mauritania	16°06'	-07°13'	280	1967	1967-1996	744,173
1300001200	AOUEINATT ZBEL	P	Mauritania	16°23'	-08°54'	200	1979	1978-1996	188
1300001400	BABABE	P	Mauritania	16°21'	-13°58'	82	1979	1979-1996	710,791
1300001700	BARKEOL	P	Mauritania	16°38'	-12°30'	200	1978	1980	-
1300002000	BELOUGUE LITHAMA	P	Mauritania	15°41'	-12°45'	-	1979	-	-
1300001600	BOGHE	S	Mauritania	16° 34'	-14° 17'	11	1919	1919-2014	280,656
1300002100	BOUMDEID	P	Mauritania	17°26'	-11°21'	200	1980	1980-1996	148,063
1300285500	BOUSTEILA	P	Mauritania	15°35'	-08°05'	-	1980	1980-1996	273,125
1300001900	BOUTILIMIT	S	Mauritania	17°31'	-14°40'	77	1921	1921-2014	182,28
1300344000	DAFORT	P	Mauritania	15°35'	-01°29'	68	1980	1980	-
1300002300	DAR EL BARKA	P	Mauritania	16°41'	-14°41'	8	1971	1969-1974	227,5
1300002600	DIONABA	P	Mauritania	17°38'	-12°26'	-	1980	1980-1996	166,857
1300002700	DJADJIBINE	P	Mauritania	15°45'	-12°29'	-	1979	1980	
1300002400	DJIGUENI	P	Mauritania	15°44'	-08°40'	222	1971	1971-1996	328,52
1300438000	FOUM-GLEITA	A	Mauritania	16°10'	-12°40'	-	1979	1986-1996	190,25
1300003000	GORFA AVAL	P	Mauritania	15°31'	-12°42'	-	1980	1980	
1300456500	GUEROU	P	Mauritania	16°48'	-11°50'	200	1978	1978-1996	179,882
1300003100	KAEDI	C	Mauritania	16°09'	-13°30'	33	1905	1906-2014	342,695
1300003200	KAEDI-IRAT	C	Mauritania	16°09'	-13°30'	33	1905	1950-1996	331,182
	KAEDI-OMVS		Mauritania	16°08'	-13°31'	33	1905	1905-1913/1930-2014	380,435
1300003400	KANKOSSA	C	Mauritania	15°57'	-11°30'	70	1954	1950-1996	358,652

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
1300543500	KEUR MACENE	A	Mauritania	16°33'	-16°14'	-	1976	1977-2009	168,968
1300003700	KIFFA	S	Mauritania	16°38'	-11°24'	115	1922	1922-2018	338,229
1300003900	KOUBENI	P	Mauritania	15°48'	-09°25'	274	1979	1979-1996	277,765
1300583000	LEXEIBA	P	Mauritania	16°13'	-01°38'	-	1979	1988-1996	226,714
1300595000	M'BAGNE	P	Mauritania	16°09'	-13°47'	15	1979	1979-1996	234,824
1300004000	M'BOUT	C	Mauritania	16°02'	-12°35'	44	1921	1921-1996	360,422
1300004100	MAGHAMA	P	Mauritania	15°31'	-12°51'	21	1979	1979-1996	308,589
1300004200	MAGTA-LAHJAR	P	Mauritania	17°31'	-13°06'	53	1978	1978-1996	160,824
1300004300	MEDERDRA	P	Mauritania	16°55'	-15°40'	25	1930	1931-1996	219,547
1300004500	MONGUEL	P	Mauritania	16°26'	-13°10'	43	1979	1979-1996	232,188
1300004600	MOUDJERIA	C	Mauritania	17°56'	-12°21'	300	1905	1911-1996	194,203
1300596000	N'BEIKA	C	Mauritania	17°59'	-12°16'	-	1980	1979-1996	370,2
1300004900	NEMA	S	Mauritania	16°37'	-07°16'	269	1922	1922-2018	251,496
1300740000	OULD-YENGE	P	Mauritania	15°32'	-11°43'	57	1979	1979-1996	370,2
1300005800	ROSSO	C	Mauritania	16°30'	-15°49'	5	1934	1934-2018	258,532
1300006100	SELIBABY	S	Mauritania	15°13'	-12°10'	60	1933	1933-2014	552,407
1300006400	TAMCHAKETT	P	Mauritania	17°16'	-10°40'	190	1933	1933-1996	213,742
1300910000	TEKANE	P	Mauritania	16°36'	-15°22'	-	1980	1990-2009	178,737
1300007000	TIDJIKJA	S	Mauritania	18°34'	-11°25'	396	1921	1907-1998	130,182
1300007300	TIMBEDRA	P	Mauritania	16°17'	-08°12'	210	1950	1929-1996	298,791
1300007200	TINTANE	P	Mauritania	16°23'	-10°10'	183	1971	1971-1996	235,792
1300007400	TOUIL	P	Mauritania	15°31'	-10°08'	274	1978	1978-1996	332,444
1300010000	ZRAVIA	P	Mauritania	16°18'	-16°32'	396	1977	1978-2009	104,52
1380010000	AERE LAO	P	Senegal	16° 24'	-14° 19'	11	1962	1962-2014	171
1380000400	BAKEL	C	Senegal	14°54'	-12°27'	25	1918	1918-2016	528
1380001300	BARKEDJI	P	Senegal	15° 17'	-14° 52'	15	1947	1947-2004	417
1380002200	BOKI DIAVE	P	Senegal	15° 53'	-13° 29'	16	1961	1967-1994	311
1380002800	COKI	P	Senegal	15° 31'	-16° 0'	43	1933	1933-2010	387
1380003100	DAGANA	P	Senegal	16° 31'	-15° 30'	5	1918	1918-2014	264

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
1380003400	DAHRA	P	Senegal	15° 20'	-15° 29'	39	1933	1933-2010	427
1380003500	DAHRA ELEVAGE	P	Senegal	15° 20'	-15° 27'		1956	1956-1994	373
1380004900	DIAGLE	P	Senegal	16° 13'	-15° 42'	18	1962	1962-1986	263
1380007300	FANAYE DIERI	P	Senegal	16° 32'	-15° 13'	10	1961	1962-2014	195
1380009400	GOUDIRY	P	Senegal	14° 11'	-12° 43'	59	1940	1940-2016	687
1380011500	KANEL	P	Senegal	15° 30'	-13° 10'	20	1963	1963-2004	401
1380012400	KEDOUGOU	C	Senegal	12°34'	-12°11'	122	1918	1918-2016	1251
1380012700	KEUR MOMAR SARR	P	Senegal	15° 56'	-15° 58'	15	1962	1962-2004	294
1380013000	KIDIRA	P	Senegal	14°28'	-12°13'	35	1918	1918-2014	649
1380015100	LINGUERE	S	Senegal	15° 23'	-15° 7'	20	1933	1933-2016	453
1380015400	LOUGA	C	Senegal	15° 37'	-16° 13'	38	1887	1919-2016	368
1380016300	MATAM	S	Senegal	15° 39'	-13° 15'	15	1918	1918-2016	446
1380019000	MPAL	P	Senegal	15° 55'	-16° 16'	10	1961	1961-2012	273
1380019200	NAMARY	P	Senegal	15°05'	-13°39'	33	1940	1940-1964	729
1380019300	NDIOUM	P	Senegal	16° 31'	-14° 39'	8	1962	1963-1968/1970-1977 /1992-2013	244
1380020200	OGO	P	Senegal	15° 32'	-13° 18'	17	1966	1967-1970 / 2003-2004	313
1380020400	OUROSSOGUI	P	Senegal	15° 38'	-13° 18'	-	1966	1970/2000-2004	384
1380760300	PETE	P	Senegal	16° 50'	-13° 56'		1976	1976-2014	255
1380021400	PODOR	S	Senegal	16° 39'	-14° 58'	6	1904	1918-2016	270
1380021700	RANEROU	P	Senegal	15° 18'	-13° 58'	33	1963	1964-2016	425
1380022000	RICHARD-TOLL	C	Senegal	16° 27'	-15° 42'	4	1905	1963-2014	187
1380925600	ROSS-BETHIO	P	Senegal	16°16' N	16°08' W		1975	1975-2010	371,0
1380022800	SAGATTA LINGUERE	P	Senegal	15° 13'	-15° 34'		1933	1935-1959	529
1380022900	SAGATTA LOUGA	P	Senegal	15° 17'	-16° 11'	41	1946	1946-2000	451
1380023200	SAINT-LOUIS AERO	S	Senegal	16° 03'	-16° 27'	4	1957	1957-2012	271
1380023300	SAINT-LOUIS VILLE	P	Senegal	16° 01'	-16° 30'	4	1848	1851-2016	354
1380023500	SALDE	P	Senegal	16° 10'	-13° 53'	11	1961	1962-2014	110
1380023800	SARAYA	P	Senegal	12°50'	-11°45'	186	1948	1949-2014	1101
1380025300	TAMBACOUNDA	S	Senegal	13° 46'	-13° 41'	49	1919	1920-2016	819

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
1380028000	VELINGARA FERLO	P	Senegal	15° 0'	-14° 41'	25	1956	1946-1980	465
1380929800	YANG-YANG	P	Senegal	15° 39'	-15° 21'	28	1918	1918-1981	465

RAINFALL DATABASE OF GAMBIA RIVER BASIN (METADATA)

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALT. (m)	Starting date	Available data	Average rainfall
1150777012	BANJUL HALF DIE	P	Gambia	13°27	16°34	2	1943	No information	No information
1150777003	BASSE METEO	M	Gambia	13°19	14°13	4	1942	No information	No information
1150777008	FATOTO	M	Gambia	13°24	13°54	2	1971	No information	No information
1150777018	GEORGETOWN	C	Gambia	13°32	14°46	1	1908	No information	No information
1150777450	JALI MFC	P	Gambia	13°21	15°58	7	1974	No information	No information
1150777015	JENOI METEO	C	Gambia	13°29	15°34	15	1946	No information	No information
1150777440	JIBANACK MFC	P	Gambia	13°13	16°11	9	1971	No information	No information
1150777023	KAUR HYDRO	P	Gambia	13°43	15°21	6	1950	No information	No information
1150777017	KEREVAN METEO	M	Gambia	13°30	16°05	15	1979	No information	No information
1150777080	NAUDE MFC	P	Gambia	13°28	14°27	1	1971	No information	No information
1150777020	SAPU METEO	M	Gambia	13°33	14°54	-	1956	No information	No information
1150777004	YUNDOUM AIRPORT	S	Gambia	13°21	16°08	26	1945	No information	No information
1170587000	LABE	S	Guinea	11°19'	-12°18'	1050	1923	No information	No information
1170617000	MALI	P	Guinea	12°05'	-12°18'	1464	1922	1995-2016	1564,54
1170618000	MAMOU	C	Guinea	10°22'	-12°05'	782	1921	1922-2016	1860,13
1170720000	PITA	P	Guinea	11°04'	-12°24'	965	1922	1925-2016	1658,54
1170842000	TOUGUE	C	Guinea	11°26'	-11°40'	868	1930	1951-2014	1510,74
1170971500	YOUKOUNKOUN	C	Guinea	12°32'	-13°07'	83	1923	1928-1977	1313,04
1380105000	BADY	P	Senegal	13°03	13°10	-	1973	1973-1980	826,29
1380000400	BAKEL	C	Senegal	14°54'	-12°27'	25	1918	1918-2016	527,81
1380000700	BALA	P	Senegal	14°01	13°10	61	1962	1962-2004	616,92
1380005200	DIALACOTO	P	Senegal	13°19	13°18	50	1918	1918-2004	924,24
1380007900	FONGOLIMBY	P	Senegal	12°25	12°01	396	1963	1963-2006	588,08
1380009400	GOUDIRY	P	Senegal	14° 11	12° 43'	59	1918	1918-2016	684,96
1380012400	KEDOUGOU	C	Senegal	12°34'	-12°11'	122	1918	1918-2016	1251,16
1380013000	KIDIRA	P	Senegal	14°28'	-12°13'	35	1918	1918-2014	649,19
1380013600	KOTIARY-NAOUDE	P	Senegal	13°53	13°27	27	1963	1963-1975	805,97
1380014500	KOUMPENTOUM	P	Senegal	13°59	14°33	18	1940	1940-2004	614,50
1380014200	KOUNGHEUL	P	Senegal	12°37	16°21	11	1932	1932-2016	776,82

ID_STATION	STATION NAME	TYPE	Country	LAT. NORD	LONG. OUEST	ALT. (m)	Starting date	Available data	Average rainfall
1380014800	KOUSSANAR	P	Senegal	13°52	14°05	17	1962	1962-2004	696,89
1380015700	MAKA-COULIBANTAN	P	Senegal	13°40	14°18	18	1930	1930-2004	726,97
1380016000	MALEME-HODDAR	P	Senegal	14°05	15°18	41	1963	1963-2004	629,26
1380018400	MISSIRAH	P	Senegal	13°33	13°31	45	1963	1963-2005	745,33
1380714100	NIOKOLO-KOBA	P	Senegal	13°04	12°41	-	1973	1973-1980	903,8
1380019900	NIORO-DU-RIP	P	Senegal	13°44	15°47	18	1980	1980-2016	818,63
1380020500	OUSSOUNKALA-BAGNOBA	P	Senegal	12°43	12°23	93	1963	1963-1980	984,45
1380808000	SALEMATA	P	Senegal	12°38	12°50	-	1973	1973-1980	1131,63
1380023800	SARAYA	P	Senegal	12°50'	-11°45'	186	1948	1949-2014	1101,18
1380025300	TAMBACOUNDA	S	Senegal	13° 46'	-13° 41'	49	1919	1920-2016	818,93
1380028000	VELINGARA CASAMANCE	P	Senegal	13° 09	13°41	38	1932	1932-2008	964,84