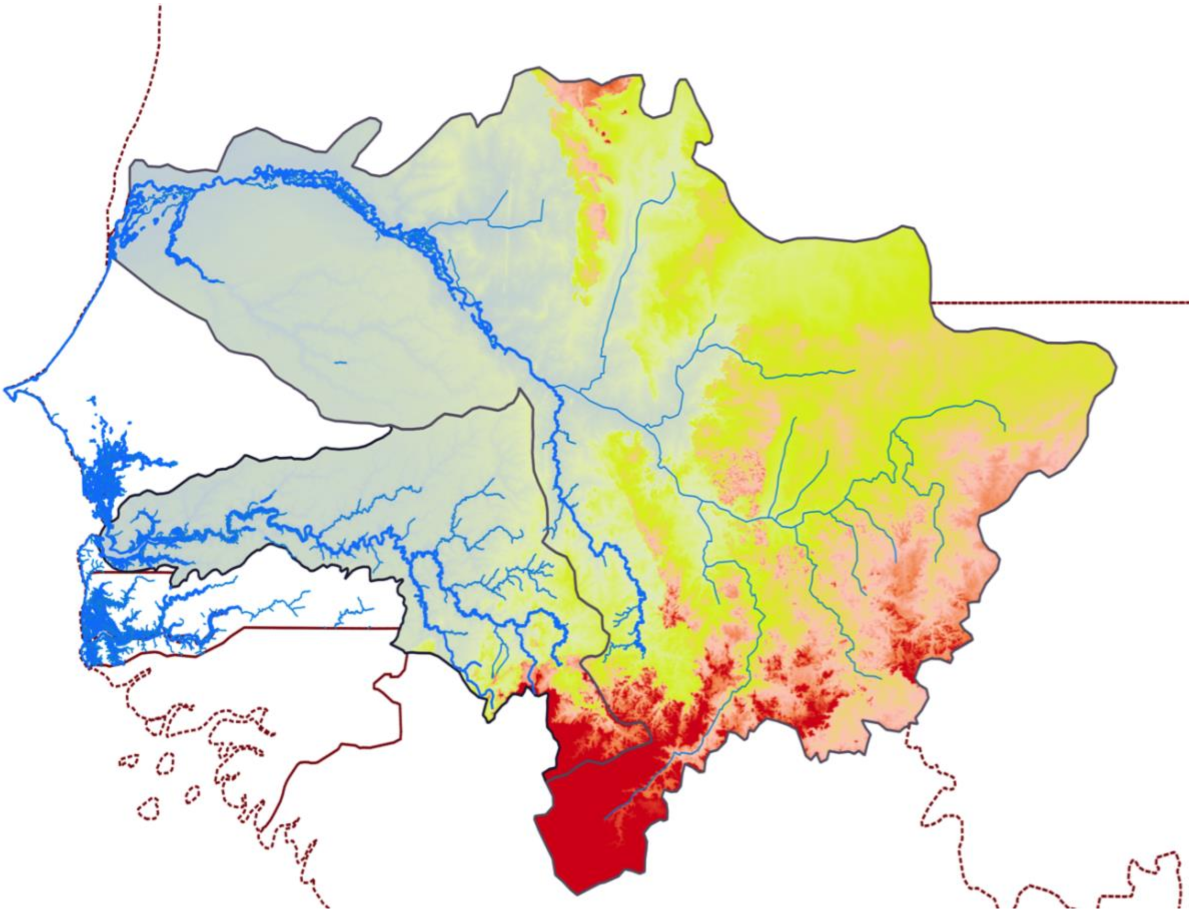
CLIMATE VULNERABILITY AND WATER RESOURCES VARIABILITY IN WEST AFRICA

SENEGAL AND GAMBIA RIVER BASIN CASES STUDIES

Progress Report



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Acknowledgments

We acknowledge efforts made by the team of doctoral and master students, to consolidate the different databases.

The data sources are, among other:

- ANACIM[1] and DGPRE[2] for Senegal national level
- Services météorologiques nationaux de la Gambie, de la Guinée et Guinée Bissau, du Mali et de la Mauritanie
- Basins agencies (OMVS and OMVG)
- National IHP focal points[3]
    - IRD archives like SIEREM or AMMA database.

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).

[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

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 the SWAT tool applied to the Bafing catchment area has given encouraging results as to the applicability of the model with a very high satisfaction degree. The model will also be tested on other sub-basins of the Senegal and Gambia Rivers, particularly in the upper basin. The next step in the modelling component of this study will be to test the WEAP model over the entire Senegal River Basin and Gambia.

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

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:	Direction de la Gestion et de la Planification des Ressources en Eau
DGPRE:	Water Resources Management and Planning Directorate
DNH:	National Directorate of Hydraulics
ECOWAS:	Economic Community of West African States
EDEQUE:	École Doctorale "Eau, Qualité et Usages de l'Eau"
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:	Schema Directeur d'Amenagement et Gestion des Eaux
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 Centres of Excellence
WASCAL:	West African Science Service Center on Climate Change and Adapted Land Use
WEAP:	Water Evaluation And Planning System

Introduction

The West African region is subject to a very high climate vulnerability for several decades (Oyebdande 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**Error! Reference source not found.**). 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.

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 present report focuses on the work done by the Senegal team from December 2017 to September 2018 and related Milestone on WA.CVA.1.1 deliverable (Report on climate database update, climate variability and trends analysis, impact assessment of climate on hydrology in Western Africa). It also described the literature review, definition of data collection and pre-analysis methodology, analysis tools identification and acquisition.

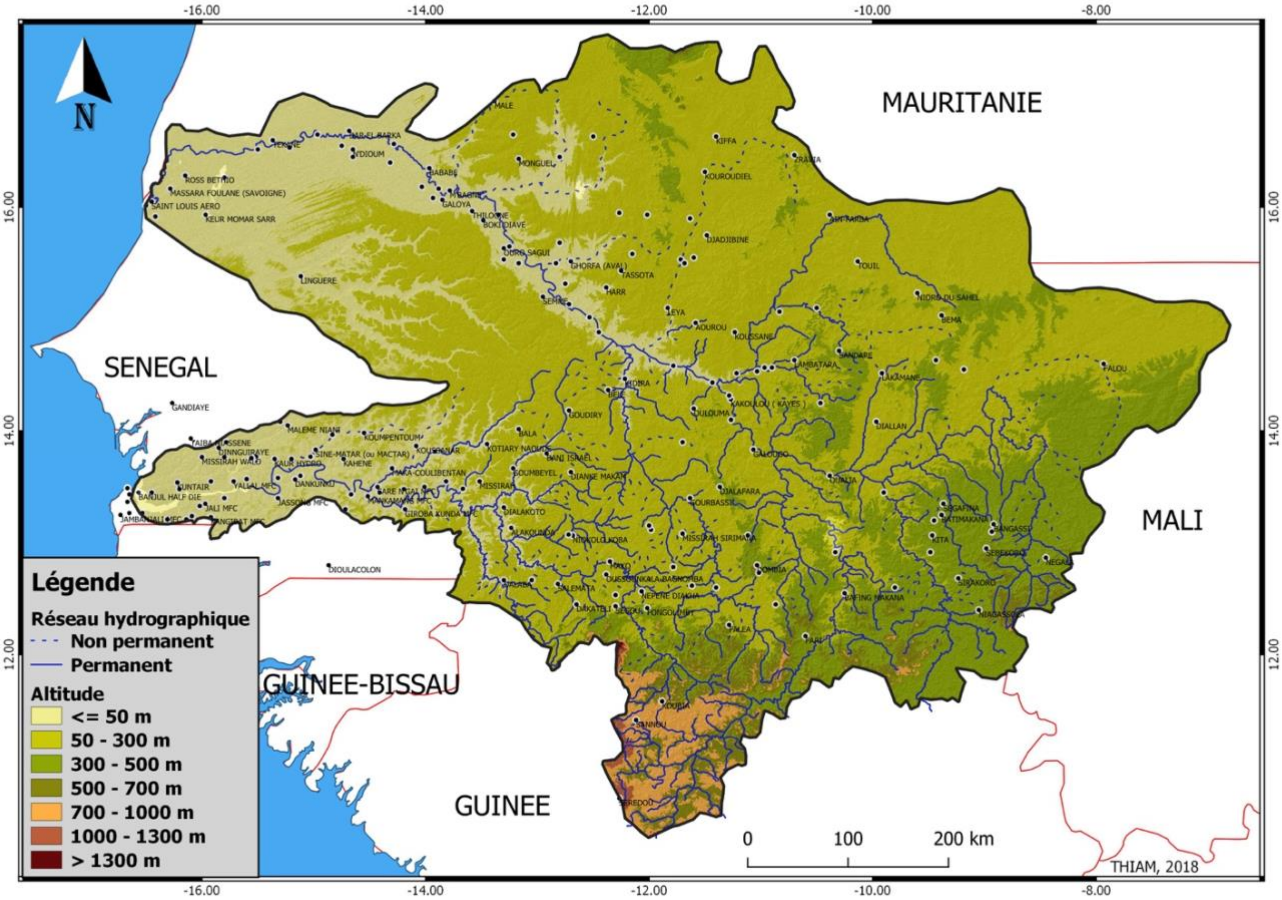


Figure 1: Presentation of studied area: Senegal River Basin and Gambia River Basin (Thiam, 2018)

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 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.

Physiography

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 m³ per year. Estimations of the available potential vary between 330 billion m³ and around 450 billion m³, 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 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).

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).

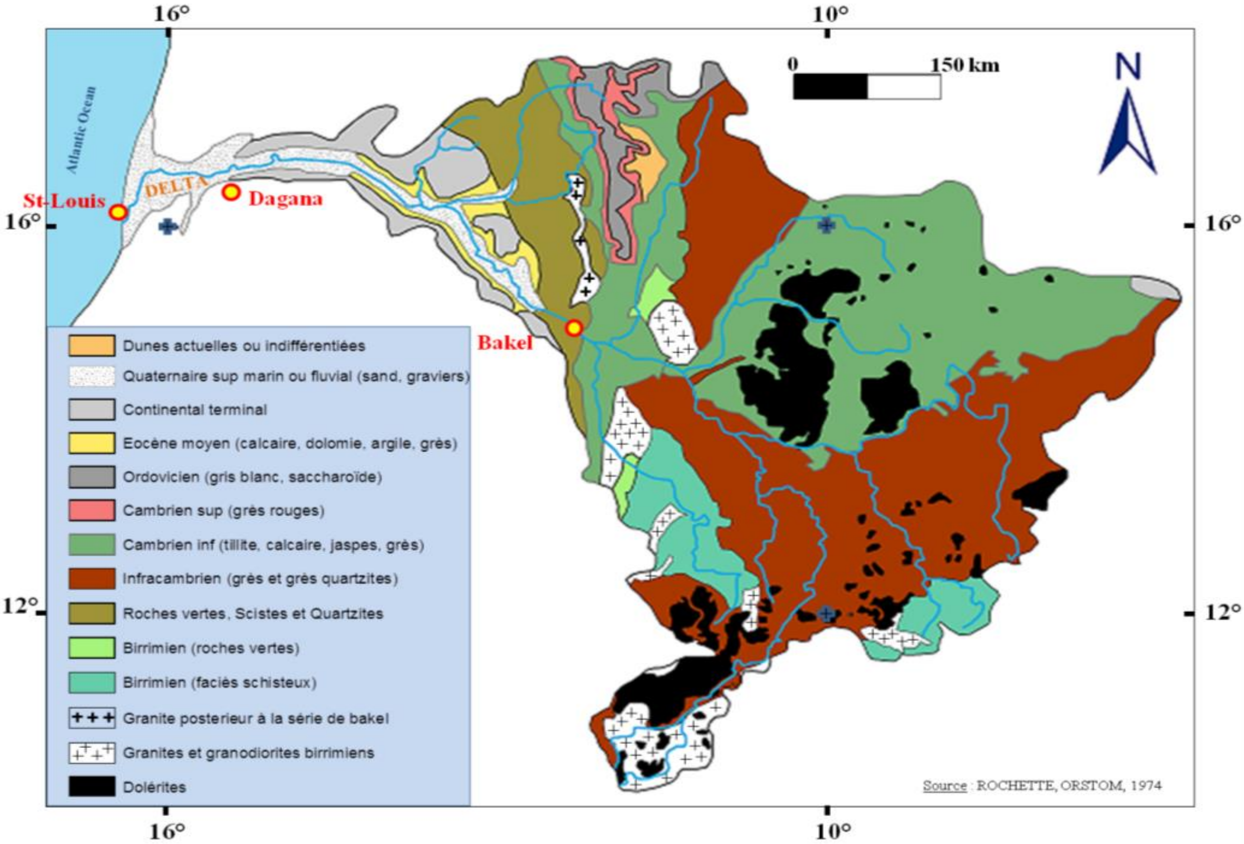


Figure 2: Geological Map of Senegal River Basin

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 sedimentary senegalo-mauritanian 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.

Socio-economic aspects

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 (inh/Km²)	Fertility Rate	Medium Age	Urban Population	HDI 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 $ton.ha^{-1}$, 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 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.

Governance and Water Resources Management

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 bed load.

Bed load 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 bed load 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 bed load. 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 (SS) varies from 25 to 250 $mg.l^{-1}$ when the flow rate varies from 800 to 2500 m3/s. 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.

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 m³. The OMVG Energy Project is 85% funded by the Chinese Group EPC; the rest is supported by all OMVG countries.

Diama dam Salt barrier (Senegal)

Manantali Regulatory dam (Mali)

Regulatory Felou dam

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

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 organs 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.

The Western African database on Climate variability

Updating of hydro-climatic database

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 Basin.

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.

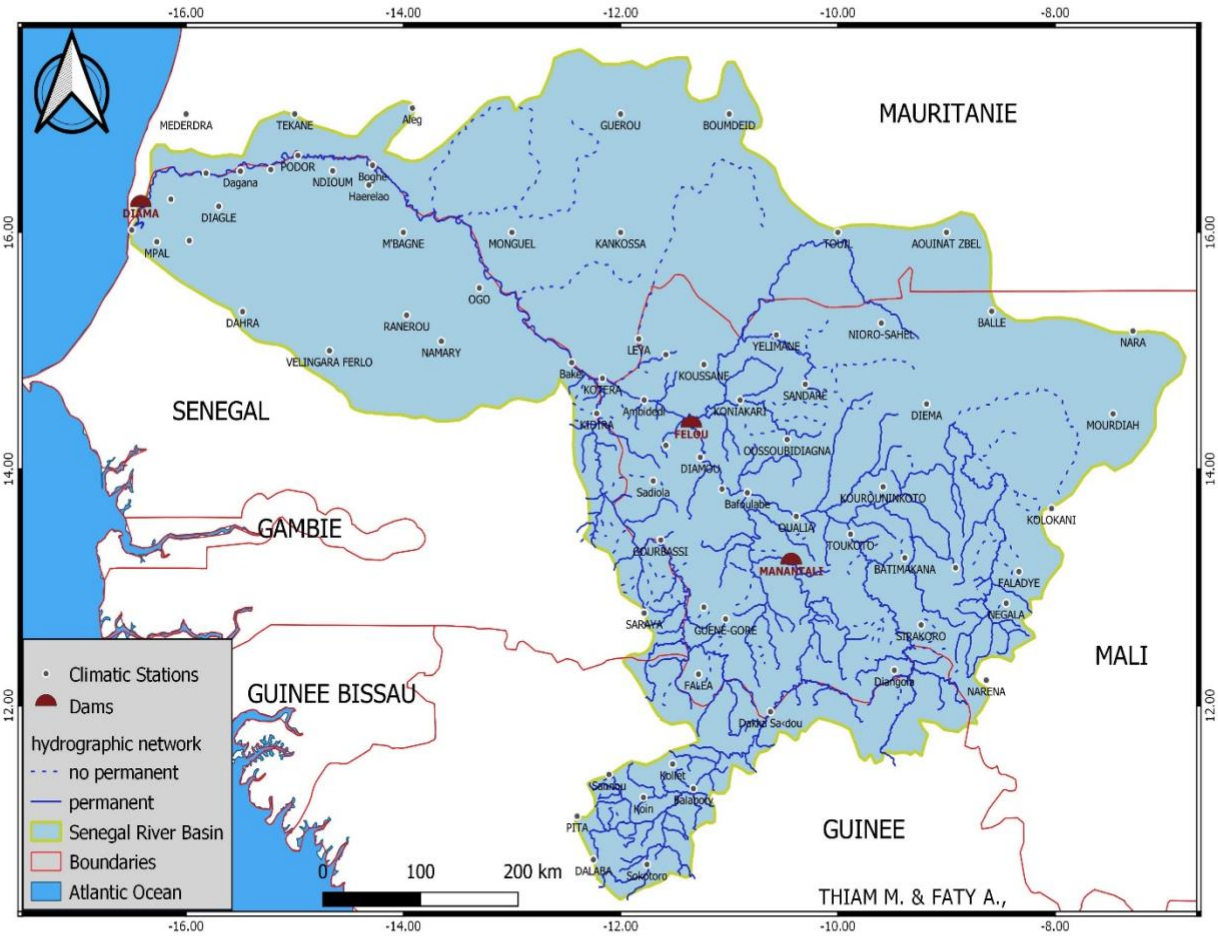


Figure 4: Ground stations for rainfall data measurements in the Senegal and Gambia River Basins

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 (77000 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 (Figure 5).

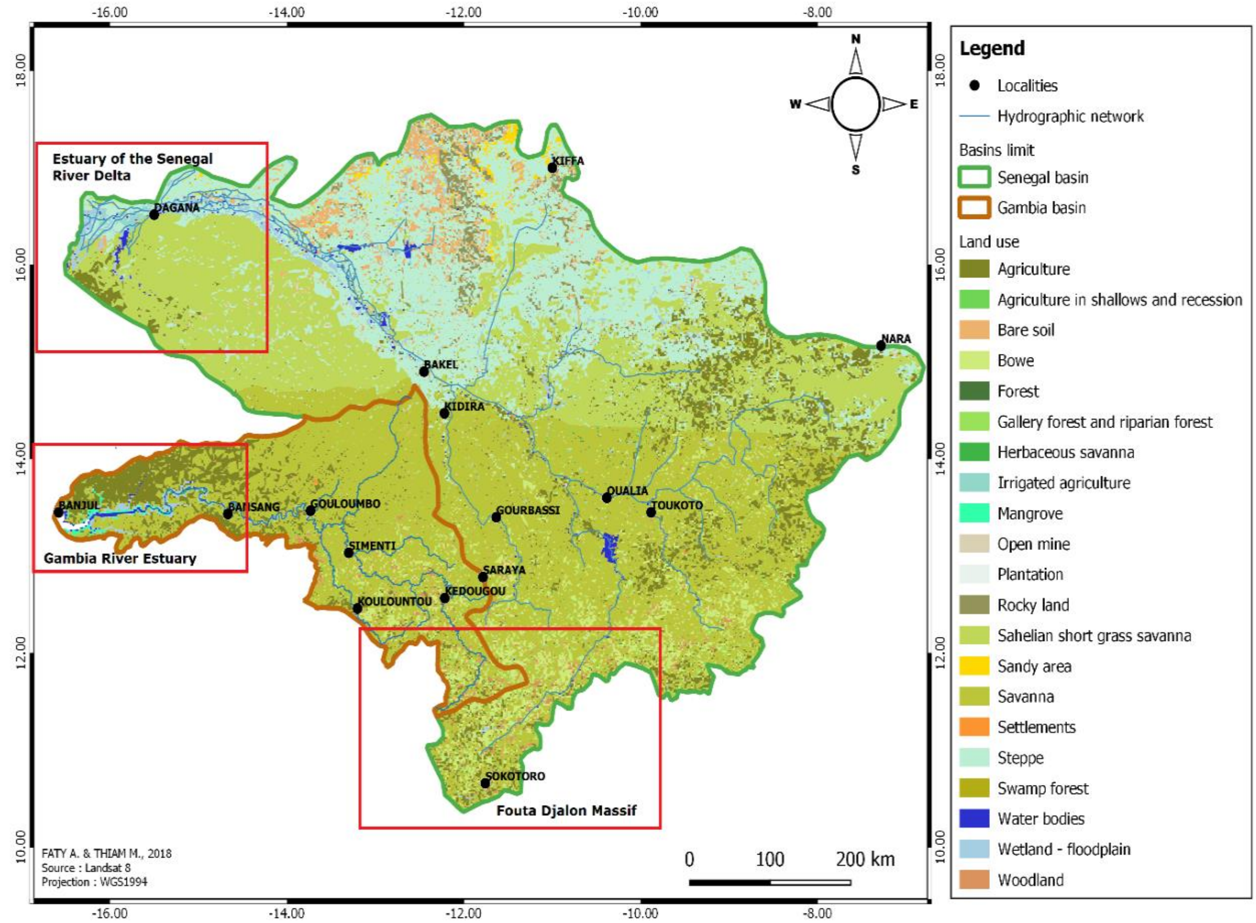


Figure 5: Land cover of the Senegal River Basin and Gambia

For both basins, digital elevation models were constructed from the SRTM90 data (Figure 6). The objective is to obtain more precise elevation data from national or international agencies such as the National Direction of Geographical and Cartographic Works of Senegal or IGN France. The objective of using remote sensing is to determine land use in the context of climate change and variability in the Senegal River Basin and The Gambia. Combination with the available cartographic data (watershed boundaries, hydrographic networks…), will help to establish a good knowledge database for these two basins.

Regarding socio-economic, some data are available through basins organizations (OMVS and OMVG) and, for Senegal country level, through the National Statistic and Demography Agency (ANSD).

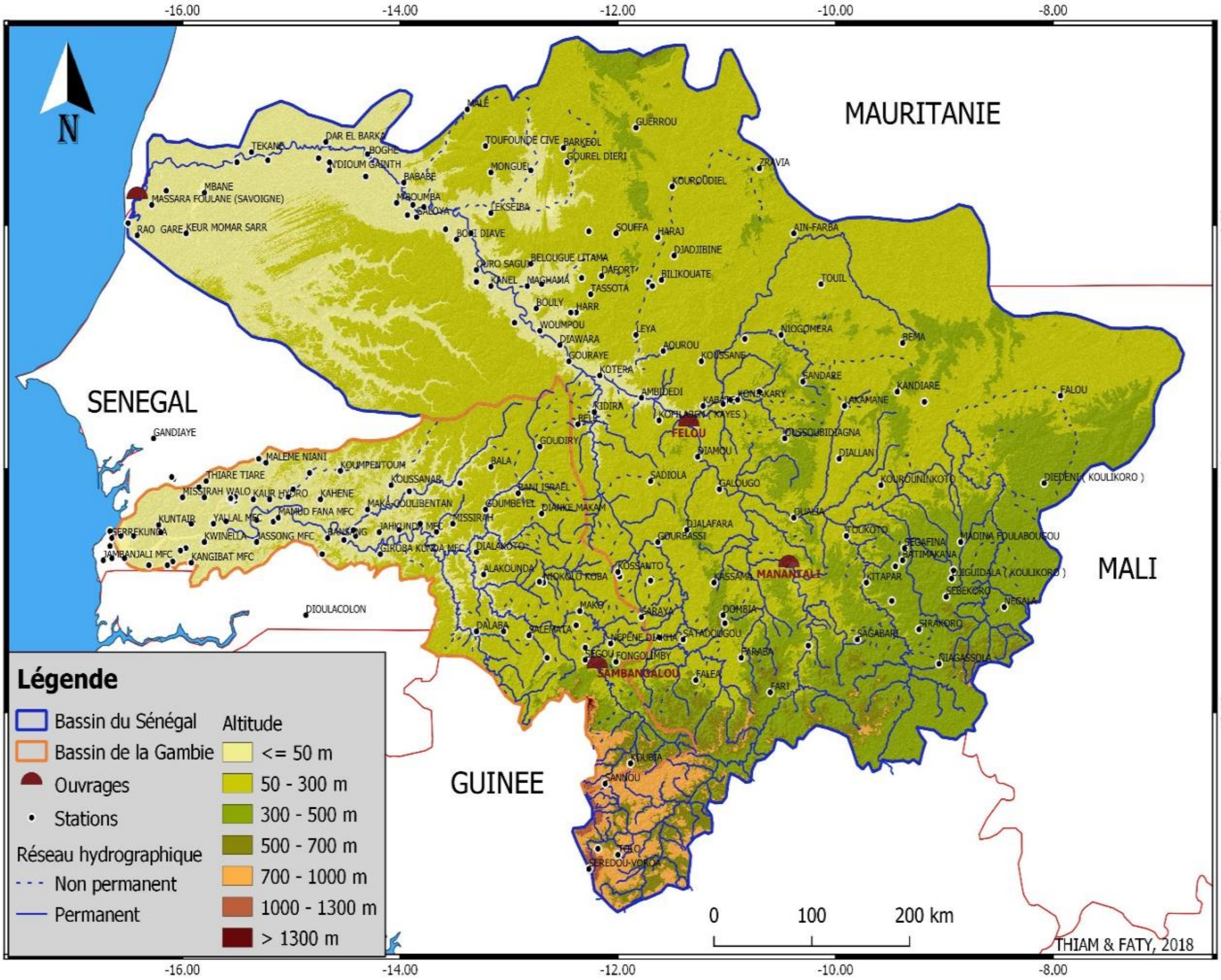


Figure 6: Digital Elevation Model of Senegal and Gambia River Basins from SRTM 90m

Methodological approach

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 meteorological 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 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	Hydraccess OMVS
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 analyzes 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 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
Iinfluence 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

Analysis 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.

Climate variability analysis in the Senegal River Basin

State of the art on climate variability in West Africa

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 (GIEC, 2007) and thus, the most exposed to the climatic risks.

In West Africa, knowledge on the evolution of the climate is still stammering and often contradictory. Indeed, there is a divergence between the forecasting climate models: some project a significant d of precipitations; others a progressive return of moisture with an extension of the vegetation in the Sahara (IPCC, 2007).

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, in Mali, to 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.

Preliminary analysis of the climate of the Senegal River Basin

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.

Figure 7: Hydro-climatic stations of the Senegal River Basin

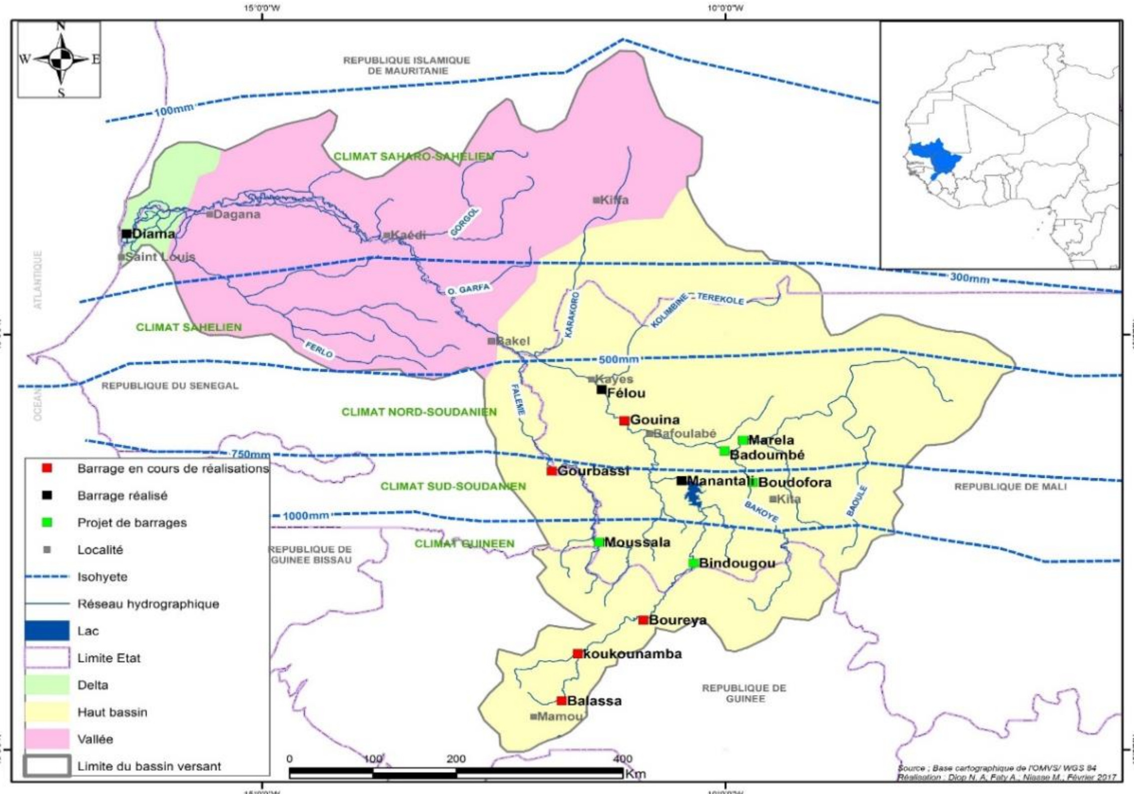


Figure 8: Map of the subset of the SRB and the variation of the isohyets

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.

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 9).

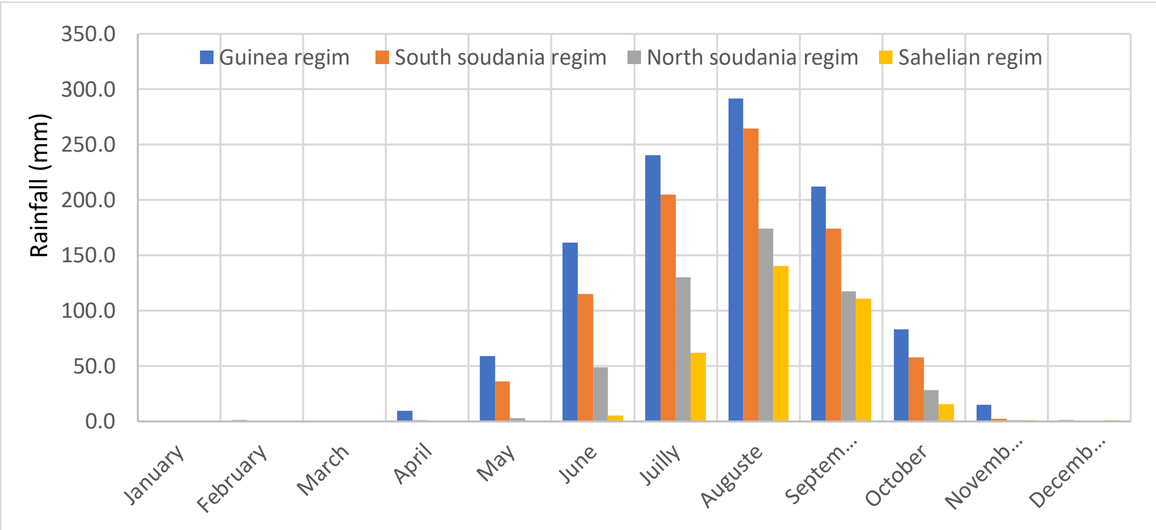


Figure 9: Average monthly rainfall by climatic zone

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 9 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).

Presentation and processing of available data

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.

Climatic data

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

Rainfall

The pluviometric 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), 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 10 shows the distribution of hydro-climatic stations and the duration of observations of these stations in the Senegal River basin.

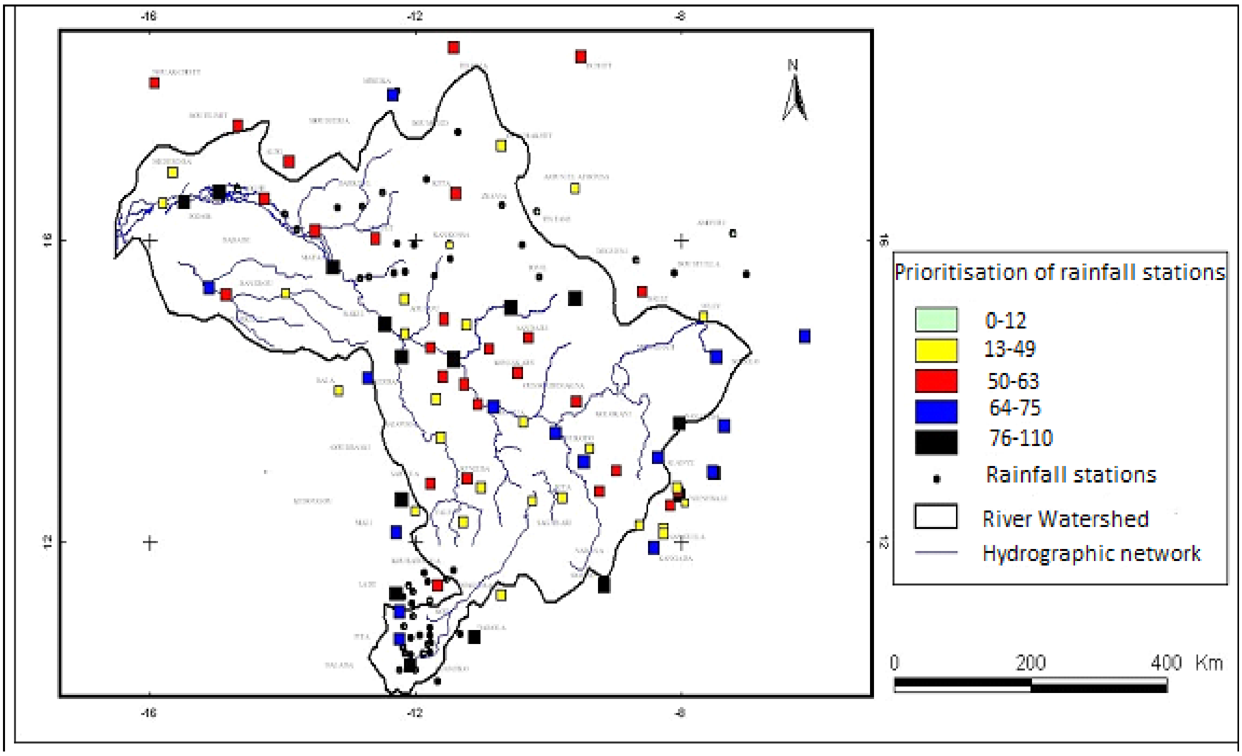


Figure 10 : Map of the rainfall network of the Senegal River basin

Analysis of climatic parameters

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 provided by the OMVS Observatory cover the period 2002 to 2016. The data for Kédougou go from 1968 to 2016 and for Bakel from 1981 to 2016.

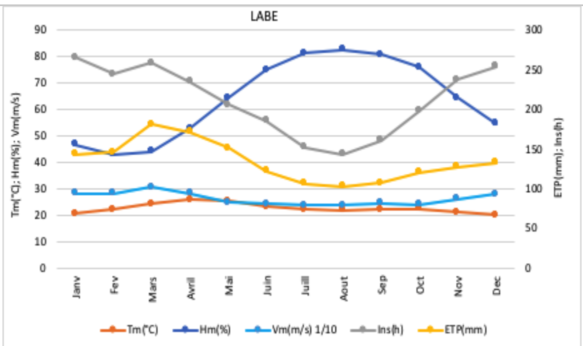
Table 5 and Figure 11 show the variations in climate parameters at the study stations. They show the division of the year into two parts:

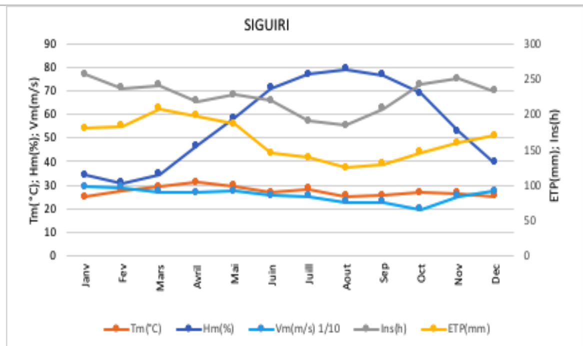
- from November to April: the dry season with the increase in the annual average temperature, potential evapotranspiration and sunstroke
- May to October: the rainy season with a sudden drop in sunstroke, potential evapotranspiration and a sharp increase in relative humidity due to the increase in cloud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

In Labé, 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





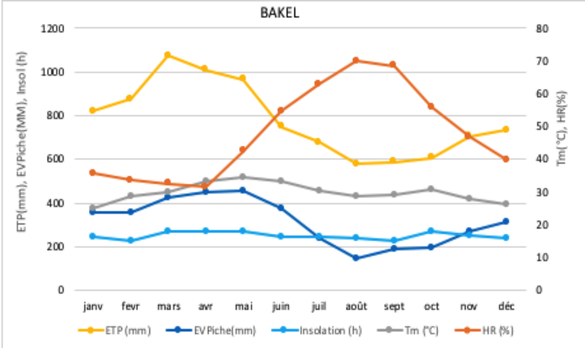


Figure 11: Monthly variation of climatic parameters

As an illustration, the wind rose at Labé station (Figure 12) 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.

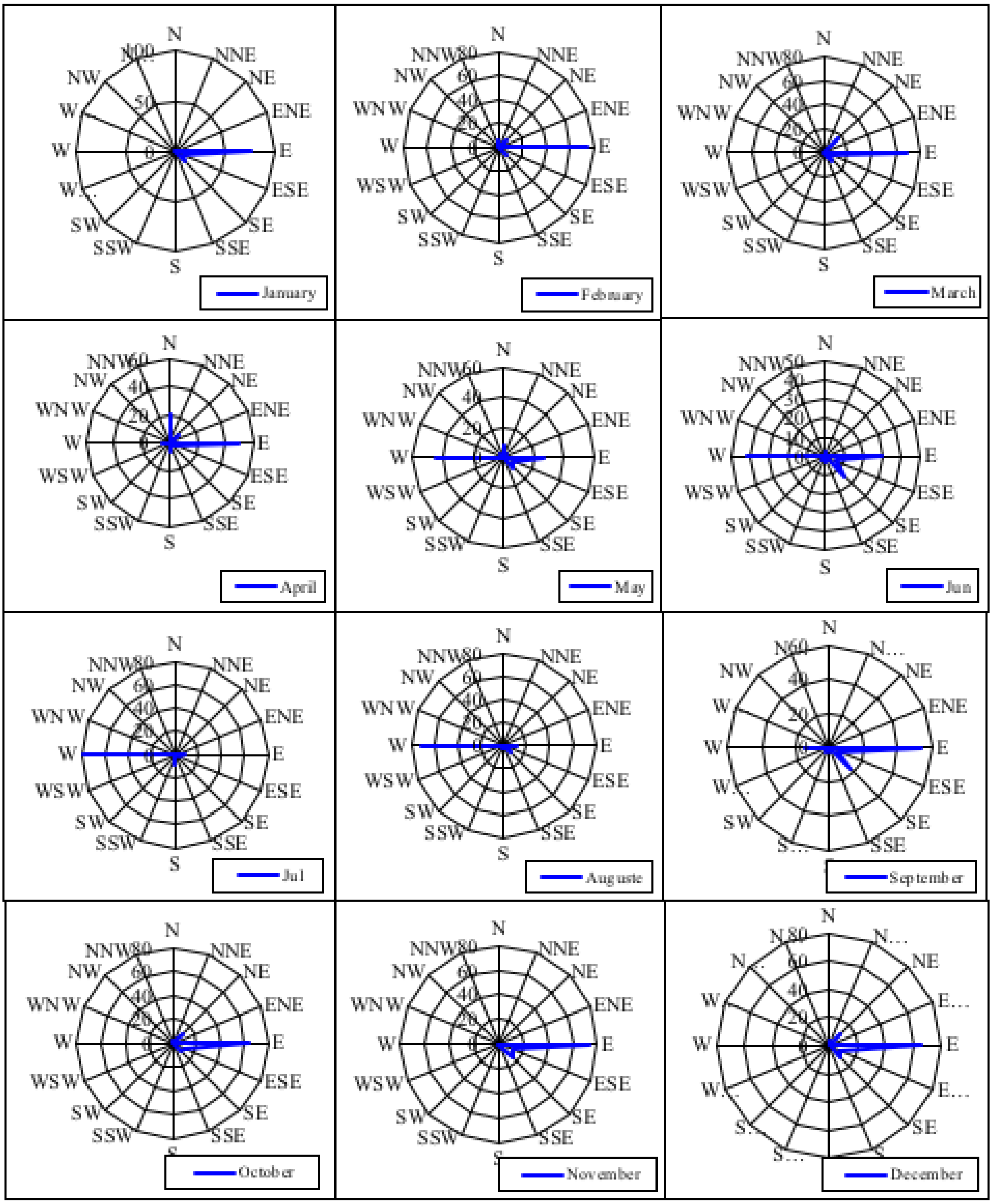


Figure 12: Wind rose at Labé Station

Rainfall analysis

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.

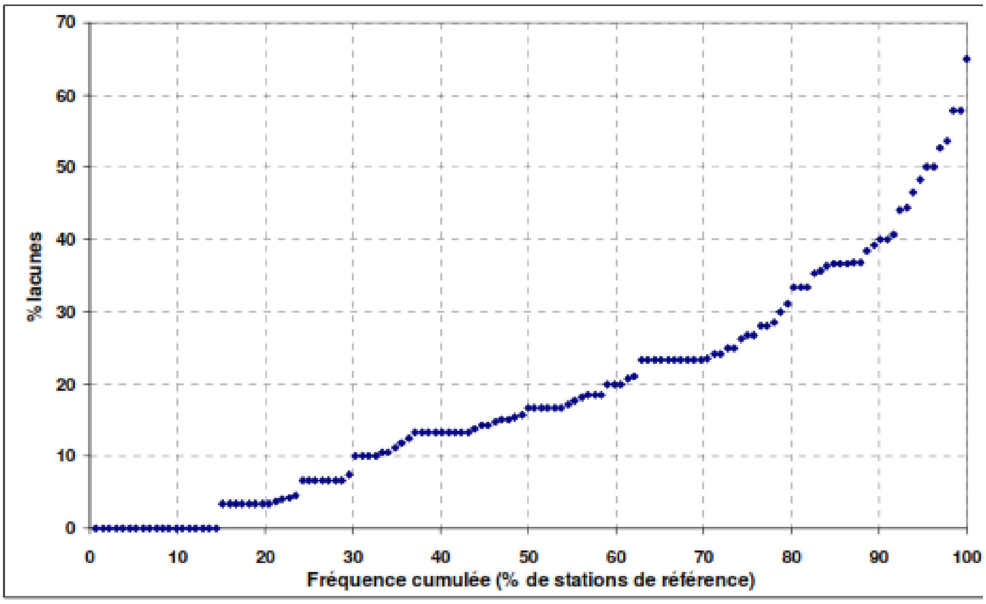


Figure 13: Percentage of gaps in extreme events

Variations in rainfall

Changes in rainfall can be assessed through fluctuations in the indices of the regional vector. Figure 14 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.

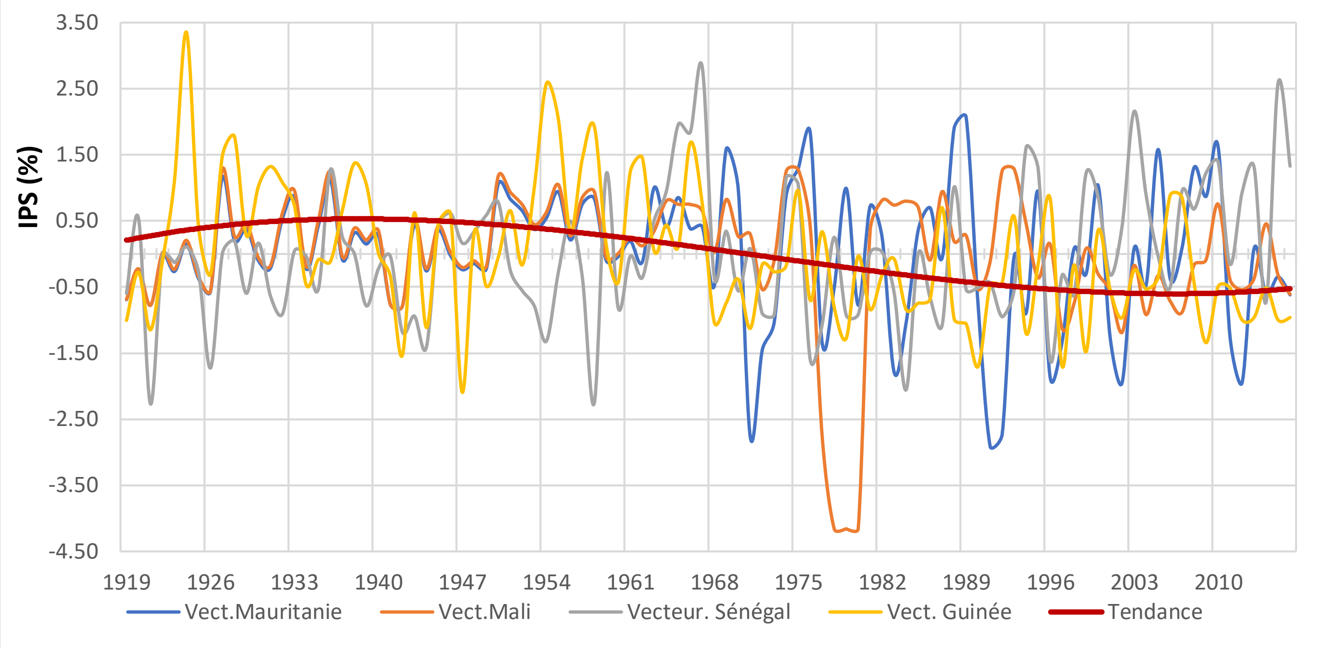


Figure 14: Changes in the indices of the three regional vectors from 1919 to 2016.

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.

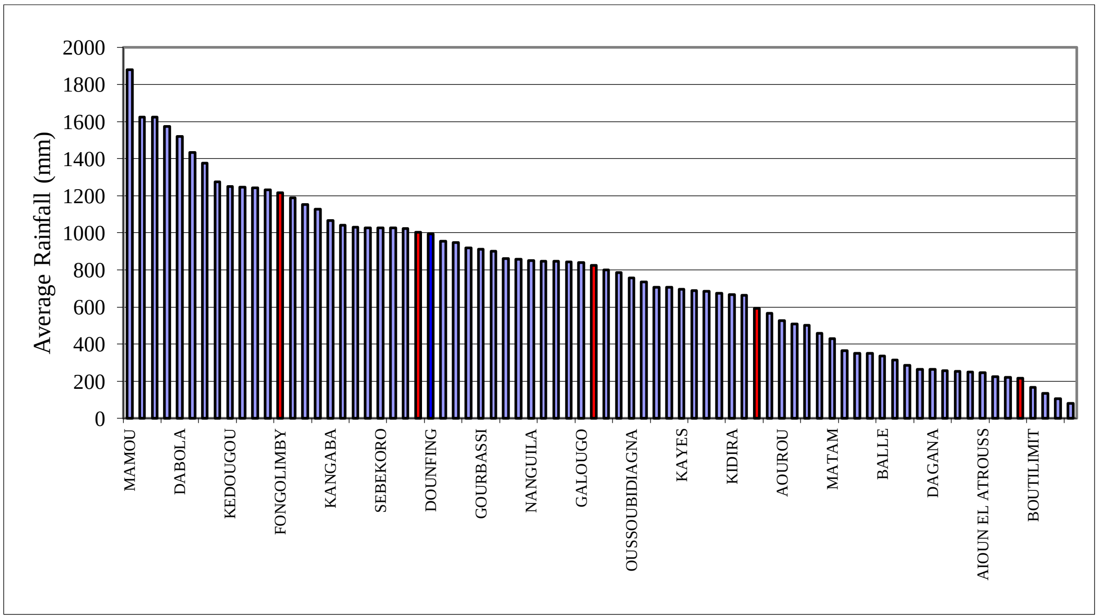


Figure 15 : Average rainfall per station over the period 1919-2016).

The decrease in annual rainfall is gradual with latitude. A correlation latitude - average rainfall shows a functional relationship between the two parameters. Figure 9 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.

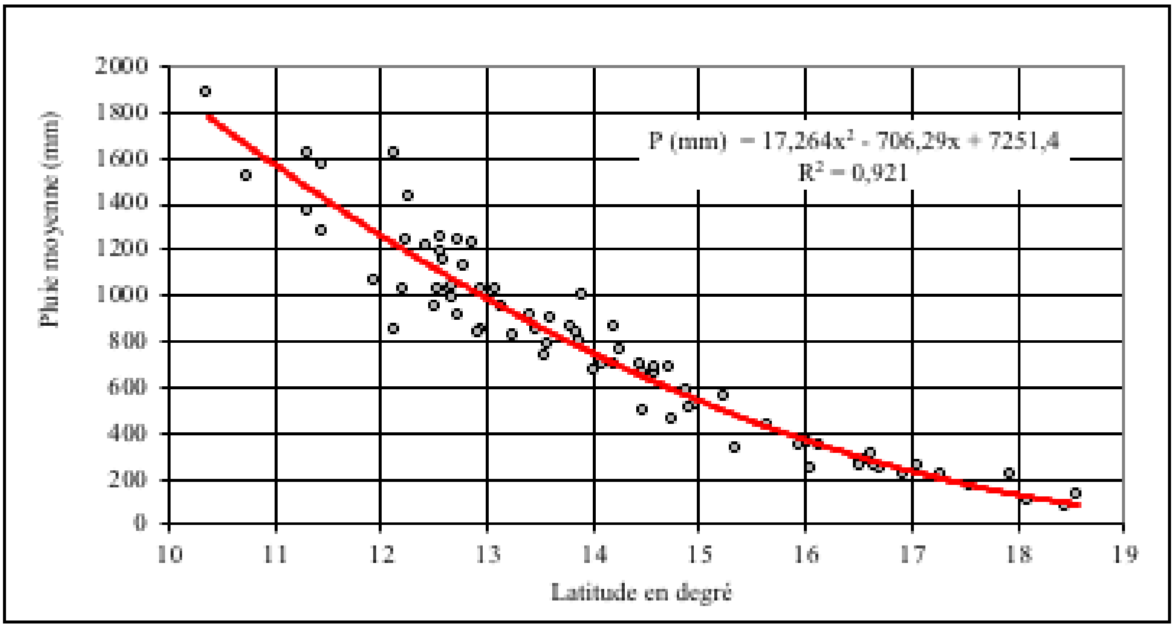


Figure 16: Correlation between precipitation and latitude (in degrees)

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 10 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.

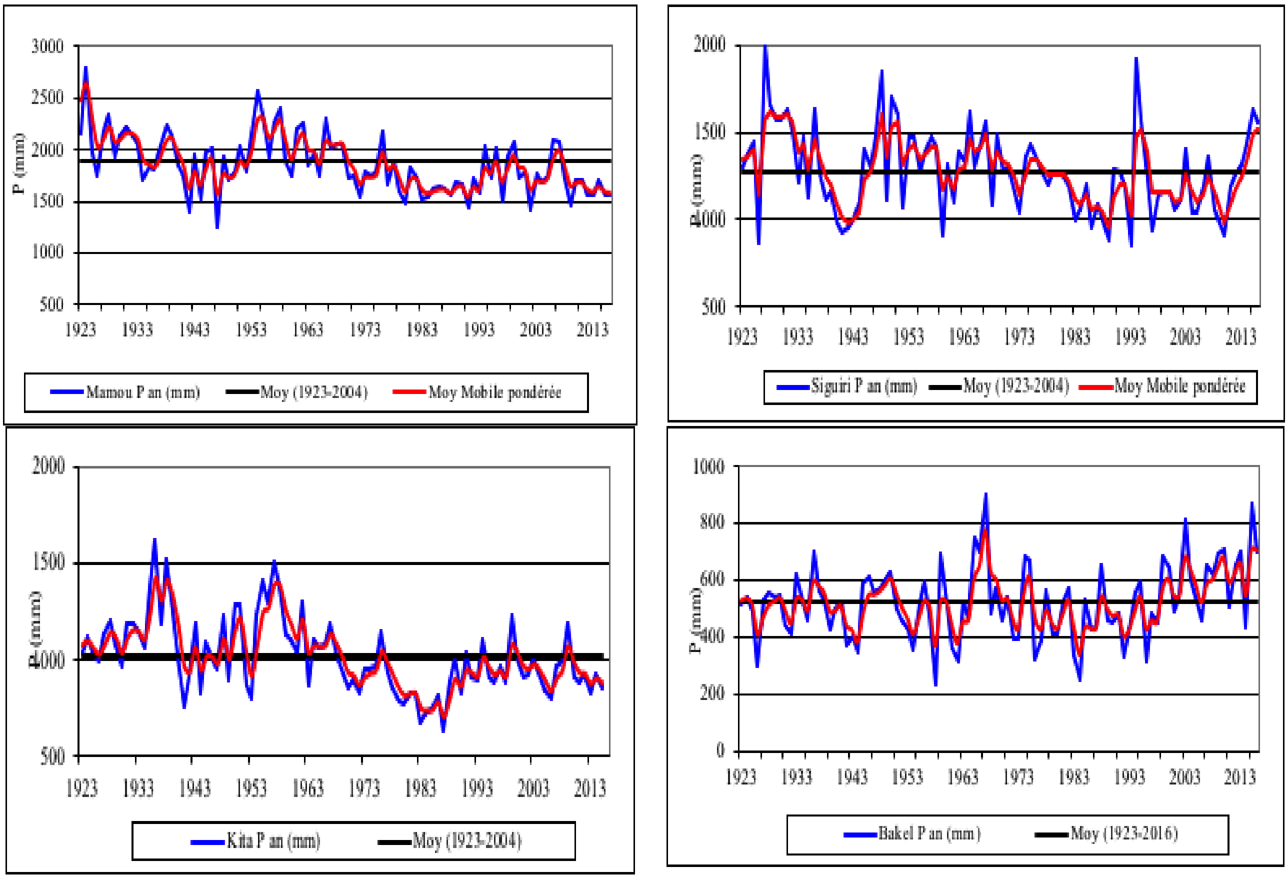


Figure 17 : Annual rainfall variations (in millimeter) in Mamou, Siguiri, Kita, Bakel and Kayes.

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.

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 18). 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

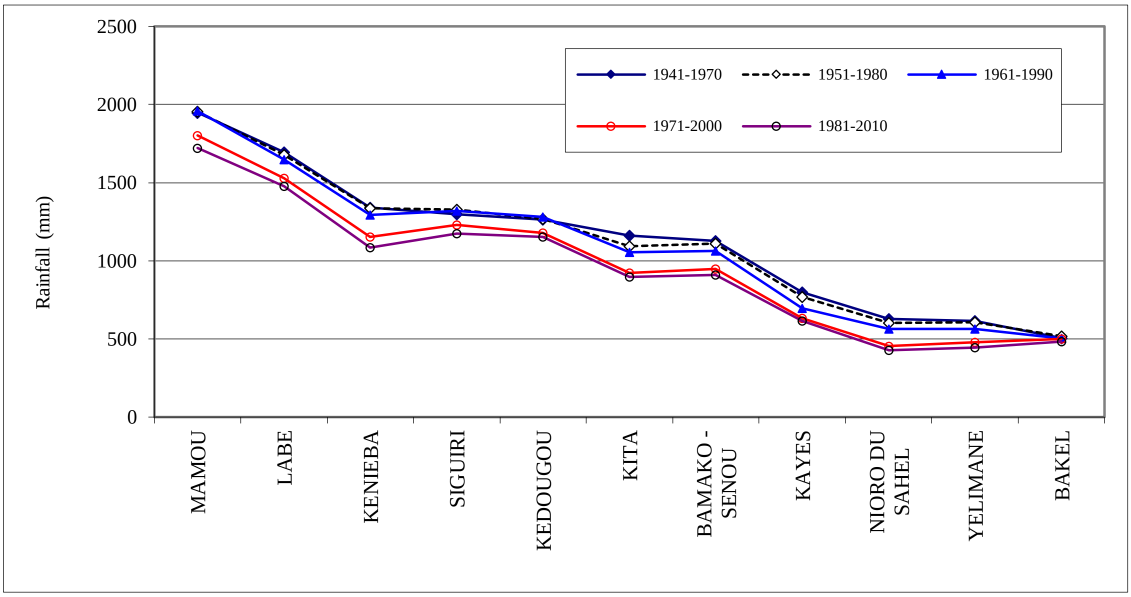
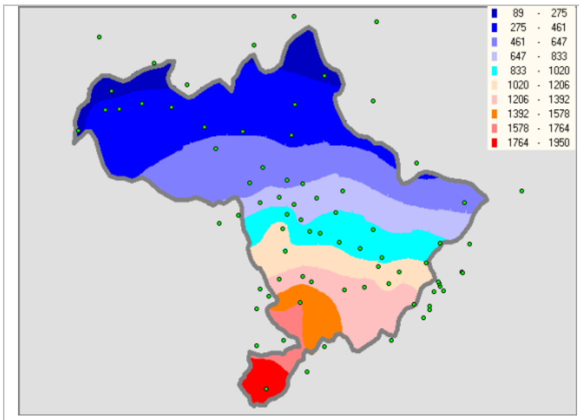


Figure 18 : Variations of the thirty-year rainfall averages at the synoptic stations

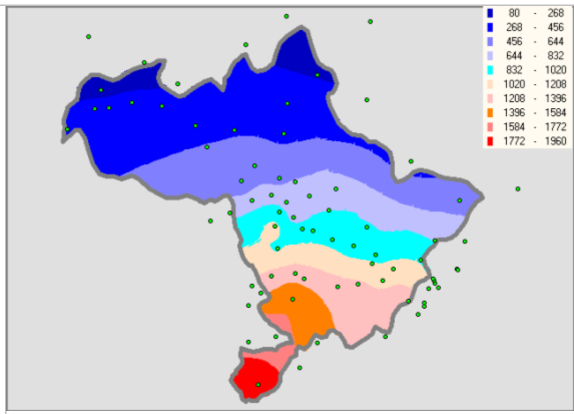
For all the stations in the basin, the 30-year averages were calculated and presented in the form of maps (Source: Senegal River Monograph, 2011
Figure 19).

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.

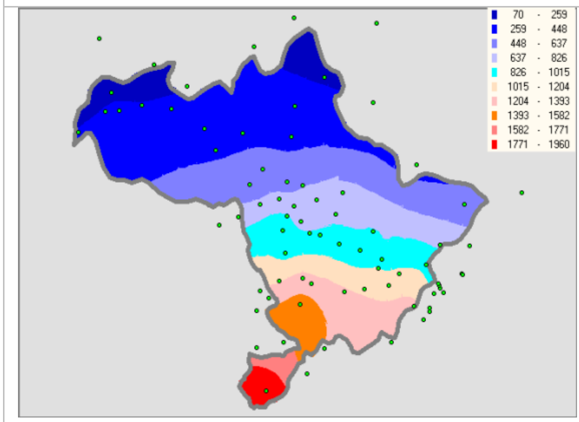
The fairly zonal distribution of precipitation is noted in accordance with the decreasing south-north rainfall gradient. In the north of the basin, the average rainfall fell from 90 mm (1941-1970) to 50 mm in 2010, representing a 45% decrease in rainfall. In areas with low rainfall, such a decrease has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



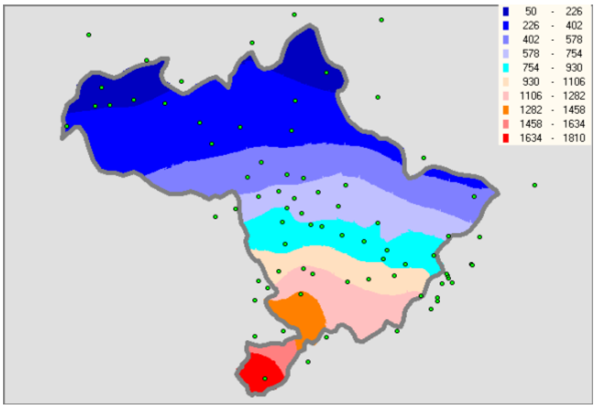
Normale 1941-1970



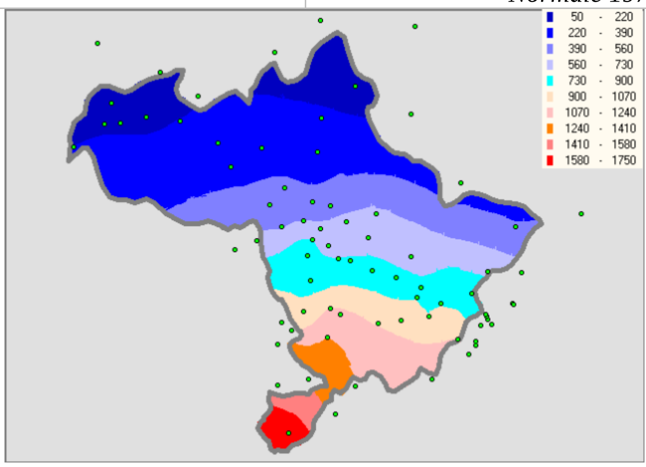
Normale 1951-1980



Normale 1961-1990



Normale 1971-2000



Normale 1981-2000

Source: Senegal River Monograph, 2011

Figure 19 : Spatial distribution of precipitation (30-year average) over the basin (in millimeters)

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.

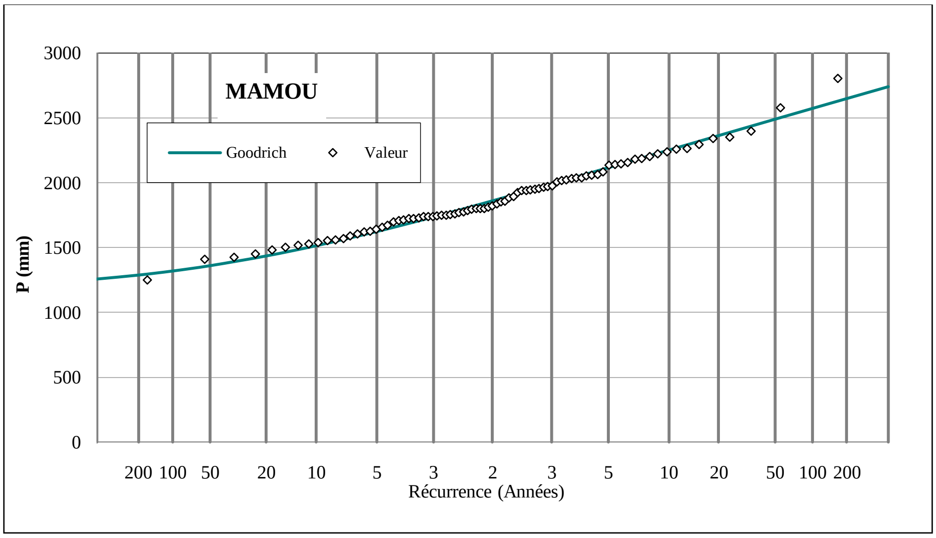
In the median year, rainfall of more than 1500 mm can be expected. At Bakel station, the median frequency of rainfall is 500 mm, a third of what is expected in the upper basin. Rodier's K3 ratio (ratio between wet and dry decadal years) is illustrative of the variation in recurrent rainfall. In the basin, 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

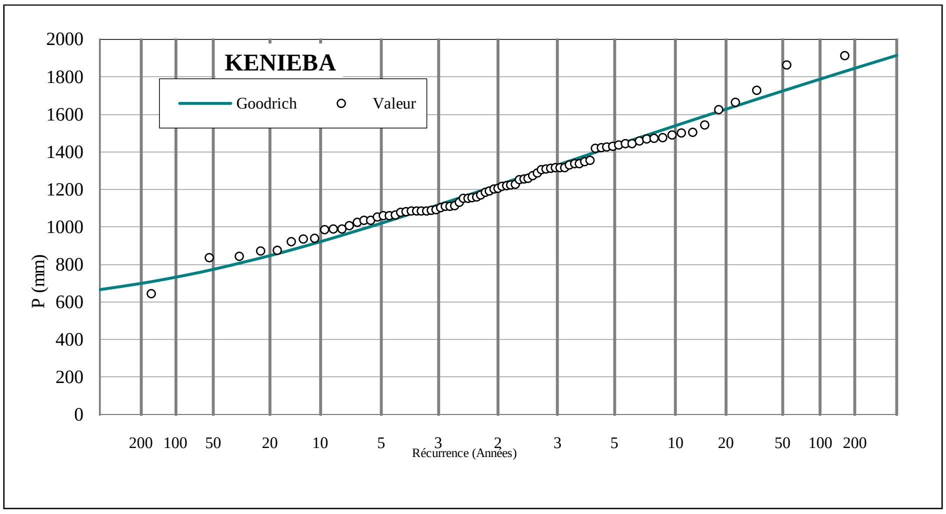
in Matam). In dry recurrences, such as the dry centennial, if for the high basin the rainfall contributions are still significant (above 1000 mm), they become very low, even random, in Bakel and Matam.

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 (Table 8).





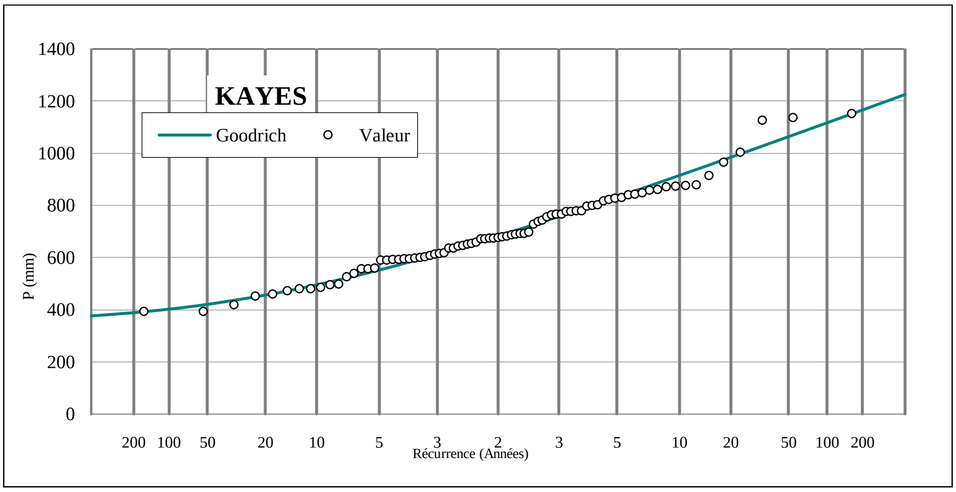


Figure 20 : Statistical adjustment of annual rainfall in Mamou, Kenieba and Kayes (1923-2016)

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

Decennial 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.

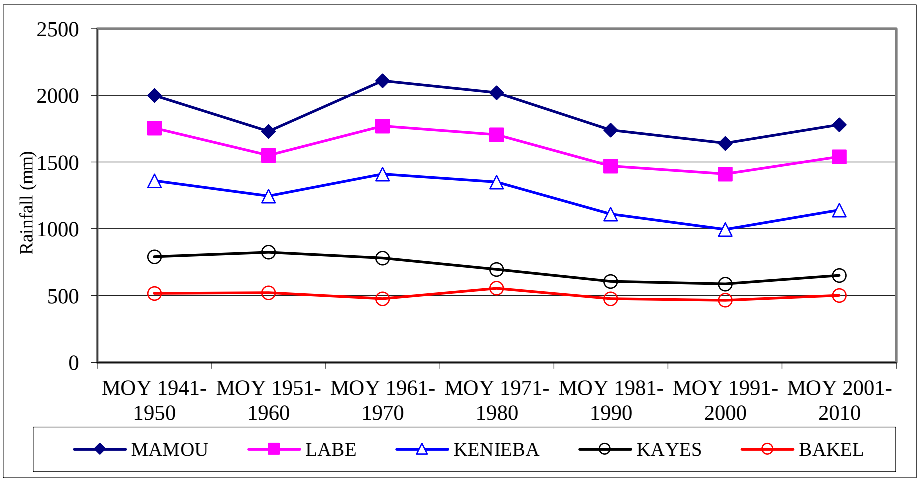


Figure 21 : Variations in ten-year average rainfall at a few stations in the basin.

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.

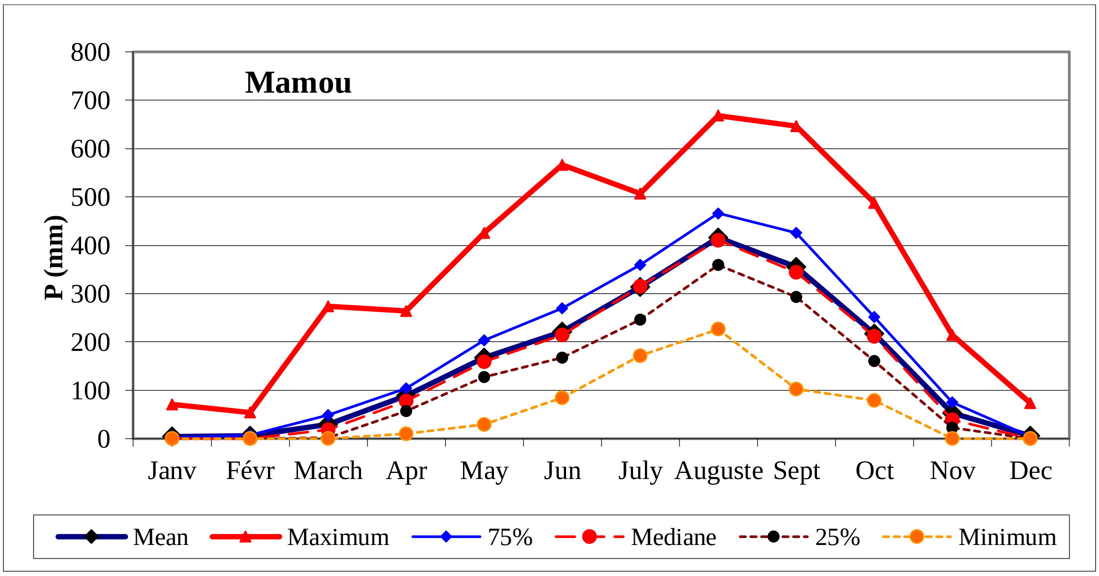
The length of the rainy season in the basin allows a permanent supply to the hydrographic network, which contributes to the sustainability of the river's flows and the recharge of groundwater.

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. Figure 22 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

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Mamou													
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
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



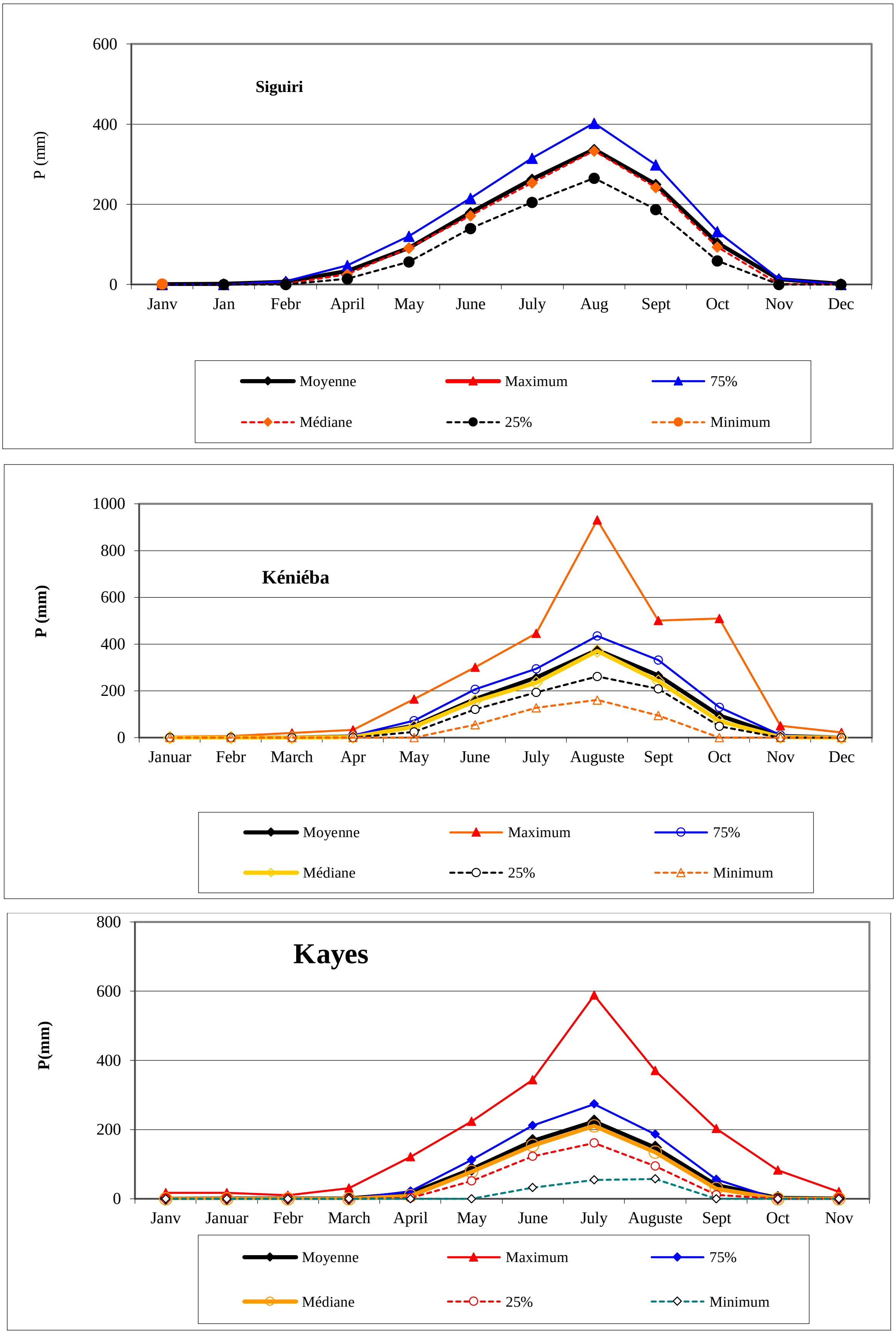


Figure 22 : Monthly rainfall profiles of Mamou, Siguiri, Kéniéba and Kayes.

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.
	Γγ , 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).

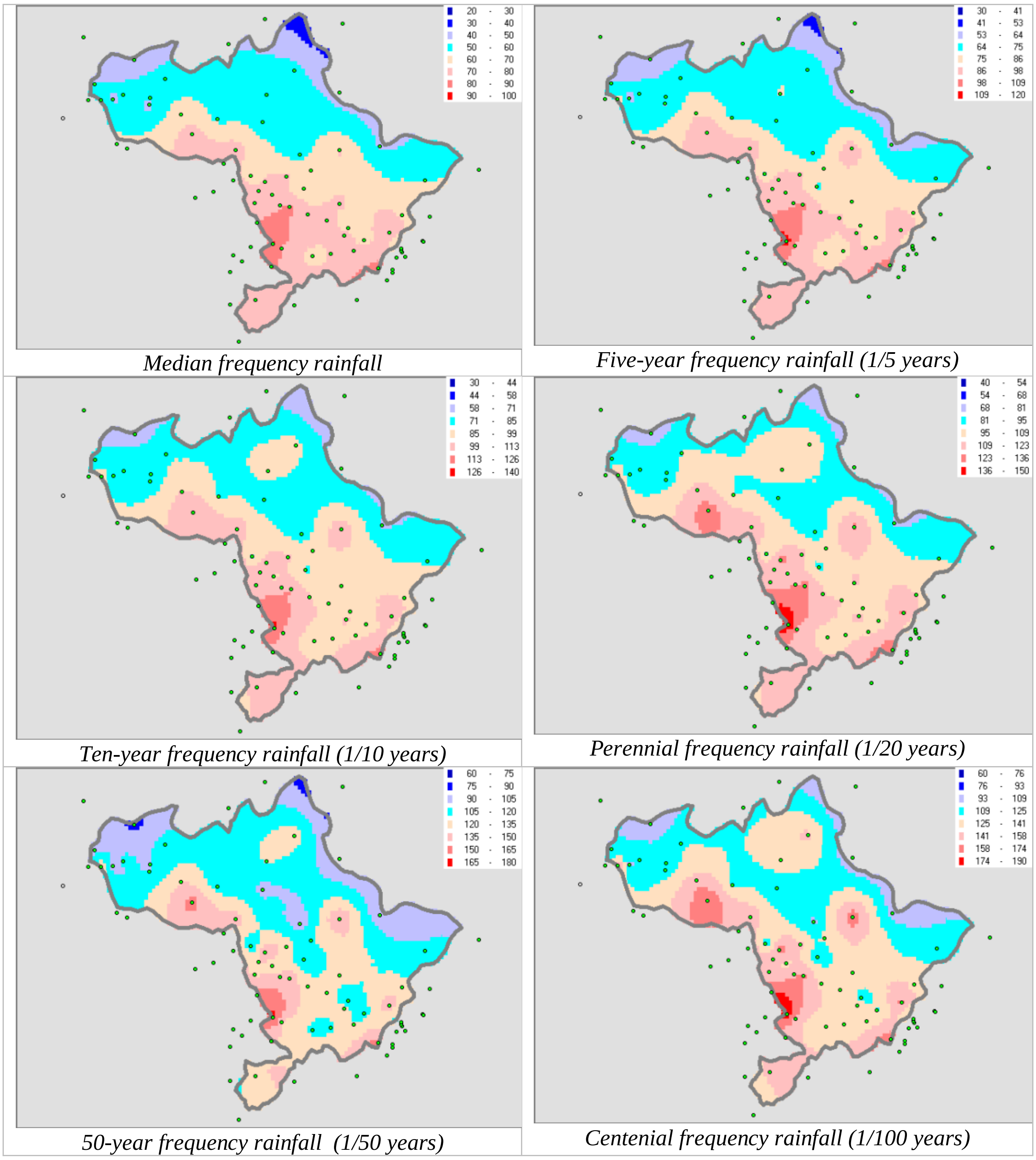
The results of the adjustment of the truncated Pearson III law to daily rainfall are recorded in the Table 11 below.

Table 11: Quantiles of recurrent daily rainfall analysed from Hydraccess

Frequency	**0,5000**	**0,2000**	**0,1000**	**0,0500**	**0,0200**	**0,0100**
Recurrence (year)	**2,0**	**5,0**	**10,0**	**20,0**	**50,0**	**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

Frequency	**0,5000**	**0,2000**	**0,1000**	**0,0500**	**0,0200**	**0,0100**
Recurrence (year)	**2,0**	**5,0**	**10,0**	**20,0**	**50,0**	**100,0**
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
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 23 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)*

Source: Hydrological monograph of the Senegal River, 2011

Figure 23 : Spatial distribution map of daily frequency rainfall (mm) over the Senegal basin.

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.

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
- Labé 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	Equipement that exists
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
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

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 3000 and 12000 $m^3.s^{-1}$, 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 8300 $m^3.s^{-1}$ in Bakel, is only 6500 $m^3.s^{-1}$ in Matam and 3200 $m^3.s^{-1}$ 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.

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 24 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 24 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.

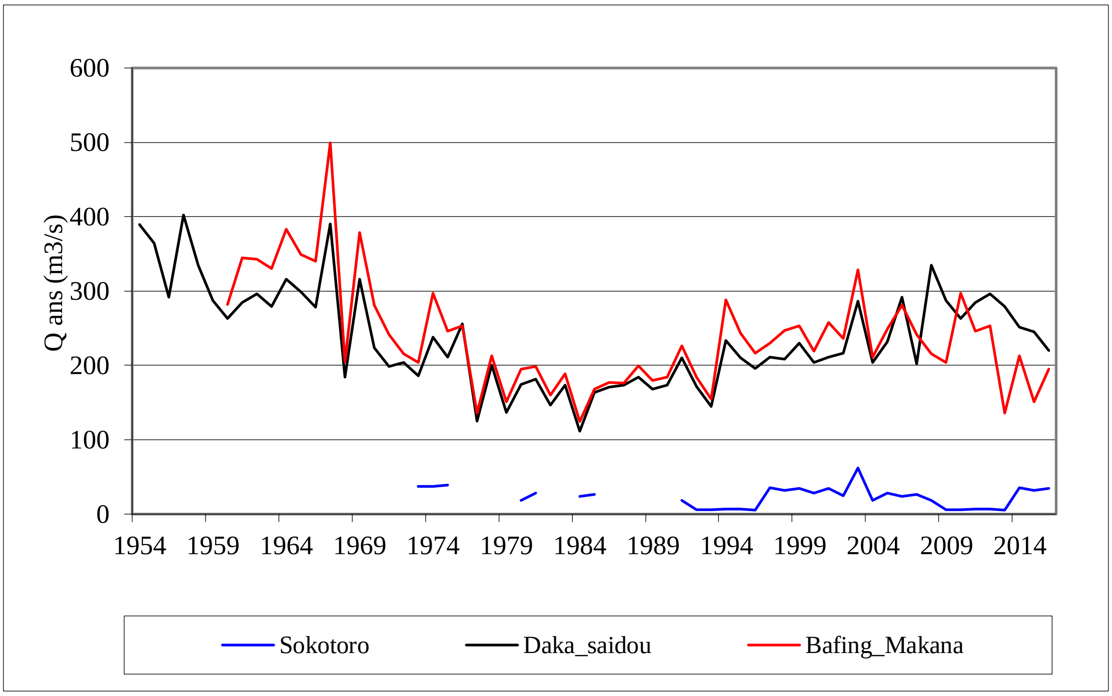


Figure 24 : Variations of the annual modules of Bafing in Sokotoro, Daka-Saidou and Bafing Makana.

Characterization of hydrological drought in the 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).

Methodological approach

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). Then a study of the flow regime to assess the level of drought in the two 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).

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 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 (Faty et al., 2017): $T = \frac{1}{k}$

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.

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 range 0 to +∞: $V_{mobilisé} = \int_0^t Q_0 e^{-kt} dt = \frac{86400 * Q_0}{k}$

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.

Hydrological drought index method

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:

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

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 sequence	HLB value	Wet sequence
0.00< IHN <-0,99	Slightly dry	0.00< IHN <0.99	Slightly wet
-1.00< IHN <-1.49	Moderately dry	1.00< IHN <1.49	Moderately wet
-1.50<IHN<-1.99	Severely dry	1.50< IHN <1.99	Severely wet
IHN < -2.00	Extremely dry	2.00< IHN	Extremely wet

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:

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

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.

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:

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

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).

Table 16: Classification of drought sequences according to the ILDH

ILDH value	Drought sequence	HLB value	Wet sequence
0.00< ILDH <-0.99	Moderately dry	0.00< ILDH	Moderately wet
-1.00<ILDH<-1.99	Heavily dry	1.00< ILDH	Heavily wet
ILDH < -2.00	Extremely dry	2.00< ILDH	Extremely wet

Analysis of the watercourse regime

The interannual evolution of Gambia's average daily flows, illustrated in Figure 25 and Figure 26, 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 25 and Figure 26), 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 $m^3.s^{-1}$.

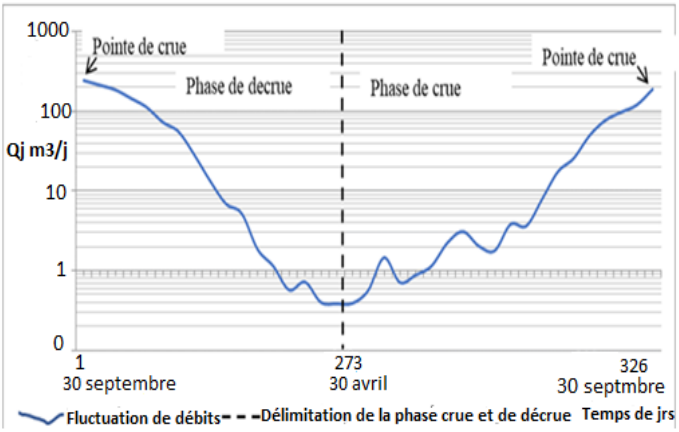


Figure 25: Fluctuation of interannual daily average flows at Bansang station (1982-2016)

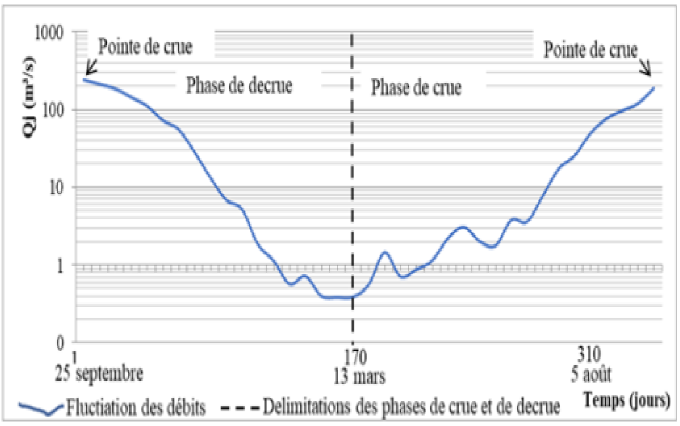


Figure 26: Fluctuation of interannual daily average flows at the Oundou Bac station (1982-2016)

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 27 (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 27).

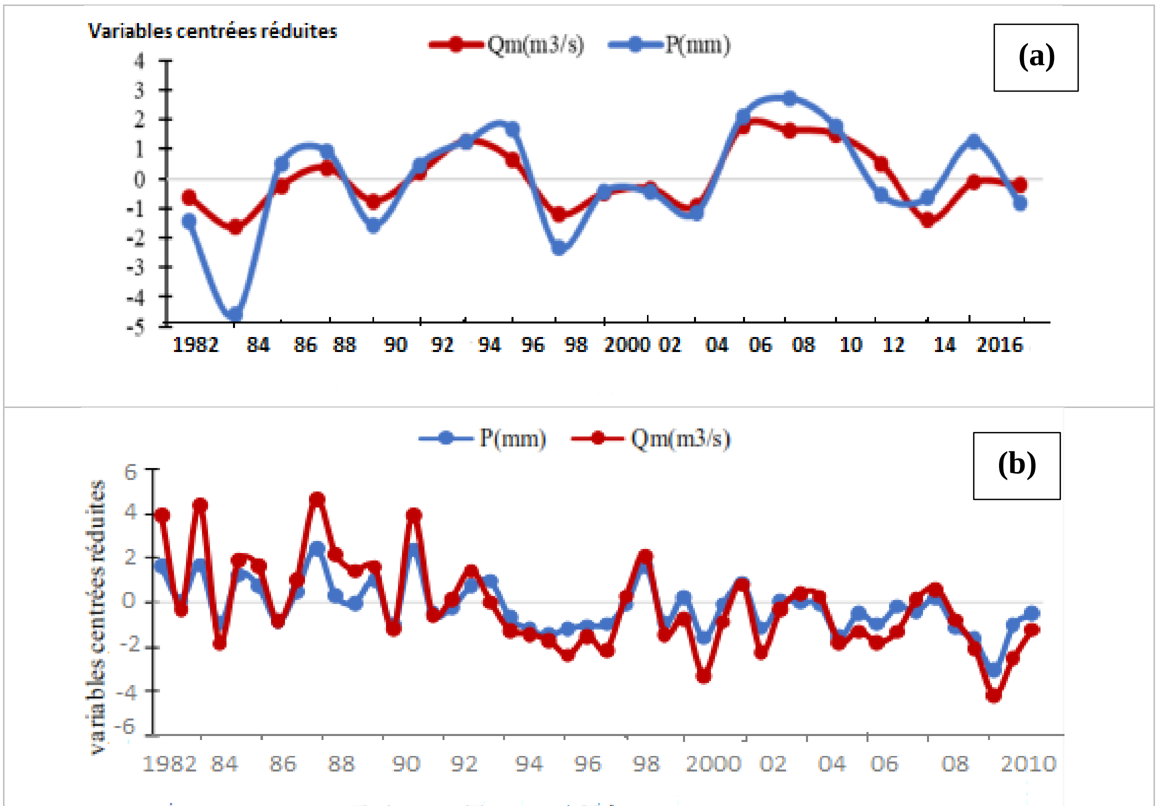


Figure 27: Variation in the drying coefficient and annual volume of water mobilized at Bansang (a) and Oundou Bac (b) stations (1982-2016)

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}. The volumes of water mobilized vary between 0.08 and 2.67 km³, with an average of 1.33 km³. 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 28a).

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 28b).

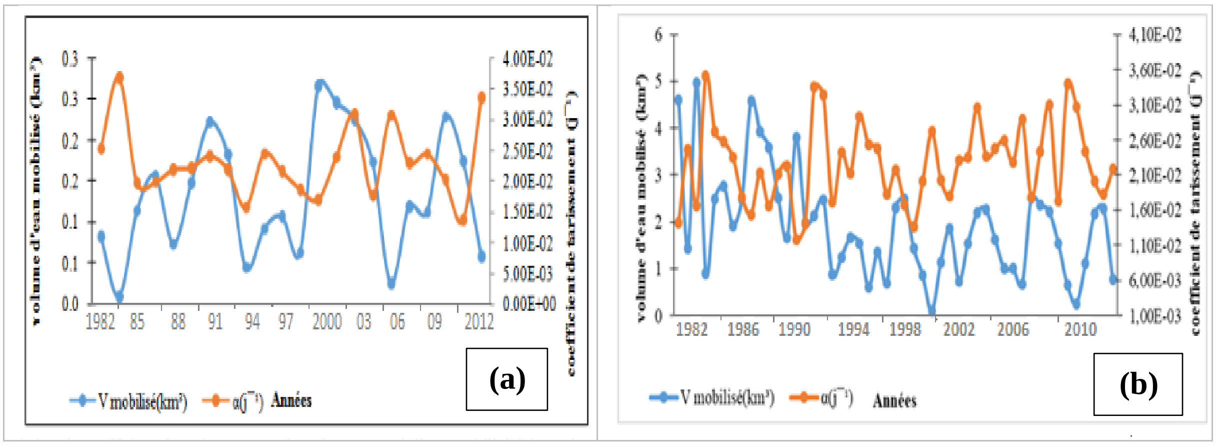


Figure 28: Variation in the drying coefficient and annual volume of water mobilized at Bansang (a) and Oundou Bac (b) stations (1982-2016)

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.

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 29.

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.

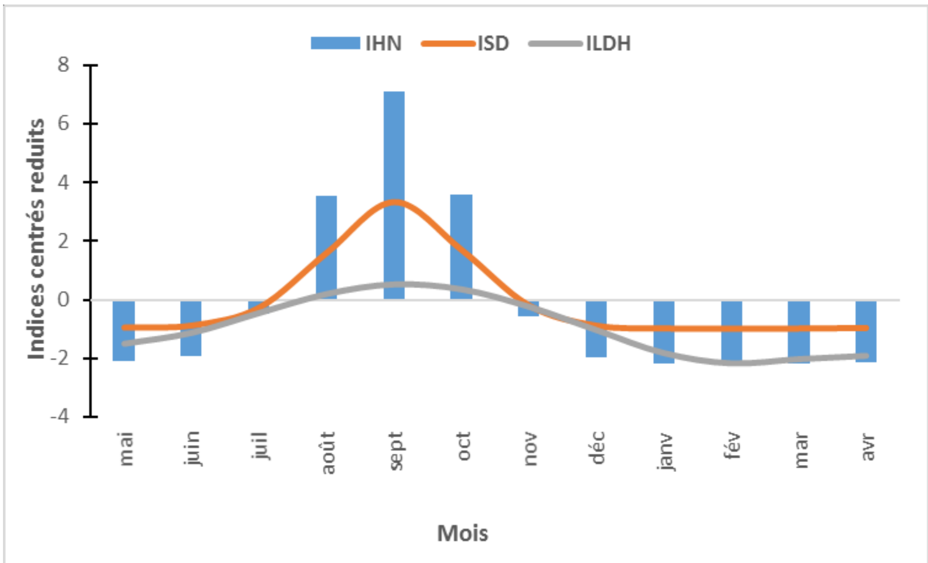


Figure 29: Evolution of hydrological drought in the short term using the HLB, ISD and ILDH (Bansang Station).

Calibration and validation of the SWAT model on the watershed of Bafing River: checking of the influence of the period of study

Since 1970 West Africa is affected by decrease of precipitation and increasing of extrem events like flods and droughts. According to Servat et al (1998) this has led to a decrease from 30 to 60% of flows in most of watersheds. Senegal River basin has significant water resources and many studies have been done in this watershed (Bodian, 2011; Diakite et al, 2013; Faty et al. (2017) and Bader 2018). However, knowledges on the water resource and its seasonal variations in the Guinean part of the basin shows weaknesses because of the missing hydrological data sets (rainfall). In this area, the Manantali dam with its multiple purpose and its reservoir can retain 12 Km^3 of water. The water resources management of this reservoir requires better knowledge of flows entrance in the reservoir.

The Bafing River

The study area is the watershed of Bafing located between 10° 30' and 12° 30' North and between 12° 30' and 9° 30' West (Figure 30). Bafing River is characterized by tropical climate with annual mean temperature is 27.6°C and annual mean rainfall of 1166 mm (*Climate-Data.org*).

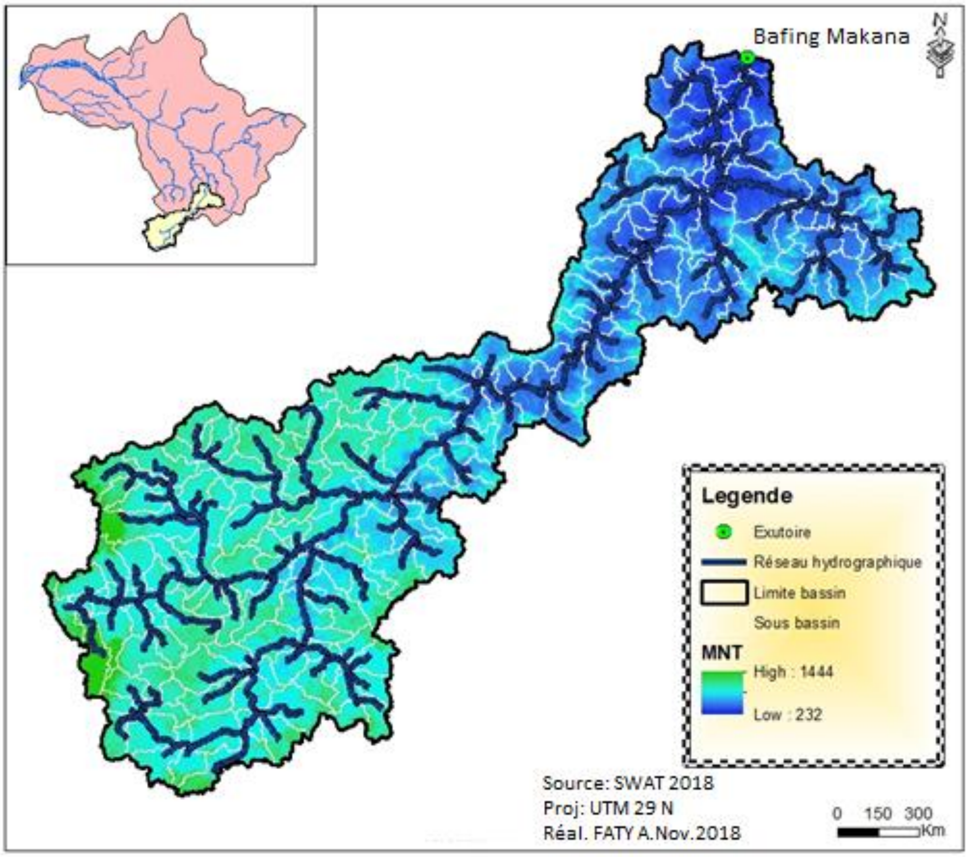


Figure 30: The study area (Bafing River Basin)

Topographical and Climate data

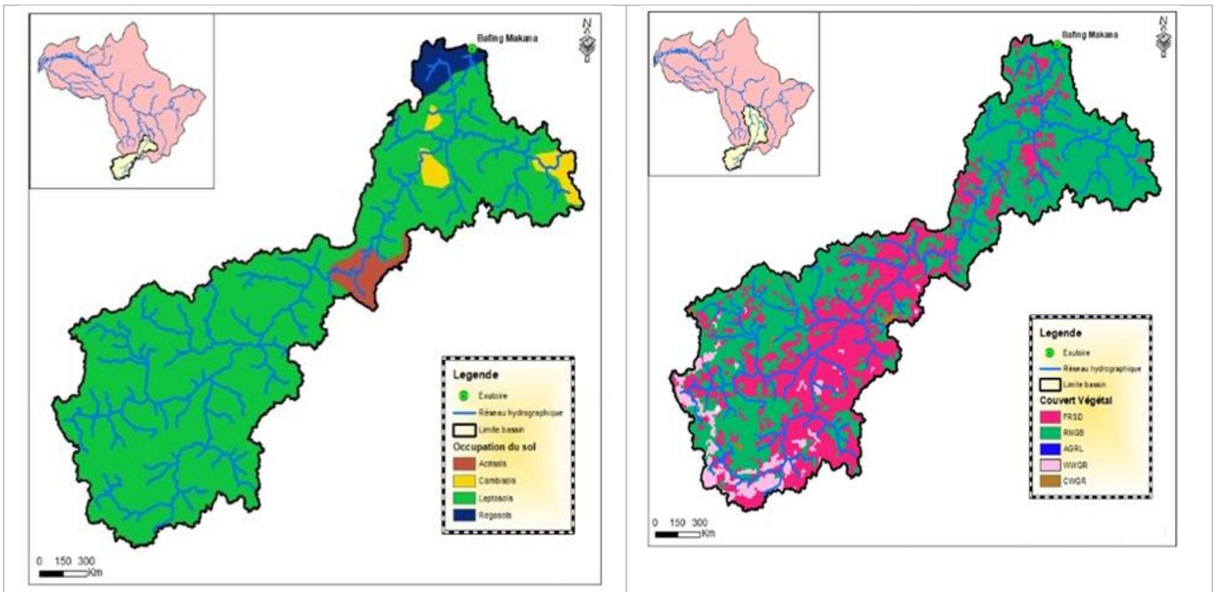
Topography of the watershed was defined by digital elevation model (DEM) clipped out from the Shuttle Radar Topography Mission (SRTM) 12.5x12.5m Digital Elevation Data (https://vertex.daac.asf.alaska.edu/?#). Rainfall, Max and Min Temperature, Solar Radiation, Relative Moisture, wind speed, were obtained on https://globalweather.tamu.edu/. The daily average flows and the daily observed precipitations come from the OMVS Database.

Soils and Land use

Land use and Land cover map downloaded from the website (http://faostat.fao.org) whose resolution is of 1x1 km for Africa datasets has been used in this study. The Bafing river watershed consists of 4 different soil classes namely Acrisols, Cambisols, Leptosols and Regosols (Figure 31). From the map, it can be observed that there is around five classes of Land cover. An acrisol is a type of soil as classified by the Food and Agriculture Organization. It is clay-rich, and is associated with humid, tropical climates. A Cambisol is a soil with a beginning of soil formation. Cambisols are developed in medium and fine-textured materials derived from a wide range of rocks, mostly in alluvial, colluvial and aeolian deposits. Leptosol, one of the 30 soil groups in the classification system of the Food and Agriculture Organization (FAO). Leptosols are soils with a very shallow profile depth (indicating little influence of soil-forming processes), and they often contain large amounts of gravel. Leptosols are unattractive soils for rainfed agriculture because of their inability to hold water, but may sometimes have potential for tree crops or extensive grazing. Regosols are characterized by shallow, medium- to fine-textured, unconsolidated parent material that may be of alluvial origin and by the lack of a significant soil horizon (layer) formation because of dry or cold climatic conditions. Regosols in mountain areas are best left under forest. Land use and management of Regosols vary widely. Some Regosols are used for capital-intensive irrigated farming but the most common land use is low volume grazing. Figure 31b shows the types of land cover in the watershed. The most important major types of land use in the basin is: FRSD, RNGS, WWGR and CWGR covering of the total basin area (Table 17, Figure 31a).

Table 17: Characteristics of the soil and land cover in the watershed of Bafing River

Corresponding land cover use in the SWAT model	Définition	Area %	Corresponding soil use in the SWAT model	Area %
FRSD	Forest Deciduous Mixed	37.2	Acrisols	2.98
RNGB	Range Brush Land	57.7	Cambisols	2.88
AGRL	Agriculture Generic	0.02	Leptosols	91.25
WWGR	Crested wheatgrass	4.5	Regosols	2.87
CWGR	Western wheatgrass	0.5		



(a) Soil classes (b) Land cover

Figure 31: Soil classes and Land cover in the Bafing watershed

Description of SWAT model

Hydrological models are often used to assess climate change. There are several types of hydrological models: black box, conceptual, deterministic. Vissin (2010) use GR2M and GR4J to assess runoff on the Niger River basin. Givati et al (2016) applied it in southern Lebanon, Israel, West Jordan and Eastern Sinaito hydrological models (WRF-Hydro and HEC-HMS) to assess the performance of simulated hydrographs driven by various precipitation sources. Bhuiyan et al (2017) use HEC-HMS for flood forecasting in the Sturgeon Creek watershed in Manitoba, Canada. Wang et al (2012) use MIKE SHE to assess the applicability in the large-scale watershed of northern Chian. Proper use of these models requires two or three phases: sensitivity analysis, calibration and Validation. The calibration consists to determine the model parameters; the validation ensures that the parameters reproduced the hydrological functioning of watershed.

Presentation of SWAT

SWAT (Soil and Water Assessment Tool) is a hydrological model that allows simulating the quantity (streamflow) and quality (pesticides, nutrients and sediments) of water (Tadesse et al. 2015; Li et al., 2015; Chuenchooklin et al., 2016). It also quantifies the impact of land management practices in large and complex watersheds.

SWAT (Soil and Water assessment Tool) was developed by USDA (Agricultural Research Service) and running to daily (Arnold and Fhorer, 2005; Mylevaganam et al., 2015). It was developed for the investigation of watersheds with surfaces going from a few hundreds of Km² to several thousands of Km² (Hallouz, 2015). SWAT system is embedded within a Geographic Information System (ArcGIS interface), in which different spatial environmental data, including climate, soil, land cover and topographic characteristics can be integrated (Abassa et al., 2016). It is a semi-empirical and semi-physical based model. It is a basin scale, continuous time, conceptual and long-term simulation model that operates on daily and hourly time step (Kaleab and Manoj, 2013). SWAT subdivides a watershed into sub-basins connected by a stream network, and further delineates Hydrological Reponses Units (HRU). HRU consists of unique combination of land cover and soils in each sub basin (Silva et al., 2015). A kinematic storage is used to predict lateral flow, whereas return flow is simulated by creating shallow aquifer. The Muskingum method is used for channel flood routing (Xuesong et al., 2009). The SWAT model is a comprehensive, continuous river system scale hydrological model that simulates interactions of major hydrological components on a daily time step. It is free and available on http://www.brc.tamus.edu./swat/. The required input data for the SWAT model are topographic, climatic, soil and land use data (Abubaker et al., 2017; Nolwenn, 2013). The simulation of the hydrological cycle is based on the water balance, which is carried out considering precipitation, evapotranspiration, surface, lateral and base flow and deep aquifer recharge. The evapotranspiration can be calculated using one of these three methods: Penman-Monteith, Hargreaves and Priestley-Taylor. The Pemman-Monteith method was selected in this case because it uses more physical parameters (daily maximum and minimum temperature, wind speed, humidity and solar radiation). In addition, the Penman-Monteith option in SWAT incorporates the effects of increased CO2 concentration on plant growth and evapotranspiration (Rodríguez-Blanco et al., 2014). The hydrological component is based on a water balance equation (Tadesse et al, 2015):

$$SW = + \sum_{i=1}^{t} \left(P_{jr} - R_{surf} - E_v - P_{perc} - Q_b \right)$$

Where P_{jr} is precipitation, P_{perc} is percolation, R_{surf} is runoff, Q_b is return flow, and E_v is evapotranspiration.

The SWAT model include many useful components and functions for simulating the water balance and the other watershed processes such as water quality, climate change, crop growth, and land management practices. After a comparison of existing modelling possibilities, the SWAT model appeared to be suitable for this study, both in terms of formalism and its applicability for large spatial and temporal scales such as the Senegal River and Gambia basins. The scientific literature also attests to its ability to be used both for climate change studies and analysis in terms of green and blue water. The implementation of this work is therefore divided into several phases:

- First step where the model is implemented in the Bafing Makana catchment area, the site selected for the study;
- The second step, a reflection is carried out to improve or validate the model's performance in order to better respond to the problem. This improvement is achieved by looking at both the hydrological representation within the hydrological cycle, but also the spatial representation of the watershed. These reflections will make it possible to carry out the calibration process of the model set up as efficiently as possible.
- The last step is the analysis of the simulation results carried out to analyze the variations in the hydrological cycle over time.

Figure 31a shows land use in the watershed in 2006. From a global point of view, we can observe the clear predominance of agricultural territories which represent 60% of the land cover, while 37% of the surface is occupied by forest areas and semi-natural environments. Artificialized surfaces covered totally or partially by water represent only 2.5 and 0.5% of the total surface respectively.

However, differences can be observed between the different territories described above: the Massif Central area is dominated by forest vegetation as well as pastoral grasslands and heterogeneous agriculture. The plain area of the basin sees forest vegetation disappearing and being dominated by irrigated agriculture and pastures.

From upstream to downstream, land use changes rapidly from forest and grassland dominance to traditional agriculture, through heterogeneous farming systems dominated by grazing.

As shown in Figure 31a, the watershed is dominated by agriculturally suitable lithosols, which explains the intense agricultural activity in this watershed. As with land use, there are significant differences depending on the areas of the catchment area considered. In the northern and somewhat central areas of the basin, there are regosols and other undeveloped soils such as lithosols or andosols, developed from volcanic materials, particularly in the Fouta Djalon Massif.

For the choice of meteorological data, only the climatic and rainfall data from the Bafing station were used on a monthly scale over the series described in the methodology section.

Sensitivity analysis

Sensitivity analysis allows reducing the number of parameters to test for effective use of the model. The sensitivity analysis and the calibrations of the model are made using the SWAT-CUP or SUFI-2 program (Koirala et al., 2012; Anaba et al., 2016; Gyamfi et al., 2016). The use of sensitivity analysis enabled identification of the most important parameters required to model the hydrological processes in the watershed of Bafing River. There are a large number of parameters in the SWAT model. The sensitivity analysis permit to detect the parameters having the most influence on the outputs of the model. In the literature we find many methods for assessment the parameters of SWAT model (Lenhart et al., 2002; Manoj, 2009). In this study we use the parameters frequently used in SWAT modeling (Jun-feng Dai, 2017; Sushant Mehan, 2016; Emile, 2015; Alejandra Stehr, 2010; Boris, 2009). A set of 22 model parameters is employed in the sensitivity analysis to obtain surface runoff, percolation, and evapotranspiration processes. The influence coefficient method is one of the most common methods for computing sensitivity coefficients in surface and ground water problems. The method evaluates the sensitivity by changing each of the independent variables, one at a time. A sensitivity coefficient represents the change of a response variable that is caused by a unit change of an explanatory variable, while holding the rest of the constant parameter (Manoj et al., 2009; Parajuli et al., 2014):

$$|C_i| = \frac{P_{moy}}{F_{moy}} \frac{\Delta F}{\Delta P}$$

Where C_i is the sensitivity index, and F_{moy} and P_{moy} are the mean of lowest and highest values of the selected range for the explanatory parameter and the response variable, respectively F is the response variable, P is the independent parameter. A higher absolute value of sensitivity index indicates higher sensitivity and a negative sign shows inverse proportionality.

Calibration and validation

The calibration-validation procedure requires the selection of two different periods: one for calibration and a one or more for validation (Bouslihim et al., 2016). The calibration procedure involved the adjustment of the SWAT parameters by using SWAT-CUP or manual such that the resulting stream flows matched the observed inflows (Jothiprakash et al., 2017). In this study the calibration is performed manually. The validation period allows to assess whether the model has been properly seated, using one or more periods where climatic conditions are different from those of the calibration period. The choice of the period of study is based on the availability of data series used as inputs: 1961-2013 for river flow, 1963-1986 and 1988-1994 for rainfall, 1979-2013 for Max and Min Temperature Solar radiation, RH, wind speed. The period 2007-2014was selected for the calibration of SWAT model. The most frequently used calibration procedure is through the optimization of model performances, which is carried out by comparing observed and simulated data. The parameters retained after the sensitivity analysis is performed are then used for the calibration step, first on the whole 8 years of period of study, and then on each year of the period of the study. This leads to nine sets of parameters. For each period of calibration, statistical criterions of goodness of fit indicated in table 18 are calculated. Therefore, it is recommended that the model is tested to check its performances in real world applications, after calibration and before using it in practice. Such testing procedure is called validation.

The validation period for Bafing watershed model is 2009-2016.

Performance evaluation of the Model

Performance of the model was evaluated in order to assess how the model simulated values fitted with the observed values. Several statistical measures are available for evaluating the performance of a hydrologic model (Jain et al., 2010; Thibault et al., 2006). They are the coefficient of determination R^2, the Nash-Sutcliffe efficiency NSE, the percent bias PBIAS and Root Mean Square Error RMSE and RSR. RSR value, which is the ratio of the RMSE to the standard deviation of the observations, can provide additional information (Table 18).

Table 18: Performance Evaluation of the Model

Statistical criterion	Equations	Value	Classification of Performance	Reference
NSE	$1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \bar{Q}_{obs})^2}$	0.75 < NSE ≤ 1.00 0.65 < NSE ≤ 0.75 0.50 < NSE ≤ 0.65 0.4 < NSE ≤ 0.50 NSE ≤ 0.4 0.4 ≤ NSE ≤ 0.70	Very good Good Satisfactory Acceptable Unsatisfactory Acceptable	*Ardoin-Bardin, 2004* *Carrasco et al. 2012*

R²	$\frac{\sum((Q_{obs}-\bar{Q}_{obs})(Q_{sim}-\bar{Q}_{sim}))^2}{\sum(Q_{obs}-\bar{Q}_{obs})^2 * \sum(Q_{sim}-\bar{Q}_{sim})^2}$			*Obiero et al. 2011;Koirala et al. 2012*
PBIAS	$\frac{\sum(Q_{obs}-Q_{sim}) * 100}{\sum(Q_{obs})}$	PBIAS < ±10 ±10 ≤ PBIAS < ±15 ±15 ≤ PBIAS < ±25 PBIAS ≥ ±25	Very good Good Satisfactory Unsatisfactory	*Sood et al. 2010*)
RMSE	$\sqrt{\frac{\sum(Q_{obs}-Q_{sim})}{n}}$	Value below half the standard deviation	Satisfactory	*Mishra et al. 2010*
RSR	$\sqrt{\frac{\sum(Q_{obs}-Q_{sim})^2}{\sum(Q_{obs}-\bar{Q}_{obs})^2}}$	0.00 ≤ RSR ≤ 0.50 0.50 < RSR ≤ 0.60 0.60 < RSR ≤ 0.70 RSR > 0.70	Very good Good Satisfactory Unsatisfactory	*Da Silva et al, 2015*

Q_{obs} Observed; Q_{sim} Simulated; $\bar{Q}_{obs}$ Mean observed; $\bar{Q}_{sim}$ Mean observed

This criterion is very useful in model assessment since its adimensional form is hoped to allow comparison of performances on different catchments or periods.

First results of the Bafing watershed modelling

SWAT model examines six (06) different sections which are: climate, hydrology, erosion, plantation growth, management and quality of water. We note here that our investigation is focused to the section's "hydrology" only. The results of sensibility analysis, calibration and validation are presented in the following paragraph.

Sensitivity

The parameters used for the flow were selected based on the literature and the SWAT documentation. The sensitivity analysis permit to detect the sensible parameters and used to calibration the model. We have used seven extensions (Sol, Hru, Sub, Rte, Gw, Sub-Largand Mgt) during sensitivity analysis and five are retained. Increasing Sol parameter was found to lead to higher surface runoff and decrease ETP. GW parameters decreasing return flow and increasing revap and recharge while HRU increasing surface runoff, return flow and recharge. Among 22 parameters are used but only 19 were retained for the calibration. In the table 19 were presented the sensibility analysis results. They revolve around surface runoff, lateral flow, return flow, recharge and revap (Table 19).

Table 19: Parameters of the model

Surface runoff	Order	Lateral flow	Order	Return flow	Order	Recharge	Order	Revap	Order
SOL_Z	1	SOL_K	1	WQMIN	1	REVAPMIN	1	WQMIN	1
SOL_K	2	SOL_Z	2	CH_K1	2	SOL_Z	2	SOL_Z	2
CN2.	3	CN2.MGT	3	SOL_Z	3	CH_K1	3	REVAPMIN	3
CANMX	4	LAT_TTIME	4	REVAPMIN	4	DELAY	4	SOL_K	4
CH_K1	5	CANMX	5	DELAY	5	SOL_K	5	DELAY	5
LAT_TTIME	6	SOL_AWC	6	SOL_K	6	CN2.MGT	6	CN2.MGT	6
SOL_CBN	7	SOL_BD	7	CN2.MGT	7	CANMX	7	CH_K1	7
SOL_BD	8	SOL_CBN	8	CANMX	8	RCHRG_DP	8	CANMX	8
SOL_AWC	9	CH_K1		SOL_BD	9	SOL_BD	9	SOL_AWC	9
CH_N1	10	CH_N1		OV_N	10	SOL_AWC	10	RCHRG_DP	10
OV_N	11	OV_N		CH_N1	11	SOL_CBN	11	SOL_BD	11
ESCO		ESCO		RCHRG_DP	12	ALPHA_BF.	12	REVAP.GW	12
EPCO		EPCO		ALPHA_BF.	13	CH_N1		ESCO	13
CH-N2		CH-N2		SOL_AWC	14	OV_N		EPCO	14
CH-K2		CH-K2		REVAP.GW	15	LAT_TTIME		ALPHA_BF	15
DELAY		DELAY		SOL_CBN		ESCO		SOL_CBN	

Surface runoff	Order	Lateral flow	Order	Return flow	Order	Recharge	Order	Revap	Order
ALPHA_BF		ALPHA_BF		LAT_TTIME		EPCO		CH_N1	
WQMIN		WQMIN.GW		ESCO		CH-N2		OV_N	
REVAP		REVAP.GW		EPCO		CH-K2		LAT_TTIME	
REVAPM		REVAPMIN		CH-N2		WQMIN.GW		CH-N2	
RCHRG_DP		RCHRG_DP		CH-K2		REVAP.GW		CH-K2	
SURLAG		SURLAG		SURLAG		SURLAG		SURLAG	

Table 19 lists the model parameters along with their ranges. Surface runoff was found only eleven parameters sensitive, while lateral flow was found to be sensitive for eight among the parameters selected for the study. Return flow and revap were found fifteen parameters sensitive and finally Recharge was showed twelve parameters sensitive. We can classify on set of parameters used for this study in order of sensitivity: Sol_Z: Soil depth; Sol_K: Saturated hydraulic conductivity (mm/h); CN2: Initial SCS runoff curve number for moisture condition II; CANMX: add description CH_K1: add description; SOL_BD: Moist bulk density (g/cm3); SolL_AWC: Available water capacity of soil layer (mm H_2O/mm soil). The extension Sol are retained as the most sensitivity parameters of swat model in this study.

Calibration and validation of model

The calibration results were presented in the following tables (Table 20, Table 21).

Table 20: Parameter values after manual calibration

Parameters	2007	2008	2009	2010	2011	2012	2013	2014	Mean	SD	RD.	2007-2014
SOL_BD	1.33	1.1	1.42	1.42	1.64	1.45	1.43	1.31	1.40	0.15	0.11	1.38
SOL_AWC	0.14	0.11	0.13	0.15	0.24	0.2	0.25	0.15	0.18	0.05	0.30	0.14
SOL_Z	152	13	100	123	126	123	112	100	99.57	41.15	0.41	100
SOL_CBN	7.27	7.54	7.27	7.27	7.69	7.27	7.27	7.27	7.37	0.16	0.02	8.12
SOL_K	254	254	254	254	254	254	254	254	254	0.00	0.00	254
CH_K1	300	300	300	300	300	300	300	300	300	0.00	0.00	300
CH_N1	0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.09	0.00	0.00	0.089
OV_N	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.156	0.16	0.00	0.00	0.116
LAT_TIME	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.04	0.00	0.00	0.035
CANMX	100	100	100	100	100	100	100	100	100	0.00	0.00	100
ESCO	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.00	0.00	0.8
EPCO	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.80	0.00	0.00	0.9
DELAY	254	254	254	254	254	254	254	254	254	0.00	0.00	254
ALPHA_BF	0.688	0.688	0.752	0.688	0.688	0.688	0.688	0.752	0.71	0.03	0.04	0.688
WQMIN	3327	3327	631	3327	621	621	621	3327	1782	1445	0.81	3327
REVAP	0.127	0.191	0.127	0.191	0.09	0.1	0.09	0.191	0.14	0.05	0.33	0.191
REVAPMIN	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.014	0.01	0.00	0.00	0.014
RCHRG_DP	0.42	0.42	0.95	0.42	0.42	0.45	0.42	0.42	0.50	0.19	0.37	0.42
CN2	39	39	39	39	39	39	39	39	39.00	0.00	0.00	39
SURLAG	20	20	20	20	20	20	20	20	20.00	0.00	0.00	20

Table 21: Criteria for evaluating the performance of SWAT model on calibration

Year	Nash	R^2	PBIAS	RMSE	RSR
2007	0.82	0.00	0.11	0.47	0.42
2008	0.51	0.68	-14.84	1.41	0.70
2009	0.90	0.92	7.02	0.55	0.32
2010	0.90	0.91	6.83	0.43	0.31
2011	0.72	0.73	12.17	0.82	0.53
2012	0.90	0.84	14.25	0.41	0.32
2013	0.91	0.92	11.80	0.50	0.30
2014	0.78	0.80	-7.45	0.81	0.47
Mean Performance	0.81	0.72	3.74	0.68	0.42

Calibration of the model from 2007 to 2014 resulted in a Nash criterion of 0.701 indicating the model's good ability to reproduce flows at the Bafing Makana reference station. The calibration results affected on each year were gave the better Nash criterion with the exception of the year 2000. On average for calibration per year we have a coefficient 0.794 see table 5. The following figures present calibration results by year.

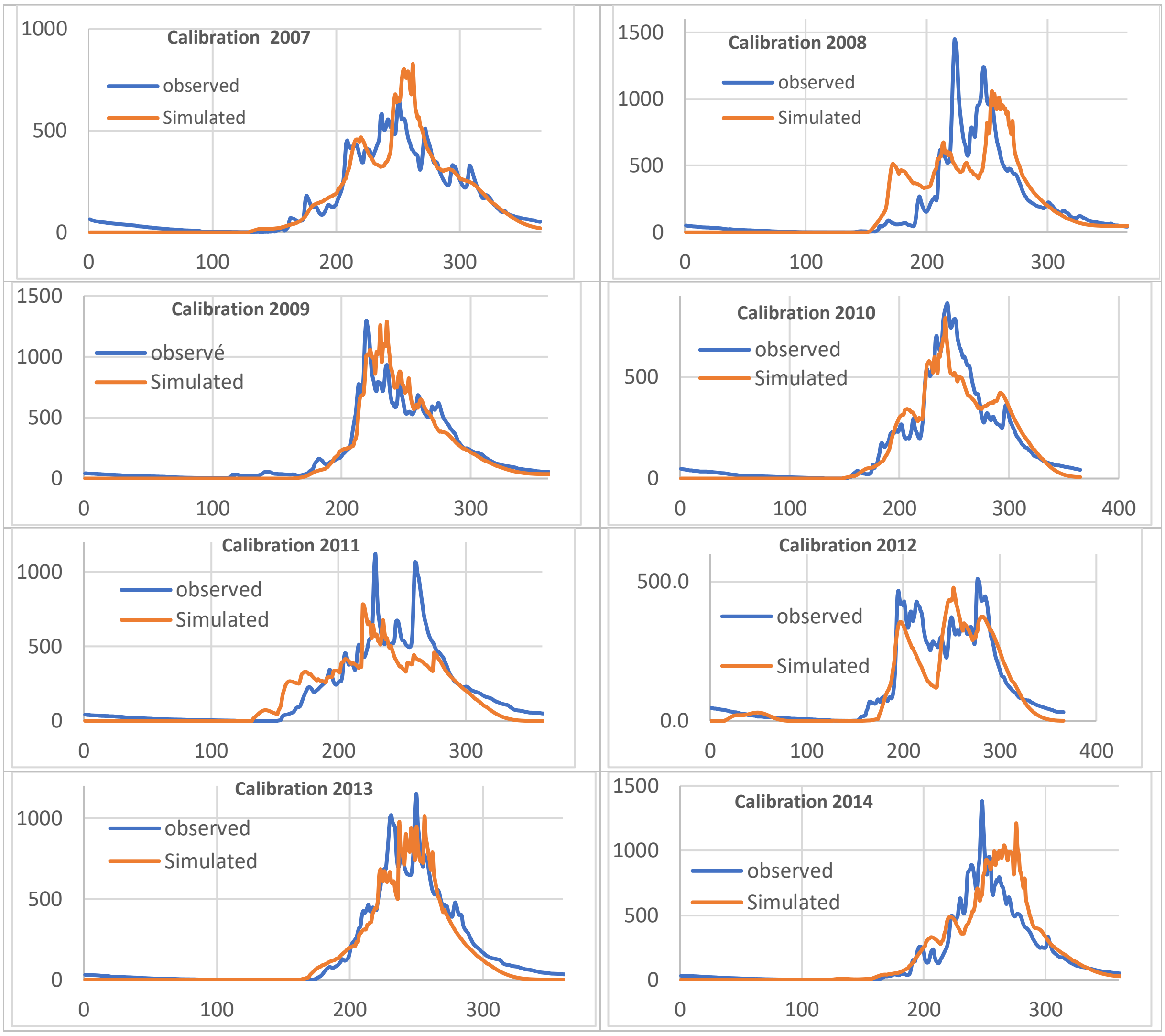


Figure 32: Calibration of the model from 2007 to 2014

The initial period was divided into 36 and the application results of parameters calibrated on the period 2007 - 2014 were presented in table 6. The duration of period goes to two to seven years. In general, the application on set was showed a satisfactory result. On average the application on set was showed a satisfactory result. On the lines A, B, D and E we note that the Nash values up grow with the period duration. On the lines C and F we note the contrary effect. This table reveals, with a few exceptions, that the quality of the Nash criterion is better when the duration of the period is long.

Table 22: Period effect

	1	2	3	4	5	6	7	8	
Period	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	
Nash (%)	0.768	0.473	0.88	0.892	0.496	0.721	0.747	0.721	
Period	**2007-2008**	**2007-2009**	**2007-2010**	**2007-2011**	**2007-2012**	**2007-2013**	**2007-2014**		
Nash (%)	0.544	0.673	0.716	0.681	0.687	0.698	0.701		**A**
Period	**2008-2009**	**2008-2010**	**2008-2011**	**2008-2012**	**2008-2013**	**2008-2014**			
Nash (%)	0.658	0.712	0.673	0.681	0.694	0.698			**B**
Period	**2009-2010**	**2009-2011**	**2009-2012**	**2009-2013**	**2009-2014**				
Nash (%)	0.888	0.771	0.77	0.765	0.756				**C**
Period	**2010-2011**	**2010-2012**	**2010-2013**	**2010-2014**					
Nash (%)	0.686	0.699	0.717	0.718					**D**
Period	**2011-2012**	**2011-2013**	**2011-2014**						
Nash (%)	0.571	0.652	0.675						**E**
Period	**2012-2013**	**2012-2014**							
Nash (%)	0.745	0.735							**F**
Period	**2013-2014**								
Nash (%)	0.734								**G**
Nash Mean Performance	0.689	0.707	0.710	0.711	0.712	0.698	0.701	0.712	

The parameters calibrated on each year were applied on the period 2007-2014 and the results were presented in the table 23. The results obtained with the parameters of 2011 were showed a better Nash criterion. The average on the set application is 0.571.

Table 23: Application of the calibrated parameters per year on the long period

Year	NSE	R^2	PBIAS	RMSE	RSR
2007	0.687	0.697	11.935	2.456	0.559
2008	0.661	0.668	4.899	2.557	0.582
2009	0.656	0.689	-10.962	2.577	0.587
2010	0.693	0.716	1.890	2.432	0.554
2011	0.241	0.695	-36.865	3.827	0.871
2012	0.573	0.703	-14.516	2.871	0.653
2013	0.394	0.694	-27.771	3.421	0.779
2014	0.688	0.698	9.613	2.455	0.559
Mean Performance	0.574	0.695	-7.722	2.825	0.643

A total 9 sets of parameters were obtained during the calibration phase. Among this sets of parameters, those from 2007-2014 were showed a better result into the calibration and application. The parameters of the period 2009-2016 were retained for the validation of the model.

The validation of this model was affected on the period 2009-2016 with the set's parameters. The results were presented in the Table 24. Into validation, the Nash criterion is 0.64 and this result is satisfactory.

Table 24: Criteria for evaluating the performance of SWAT model on validation

Years	Nash	R^2	PBIAS	RMSE	RSR
2007	0.63	0.67	24.84	3.07	0.61
2008	0.64	0.66	15.33	3.03	0.60
2009	0.63	0.63	5.21	3.08	0.61
2010	0.64	0.66	16.10	3.00	0.60
2011	0.42	0.60	-18.69	3.84	0.76
2012	0.60	0.63	1.51	3.17	0.63
2013	0.52	0.61	-10.04	3.50	0.69
2014	0.62	0.65	23.01	3.12	0.62
Mean Performance	0.59	0.64	7.16	3.22	0.64

The Figure 33 shown the results of calibration and validation. Globally the model seems to describe well the functioning of the basin.

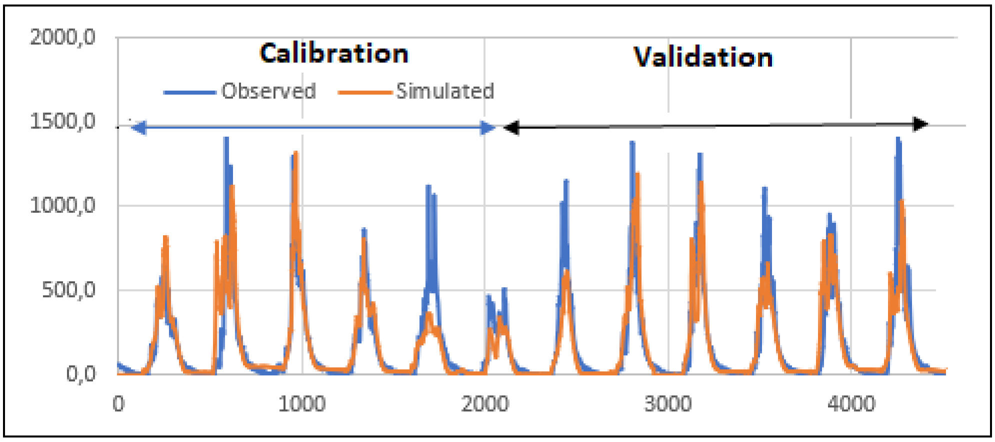


Figure 33: Calibration and Validation results (which period refers? 0-5000 is the day? So it is about 15 years period 2000-2016

The objective was to calibrate and validate the SWAT model on Senegal River at upstream. The method used is to do sensitivity analysis for detecting the most sensitivity parameters. The model is calibrated and validated on the Bafing River watershed. The application of the set of parameters on the years of the period not only allows to see the variation of the Nash following the length of the period but also it allows to see the irregularities that are hidden in the long period. The results obtained show clearly that the long period have gave the best value of Nash criterion. The parameters of the period 2007-2014 were retained for model calibration Model performance during calibration is better than during the validation period. The model can be used to study the long-term impact of management modes.

Conclusion and way forward

Rainfall and hydrological data constitute critical knowledge base for water resources assessment and for decisions making. Thus, we will have to cooperate with basin organizations (OMVS and OMVG) to collect all the information and data from the stations.

This report has highlighted the main fluctuations in the rainfall and hydrological regime in the Gambia River Basin. 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 the dry periods and their intensity. The analysis of the rain-flow relationship showed a synchronous trend throughout the study chronicle. Hydrological drought indices indicate that the most intense droughts have occurred since 1970.

The hydrological modelling with SWAT applied to the Bafing watershed has given encouraging results on the applicability of the model with a good level of satisfaction. The model will also be tested on other sub-basins in Senegal, particularly in some areas of the upper basin. The next step in the modelling component of this study will be to test the WEAP model over the entire Senegal River basin.

The following actions have been carried out:

- Creation of a rainfall database of the Senegal River Basin;
- Creation of a hydrometric database (water flow) of the Senegal River Basin;
- Acquisition of Modis Terra satellite images for land cover / land use mapping;
- Development of environmental Database (GIS) for highlighting environmental issues in the selected hotspots (Senegal River Estuary, Gambia River Estuary and Fouta Djalon Mountain)
- Updating the former Senegal ACEWATER1 database with the 24 rain gauging stations for climate vulnerability

However, some problems still remain:

- Some rainfall and hydrometric stations and data of Mauritania and Guinea are missing;
- Lack of climate data (temperatures-moisture-evaporation) at the basin scale (Senegal and Gambia River Basins);
- Problems with the acquisition of rainfall and hydrometric and also socio-economic data from the Gambia River Basin.

The next steps will be:

- Complete the rainfall and hydrological data of the two basins (Senegal and Gambia). For other data from stations outside country, the completion will use alternatives sources from several sources like AGHRYMET, ABN[4] and also from other WANWATCE members (KNUST[5], NWRI[6], and UNIBEN[7]).
- For some gaps identified, alternative data sources like climate re-analysis and/or satellite data will be collected, integrated to the database and used according to their level of precision. This action can concern the Gambia River Basin where many gaps have been identified in the data.
- Analysis of climate variability in Senegal using REFRAN-CV and comparison with former results of ACEWATER1
- Extension of the climate analysis with REFRAN-CV on Senegal to other parameters such as temperature, relative humidity, evaporation and winds.
- Reflection on extreme events assessment (rainfall, temperature, moisture, winds and evaporation)

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- Application of the SWAT model to other sub-basins of the Senegal River and consideration of its extension to the entire basin.
- Develop the first approaches for the development of the WEAP model in the two basins studied (Senegal and Gambia)
- As part of this work, the R software will be used for the determination of statistical parameters and realization of graphics.
- Consolidate and formalize a documentary database on the two basins of the Senegal and Gambia rivers (consider developing an interface under Access 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)

CODE_STATION	STATIONS	TYPE	PAYS	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

CODE_STATION	STATIONS	TYPE	PAYS	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
1270042400	SIRAKORO	P	Mali	12°41'	-09°14'	369	1951	1950-1998	1029,51

CODE_STATION	STATIONS	TYPE	PAYS	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
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
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

CODE_STATION	STATIONS	TYPE	PAYS	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
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
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

CODE_STATION	STATIONS	TYPE	PAYS	LAT. NORD	LONG. OUEST	ALTITUDE (meters)	Starting Date	Available data	Average rainfall (mm)
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
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)

CODE_STATION	STATIONS	TYPE	PAYS	LAT. NORTH	LONG. WEST	ALTITUDE (meters)	Starting Date	Available Data	Average rainfall (mm)
1150777012	BANJUL HALF DIE	P	Gambia	13°27	16°34	2	1943		
1150777003	BASSE METEO	M	Gambia	13°19	14°13	4	1942		
1150777008	FATOTO	M	Gambia	13°24	13°54	2	1971		
1150777018	GEORGETOWN	C	Gambia	13°32	14°46	1	1908		
1150777450	JALI MFC	P	Gambia	13°21	15°58	7	1974		
1150777015	JENOI METEO	C	Gambia	13°29	15°34	15	1946		
1150777440	JIBANACK MFC	P	Gambia	13°13	16°11	9	1971		
1150777023	KAUR HYDRO	P	Gambia	13°43	15°21	6	1950		
1150777017	KEREVAN METEO	M	Gambia	13°30	16°05	15	1979		
1150777080	NAUDE MFC	P	Gambia	13°28	14°27	1	1971		
1150777020	SAPU METEO	M	Gambia	13°33	14°54	-	1956		
1150777004	YUNDOUM AIRPORT	S	Gambia	13°21	16°08	26	1945		
1170552000	KOUNDARA	S	Guinea	12°35	13°20	90			
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
1170758000	SAREBOIDO	P	Guinea	12°25	13°35	82			
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
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
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