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Recent hydrological evolutions of the Senegal River flood (West Africa)

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Abstract

The flood of the Senegal River is a resource for the populations of the Senegal Valley, who practice agriculture, fishing and livestock farming in the annually flooded areas. The objective of this paper is to investigate the hydrological evolution of the Senegal River flood since the drought of the 1970s and the construction and management of the Manantali Dam. To this purpose, the paper analyses the evolution of several parameters of the flood hydrograph and defines the factors that determine the intensity of the flood. Also, a follow-up of the flooded areas in the valley is carried out using remote sensing. The results show that the flood hydrograph has been similar since the 1970s drought, due to the reduction in contributions from the Bafing after the construction of the Manantali Dam. As a result, the high floods depend now on the rainfall pattern in the Sudano-Sahelian zone of the watershed.

Keywords

flood, Senegal, transboundary watershed, flood remote sensing, West Africa

1. Introduction

Wetlands and floodplains provide many ecosystem services that rely on the seasonal watering allowed by flood-pulses (Junk et al., 1999). The duration, frequency and intensity of floods are parameters influencing the ecological productivity of floodplains (Junk and Wantzen, 2004). Ecosystem services are numerous: hydrological regulation (water storage, contribution

to streamflows, sediment retention) or biogeochemical regulation (exports and storage of chemical elements, denitrification); support for ecological habitats or cultural services linked to the spiritual value of the site. Nevertheless, provisioning services are the most recognised by local communities, since wetlands provide support spaces for many activities: agriculture, gathering, wood collecting, fishing or livestock breeding (Adams, 1993). Farming in wetlands is traditionally a flood recession agriculture, which follows fluctuations in water levels and the inundation of fertile land. This system is present throughout Africa, from the Zambezi to Niger, from the Congo River to the Omo, Lake Chad and the Senegal River. Floodplains provide a particularly important agricultural area in semi-arid environments, where rainfall is often insufficient for the practice of rain-fed agriculture. Floodplains are complex systems built on hydro-social relationships (Laborde et al., 2018) where flooding is the primary process leading to their role as a resource. Climate change and variability affect flood patterns and water supply to wetlands. Floodplains are vulnerable to hydrological changes, whether related to natural fluctuations or anthropogenic changes such as the construction of dams and the subsequent flow modifications or regulation. Numerous studies conducted in Africa have shown the negative effects of the decrease in flooded areas on the reduction of the overall productivity of the river ecosystem (Richter et al., 2010; Lacombe and McCartney, 2016) and more specifically on agriculture, livestock and fisheries (Kimmage and Adams, 1992; Magrin and Seck, 2009; Hamerlynck et al., 2011).

In the Senegal Valley, the flood is a major factor determining the socio-ecological functioning of the region since many rural activities coexist (fishing, livestock farming, flood recession agriculture, irrigation). The Senegal River Valley is a densely populated area due to this relatively abundant water resource. Flood recession agriculture is essentially practiced in the middle valley, between Bakel, Matam and Podor (Boutillier et al., 1962). It is based on the cultivation of sorghum, maize, cowpea and sweet potatoes which follows the annual recession

of the flood waters occurring between October to January. Flood-recession cultivated areas vary annually according to the intensity and duration of the flood (Lericollais and Schmitz, 1984; Sall et al., 2020). Most of valley households practice this kind of farming when flooding is sufficient. According to the National Agency of Statistics and Demography (In French Agence Nationale de la Statistique et de la Démographie-ANSD) surveys conducted at the regional level, 40% of households practice flood recession agriculture (ANSD, 2013), while locally in some villages of the floodplain, this percentage reaches around 80% (Bruckmann, 2018). Flood recession cultivated areas corresponds to about half of the areas flooded annually (Bonneau, 2001; Bruckmann, 2018), thus the soil water recharge from the flood is a major factor for agriculture. Concerning the other half of the flooded areas which is not cultivated, it is composed of spaces where the water recharge was insufficient for agriculture, of bottoms of basins where the water remained too long to be cultivated in time, or of flooded areas where cultivation is impossible (presence of trees, infertile soils).

The Senegal River watershed has experienced several changes in rainfall and runoff patterns. Since the beginning of the 20th century, the major break was observed after 1969, with a significant decrease in rainfall that was observed throughout West Africa and described as the "Great Drought" (Mahé and Olivry, 1995; Paturel et al., 1998; Mahé and Paturel, 2009; Descroix et al., 2016; Bodian et al., 2016; Bodian et al., 2020). The reduction in rainfall is spatially heterogeneous: from significant in the Sudanian zone, it is lower in the Guinean zone where the upstream part of the Senegal River basin is located in the Fouta-Djalon Highlands (Lebel and Ali, 2009). Niger and Gambia rivers have also their springs in Fouta-Djalon. The decrease in rainfall has also affected flows in the main West African river basins, causing a reduction in the most rivers streamflows. In the Sahelian zone, this decrease in rainfall was followed by an increase in local streamflows (Descroix et al., 2009; Descroix et al., 2013), while in the Sudanian zones, streamflows decreased two to three times more than the rainfall

does (Mahé et al., 2003). In the Senegal Valley, drought has had negative impacts on traditional production systems and has justified the development of irrigated agriculture (Boutillier and Schmitz, 1987; Schmitz, 1986). The Manantali Dam was built on the Bafing River in 1987 to regulate and secure water resources (Figure 1). The Bafing is the Senegal's main tributary, it contributes on average at 40% of its total discharge at its mouth in St Louis. Downstream, the Manantali Dam increased flows during the dry season, but did not allow an increase in flows on an annual scale, nor on the scale of the flood period (Sambou et al., 2009). Since the end of the 1990s, a relative increase in annual rainfall in the region has been observed (Descroix et al., 2016), which has led to a slight increase in flows in the upper Senegal River basin (Descroix et al., 2018; Bodian et al., 2020).

After the completion of the Manantali Dam, the flood has been at the center of controversies and conflicts in water management. In the initial project, the dam had to either produce an artificial flood or support the natural flood to ensure flood-related activities, particularly flood recession agriculture (Albergel et al., 1993; Magistro & Lo, 2001). Numerous studies to determine the optimal management rules in order to satisfy the different water uses were carried out during the dam building (Bader, 1992; Bader et al., 2003; Lamagat & Bader, 2003). Allowing high floods from the Manantali reservoir conflicts with other water allocation objectives : releasing high flows (above $500 \text{ m}^3\text{s}^{-1}$) reduces the dam power production and may also reduce the involvement of the population in irrigation (Fraval et al., 2002; Bader et al., 2003). The idea of an artificial flood was quickly abandoned in management plans for reasons of incompatibility with the different needs (Bader and Albergel, 2015), a phenomenon observed elsewhere in Africa (Scudder & Acreman, 1996). Despite the absence of conflicts in water management on a transboundary scale (Niasse, 2004; Bruckmann, 2021), the definition of efficient management rules that reconcile electricity

production and traditional uses is still required (Raso et al., 2014; Raso et al., 2020; Tilmant et al., 2020). Similarly, there is no regular monitoring of flooded areas even though they constitute a strong socio-environmental issue for societies. There are also few studies about the solid sedimentary load brought by flood to soil fertility. Faced with the future development of hydroelectric dams that will constrain flows even more, it appears essential to improve the understanding of spatio-temporal changes in the flood regime that conditions the hydrological, ecological and socio-economic functioning of the Senegal River valley.

The objective of this paper is to reconstitute the evolution and dynamics of the functioning of the Senegal River flood, in order to highlight the factors and elements that condition the flood processes at the basin scale in the context of the hydrological changes in the post-dam context. What are the dynamics of the flood in the context of a partially controlled regime and rainfall variability? The paper presents an evolution of the flood hydrograph parameters since 1950 to quantify the impacts of drought and the Manantali Dam on flood regimes. It also shows the evolution of the annually flooded areas in the valley based on remote sensed data to link them to hydrological conditions. Finally, more precisely, the paper aims to analyse the contribution of the different sub-watersheds to the flood, according to the periods and to a typology of floods.

2. Material and methods

2.1. The study area

The Senegal River basin (280 000 km²) extends from latitudes 10°N in Guinea to 17°N in Mauritania. In West Africa, the West African monsoon is the main factor controlling rainfall distribution; its extension and duration are driven by the ground evolution of the Inter Tropical Convergence Zone (ITCZ); it generally extends from June to October. The northern Sahelian zone has an average rainfall of about 200 to 300 mm/year, while the Guinean humid

zone of the Fouta-Djalon receives annual rainfall ranging from 1500 to 2000 mm. The Senegal River basin is shared by four countries, Guinea, Mali, Senegal and Mauritania. Water management is entrusted to a transboundary basin organization: the OMVS (In French Organisation pour la Mise en Valeur du fleuve Sénégal) based in Dakar. The vast floodplain extends from Bakel to the mouth at Saint-Louis over a distance of more than 500 km (Figure 1). It is generally divided into three different parts by Senegalese people and geographers: “high valley” from Bakel to Matam, “middle valley” from Matam to Dagana, and Senegal delta downstream from Dagana. The water supply of the valley is based almost exclusively on water inflows from the upper basin upstream from Bakel (98%) (OMVS, 2005). The annual flood, between August and November, thus plays a crucial role in the valley's water resources. The hydrograph of the Senegal River can be divided into two periods (Figure 2): a low-water period between January and May, followed by a flood period between June and December following the rainy season. The median daily flow between 1951 and 2018 is $181 \text{ m}^3\text{s}^{-1}$ and the mean flow is $596 \text{ m}^3\text{s}^{-1}$.

2.2. Data

For this study, we used a combination of daily observed stream-flows data, gridded precipitation product and remotely sensed datasets to describe recent flood dynamics in Senegal river basin.

2.2.1. Hydrological and pluviometric data

The hydrometric data used in this study come from the OMVS Hydraccess database (IRD, 2008) that contains 103 stations, from whose only 17 are currently providing data. The stations belong to the hydraulic services of the countries concerned, but OMVS collects and centralizes these data. The stations were provided with calibration curves between 1997 and 2000, during the Reservoir Optimization and Management Program (In French: Programme d'Optimisation de Gestion des Réservoirs) (OMVS & IRD, 2002) which were updated in

2012 (Bader, 2013). In this study we use data from the stations of Bakel on Senegal River, Dakka Saidou on the Bafing River, Oualia on the Bakoye River and Goubassi on the Falémé River (Figure 2 & Table 1). The main stations of the watershed have data since 1903. However, until the 1950s, the annual series had too many gaps. In order to harmonize the time period of analysis between stations, only data between 1955 (1951 for Bakel) and 2018 were selected. The data used is that of the homogenized base, in which all gaps are reconstructed (see Bader and Cauchy, 2013).

To assess annual rainfall inputs to the upper basin, we also use the IMERG GPM Final Precipitation L3 1 month 0.1-degree x 0.1-degree V06 (GPM_3IMERGM) data. These gridded data are the continuation of the TRMM mission data and are available daily since June 2000. They have the advantage of offering a spatialized and homogeneous product over the study area (Huffman & *al.*, 2019).

2.2.2. Remote sensing data

This study uses MODIS remote sensing data to monitor flooded areas in the Senegal Valley. MODIS data have the advantage of regular availability since January 1, 2000 with a temporal frequency much higher than other datasets, such as SPOT or LANDSAT already in use in the Senegal Valley (Mané and Fraval, 2001; Sandholt et al., 2003). The MODIS MOD09A1 data are reflectance values, provided every 8 days, and already corrected for atmospheric effects. These images have a spatial resolution of 250 and 500 m, but as the Shortwave Infrared (SWIR) band only exists in the 500 m resolution, this is the one used in this study. This moderate resolution is still sufficient for flood detection on a regional scale in semi-arid environment (Ogilvie et al., 2015). MODIS images have shown their effectiveness in

detecting and monitoring flooded areas using different methods (Xiao et al., 2005; Pricope, 2013; Ogilvie et al., 2015; Hu et al., 2015;). The MODIS image selected to map the annually flooded areas is searched in a time window close to the peak flood at Bakel. The image detecting the most watered areas is then selected, in order to map the annual maximum flood extent over our study area.

2.3. Flood parameters analysis

Prior to the analysis of the evolution of flood parameters, a quick study of the homogeneity of the hydrological series is carried out to define the hydrological periods and to compare them with those defined by previous works of Sambou et al. (2009) at the Manantali Dam, Diop et al. (2017) in the upper basin and Bruckmann (2016) at Bakel gauge station. The periods are determined from the non-parametric test of Pettit at Bakel station for the flows of June to December. The analysis of flood parameters is first based on the Indicator of Hydrological Alteration method developed by Richter et al (1998). This approach is based on a multivariate approach to quantify the hydrological alterations and to define the degree to which anthropogenic disturbances (post-dam regime) will influence the hydrological regime within an ecosystem (Richter et al., 1998). In this approach, various hydrological parameters are defined in terms of flows, timing, frequency, duration and rate of change to measure hydrological alteration. This method has already been validated for assessing the impacts of dams on hydrological regimes (Maingi and Marsh, 2002; Yang et al., 2008). It is particularly effective for watersheds where only one dam exists. The method is based on the calculation of averages of each parameter for different hydrological periods, as well as their coefficient of variation for the same periods. Within the framework of this study, the indicators selected allow the description of the hydrograph of the Senegal River flood (Figure 3). Ten indicators describing the shape of the flood hydrograph were selected to quantify the evolution of the

flood following the installation of the Manantali Dam : the mean flow in September, the maximum flow (Q_{max}), the maximum flow exceeded during 7, 20 and 30 consecutive days (Q_{max7} , Q_{max20} , Q_{max30}), the date of the flood peak, the duration of the flood corresponding to the number of days when the flow is higher than the third quartile Q_3 of the daily mean flows of the period, the mean volume discharged between June and December, the duration of the rise of the flood, the duration of the flood-recession. The rise and fall times are determined by calculating the number of days separating the flood peak (Q_{max}) from the third quartile flow Q_3 . The calculation of the parameters is only done for the months of June to December, during the flood period to exclude low water flows.

2.4. Flood monitoring with remote sensing

The POGR (In French: Programme d'Optimisation de Gestion des Réservoirs) has made a census and a compilation of data on the flooded areas each year between Matam and Dagana for the period 1946-2000. This collection work was carried out by the French Research Institute for Sustainable Development (IRD), using different data sources: from aerial overflights before the 1970s, then field data and hydraulic modelling (Lamagat, 2001), to the use of remote sensing from the end of the 1990s (Bonneau, 2001). The monitoring by remote sensing of flooded and cultivated areas in flood recession/irrigation has been the subject of different studies: in 1987 by the OMVS, at the beginning of the 2000s within the framework of the POGR (OMVS and IRD, 2002) and by Mané and Fraval (2001). This work was carried out using SPOT images, but was never reproduced beyond the project in which it was carried out because of the high cost of these images. The MODIS medium spatial resolution images are therefore of interest for the regular monitoring of flooded surfaces.

In order to validate the use of MODIS images, a Landsat TM image from September 29, 2009 is compared to a MODIS image from September 30, 2009 on a test area around the

floodplain. The detection of water surfaces is performed using spectral indices to differentiate the water areas. Four existing indices are tested to select the most efficient one, these indices differ according to the spectral bands that they combine : the NDVI (Normalized Difference Vegetation Index), the DVEL (Difference Value between – the Enhanced Vegetation Index and the Land Surface Water Index) developed by Xiao et al (2006) and two other Normalized Difference Water Indices (NDWI) : the first NDWI (NDWI_{Red}) is based on the difference between red bands (RED) and the shortwave infrared (SWIR) and was developed by Rogers and Kearney (2004). The other one (NDWI_{Green}) is based on green and SWIR bands (McFeeters, 1996) and was used at a local scale by Sall et al. (2020) on the Senegal River basin at Podor gauging station. These indices are tested empirically on the Landsat TM image according to their values on different landscape elements (Table 2). The NDWI_{Red} appears to be the most efficient since it distinguishes more effectively the flooded areas that are visible at high spatial resolution. Compared to NDWI_{Green}, the detected threshold values for water are higher, which allows easier downscaling between Landsat (30 m) resolution with MODIS images (500 m). NDWI_{Red} (Eq. 1), hereafter referred as NDWI, has been used by different authors for the detection of flooded areas in different tropical zones (Léauthaud et al., 2012; Pricope, 2013) and has already proven its ability to detect flooded area in the Inner Niger Delta (Rogers and Kearney 2004).

$$NDWI = \frac{\rho_{Red} - \rho_{SWIR}}{\rho_{Red} + \rho_{SWIR}} \quad (1)$$

where ρ_{Red} and ρ_{SWIR} are the reflectance values in respectively the red and SWIR bands.

Faced with other results such as those of Sakomoto et al (2007), who themselves cite the results of Rogers and Kearney (2004), the NDWI threshold was adapted to the environmental conditions of the Sudano-Sahelian zone of the Senegal River Valley. The NDWI threshold value for detecting the presence of water on MODIS images has been empirically set to 0.

Areas outside the floodplain and cultivated irrigated perimeters have negative values, whereas flooded pixels and river pixels have large positive values. As a result, some pixels considered as flooded areas are confused with irrigated perimeters, when spectral conditions are close, generally in areas where the water depth is shallow. It thus seems correct to think that the low NDWI values observed here compared to studies elsewhere are related to the characteristics of the environment: a low vegetation cover and many areas of bare soil. Finally, a mask of the permanent water areas is made from a Landsat TM image of May 2013, it includes the different tributaries and ponds in water all year round.

3. Results

3.1. Flood parameters evolution

The interannual evolution of the flood at the Bakel station reveals three distinct periods (Figure 4). Pettit's homogeneity test on the streamflows at Bakel indicates a break in 1970 for the mean annual and mean flood flows (June to December), with a decrease of 47% and 34% respectively. On the flows during the low-water period (January to May), the Pettit test shows a break from 1990 onwards. All these results are similar to those of Sambou et al. 2009, with ten years of additional measurements. Between 1951 and 1968 i.e. during the wet period, the total volumes flowing during the flood period (June to December) are 27 km³ annually on average with a maximum value of 34 km³ in 1954 and a coefficient of variation of 0.22. During this wet period, the average volumes discharged annually by the flood are strictly higher than the average for the whole period 1951-2018, which is 17 km³ of annual total streamflow (Figure 5). This period is followed by a transition period between 1969 and 1976 which marks the onset of drought and is characterized by a decrease in flows during flood periods and an alternation of low and high floods. The average volumes discharged annually during the flood period was 19 km³ and ranged from 9.8 km³ in 1972 to 24 km³ in 1974. Then the annual dotation of 7.5 km³ for the three countries interested for irrigation appears as

sufficiently “prudent”. This dotation was confirmed in 2002 during the implementation of the Water Charter. The definitive installation of the hydrological regime of drought is observed from 1976, the year from which the flows in periods of flood are strictly lower than the average. This installation also follows the break observed in 1975 on the annual flows in the upper basin of the Bafing.

The average volumes discharged at Bakel thus was 10.5 km^3 between 1976 and 1993, ranging from a maximum of 15.3 km^3 in 1978 and a minimum of 6.2 km^3 in 1987. The value of the year 1987 is not linked to a natural rainfall deficit, but is characterized by the filling of the reservoir of the Manantali Dam by the waters of the Bafing River basin flood, which drastically reduced the flow downstream from the dam. After the construction of the Manantali Dam, and more particularly in 1994, a slight increase in volumes (14.7 km^3) was observed, accompanied by greater variability (coefficient of variation of 0.31 against 0.25 for previous periods), characterized by the existence of high floods some years. The high flood volumes recorded for years 1999, 2003 and 2012 ($> 20 \text{ km}^3$) are linked to heavy rainfall in the Senegal watershed, while the exceptional high flood in year 1994 is explained by the large releases of water from the dam carried out for test reasons : the releases reached $1760 \text{ m}^3\text{s}^{-1}$ in September 1994 and they remained above $1000 \text{ m}^3\text{s}^{-1}$ until December 21, inducing a flood hydrograph very different from the natural hydrograph.

The evolution of the flood hydrograph at Bakel station shows a general decrease in flood volumes between the natural hydrological regime and the artificial regime (Figure 5). The hydrograph of the pre-drought period is characterized by a high peak flow ($> 4000 \text{ m}^3\text{s}^{-1}$) whereas after the 1970s flows are reduced ($< 2000 \text{ m}^3\text{s}^{-1}$). This observation is similar to other neighboring rivers such as the Niger (Bricquet et *al.*, 1996). It must also be put into

perspective by the fact that the 1951-1970 period is considered to be hyper-wet in West Africa, which may explain the high flows during this period. The interesting observation is that after the Manantali Dam closing in 1987, the flood hydrograph shows no significant change, the average daily flows from 1988 have remained almost equivalent to those of the period 1970-1988, a slight increase in the peak is observed, while the recession curve remains similar as the one of the drought period (Figure 4).

The comparison of flood parameters between periods shows a general reduction in the water resource available during the flood since the drought period of the 1970's (Table 3). The streamflow and volume parameters were reduced by 50% between the wet (1951-1970) and the dry periods (1971-1987). The peak flood decreased from $5835 \text{ m}^3\text{s}^{-1}$ to $2807 \text{ m}^3\text{s}^{-1}$, while the average flow in September decreased from 3937 to $1738 \text{ m}^3\text{s}^{-1}$. However, it should be noticed that nowadays the flood stored in the Manantali reservoir is spread over the 12 months of the year, which has led to an increase in dry season streamflows. The main signal observed here is the decrease in flood duration parameters which were reduced by 58%. The duration of the flood, when the flow is above $1456 \text{ m}^3\text{s}^{-1}$ (3th quartile of daily flow during flood months) has reduced from 76 days to 32 days. The decrease in streamflow and in the duration of the flood period drastically reduced the volumes of water available for flooding the wetlands, which fell by 55% between the two periods. The variability of all the parameters increased, with in particular a very strong increase in the coefficients of variation of the flood durations, rise and recession times. The coefficient of variation of the duration of the flood recession period increased from 0.36 to 0.88, while the date of the flood peak was slightly advanced by 13 days. In the middle Senegal river valley at Podor, 400 km downstream from Bakel, the average day of the maximum water height was advanced by one month, from October 2 to September 3, showing a faster speed of runoff between Bakel and Podor and a

drop-in filling the flooded areas. The same evolution is noticed in the red flood of the Niger river at Niamey station (Descroix et al., 2012; Descroix et al., 2018) and in the Sirba during the drought (Amani et Nguetora, 1996)

The interesting fact is that, since the Manantali Dam construction in 1987, most of the parameters remained at values close to those of the drought period (1971-1987). The September flow rate and the volume discharged during the flood period have only increased by 15% since the drought years. Parameters of maximum flow values during 1, 7, 20 and 30 days have remained similar between the dry period and the actual post-dam period. The duration of the recession has increased by 20% showing greater support of the flows over time by the upper basin. In general, the coefficients of variation of the different parameters became lower after dam construction (from 0.5 to 0.3) showing an increased regularity of the hydrological processes contributing to the flood. Nevertheless, the duration of the flood and the rise and recession times is still as variable as during the drought period. These duration parameters are important for the performance of flood recession agriculture in the Senegal Valley, as the duration of water stagnation is important for soil water recharge. Indeed, most farmers practicing flood recession agriculture define a threshold of recharge efficiency starting from 30 days of flooding (Bruckmann, 2018).

3.2. Interannual variability of flooded areas in middle Senegal river valley

To actualize the IRD database after 2000, the annual flood extent at the flood peak between Matam and Podor is monitored each year with MODIS. The values in 2000 are different between our analysis based on remote sensing (52 000 ha) and the IRD database (102 000 ha) whose data comes from modelling for that year. Flooded areas show a high interannual variability with a coefficient of variation of 0.7 (Figure 6). Flooded areas vary widely from year to year, more than discharge parameters, but close to flood duration parameters. The areas flooded in 2002, 2004, 2005, 2014 and 2017 are lower than 50 000 ha (Figure 7). In

2006, only 6,392 ha were flooded, whereas the flooded areas exceeded 150 000 ha in 2003, 2007, 2012, 2013 and 2015. The years 2003 and 2012 are the most flooded (> 200 000 ha). Compared to IRD data of flooded areas available since 1956, annual flooded areas after Manantali construction are closely similar to flooded areas during drought period (Figure 6). Important flood during 1999, 2003 and 2012 represent levels close to those before the 1970s (Bonneau, 2001).

The total area of the floodplain analysed here is 454,907 ha, of which 44% are never flooded (i.e. around 200 000 ha), 26% are flooded less than one year in five, 8% every other year and barely 1% of the surface is flooded annually. The most regularly flooded areas are generally found in the heart of large basins in the immediate proximity of the tributaries which drain the floodplain (Figure 8). There is a flood gradient around these basins: in the center are the most frequently flooded areas. Using the SRTM data, it can be observed that the areas never flooded are those located at an average elevation of 12 m or more, while the areas that are flooded every year are all located below 10 m. Areas flooded less than once every 5 years are located at an average altitude of 11m. The other zones with higher frequencies are located on average between 10 and 11 m. This shows the importance of flood parameters (heights, flows and duration) as well as the existence of microtopographic factors on which the connection and filling of the basins will depend.

In order to define the hydrometric thresholds (minimum water levels) allowing flooding and flood recession cultures, we analyse the relationships between flooded areas and hydrometric variables for the period 1955-2018, due to the homogeneity of the acquired data. For this purpose, hydrometric variables that have the strongest correlations with the flooded areas (coefficients r greater than 0.85) are used to determine hydrometric thresholds. Five

parameters are thus selected to allow the definition of a flood hydrograph for several values of flooded surfaces: the duration, the maximum flow, the flow exceeded during 7, 20 and 30 days. Water level during the flood is also an important factor, especially the water level exceeded during 30 days ($r=0.94$). The number of days when the flow exceeds the third quartile of average flows during flood period (i.e. $1456 \text{ m}^3\text{s}^{-1}$) is also correlated with the variation in the areas flooded and is highly dependent on the flow of the peak flood. This third quartile can be considered as a filling tipping point for an inundated surface of 100 000 ha. In Bakel it corresponds to a water height of approximately 590 cm. In the POGR (IRD, 2001) the optimized artificial hydrographs showed that to obtain areas of more than 50,000 ha cultivable in recession (i.e. about 100 000 ha gross flooded), the height at Bakel had to exceed 661 cm for 30 days (in Bakel the threshold to define the flood in the OMVS studies is 675 cm). To reach 100 000 ha of cultivable areas (i.e. more than 200 000 ha flooded), the height must be 991 cm, corresponding to a discharge of $3500 \text{ m}^3\text{s}^{-1}$ (OMVS & IRD, 2000). These thresholds are closer to those obtained in our study. These thresholds are related to the topography of the floodplain, in particular the heights of the entry points and feeder channels. These are numerous and can be several per flooded basin, which complicates the implementation of precise hydraulic models without the help of elevation data at the centimetric scale. Hydrometric thresholds have been determined empirically based on hydrological factors strongly correlated with the flooded areas (Table 4). There are threshold effects in relation to heights, maximum flow and flow duration. To exceed 100 000 ha flooded between Matam and Podor (approximately 50 000 ha cultivated in recession), the peak flow must exceed $3\ 000 \text{ m}^3\text{s}^{-1}$ and 9 meters of water height at Bakel, values similar to those of POGR. For the flooded areas to exceed 200,000 ha, the water height must exceed 8 m for 30 days, the peak flow must be higher than $4,900 \text{ m}^3\text{s}^{-1}$ and the duration of the flooding must be longer than 60 days for flows above $1,456 \text{ m}^3\text{s}^{-1}$. The micro-topography has an

essential role in the water supply of the floodplain, it can be observed that the topographic thresholds to be submerged vary strongly with an amplitude of more than 4 m between 50 000 and 250 000 ha. Approximately one meter of additional water at Bakel station is needed to flood 50,000 ha more.

3.3. Sub-watershed spatio-temporal contribution to Senegal river flood

To assess the origin of flood, the contribution of each tributary to the flood. To do this, we analyse the proportion of the volumes flowing each year between July and November at Dakka Saidou, Oualia, Gourbassi and Manantali with the volumes flowing at Bakel between 1955 and 2018. The cumulative volumes of the three main tributaries corresponds on average to 74% of volumes in Bakel. There is therefore a local contribution of 26% which comes mainly from the lower part of the basin of Bafing, downstream from Manantali (a section of about 400 km length), but also from the Sahelian tributaries, Kolimbine & Karakoro. In this study, this area is named lower Bafing and Sahelian tributaries watersheds (LBST). The Bafing is the main tributary contributing to flood volumes with 34% in average between 1951 and 2013. The Bakoye and Falémé sub-watersheds have each contributed about 20% over the same period. From the 1970s, these contributions decreased between 14 and 16%, while the contribution of Bafing increased to 43% between 1971 and 1987, reaching exceptionally 74% in 1983. The Bafing supported the water supplies during the drought period due to the lower decrease in precipitation over Fouta Djallon and the lower decrease in depletion coefficient in this sub-basin (Descroix et al., 2020). From 1987, following the construction of the Manantali Dam, the contribution of the Bafing is calculated with the discharge measured at Manantali, because the dam controls all the water supplies downstream. The contribution of the dam is gradually decreasing, but remains significant for some years, as in 1992 and 2001 (50%). Between 1987 and 2018, the Bafing contributions were on average 31% of the total flow, and 21% for each of the other two tributaries (Figure 9).

After dam construction, the main change in flood supplies at the entrance of the valley was observed from 2004 following the installation of the five electrical generators at Manantali Dam (Figure 10). From this period, the electric power production has become a management priority, which limits flows to a maximum of $500 \text{ m}^3\text{s}^{-1}$ to ensure efficient production. Between 1988 and 2003, the Manantali Dam supported the Senegal flood (Figure 11). Releases were carried out during the flood cycle with an average flow in September of $675 \text{ m}^3\text{s}^{-1}$. Following the installation of the hydropower plant, from 2004 onwards, the average flow in September thus rose to $200 \text{ m}^3\text{s}^{-1}$. Comparing the volumes flowing from Bafing at Dakka Saidou and Manantali with those from Bakel indicates a decrease in correlation between the period 1955-1987 ($r=0.92$) and the period 1988-2018 ($r=0.48$). The year 1990 is an exception since the average flow was very low due to a dam filling test, which minimized the downstream flows.

Over the 2004-2013 period, the contribution from Bafing decreased down to 25%, while contribution of Bakoye and Falémé Rivers watersheds rose to 22%. This reduction of contributions from the Bafing River has the effect of increasing the contributions from the uncontrolled part of Bafing and the Sahelian tributaries, it increased from 25 % before 2004 to 30 % after 2004. The management of the flood water at Manantali made the flood completely dependent on the uncontrolled tributaries. During heavy floods, the local contribution is significant, generally greater than 30%. In 1974 (peak flood at $6767 \text{ m}^3\text{s}^{-1}$) the local contribution was 36%, against 28% for the Bafing and 17% for each of the two other tributaries. During the 2012 flood (peak flood at $4056 \text{ m}^3\text{s}^{-1}$) the local contribution was 44% against 17% for the Bafing (dam), 18% for the Falémé and 21% for the Bakoye. Since 2004, the source areas of the flood have been distributed equitably between the Bafing, Bakoye and Falémé (Figure 11), with an increase of other contributions. The management of the

Manantali Dam has been moving towards a "no-flood" dam management since 2004, as feared by researchers from Institute for Development Anthropology (Horowitz et al., 1990) and A. Adams (2000). Since 2002, when two of the five generators were installed flood releases have become flood supports, whereas the reservoir has the capacity to sustain floods during low flow years (Bader and Albergel, 2015). This situation is always making good flooding possible, but increasing the irregularity according to the spatial distribution of the rainfall in the Sudanian and Sahelian watersheds.

3.4. A synthesis of factors influencing flood

In order to understand the factors conditioning the upstream water supply at Bakel, the information on hydrometric parameters, sub-catchment contributions and rainfall for floods between 2001 and 2018 are analysed. A typology of the floods is performed from a hierarchical classification on main components based on their hydrometric and pluviometric characteristics of annual floods. Results of this classification lead to three types of floods that can be categorized as low (years 2002, 2004, 2006, 2014 and 2017), medium (years 2001, 2005, 2007, 2008, 2010 and 2011) and high (years 2003, 2009, 2012, 2013, 2015, 2016 and 2018).

Hydrometric characteristics and flooded surfaces logically increase with the intensity of the flood (Table 5). For floods considered as medium, Q_{max} and Q_{max7} are close to the mean of the period, i.e. 2871 and 2530 m^3s^{-1} respectively, while their values deviate from it for low or high floods. Highest floods are characterized by higher values of Q_{max20} and Q_{max30} and thus influence the volume discharged. In this sense, flood durations, as well as rise and flood times, have major roles in the intensity of the inundation in the valley. When their values deviate from the mean, floodings are low or high. This is particularly the case for the very high floods (2003 and 2012), which have flood durations of more than 68 days with an average decreasing phase of the flood time of 53 days. The weakest floods ($< 1456 m^3s^{-1}$)

have a very short duration, on average 9 days with a strong rise (2 days) and an equally rapid fall (7 days). Again, the typology shows the influence of flood durations on the flood intensity and the flooded areas in the valley. This highlights the significance of maintaining high flows at the Manantali Dam for a sufficient period of time (2 months) to ensure the hydro-ecological functioning of the Senegal valley. The contributions of the various sub-catchments to the volume of water discharged in Bakel indicate that low floods are characterized by low contributions from the Bakoye (-20%) and low Bafing and Sahelian tributaries sub-basin (LBST), while contributions from the Bafing river to the Manantali reservoir are significant (+30%). Since the drought period, the Bafing river and the Manantali Reservoir have supported river flows during years of water scarcity, due to higher rainfall conditions in the Upper Bafing. This situation shows the importance of supporting the flows of the Senegal River through a larger contribution from the Bafing (Manantali) during the driest years. However, these contributions from the dam remain low in volume in order to limit losses in hydroelectric production. Medium floods have high contributions from the Bakoye, normal contributions from the Falémé and Bafing, but receive a lower contribution from the LBST zone, while high floods have higher contributions from the Bakoye (Figure 12). High floods are characterized by a deficit in the contributions of the Bafing from Manantali Dam (-25%) and by a greater contribution from the LBST watershed (+18%). Manantali's contributions to the flood have exceeded the average for low and medium years, and deficit for high floods, which shows the negative influence of regulation on high flow values. In wet years, the dam limits releases to $500 \text{ m}^3\text{s}^{-1}$, which is a relatively low flow rate compared to the Bakel flood. By analysing the rainfall in the upper Senegal watershed for these flood typologies, it is clear that in years of high floods, the entire Upper Senegal watershed observes positive relative deviations from the average rainfall between 2001 and 2018. Rainfall excess can reach 30% in some areas, particularly in the Kayes region, which explains the significant contributions of

the LBST watershed during these years. The year 2012 and its high flood was characterized by much higher than average rainfall (up to 70%) in the Sahelian zone of the upper basin in the Kolimbine and Karakoro sub-basins. This high rainfall also explains the significant contribution of the LBST watershed in 2012 (44%), whereas on average the contribution of this watershed is 27%. It should also be noted that during high floods, the Bafing River in its Guinean zone receives normal inflows, which shows the importance of rainfall of the LBST zone of the upper basin in the processes leading to very high floods in the post-dam period. For average floods, the deviations are around the average (between -10 and +10%) on most of the upper basin with exceptions on the upper Bakoye, where they are higher. Finally, for low floods, rainfall relative deviations are negative in most of the basin, with values as low as -35% in some areas upstream from Bakel and in the Sahelian part. However, the Guinean part of the Bafing basin receives slightly above average rainfall (between 0 and +12%).

Conclusion

The Senegal River flood has suffered a generalized alteration of its functioning after the reduction of hydrological parameter values and the increase of their variability during the drought of the 1970s. During this period, the Bafing River has become the main contributor to the flows during the annual flood period due to a lower reduction of its flows compared to the Falémé and Bakoye rivers. This is explained by the position of the Bafing River in the Guinean zone. Since the drought and the Manantali Dam construction in 1987, the Senegal River flood hydrograph has remained almost constant, despite a slight reduction in the inter-annual variability of the hydrograph parameters.

The main consequence of the Manantali Dam in the evolution of the flood consists in the reduction of the Bafing's contribution to the flood. Since 1987, flood water has been stored in the Manantali reservoir to be distributed throughout the year to allow for regular power

generation. The contribution from the Manantali Dam has been reduced since 2004, following the installation of all the electric turbines of the dam and the end of the water releases during the month of September. Since then, the contributions of the various sub-basins have become balanced, making the flood more sensitive to spatio-temporal variations in rainfall in the uncontrolled basins. In fact, since 2000, it has been observed that contributions to flows during low flood years come mainly from the Bafing River through the Manantali Dam. In contrast, high floods, such as the one in 2012, depend on excess rainfall in uncontrolled basins and in particular in the LBST basin, much of which is located in the Sahelian zone.

The flooded area in the Senegal Valley has also followed the same reduction since the 1970s. There is a very high inter-annual variability in the flooded areas, since only 18% of the floodplain can be considered as regularly flooded (i.e. every year). Flooding in the valley depends essentially on the maximum heights and flows. Thus, the flood in September must exceed a peak flow of $3000 \text{ m}^3\text{s}^{-1}$ to flood 100,000 ha, which corresponds to about 50,000 ha cultivated in the middle valley of Senegal River.

Changes and inter-annual variability of the flood are linked simultaneously to natural variations in rainfall and to the management of the Manantali reservoir, which is nowadays in a logic of a no-floods management, in order to maintain the hydroelectric production. This management appears to be in contradiction with the Water Charter, set up in 2002, which prones an equitable distribution of water between the various uses. The reduction in contributions from the Bafing River limits the flooding of the Senegal River Valley during years of low to average rainfall, which impacts the livelihoods downstream. Indeed, the thousands of households that depend on flood water in the middle Senegal River valley must

adapt to a very high inter-annual variability of the flood, which mostly reduces the effectiveness of flood recession agriculture and fishing.

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Table 1 – Used Discharge data

Watershed	Stations	Area (km ²)	Start of record
Bafing	Dakka Saidou	15660	27/05/1952
	Manantali Dam	32450	19/07/1987
Bakoye	Oualia	78154	01/06/1954
Faleme	Gourbassi	16264	02/01/1954
Senegal	Bakel	220800	26/06/1950

Table 2 – Index values for several land covers over Senegal river valley. DVEL is Difference Value between EVI (Enhanced Vegetation Index) and LSWI (Land Surface Water Index) ; NDWI is Normalized Difference Water Index.

	Flooded areas	Irrigated perimeters	Non-flooded areas	River
DVEL	-0,40	-0,10	0,03	-0,34
NDWI	-0,09	0,28	0,27	0,01
NDWI Green	0,10	-0,20	-0,23	0,04
NDWI Red	0,48	-0,16	-0,33	0,36
NDWI Red MODIS	0,20	-0,27	-0,29	-

Table 3 – Comparison of the 10 hydrological parameters describing the flood hydrograph of Senegal river at Bakel. Data source: OMVS database

Parameters	1951-1970		1971-1987		1988-2019	
	<i>X</i>	<i>σ</i>	<i>X</i>	<i>σ</i>	<i>X</i>	<i>σ</i>
September mean discharge (m^3s^{-1})	3937	0.33	1738	0.46	1987	0.32
Maximum daily discharge (m^3s^{-1})	5835	0.30	2807	0.54	2918	0.30
Qmax day	260 (16 sept.)	0.04	247 (3 sept.)	0.05	247 (3 sept.)	0.05
Flow exceeded for 7 days (m^3s^{-1})	5560	0.31	2618	0.57	2756	0.32
Flow exceeded for 20 days (m^3s^{-1})	3962	0.30	1806	0.46	1953	0.33
Flow exceeded for 30 days (m^3s^{-1})	3323	0.26	1607	0.42	1583	0.39
Flow exceeded for 90 days (m^3s^{-1})	1138	0.21	586	0.41	590	0.39
Average volume from June to December (billion m^3)	27.2	0.22	12.6	0.37	14	0.33
Average duration of the flood (periods where $Q > 3\text{rd}$ quartile, i.e. $1456 \text{ m}^3\text{s}^{-1}$)	76	0.20	32	0.74	34	0.63
Average flood rises time (days)	42	0.29	15	0.90	13	0.79
Average flood recession time (days)	35	0.36	18	0.88	22	0.67

Table 4 – Hydrometric thresholds for different variables established from linear regression for flooded areas from 50 000 to 200 000 ha. Data source: OMVS database

Hydrometrics thresholds	Duration (day)	Qmax (m³s⁻¹)	Qmax7 (m³s⁻¹)	Qmax20 (m³s⁻¹)	Qmax30 (m³s⁻¹)	Hmax30 (cm)
Correlation coefficient r	0,89	0,94	0,94	0,96	0,95	0,94
50 000 ha	22	2101	1803	1376	1163	524
100 000 ha	36	3063	2692	2053	1725	628
150 000 ha	50	4024	3581	2731	2286	733
200 000 ha	63	4986	4471	3408	2848	837
250 000 ha	77	5948	5360	4085	3409	942

Table 5 – Comparison of the flood parameters of the four "typical" floods. Data source: OMVS database; IMERG-GPM 2001-2018

Flood typology	Low	Medium	High
Years (n)	5	6	7
Flooded areas (ha)	13 628	68 721	152 077
Maximum flow rate (m³s⁻¹)	1719	3026	3588
Volume flowed between June and December (billion m³)	9,8	13,4	18,6
Flow exceeded 20 days at Bakel (m³s⁻¹)	1174	1820	2574
Flow exceeded 30 days at Bakel (m³s⁻¹)	1060	1382	2249
Flood-recession time (days)	7	18	33
Number of days >Q3 (1456 m³s⁻¹)	9	29	56
Average rainfall in the Bakel watershed 220,800 km²	759	795	881
Average rainfall in the Bakoye watershed 78,154 km²	757	826	890
Average rainfall in the Bafing watershed (upstream of Manantali dam) 32,450 km²	1235	1155	1250
Average rainfall in the Falémé watershed 28,703 km²	961	1011	1133
Bakoye contribution (%)	17	24	24
Bafing/Manantali contribution	36	28	21

(%)			
Falémé contribution (%)	22	22	22
Contribution of LBST - low			
Bafing (downstream of Manantali)	24	25	33
and Sahelian tributaries (%)			

Figures

Figure 1. Senegal river watershed and hydrological stations used in this study

Figure 2. Average daily streamflow at the Bakel station over the period 1951-2018. Data source: OMVS

Figure 3. Relationship between the shape of the flood hydrograph and the hydrological parameters analysed

Figure 4. Average hydrograph for the three hydrological periods. Data source: OMVS

Figure 5. Interannual evolution of standardized mean discharge for JJASOND at Bakel station between 1951 and 2018. Data source: OMVS

Figure 6. Flooded area every year in middle Senegal river valley between Matam-Podor since 1946 using IRD database (blue), MODIS (this study) and average for each hydrological period (black). Data source: IRD, MODIS

Figure 7. Maximum flooded areas between 2000 and 2019. Flooded area is detected using $NDWI > 0$. Data source : MODIS MOD09A1

Figure 8. Flood frequency in the Senegal valley between 2000 and 2019. Data source: MODIS-A09; SRTM

Figure 9. Contribution of the main sub-basins to the flood volume in Bakel in percentage between 1955 and 2013. Data source : OMVS

Figure 10. Average daily flows downstream of the Manantali dam for the periods 1988-2003 (blue) and 2004-2018 (red). Data source: OMVS

Figure 11. Spatial distribution of the average contribution to the annual flood in Bakel of the different sub-watersheds of the upper Senegal river for different periods: 1951-70 (humid period), 1970-87 (drought), 1988-2004 (artificial regime), 2004 -13 (artificial regime & electric power driven).

Figure 12. Relative deviations of rainfall from the 2001-2018 average for different types of floods. Datasource: GPM_3IMERGM

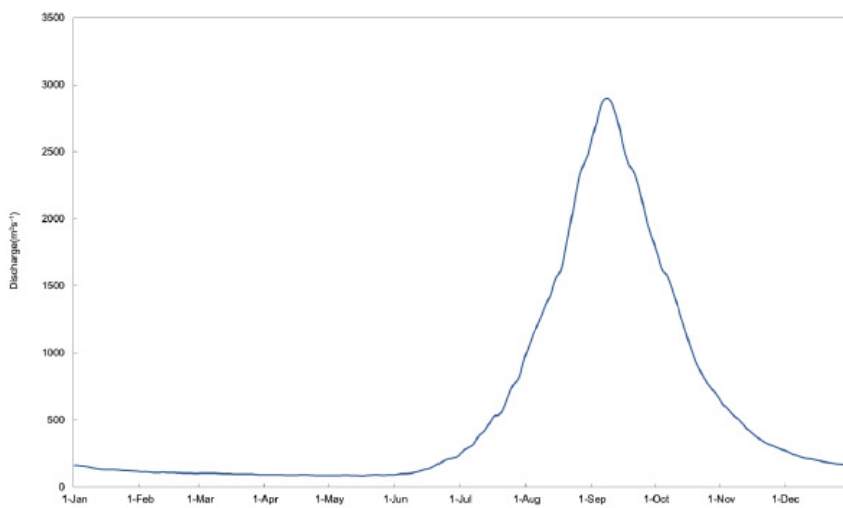
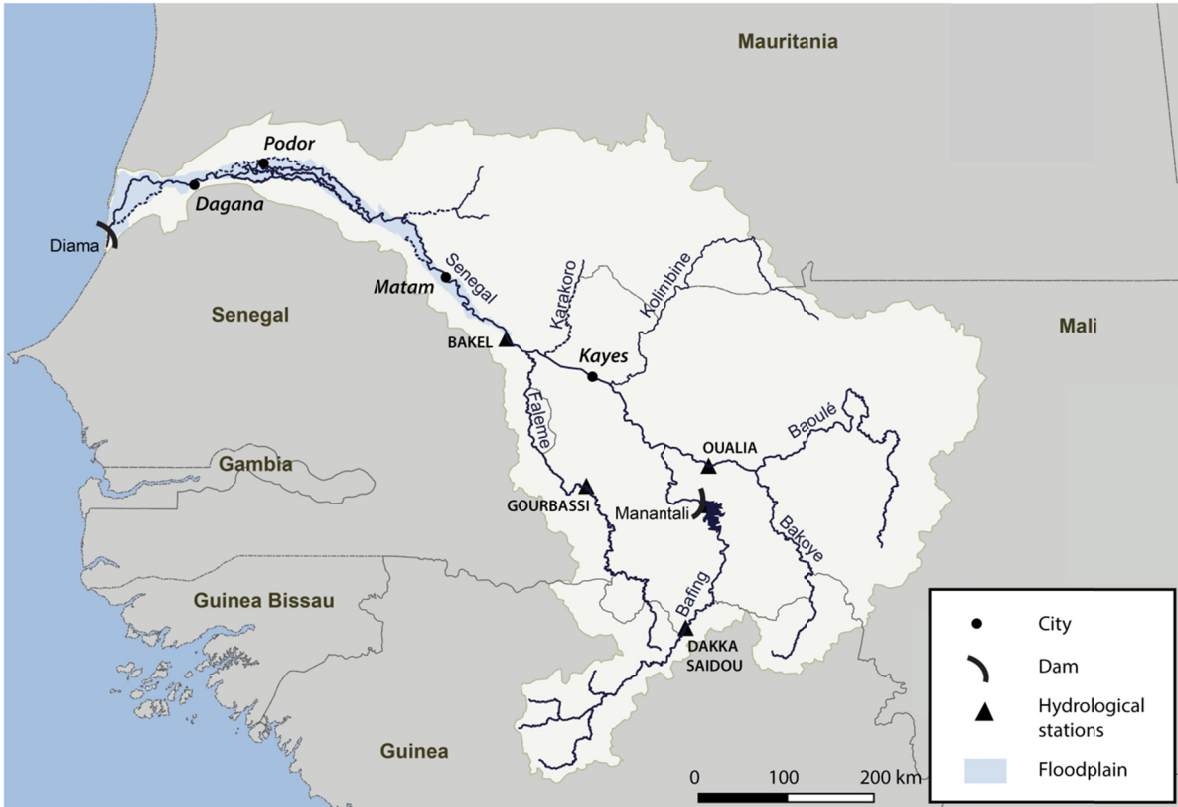


Figure 2 – Average daily streamflow at the Bakel station over the period 1951-2018. Data source : OMVS

292x175mm (236 x 236 DPI)

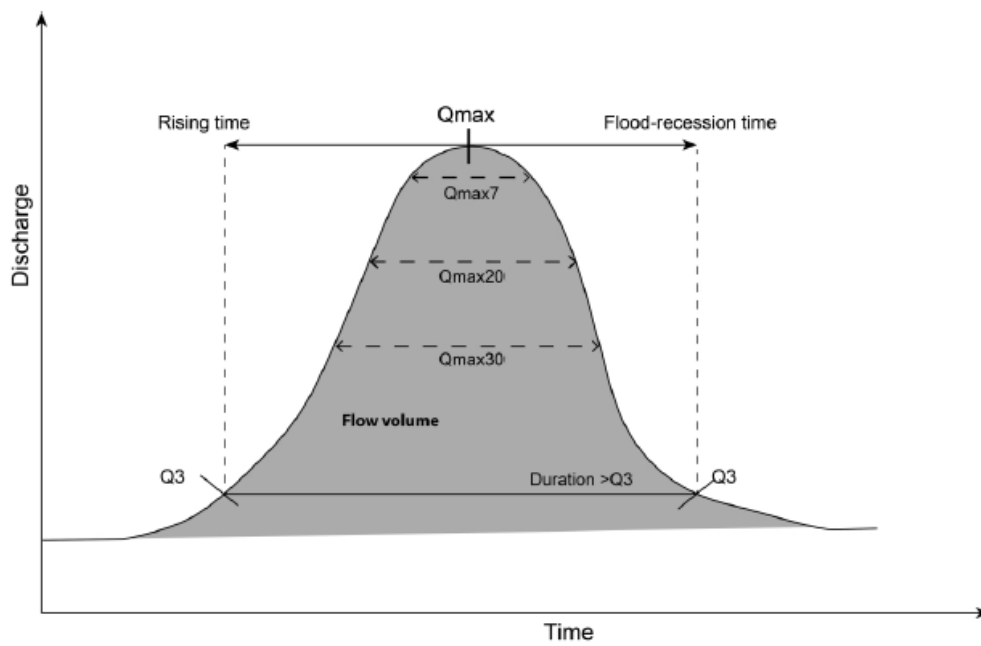


Figure 3 – Relationship between the shape of the flood hydrograph and the hydrological parameters analysed

613x397mm (236 x 236 DPI)

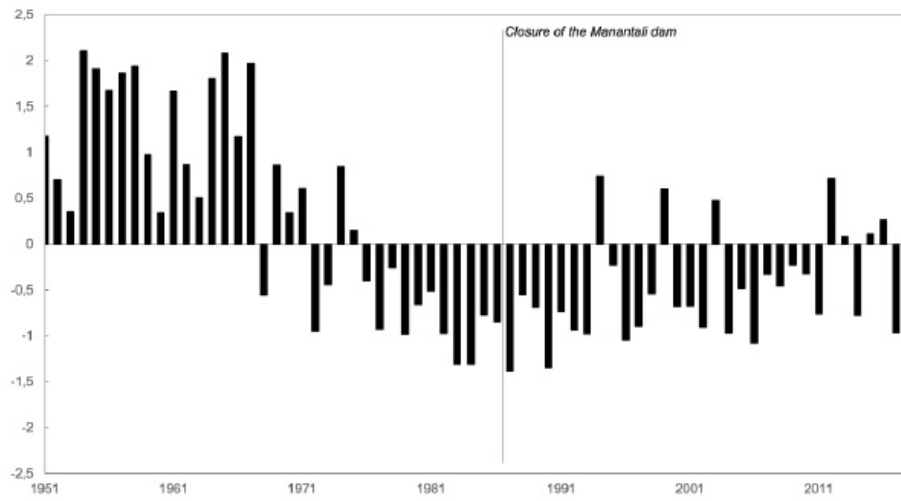


Figure 4 – Interannual evolution of standardized mean discharge for JJASOND at Bakel station between 1951 and 2018. Data source : OMVS

244x144mm (236 x 236 DPI)

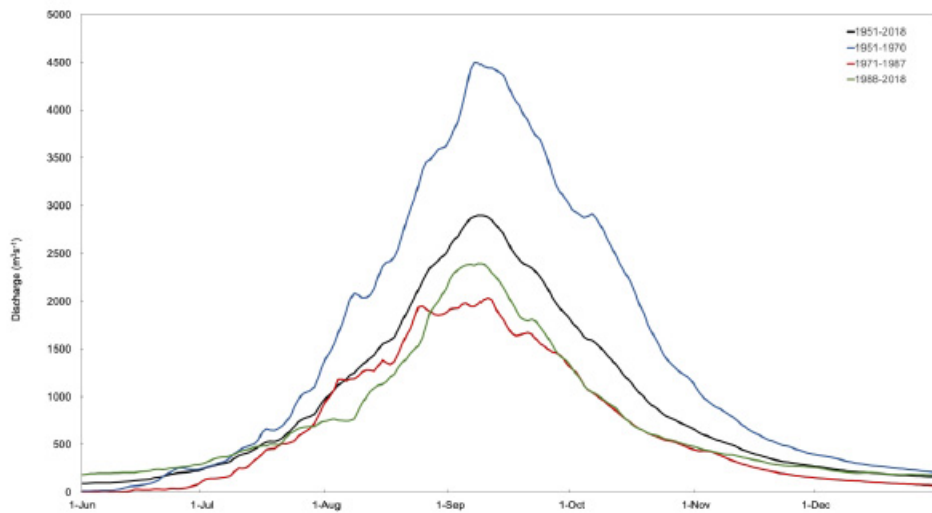


Figure 5 – Average hydrograph for the three hydrological periods. Data source : OMVS

313x174mm (236 x 236 DPI)

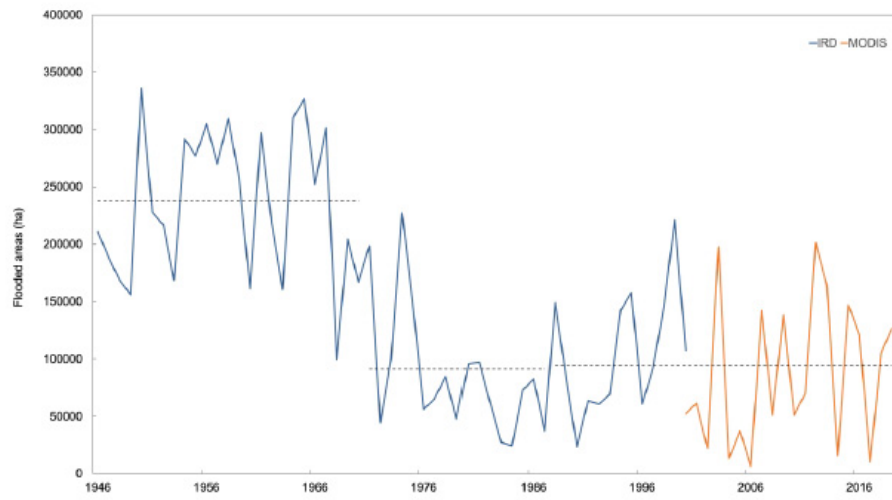


Figure 6 - Flooded area every year in middle Senegal river valley between Matam-Podor since 1946 using IRD database (blue), MODIS (this study) and average for each hydrological period (black). Data source: IRD, MODIS

264x151mm (236 x 236 DPI)

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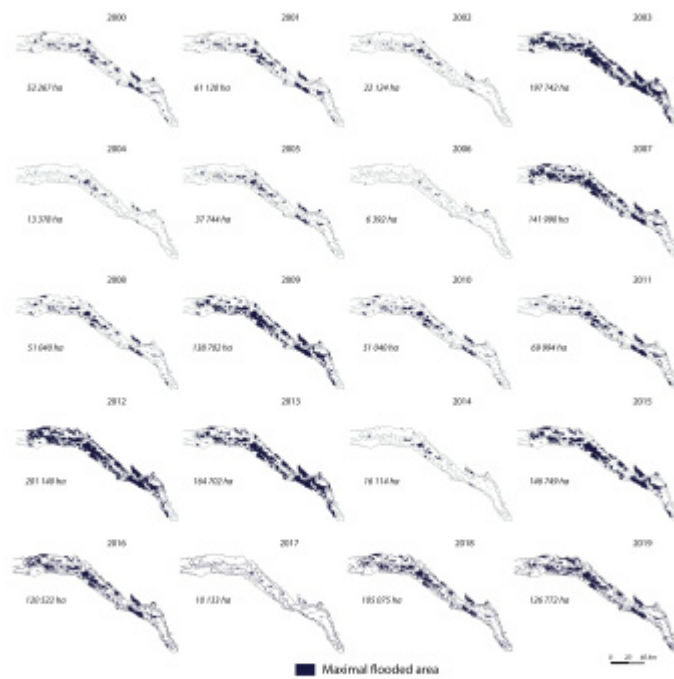


Figure 7 - Maximum flooded areas between 2000 and 2019. Flooded area is detected using NDWI > 0. Data source : MODIS MOD09A1

605x536mm (236 x 236 DPI)

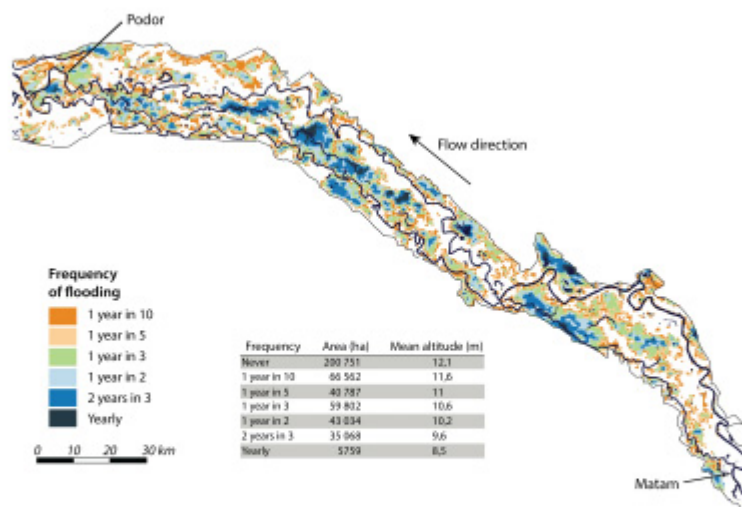


Figure 8 - Flood frequency in the Senegal valley between 2000 and 2019. Data source: MODIS-A09; SRTM

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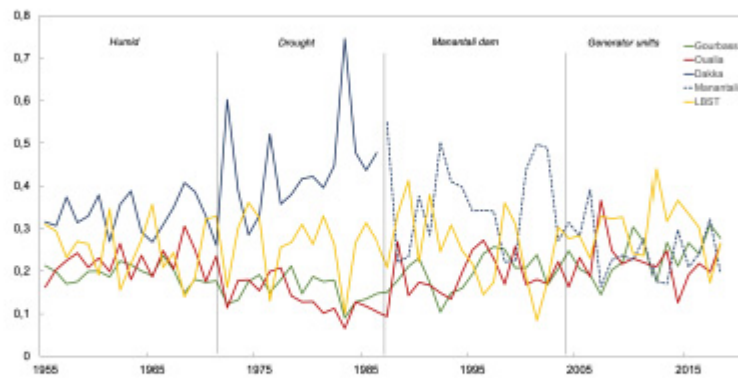


Figure 9 - Contribution of the main sub-basins to the flood volume in Bakel in percentage between 1955 and 2013. Data source : OMVS

227x123mm (236 x 236 DPI)

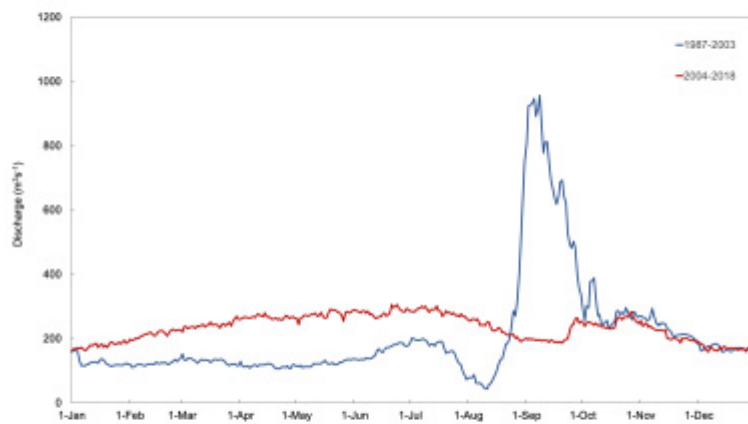


Figure 10 – Average daily flows downstream of the Manantali dam for the periods 1988-2003 (blue) and 2004-2018 (red). Data source: OMVS

240x139mm (236 x 236 DPI)

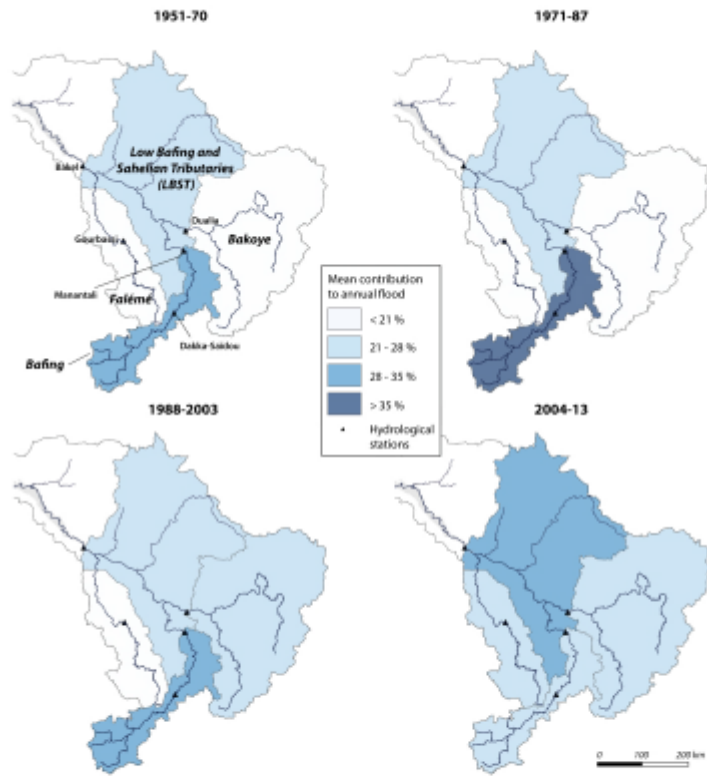


Figure 11 – Spatial distribution of the average contribution to the annual flood in Bakel of the different sub-watersheds of the upper Senegal river for different periods: 1951-70 (humid period), 1970-87 (drought), 1988-2004 (artificial regime), 2004 -13 (artificial regime & electric power driven).

557x570mm (236 x 236 DPI)

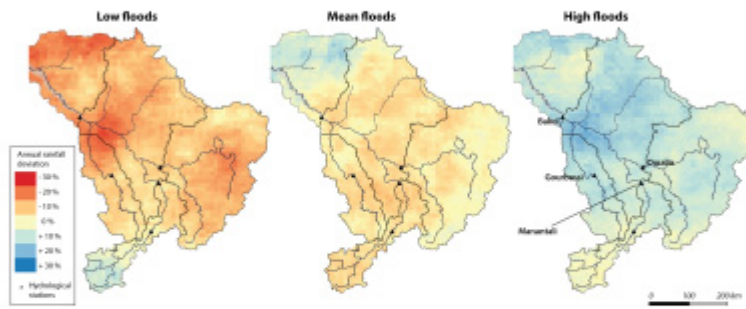


Figure 12 – Relative deviations of rainfall from the 2001-2018 average for different types of flood:
 Datasource: GPM_3IMERGM

544x228mm (236 x 236 DPI)