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Floods and Humanitarian Disasters in the Senegal River Basin

Coura Kane

Department of Sustainable Development, Alioune Diop University, Bambey, Senegal
Email: coura.kane@uadb.edu.sn

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Abstract

Floods in the Senegal River basin have become recurrent despite rainfall variability. The first major overflows after the construction of the Diama (1985) and Manantali (1988) dams were observed during the 1994-1995 high-water season, even though the flood was moderate. The estuarine area was not spared the fury of the waters, particularly the city of Saint-Louis, which at the time benefited from an emergency protection plan. The Senegal River valley is becoming increasingly accustomed to floods leading to population displacement and the submersion of hydro-agricultural development. During the 2023-2024 hydrological year, the Senegal River basin was severely affected, resulting in a major humanitarian crisis. However, early warning systems, including those of Agrhymet, the Senegal River Development Organization (OMVS), meteorological services National Civil Aviation and Meteorology Agency (ANACIM), and national hydrological services Water Resources Management and Planning Department (DGPRE), had provided early information on rainfall and annual flood evolution in the sub-region. Flooding in the Senegal River basin has had a significant impact on the environment. The article analyzes the flood of 2023-2024, which severely affected several communities. The Standardized Flow Index (SFI) and break detection method are used to analyze the hydrological situation. Statistical analysis of flood frequency based on return periods was determined by Hyfran Plus. The results show that the 2023-2024 hydrological year is not exceptional. Extreme events have return periods of ten years. Adaptation measures, such as strengthening flood protection infrastructure and water resource management, are needed to increase the resilience of populations and ecosystems.

Keywords

Watershed, Natural Disaster, Humanitarian Challenge, Flooding, Vulnerability

1. Introduction

West Africa suffered a long rainfall deficit during the second half of the 20th century (Nicholson et al., 1999) from 1968 until the 1990s, with specific end dates varying throughout the area (Descroix et al., 2018). The rainfall distribution is characterized by irregularity, both in time and in space (Omotosho et al., 2000). Recently, West Africa has witnessed an increasing number of damaging floods that raise the question of a possible intensification of the hydrological hazards in the region (Wilcox et al., 2018). In the same, in the Sahelian zone since the early 1990s, both total rainfall and streamflow amounts have increased compared to the drought decades of the 1970s and 1980s, though they remain lower than in previous pre-drought decades (Lebel & Ali, 2009; Mahé & Paturel, 2009; Panthou et al., 2014; Tarhule et al., 2015; Diop et al., 2017). The increase was accompanied by higher interannual variability (Lebel & Ali, 2009; Panthou et al., 2014) and overall persistence of drought conditions under certain indices (L'Hôte et al., 2002; Ozer et al., 2009). The Sahel drought has induced hydrological change: for the same amount of rainfall, less water can infiltrate, and more water runs overland due mostly to the land degradation induced by land use (Mahé & Paturel, 2009). The well-known droughts in the 1970s have led to a decline in water flows in many African river basins. Also, the Senegal River Basin, which is situated in West Africa, has faced those droughts (Mbaye et al., 2015). The Senegal River basin faces a number of hydrological hazards, notably droughts and floods. It has a high vulnerability index, characterized by significant exposure to climatic hazards, coupled with a moderate capacity to adapt. Runoff from the Senegal River is marked by high inter-annual variability. The Senegal River basin experienced a climatic break in the 1970s, which led to a drop in mean annual runoff, as well as in maximum annual and minimum annual water levels. A significant recovery in mean annual runoff was observed from 1994 onwards, attesting to a new, wetter climatic period than that of the 1970s and 1980s in the Senegal River basin. Moreover, since the late 1980s and early 1990s, mean annual runoff in the river valley has been reinforced by the cumulative effect of dams (through their impact on land use) and climatic variability. Today, the river valley is witnessing an upsurge in flooding (Cisse et al., 2014). However, floods are not exceptional. The article presents the evolution of hydrological parameters since 1903 at the Bakel station, which has a long series of observations to characterize the 2024 flood and water levels at stations in the upper basin. OMVS has set up early warning systems that should help reduce the vulnerability of populations. However, adaptation strategies are only being put in place belatedly, which is having an impact on people's resilience. A large-scale national solidarity campaign has been launched to help the victims of the hydrological disaster.

2. Materials and Methods

2.1. Study Area

Three geographical areas, namely the delta, the valley, and the upper basin (**Figure**

1), make up the river basin, each with different environmental characteristics (National Research Council, 2003). The Senegal River is the second longest river in West Africa, with a watershed shared between four riparian states: Guinea, Mali, Mauritania, and Senegal, covering an area of 340,000 km^2 (Mendoza et al., 2025). Rainfall significantly affects the river flow rate in the upper basin, with a high-water stage from July to October and a low-water stage from November to June. August and September correspond to the period of highest water levels, ending in October (Cheikh et al., 2013). According to Bodian et al. (2011), annual rainfall averages 1490 mm. The convergence of air masses known as the Intertropical Convergence Zone (ITCZ) is a factor that contributes to the dynamics of weather systems and to variations in the prevalence of monsoon flows depending on the season and geographical region (Bodian et al., 2016). This regime, with significant interannual variability in flow rates, highlights the river's dependence on precipitation.

In terms of soil, deep permeable sandy soils are more prevalent than lateritic soils. Rock outcrops are not widespread, and most of the area consists of shallow soils. Rainfall can reach over 180 mm/year in the north and over 1900 mm in the south (Andersen et al., 2001). The rainfall gradient has an impact on the mainly natural vegetation, which consists of semi-arid savannah in the northern part and sub-humid forest in the southern part (Mbaye et al., 2015; Stisen et al., 2008; Ndiaye et al., 2024).

Figure 1. Senegal river basin.

Large-scale developments, notably the Diama and Manantali dams, have been built to mitigate the impacts of climate change. These hydraulic infrastructures have led to changes in the flow of the Senegal River. A recovery in rainfall seems to have begun in the 1990s, which caused floods.

2.2. Data

The variability of water resources was analyzed using hydrological data from the DGPRE. Statistical analysis of time series data, whether hydrological or meteorological, is one of the tools used to identify climatic variations and to perform frequency analysis. In this context we have prioritized it to detect any possible break for the 2024 hydrological year, marked by an exceptional flood. The analysis is based on hydrological data from 1950 to 2024 at the Bakel station. Located downstream from the confluence of the main tributaries (Bafing, Bakoye, Falémé), the Bakel receives nearly all of the runoff from Guinea and Mali. It is crucial for measuring the total volume of water entering the Senegal River valley.

Rainfall data for stations in the upper basin are those of the OMVS (**Table 1**).

Bakel station covers the period 1950-2024 and includes 77 gaps. This period mainly concerns the hydrological year 1950-1951, which has a total of 55 gaps. The gaps have not been addressed.

Table 1. Stations studied in Senegal River basin.

Stations	Latitude	Longitude	Start Date	End Date	Duration of monitoring	Gaps
Bakel	14.90	−12.45	01/01/1950	30/12/2024	74 years	77
Kidira	14.45	−12.21	01/10/2024	31/10/2024	1 month	0
Gourbassi	13.40	−11.63	01/10/2024	31/10/2024	1 month	0
Kayes	14.45	−11.45	01/10/2024	31/10/2024	1 month	0
Oualia	13.60	−11.38	01/10/2024	31/10/2024	1 month	0
Bafing Makana	12.55	−10.28	01/10/2024	31/10/2024	1 month	0
Daka Saidou	11.95	−10.61	01/10/2024	31/10/2024	1 month	0
Diangola	12.8	−9.48	01/10/2024	31/10/2024	1 month	0

The mapping of areas affected by flooding was carried out using satellite images obtained from https://earthexplorer.usgs.gov/ dating from June 2024 and September 2024.

2.3. Parameters Analysis

In hydrology, the Standardized Flow Index (SFI) used by Houessou (2016), Totin et al. (2016), and Koungbanane et al. (2020) is used for flow hazard. Based on annual flows from the Bakel station,

The index flow standardized was calculated with the following formula:

$$z = \frac{y - \mu}{\sigma} \quad (1)$$

Equation (1) is:

y: the unit value of the parameter under consideration.

μ: the meaning of the variable.

σ: the standard deviation of the variable.

The index values (**Table 2**) can be used to rank the hydrological years.

Table 2. Classification of SFI values.

≥2.0	Extreme wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderate wet
−0.99 to 0.99	Close to normal
−1.0 to −1.49	Moderate dry
−1.5 to −1.99	Very dry
≤−2	Extreme dry

Source: McKee et al., 1993.

SPI is calculated based on the annual mean flow. Climatic variability analysis tools, in this case Khronostat, were used. The examination of the series focuses on annual maximum flows at the Bakel station. The main interest is to assess the significance of detected trends. This will enable us to see whether these local non-stationarities are due to chance or to a real change of climatic origin (Pujol et al., 2007). The procedures are Hubert segmentation, Buishand and Bois ellipse test, and the Pettit test. The tests highlight changes in climate parameters and enable breaks in climate series to be identified. These break detection tests enable climate variability to be studied to highlight the downward trend in precipitation observed in the Sahel region since the 1970s. The Khronostat software is adapted to climatic, hydrological, and meteorological variables (Traore et al., 2017; Amadou, 2019). Hydrological indices were used to analyze extreme hydrological events at the Bakel station. Frequency analysis using Hyfran Plus software can be used to determine the risk associated with extreme hydrological events. The Bakel station determines most of the flow in the Senegal River valley. This statistical method involves studying historical events to assess the probability of their future occurrence.

3. Results

3.1. Flows Characterization of Bakel Station

To determine the extreme flows of the upper basin, the standardized flow index was calculated. Calculating the flow index in the upper basin makes it possible to characterize extreme flow rates at the scale of the Senegal River Basin (Ndiaye et al., 2023). According to Faye (2023), the upper basin generates more than 80% of the river's inflow at Bakel. This latter is considered the main monitoring station of the entire Senegal Basin, captures the flow from the three main tributaries, and records 95% of the river (Faye, 2014). The Standardized Flow Index (**Figure 2**) reveals an interannual distribution between a wet period and a dry season at Bakel station within the Senegal River Basin.

Figure 2 shows the extremely wet hydrological years (1950-1951), which recorded 2.50, and the very dry years (1984-1985). The 2023-2024 hydrological year is close to normal. During the dry period of the 1970s, the hydrological functioning of the Senegal River was disrupted due to a decrease in its flow (Bruckmann et al., 2022).

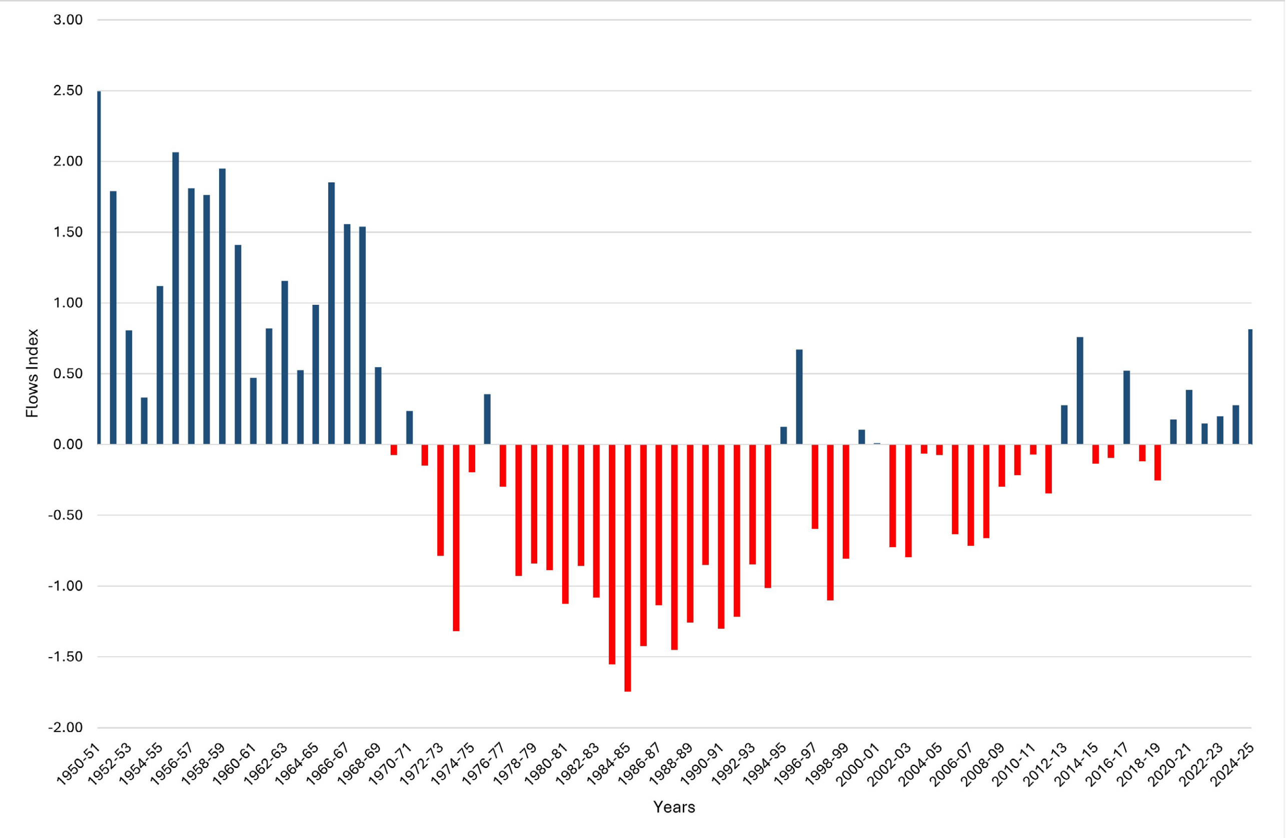

Figure 2. Standardized flow index Bakel (1950-2024).

Significant interannual variability in flow rates highlights the river's dependence on rainfall, which is characterized by irregularity. Before the rainfall deficit, the Senegal River basin recorded high flows, but since the dry season, river flows have declined dramatically. The recent period has been marked by rainfall characterized by strong interannual variability, which has an impact on river flows (Sakho et al., 2017). The return to wetter years in recent times has influenced changes in river flows in the Senegal River basin. This situation is linked to climate change, which manifests itself in extreme events such as floods, droughts, and natural disasters. This poses a major challenge for populations due to its negative impact on the socio-ecological system. Developing countries remain vulnerable to these events due to their limited capacity to adapt (Ndiaye et al., 2024). In 2024, uncontrolled rivers such as the Faleme and Bakoye caused the water to rise and overflow, in addition to the releases from Manantali, whose alert level was reached due to particularly abundant rainfall. The flooding is not due to releases from the Manantali Dam but to a combination of climatic and hydrological factors in the Senegal

River basin. The dams on the Senegal River help regulate flow rates. The Manantali dam contributes to increased flow rates during the dry season, but on an annual basis, it has not led to an increase in flow rates (Sambou et al., 2009). This dam has controlled downstream flows since its implementation in 1987 (Bruckmann et al., 2022). As mentioned by several authors (Descroix et al., 2016; Descroix et al., 2018; Bodian et al., 2020), annual rainfall has increased relatively since the early 2000s, which will impact river flow in the upper basin of the Senegal River. The Manantali dam regulates flows to support low-water levels for irrigated agriculture and navigation, to control high floods to limit their catastrophic effects, and to support low floods to guarantee sufficient flooding of the major bed for flood recession farming and to maintain the ecological balance (Bader et al., 2003). High water levels were recorded throughout the year, resulting in catastrophic flooding. Analysis of the hydrological time series from the Bakel station since 1950 shows that the 2024 flood was not exceptional compared with the 1950-1951 hydrological year to those recorded, when flow rates exceeded 5000 m^3/s. The impacts were exacerbated by the socio-Socio-ecological systems' vulnerability.

Buishand's ellipse (**Figure 3**) is parametric, and Hubert's segmentation is non-parametric. Hubert's segmentation method simultaneously determines the average of each sub-series on either side of an identified break.

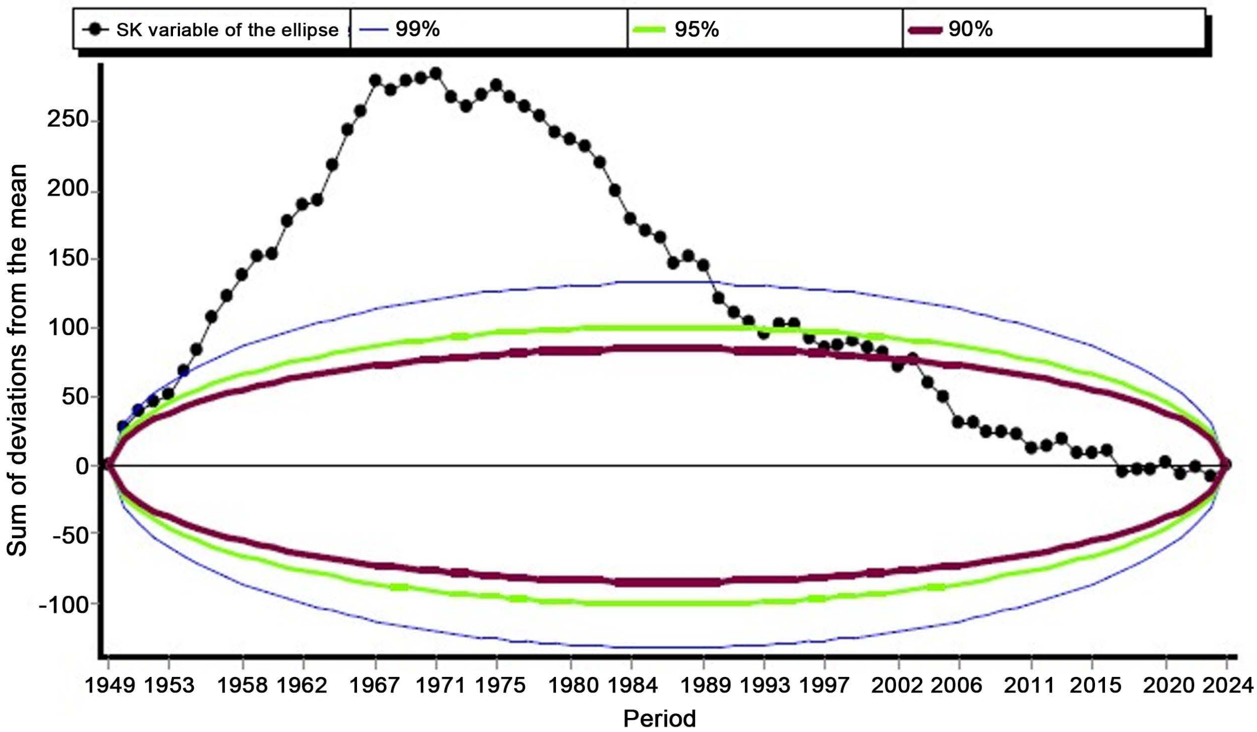

Figure 3. Buishand diagram for Bakel station (1950-2024).

Hubert's segmentation with a 1% Scheffe significance test highlights four significant periods (**Table 3**). The segmentation did not reveal a negative break. No break was detected in 2024. Hubert's segmentation procedure determines if a time series is stationary. If not, it divides it into as many homogeneous sub-series as possible (Hubert et al., 2007). It partitions the series into two sub-series: 1950-1967, 1968-2024, which recorded average flows of 4199 m^3/s and 1995 m^3/s, respectively.

Table 3. Hubert's Segmentation.

Beginning	End	Average	Standard deviation
1950	1967	4199	1023
1968	2024	1995	706

Although the flow rates at the Bakel station are high, the 2023-2024 hydrological year is not exceptional compared to other years. During this period, more than 2000 m^3/s were recorded at the Bakel station in September. Furthermore, Hubert's segmentation shows that the period 1968-2014 recorded an average of 1995, which indicates that the dry sequence is still prevalent in the area.

Analysis of flows at the Bakel station requires statistical tools to determine extreme hydrological events. It is in this context that the Hyfran Plus software is used to estimate peak flows corresponding to different return periods. Flood risks can be assessed using Hyfran Plus software, which performs a frequency analysis of floods based on return periods (Aksoy, 2025). Maximum annual flows covering the period from 1950 to 2024 were used. **Table 4** shows the flow characteristics.

Table 4. Flow characteristics at the Bakel station.

Number of years	74
Minimum	678
Maximum	5890
Average	2520
Standard deviation	1230
Median	2420
Coefficient of variation (Cv)	0.488
Skewness coefficient (Cs)	0.920
Kurtosis coefficient (Ck)	3.24

The low coefficient of variation shows that runoff is very high at the Bakel station. Statistical analysis with the adjustment of the data according to different laws made it possible to choose the most suitable law for the series. Four laws (Normal, Gamma, Gumbel, log-normal) were tested for the fit. The lognormal law shows a significant trend and is the most suitable for the series. The choice of this distribution was also guided by the results of the criterion-based comparison of the distributions tested, which made it possible to select the appropriate frequency model. The BIC and AIC values are lower for the lognormal distribution (Table 5).

Table 5. Comparison of laws by criterion.

Model	No. of parameters	XT	P(Mi)	P(Mi|x)	BIC	AIC
Lognormal	2	7131.490	25.00	37.68	1272.991	1268.356
Gamma	2	6225.330	25.00	37.03	1273.025	1268.390
Gumbel	2	6385.240	25.00	25.27	1273.790	1269.155
Normal	2	5388.174	25.00	0.02	1287.828	1283.193

P(Mi): A priori probability; P(Mi|x): A posteriori probability (Method of Schwartz); BIC: Bayesian information criterion; AIC: Akaike information criterion.

There is also a good fit between the frequency distribution of the sample and the lognormal distribution. The fit is satisfactory, and the confidence interval for the sample at the 95% threshold contains the values (Figure 4).

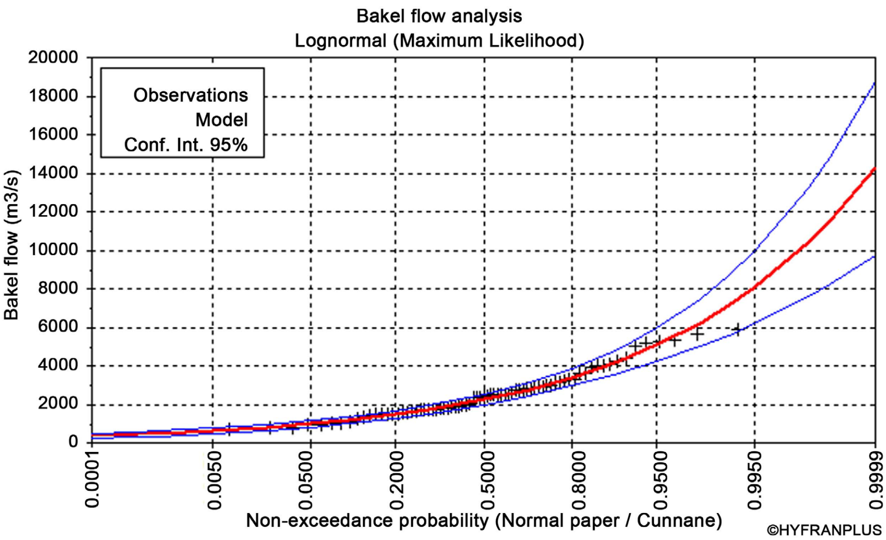

Figure 4. Adjustment of the lognormal distribution.

The results obtained by fitting the lognormal distribution show that 95% of the points are within the confidence interval and H0 is accepted with a significant trend of 5%.

Determining the return period of maximum flows is useful information for better understanding whether an event is exceptional or not. The probability of rare events occurring is low. The stochastic approach shows that the return period for flows of more than 4000 m^3/s is ten years. This flow corresponds to a height of 10 m at the Bakel station, which exceeds the alert level of 10 m. We therefore consider a flow of more than 4000 m^3/s to be the critical threshold for flooding. This flow has a ten-year frequency (Table 6).

Table 6. Return periods for peak flows.

Period return	5	10	20	50	100
Non exceedance probability	0.800	0.900	0.950	0.980	0.900
Maximum peak flow	3410	4240	5080	6230	7130

The frequency analysis shows a probability of not exceeding the return frequency. The extreme flows therefore have return periods of 10 years with a probability of not being exceeded of 0.900.

3.2. Analysis of the 2023-2024 Annual Flood and Its Overflow in the Valley

The hydrology of the Senegal River is influenced by both climate variability and the effects of the Diama and Manantali dams since their commissioning. Aghrymet had forecasted a generally wet rainy season across the Sahel region, with late-to-normal start dates in the Sahel-Central and early-to-normal start dates in the Sahel-West and East, late-to-normal end dates, short dry sequences at the beginning of the season in the Sahel-West and medium-to-long sequences in the Sahel-East, and generally long sequences towards the end of the season across the Sahelian strip; and generally above-average runoff in the main Sahelian river basins. The Senegal River Basin Organization closely monitored the hydrological situation of the Senegal River, marked by exceptional rainfall (Table 7) leading to high flows on the Senegal River. It issued alerts and warned of the risk of the alert level being exceeded at the Bakel, Matam, and Podor stations.

Table 7. Rainfall (mm) at upper basin stations between May 1 and October 13 (hydrological year 2023-2024).

Station	River	Cumulative May 1 to end of September	October 1st to 13th	Total
Dakka Saidou	Bafing	1165.50	268.50	1575.8
Bafing Makana	Baking	1171.30	96.10	1327.40
Manantali	Bafing	758.75	65	823.75
Oualia	Bakoye	564	0	564
Gourbassi	Faleme	941.2	19	996.2
Kidira	Faleme	654.2	29.5	683.7
Kayes	Senegal	504.5	35	539.5
Bakel	Senegal	552.10	29.20	581.30

Source: OMVS, 2024.

During this period, the total flow volume recorded at Bakel reached 10.848 billion cubic meters of water. Notably, 83% of this volume originated from uncontrolled tributary inflows (**Table 8**). The situation had already reached catastrophic levels, and the controlled water releases from the Manantali Dam implemented to ensure the dam's structural safety further exacerbated the rising water levels, leading to overflow and flooding in the upper valley.

Table 8. Inflows from uncontrolled tributaries (hydrological year 2023-2024).

Bakoye at Oualia	25.86%	2.712 billion·m^3
Faleme at Gourbassi	27.81%	3.016 billion·m^3
downstream Manantali	16.74%	1.816 billion·m^3
Inputs from intermediate watershed	29.59%	3.209 billion·m^3

Source: OMVS, 2024.

By the second half of October, multiple stations reached maximum alert levels. At the upstream Manantali station, the normal reservoir level is 208.05 m IGN, and the exceptional level is 211 meters. The dam on the Bafing River retains 11 billion·m^3 of water, protecting against extreme events like droughts and floods while generating electricity for riparian states. However, during exceptional floods, water is released for dam safety. Manantali Dam reached its maximum capacity of 208.05 m IGN on Thursday, October 3, 2024. October 2024 flows were comparable to the exceptional 1999 flood when the river basin experienced major flooding. In 1999, Bakel station reached 10.91 m on August 30 compared to 10.22 m on August 11, 2003 (the year of the river's terminal breach). Bakel's alert level is 10 meters, while Matam's is 8 meters.

By October 12, Bakel's water level had already reached 10.70 meters, exceeding the alert threshold. From mid-October, the hydrological situation became critical for the entire upper basin and valley. On October 14, Kayes recorded 9.65 m (declining trend), while Bakel reached 11.53 m, rising to 11.66 m by October 15 before decreasing on the 16th. Matam increased from 8.53 m (October 14) to 8.65m (October 15). Orange alerts remained active for all riverside communities, with Bakel approaching red alert status. Peak water levels occurred in the second week of October (starting October 9, **Figure 5**), maintaining high water for at least fifteen days, exacerbated by releases from Manantali Dam. In the valley entrance, water levels rose rapidly to alert thresholds. The upper basin concentrated flows, causing overflows downstream of Bakel station. Diangola station on the Bakoye recorded significant levels that substantially contributed to the Senegal River's hydrology.

Water levels remained high between October 13 and 17, 2024. The Kidira and Bakel stations recorded values at or above the alert threshold of 10 m IGN. The Senegal River's annual flood occurs after the African monsoon passes over the Fouta Djallon highlands and typically extends from late August to November in the valley, located in the downstream part of the watershed (Bruckmann, 2018). On October 15, an orange alert warned riverside communities, with some areas, notably Bakel, Matam, and Podor, escalating to red alert status. These stations recorded levels of 11.66 m, 8.65 m, and 5.55 m, respectively, surpassing their alert thresholds of 10 m, 8 m, and 5 m.

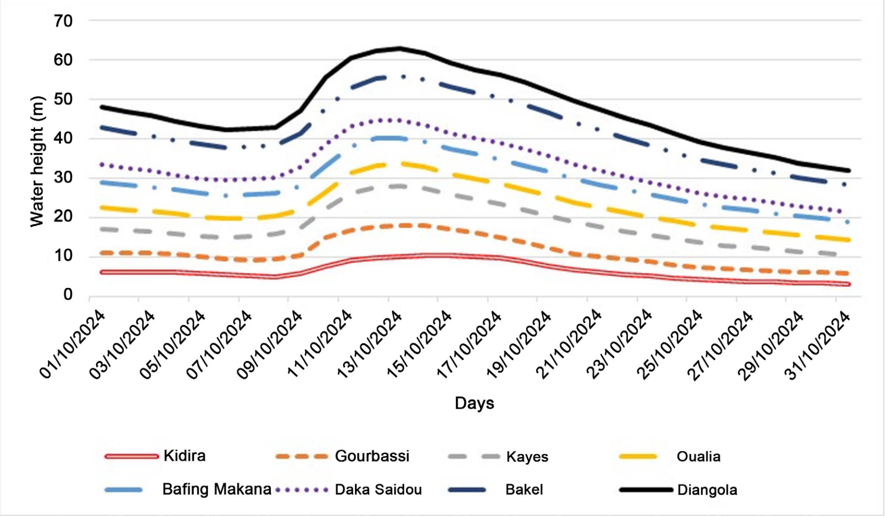

Figure 5. Water level trends at the main hydrological stations in the upper basin (October 2024).

3.3. Discussions

The Senegal River Basin is exposed to a variety of climatic hazards, including drought and recurrent flooding. All these hazards place populations in situations of social and economic vulnerability and contribute to multiplying the risks directly affecting their lives and the stability of the territories. The hydrological systems of African river basins are complex and highly vulnerable to climate variability. This vulnerability poses significant challenges in terms of water security challenges and environmental changes (Adeyeri, 2025). Hydrological systems are disrupted as climate change continues (Nazeri Tahroudi, 2025). The floods had a negative impact on the populations, who at times lost either their homes, their land, or both simultaneously. Figure 6 shows the flooded areas in 2024. According to the final report on flood management in the Bakel Department of the Bakel Prefecture (2025), 55,600 people were affected, 1830 households were impacted, 2664 farmers were affected across an area of 1620 hectares, and 4 health clinics and 20 schools were submerged by floodwaters. The total damage was estimated at $13626039.73. The floods caused the destruction of habitats and cut off roads, which significantly affected the movement of people and goods. The issues generally manifest in terms of hygiene, unhealthy environments, and waterborne diseases. In the Matam area, following the recession of floodwaters, diseases appeared in the Dande Mayo region. These include malaria, dengue fever, diarrhea, and respiratory infections. In general, children are the most affected.

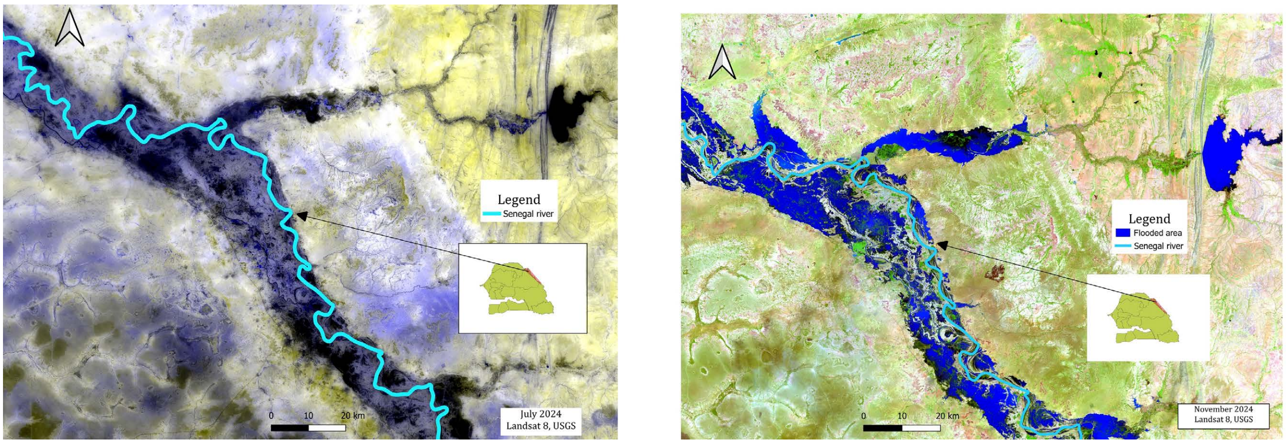

Figure 6. River overflows in Senegal river valley.

As late as November, some schools had still not opened. Flood impacts are particularly devastating for vulnerable groups. Proper management of water infrastructure must include public information and awareness campaigns about imminent dangers. Local populations were caught off guard without sufficient time to take precautions or find safe shelter. In traditional systems, communities were better prepared to relocate to Dieri areas that never flooded. Today, uncontrolled urbanization has largely eliminated this option.

4. Conclusion

The Senegal River floods caused major damage to socio-ecological systems while sparking solidarity efforts from authorities and private donors to provide emergency food aid to victims. However, the flood itself was not exceptional. Rather, the combination of intense rainfall over a short period and large water releases from Manantali Dam overwhelmed the upper basin. Strategically, authorities were unprepared to handle the massive influx of floodwaters. While the OMVS and National Hydrological Services' early warning systems functioned well in predicting water levels, they failed to generate adequate social response. Neither the government nor civil society mounted a response commensurate with the scale of the disaster. Adaptation measures, such as strengthening flood protection infrastructure and water resource management, are needed to increase the resilience of populations and ecosystems. Understanding climate risks and their impacts is a prerequisite for adopting strategies to adapt to, mitigate and govern climate change.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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