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Variability, Trends, and Breaks in Hydroclimatic Data in the Senegal River Watershed: The Case of Daka Saidou-Manantali-Bakel

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Abstract

The Senegal River basin is subject to significant hydroclimatic variability, and given the growing influence of water management projects, this study focuses on analyzing trends, shifts, and variability in hydroclimatic parameters along the Manantali-Bakel corridor to assess the combined effects of, on the one hand, climate change and, on the other hand, regulation by the Manantali Dam. In this study, the analysis focuses on hydrometric data from Bakel and several sub-basins (Bafing, Faleme, Gourbassi, Oualia, and Dakka-Saidou), as well as precipitation data observed between 1987 and 2024. The methods used include the Mann-Kendall test, Pettitt's trend-break test, the Bayesian approach by Lee and Heghinian, and the analysis of autocorrelation plots. The results reveal high interannual variability in streamflow and precipitation, marked in particular by significant negative trends in May and June (Kendall's τ ranging from −0.37 to −0.41; $p < 0.05$) associated with deficits exceeding 95%, and marked changes in the hydrological regime known to result from the impact of flow regulation, with statistically significant breaks identified by the Bayesian approach (maximum likelihood of 0.32 at Bakel and 0.70 at Dakka-Saidou). The very low signal persistence observed limited to lags 1 through 5 and 9 through 10 in the autocorrelation plot for the Bakel station may indicate that climatic and anthropogenic forcings have had a more significant impact on recent changes in water resources.

Keywords

Senegal River Basin, Hydrological Variability, Climate Change, Manantali, Bakel

1. Introduction

The Senegal River basin is a vital resource for Guinea, Mali, Mauritania, and Senegal, particularly for agricultural, energy, and domestic activities, among others, that seek to make use of the available water. Hydrogeoclimatic variability has been particularly pronounced in West Africa since the 1970s: decreased precipitation, recurring droughts, further rises in temperatures, and so on, all of which are causing lasting damage to hydrological regimes [1]. Recent studies show that the Senegal River basin continues to exhibit significant hydroclimatic variability despite a partial recovery in precipitation since the 1990s. The analyses conducted by [2] highlight the persistence of changes in the hydrological regime associated with the climate non-stationarity observed throughout West Africa. For the Senegal River basin, several studies have highlighted climatic and hydrological changes resulting from the regulation of the large Manantali and Diama dams on river flows [3]. Less well documented is the respective contribution of climatic and anthropogenic factors to recent changes in water resources measured between Manantali and Bakel, against a backdrop of increasing anthropogenic pressures. The objective of our research is to characterize the variability, trends, and shifts in hydroclimatic parameters over the period 1987-2024 using statistical tests applied to time series of precipitation, temperature, and discharge measured in this key sector of the basin.

2. Geographical Location and Description of the Study Area

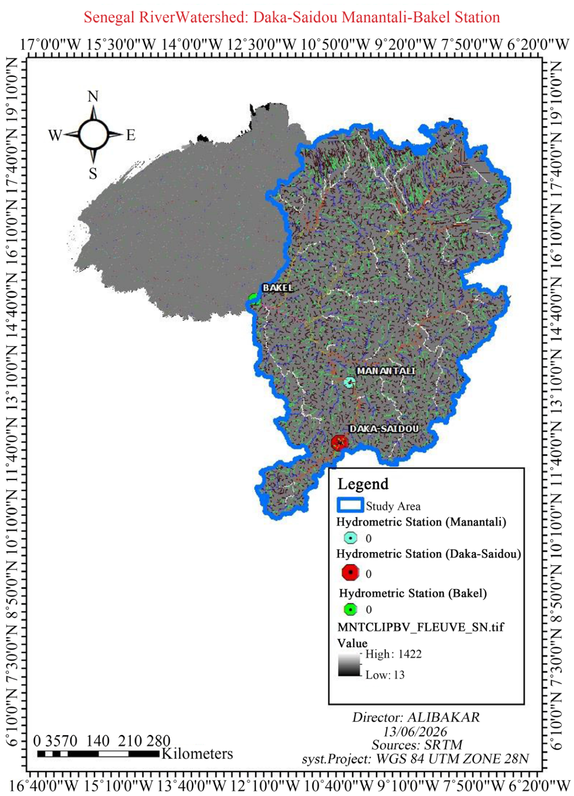

Figure 1. Location of the Senegal River watershed, along the Daka-Saidou Manantali-Bakel axis.

The study area corresponds to the section of the upper Senegal River watershed located between the Manantali Dam and the Bakel hydrometric station, including the Daka-Saïdou station. This sector is part of the Senegal River basin, which is 1700 km long and drains an area of 300,000 km^2 spread across Guinea, Mali, Senegal, and Mauritania, and lies between 10˚20' and 17˚ north latitude and 7˚ and 12˚20' west longitude [4]. The Bafing, the Bakoye, and the Falém, three tributaries that originate in Guinea, make up the upper watershed, which supplies more than 80% of the river's flow at Bakel [4]. The Manantali Dam, built on the Bafing River, regulates most of the flow reaching Bakel, whose watershed covers 218,000 km^2 and has an average annual discharge of approximately 676 m^3/s [5]. This area was also used as the setting for hydrological modeling using SWAT based on DTMs [6].

Figure 1 presents a map showing the location of the Senegal River basin: Daka-saidou, Manantali, and Bakel.

3. Data and Methodologies

3.1. Data Organization and Methodology

Daily hydroclimatic observations covering the period 1987-2024 were compiled from hydrological and meteorological monitoring networks within the upper Senegal River basin. Streamflow data were provided by the Organization for the Development of the Senegal River (OMVS) [7] and include daily discharge records from the Bakel hydrometric station as well as the Daka-Saidou and Manantali stations, which characterize the upstream hydrological response before and after regulation by the Manantali Dam [5]. The analysis also incorporated precipitation and air temperature series collected at the corresponding meteorological stations covering the same observation period. Prior to statistical analysis, all datasets were subjected to quality-control procedures including consistency checks, screening for anomalous values, and verification of temporal continuity [8]. Missing observations were evaluated before analysis and, where necessary, treated using standard hydrological quality-control procedures to preserve the homogeneity of the time series [8].

To ensure consistency throughout the study, all hydroclimatic variables were aggregated from daily observations into monthly, seasonal, and annual series according to the objectives of each statistical analysis. The hydrological year was defined from May to April, corresponding to the seasonal rainfall-runoff cycle that characterizes tropical rivers in the Senegal River basin [9].

The study investigates the combined influence of climatic variability and river regulation by comparing stations directly affected by dam operations (Bakel) with upstream stations that retain a more natural hydrological regime (Daka-Saidou and Manantali). This comparative framework provides the basis for distinguishing large-scale climatic forcing from anthropogenic regulation effects [5] [10].

The time series were analyzed using KhronoStat software to identify trends, breaks, and climate variability. The detection of regime shifts is based on the Pettitt test [11], while the analysis of long-term trends is performed using the Mann-Kendall test [8] [9]. These methods make it possible to characterize the temporal evolution of the data by highlighting trends, breaks, and interannual variability.

3.2. Statistical Tests

The methods used are based primarily on the calculation of flow coefficients, and the resulting data sets are then subjected to two statistical tests. The statistical analyses were carried out using different temporal aggregation levels depending on the objective of each method. Daily discharge observations were aggregated into monthly, seasonal and annual series. The Mann-Kendall test and Sen's slope estimator were applied to monthly, seasonal and annual hydroclimatic series. Pettitt's test and the Bayesian Lee-Heghinian change-point analysis were performed on annual series to detect abrupt regime shifts, whereas autocorrelation analysis was conducted on annual discharge series to evaluate serial dependence. Throughout this study, the hydrological year extends from May to April.

3.3. Bayesian Change-Point Analysis

To complement the Pettitt test, a Bayesian change-point analysis based on the method proposed by Lee and Heghinian was performed. Unlike classical change-point tests, this Bayesian framework estimates the posterior probability of the occurrence of a change point together with the magnitude of the associated shift. The method assumes that the observed series consists of two homogeneous segments separated by an unknown break date. Posterior probability distributions were used to identify the most probable year of regime change and to quantify the uncertainty associated with this estimate. This complementary approach provides a probabilistic interpretation of hydrological regime shifts and improves the robustness of change-point detection [12].

3.4. Calculation of Monthly, Seasonal, and Annual Discharge Coefficients

The hydrological regime is a watershed's response to stable physical factors, climatic variations, and anthropogenic factors [10] [11]. Because tropical rivers are fed exclusively by rainfall, the hydrological year begins in May and ends in April. The hydrological regime is studied using the monthly discharge coefficient (CMD), which is the ratio of the discharge for a given month to one-twelfth of the average annual discharge. It is calculated as follows (Equation (1)):

$$\text{CMD} = \frac{\text{monthly flow rate}}{\text{one-twelfth of the average annual flow}} \tag{1}$$

The CMD is used to define periods of high water and periods of low water. According to Sen's classification [13], a CMD greater than or equal to 1 corresponds to a period of high water, and a CMD less than 1 corresponds to a period of low water. Two river regimes are distinguished at the study stations: the transitional tropical river regime (4 months of high water) and the pure tropical river regime (3 months of high water).

On a multi-year scale, the flow coefficients (or interannual flow indices, IEI), defined as the ratio of the average annual (or seasonal) discharge to the interannual average discharge of the time series, are calculated as follows (Equation (2)):

$$\text{IEI} = \frac{\text{average annual flow rate}}{\text{average interannual flow for the series}} \quad (2)$$

On a seasonal scale, runoff coefficients (or seasonal runoff indices, IES) are calculated using the following formula (Equation (3)):

$$\text{IES} = \frac{\text{average flow rate during the high-water period}}{\text{average annual flow rate}} \quad (3)$$

Using series of monthly (CMD), seasonal (IES), and interannual (IEI) flow coefficients or indices, a set of tests is employed in this study to detect potential changes at a significance level of 0.01.

3.5. Pettitt Test

In the context of analyzing trends, breaks, and variability in climate data, the Pettitt test [11] is a widely used nonparametric statistical tool for detecting breaks in homogeneity in climate time series. This test aims to identify the existence of an abrupt change at an unknown date within the series, generally associated with a significant change in the average level of the variability under study [11].

The method is based on a formulation derived from the Mann-Whitney test, applied sequentially to all possible partitions of the time series. It relies on analyzing the signs of the differences between observations, which allows for the construction of a cumulative statistic reflecting the contrasts between the subperiods preceding and following a given point in time. When the null hypothesis of homogeneity of the climate series is rejected, the test provides an objective estimate of the break date, corresponding to the maximum value of the test statistic.

The statistical significance of the detected break is assessed using the p-value associated with the Pettitt statistic, which allows us to determine whether the observed change exceeds the natural variability of the time series at the chosen confidence level. Due to its nonparametric nature and its robustness with respect to non-normal distributions, the Pettitt test is particularly well-suited for studying climate change, especially for identifying temporal discontinuities that may influence the interpretation of long-term climate trends and variability. Consequently, the occurrence of abrupt changes in certain statistical parameters of hydroclimatic time series, particularly their mean is a possible cause of a break in the homogeneity of these series. The variable to be tested is the maximum absolute value of the Pettitt variable ($U_{t,N}$). The approximate probability of exceeding a given value k allows us to assess the significance of the break. The absence of a break in the series of size N constitutes the null hypothesis. If the null hypothesis is rejected, an estimate of the year of the break is given by the time t at which the variable reaches its maximum absolute value $U_{t,N}$. The implementation of the test assumes that, for every time t ranging from 1 to N, the sequences $((x_i), i = 1, t)$ et

((x_i), $i = t + 1$), N belong to the same population.

That is $D_{ij} = \text{sign}\left(x_i - x_j\right)$.

$$\text{let's} \begin{cases} x > 0 \Rightarrow \text{sign}(x) = 1 \\ x = 0 \Rightarrow \text{sign}(x) = 0 \\ x < 0 \Rightarrow \text{sign}(x) = -1 \end{cases}.$$

Let us consider the variable $U_{t,N}$ such that:

$$U_{t,N} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} D_{ij}$$

The approximate probability of exceeding a value k is:

$$\text{Prob}\left(K_N > k\right) \approx 2\exp\left(-6k^2 / \left(N^3 - N\right)2\right) \tag{4}$$

This test was conducted using the KhronoStat software developed by the French National Research Institute for Development (IRD).

3.6. Interannual Assessment of Flow Rates

Hydrological variability was monitored using centered and derived weighted moving average methods and Pettit's break detection test.

3.7. Determination of Precipitation Variations (Deficits) and Streamflow Rates, and Their Mapping

This method is used to determine the percentage change in the average of the series under consideration (rainfall, flow rate, etc.) over a subperiod Ti around that time T considered [3]. For hydroclimatic variables whose time series exhibit a break, this method specifies the percentage change in the mean around the break date and is calculated using the following formula:

Deficit (D) = (average after break – average before break)/average before failure

$$D = \frac{\overline{x}_j}{\overline{x}_i} - 1 \tag{5}$$

where:

$\overline{x}_j$: period average break.

$\overline{x}_i$: average for the period prior to the break.

This method also makes it possible to track changes in precipitation and streamflow over time during a predefined reference period.

3.8. Mann-Kendall Test and Sen's Slope Method

The Mann-Kendall test [3] [14] was used to assess trends in precipitation Tmax and Tmin. This is a nonparametric test, which does not require the data to follow a normal distribution. The Mk test is based on a null hypothesis (H_o), which states that there is no trend the data are independent and randomly ordered and this hypothesis is tested against the alternative hypothesis (H_a), which assumes that a trend exists [3].

The true slope (change per unit of time) was estimated using Sen's slope estimator (SS) [10].

The results of the MK test may be influenced by the presence of autocorrelation in the time series. Therefore, a serial correlation test was conducted prior to applying the MK. This was done by calculating the serial correlation coefficient with a lag of (lag^{-1}), r_1, for a two-tailed test at a 5% significance level [5] [9] [15].

The lag^{-1} autocorrelation coefficient was first evaluated before applying the Mann-Kendall test. Because the observed serial dependence remained weak and did not substantially affect the long-term monotonic behaviour of the series, the standard Mann-Kendall procedure was considered appropriate. The autocorrelation analysis was therefore used primarily as a diagnostic tool for interpreting the persistence of hydrological variability rather than for modifying the original time series. This approach is consistent with recommendations for hydroclimatic time series analysis reported in the literature [16] [17].

In fact, the Mann-Kendall test made it possible to detect any gradual changes in the time series of extreme variables. Mann [14] and Kendall [15], this nonparametric, rank-based test is used to determine whether the correlation between time and the variable of interest is significant or not. That is $(x_1, \cdots, x_n)$ a sample of independent values associated with a random variable X whose stationarity we are trying to assess. The Mann-Kendall statistic is defined as follows (Equation (6)):

$$S = \sum_{i=1}^{n-1} \sum_{i=1+1}^{n} \operatorname{sign}\left(x_i - x_j\right) \tag{6}$$

where n is the length of the sequence, x_i et x_j are two generic values from the sequence, and the function

$$\operatorname{sign}\left(x_i - x_j\right)$$

is defined by the following Equation (7):

$$\operatorname{sign}\left(x_i - x_j\right) = \begin{cases} 1, & \text{if } \left(x_i - x_j\right) > 0, \\ 0, & \text{if } \left(x_i - x_j\right) = 0, \\ -1, & \text{if } \left(x_i - x_j\right) < 0. \end{cases} \tag{7}$$

The S statistic therefore represents the number of positive differences minus the number of negative differences found in the analyzed time series. If the null hypothesis holds, there is no trend in the correlation data between the variables under consideration and time, and every possible order of the data set is equally likely. In this case, the statistic S approximately follows a normal distribution with mean $E(S)$ and variance $Var(S)$ defined, respectively, by the following Equation (8) and Equation (9):

$$E(S) = 0$$

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p \left(t_p - 1\right)\left(2t_p + 5\right)\right] \tag{8}$$

where n is the number of non-missing data points, t_p is the number of values in the p^{th} group and q is the number of tied ranks. The second term represents an adjustment for linked or censored data. The values of S and $Var(S)$ are used to calculate the standardized statistical test Z which is given by the following Equation (9):

$$Z = \begin{cases} \frac{s-1}{\sqrt{var(s)}} & \text{if } S > 0, \\ 0 & \text{if } S = 0, \\ \frac{s-1}{\sqrt{var(s)}} & \text{if } S < 0. \end{cases} \tag{9}$$

The presence of a statistically significant trend is assessed by examining the Z-value. The null hypothesis (H_0) states that there is no trend, and the alternative hypothesis (Ha) states that there is a trend in the time series. A positive Z-value indicates an upward trend over time, while a negative Z-value indicates a downward trend. If the monotonic trend rises or falls relative to a significance threshold p, the null hypothesis (H_0) is rejected. In this study, the significance threshold of 0.01, the highest for this test was applied, and a p-value was obtained for each analyzed time series.

It is also possible to obtain a nonparametric estimate of the magnitude of the trend slope [18]. Thus, Sen's slope method [13], which was applied to determine the magnitude of the change, is obtained using the following formula (Equation (10)):

$$b = \text{Median}\left[\frac{x_i - x_j}{j - i}\right], \text{for } i < j \tag{10}$$

where b is the slope between the data points x_j and x_i measured at times j and i, respectively.

4. Results

Variability and Trends in the Basin's Climate Patterns

The Kendall tests in **Table 1** indicate significant negative trends during the early rainy season, particularly in May ($\tau = -0.37$ and -0.41) and June ($\tau = -0.28$ and -0.33; $p < 0.05$), reflecting a marked decrease in runoff during the onset of the hydrological year. For June, Pettitt's test identifies a significant break around 1990, associated with deficits of approximately 70%, whereas no statistically meaningful break was retained for May after revision of the series homogeneity assessment. In contrast, August, March, and April exhibit weak positive trends, accompanied by positive changes after the detected break years (1990-1996), suggesting a partial seasonal redistribution of runoff and a gradual recovery of water availability during the later part of the hydrological cycle. Overall, the results highlight a strong sensitivity of the basin to Sahelian hydroclimatic variability, with the most pronounced declines occurring at the beginning of the rainy season and more moderate recoveries during the wettest months [19].

Table 1. Analysis of monthly hydroclimatic trends and discontinuities in the Manantali Aval and Faleme River Basins in Gourbassi (Unregulated basins).

(1a)	Manantali Aval Basin Unmanaged Basin				Faleme Reservoir in Gourbassi Unregulated Reservoir			
	Kendall's τ	Slope	A Year of Change	Variation	Kendall's τ	A Year of Change	Variation	Slope
May	−0.37*	0	None	-	−0.41*	None	-	−0.010
June	−0.28*	−0.001	1990	−70.3	−0.33*	1990	−68.9	−0.008
July	−0.15	−0.006	None	-	−0.18	-	-	−0.004
August	+0.11	+0.02	1994	+45.8	+0.14	1994	+39.7	+0.006
September	−0.07	−0.02	1998	−51.9	−0.09	1998	−46.3	−0.003
October	+0.01	+0.007	None	-	+0.02	-	-	+0.001
November	+0.02	+0.001	None	-	+0.03	-	-	+0.0005
December	+0.05	+0.0003	None	-	+0.06	-	-	+0.001
January	−0.06	0	1998	−60.3	−0.08	1989	−48.5	−0.001
February	−0.13	0	1994	−53.8	−0.15	1994	−52.0	−0.002
March	+0.17	0	1990	+64.8	+0.12	1990	+58.4	+0.003
April	+0.22	0	1996	+89.0	+0.20	19961975	+72.1	+0.005
Year	−0.05	−0.002	None	-	−0.45	None	-	−0.020
Maximum	+0.35	+0.015	1991	+89.0	−0.38	1989	−65.8	+0.009
Minimum	−0.08	−0.005	None	-	−0.30	1988	-	−0.018
High-water period	+0.11	+0.02	1990	−51.1	−0.30	1990	+0.012	+0.014
Low-water period	−0.06	0	1993	-	+0.18	1993	−0.004	−0.016

τ = Kendall's tau; (−): downward trend; (+): upward trend; (*): significant trend; (None): absence of a break; Variation: index of change in the average on both sides of the break; white box: undeveloped pond; landscaped pond.

Table 2. Comparison of hydrological trends between the Bafing Basin in Dakka-Saidou (Unregulated) and the Senegal River Basin in Bakel (Regulated): findings from Kendall's Test and Pettitt's Method.

(1b)	Bafing Reservoir in Dakka-Saidou Unimproved Reservoir				Senegal River Basin in Bakel Developed Basin			
	Kendall's τ	Slope	A Year of Change	Variation	Kendall's τ	A Year of Change	Variation	Slope
May	−0.44*	−0.012	None	–	−0.40*	None	–	−0.010
June	−0.36*	−0.010	1990	−72.8	−0.32*	1990	−69.5	−0.008
July	−0.21	−0.005	None	–	−0.18	–	–	−0.004
August	+0.17	+0.008	1994	+42.6	+0.16	1994	+46.2	+0.007
September	−0.11	−0.004	1988	−53.2	−0.09	1988	−49.6	−0.003
October	+0.02	+0.001	None	–	+0.02	–	–	+0.001
November	+0.04	+0.0006	None	–	+0.03	–	–	+0.0006
December	+0.09	+0.001	None	–	+0.08	–	–	+0.001
January	−0.09	−0.001	1988	− 46.7	−0.06	1988	−44.1	−0.001
February	−0.16	−0.002	1990	−51.3	−0.13	1990	−48.9	−0.002
March	+0.18	+0.003	1989	+63.9	+0.14	1989	+61.3	+0.003
April	+0.25	+0.006	1999	+80.5	+0.22	1999	+77.6	+0.005
Year	+0.30	+0.011	None	–	+0.28	None	–	+0.29
Maximum	+0.20	+0.008	1990	−51.3	+0.22	1990	−69.5	+0.011
Minimum	−050	−0.019	None	–	−0.37	None	–	−0.015
High-water period	+0.36	+0.015	1997	+80.5	+0.22	1997	+77.6	+0.014
Low-water period	−0.40	−0.015	1992	−53.2	+0.18	1992	−0.004	−0.014

Table 2 shows similar hydroclimatic trends in the Bafing Basin at Daka-Saidou and the Senegal River Basin at Bakel despite downstream flow regulation by the Manantali Dam. Significant negative trends are observed in May and June, whereas August, March, and April exhibit slight positive trends, indicating a partial seasonal recovery after the early 1990s. Annual trends remain positive in both basins (τ = +0.30 at Daka-Saidou and τ = +0.28 at Bakel), suggesting that regional climatic variability is the dominant driver of long-term changes. However, the stronger positive trend during the high-water period at Daka-Saidou (τ = +0.36) compared with Bakel (τ = +0.22) reflects the moderating influence of dam regulation on downstream flow dynamics [3].

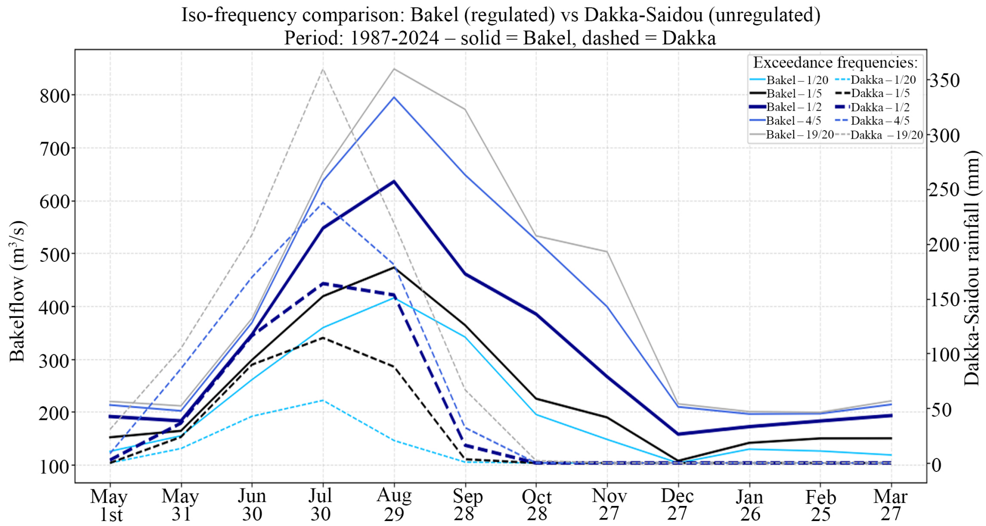

Figure 2. Comparative iso-frequency analysis of the hydrological regimes of the Senegal river in a developed (Bakel) and undeveloped (Dakka-Saidou) context over the period 1987-2024.

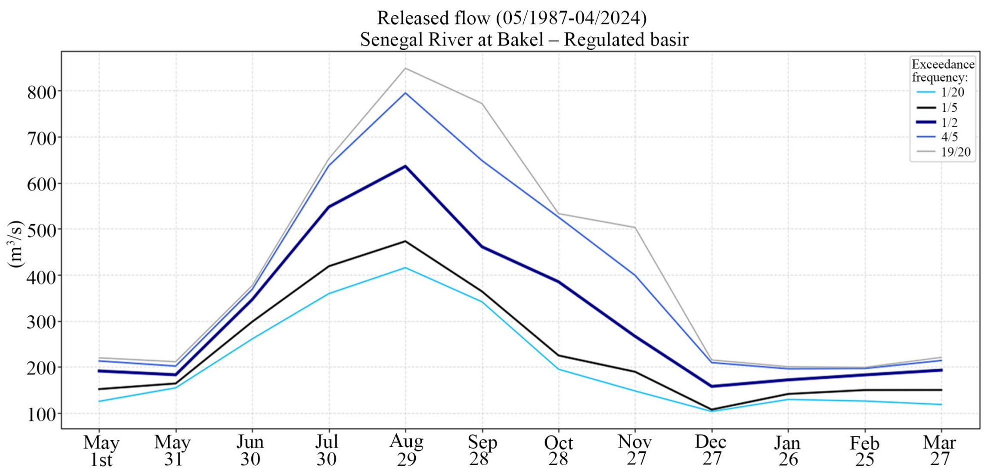

Figure 3. Frequency distribution of discharge rates released from the Manantali Dam and recorded at the BAKEL station (Senegal River): statistical characterization of the operational management of the developed basin (1987-2024).

Figure 2 shows a comparison of the exceedance curves at the two stations, highlighting the attenuation and smoothing of the hydrological signal caused by anthropogenic regulation of the watershed, which are particularly pronounced during flood events.

Figure 3 illustrates the high interannual variability of controlled releases, ranging from severe low-flow conditions (19/20) to sustained artificial floods (1/20) reaching nearly 850 m³/s in August.

Figure 4 A comparison of the monthly hydrographs for 1990 and 1994 reveals differences in peak discharge of more than 350 m³/s in August, reflecting the combined impact of Sahelian rainfall variability and water infrastructure management strategies.

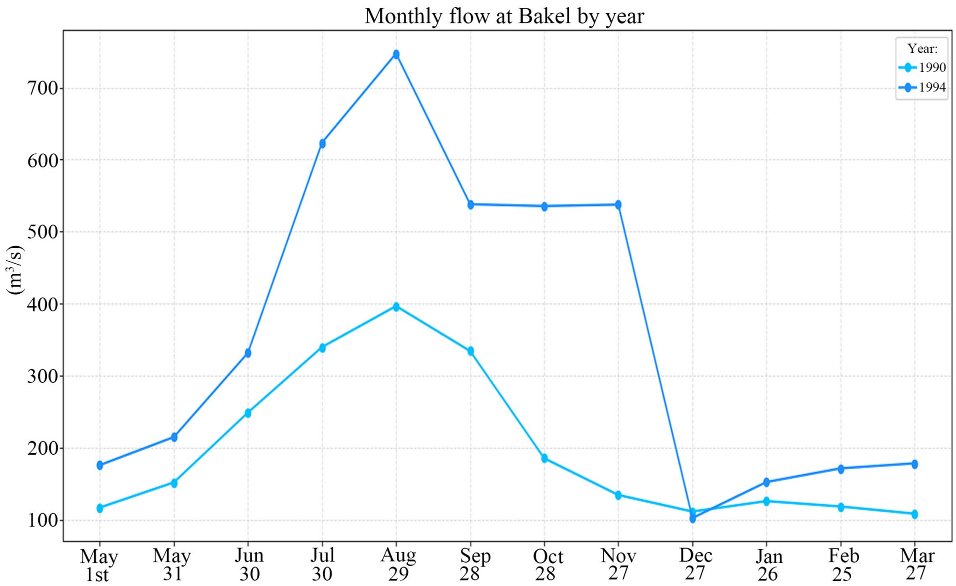

Figure 4. Year-to-year contrasts in the monthly hydrological regime at Bakel: a comparative analysis of a deficit year (1990) and a surplus year (1994) in a regulated lower basin context.

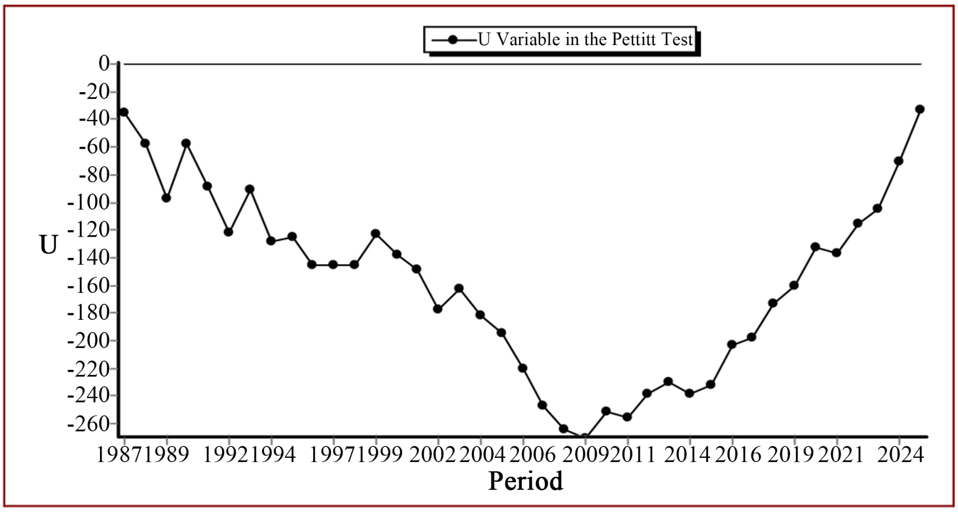

Figure 5. Application of the Pettitt test to the rainfall series from the Gourbassi station (1987-2024): identification of a hydrological break and analysis of rainfall recovery dynamics.

Figure 5 The Pettitt test at Gourbassi shows a continuous negative trajectory from 1987 to the mid-1990s, with the U statistic decreasing from 0 to about -120 around 1994 and reaching a minimum close to −200 between 1998 and 2002. This indicates a significant downward shift in the discharge series, confirmed at the 95% - 99% confidence level. The series remains at low values after 2005, suggesting a persistent deficit regime with no clear recovery phase.

Figure 6 illustrates a progressive decline in the Pettitt U statistic at the Manantali station from 1987 onward, decreasing from 0 to approximately −220 during the early 2000s. This pattern indicates a marked shift in the annual discharge series, reflecting a persistent hydrological deficit over the study period. The Pettitt test confirms the presence of a statistically significant change point at the 95% confidence level, although no clear recovery phase is observed toward the end of the record.

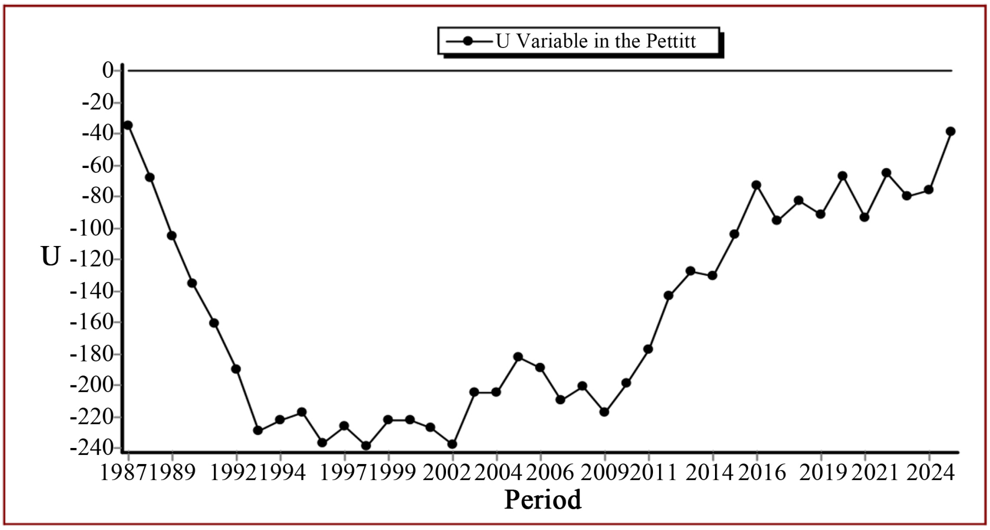

Figure 6. Detection of a change point in the Manantali hydrological series (1987-2024) using Pettitt's test, highlighting a persistent hydrological regime shift.

Figure 7 shows that the posterior probability density is strongly concentrated around 1992-1993, indicating that the most likely change point in the Bakel discharge series occurred during this period. Secondary probability peaks are also observed between 2006 and 2011, suggesting additional but less probable regime shifts. The amplitude distribution is centred on positive values, with a maximum around +80 $m^3 \cdot s^{-1}$, indicating a moderate but statistically significant increase in mean annual discharge after the detected change point. These results suggest a transition toward a new hydrological regime, likely associated with the combined effects of regional hydroclimatic variability and flow regulation by the Manantali Dam.

Figure 8 reveals an extremely concentrated peak in the probability density in 1993 with a value of approximately 0.70, the highest value among the stations analyzed, suggesting a particularly distinct and precisely dated hydrological break at

Dakka-Saidou with very low uncertainty. The distribution of the amplitude is centered around +20, with a narrow spread, indicating a positive regime shift of small magnitude but high significance, reflecting a hydrological transition that was more abrupt and less gradual than at the Bakel station.

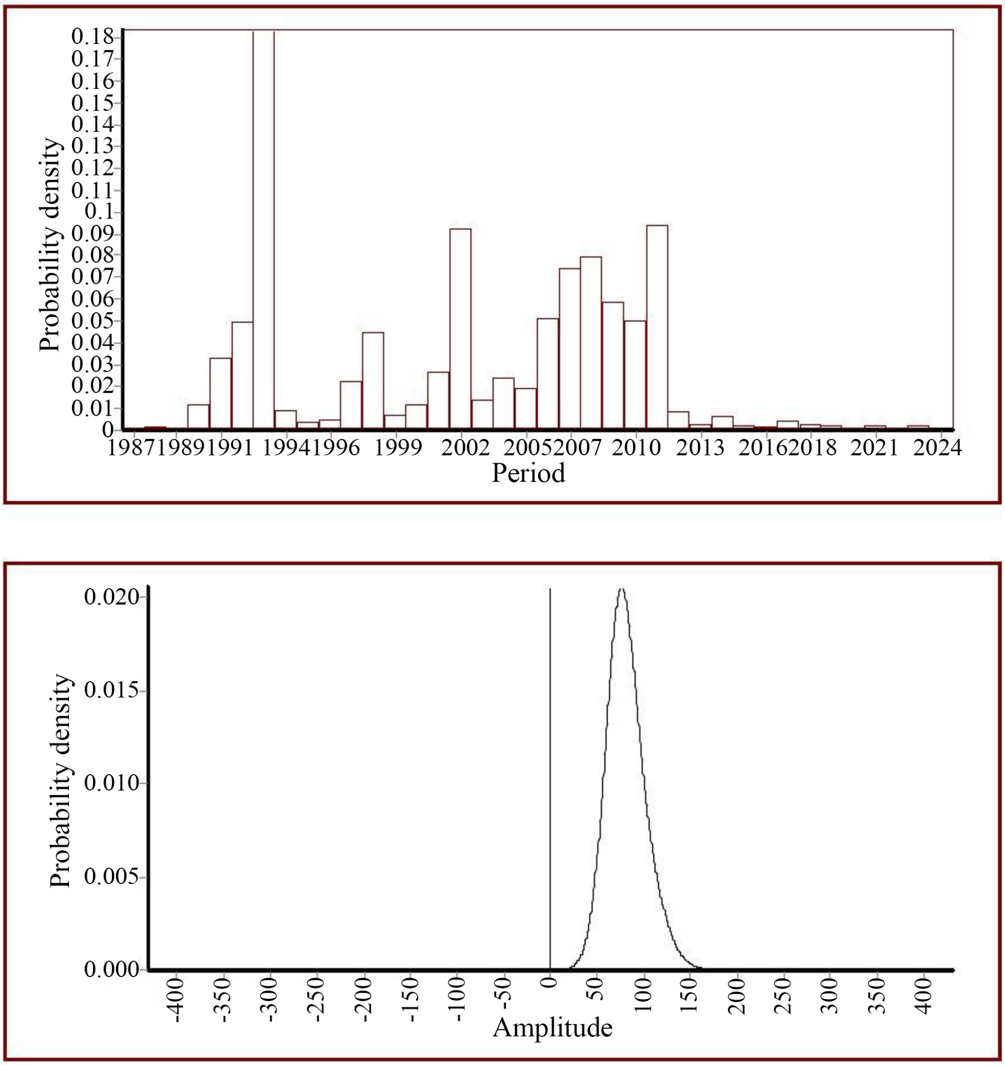

Figure 7. Bayesian analysis of break detection in the hydrological time series from the Bakel station (1987-2024): probability distribution of the break date and estimation of the magnitude of the change.

The autocorrelation plot for the Bakel station **Figure 9** reveals significant persistence in discharge at lags 1 through 5 and 9 through10, with coefficients exceeding the 99% confidence threshold, reflecting strong hydrological memory and a multi-year cyclical structure characteristic of Sahelian river regimes influenced by the variability of the West African monsoon. The slight attenuation observed at lags 6 - 8 suggests a partial breakdown of this persistence, possibly linked to interannual climate anomalies or to groundwater storage effects in the Senegal River basin.

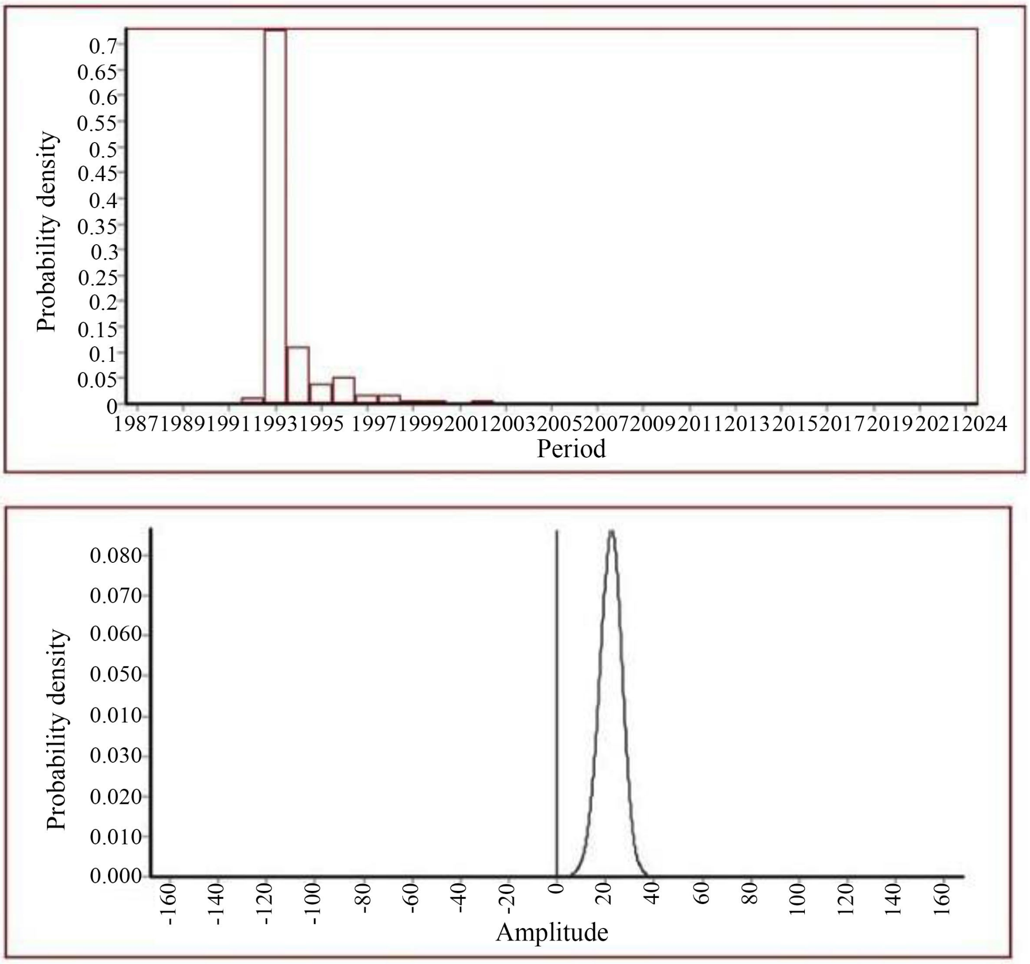

Figure 8. Probabilistic estimation of hydrological break at the Dakka-Saidou station (1987-2024): identification of a regime-shift date and characterization of its magnitude using a Bayesian approach.

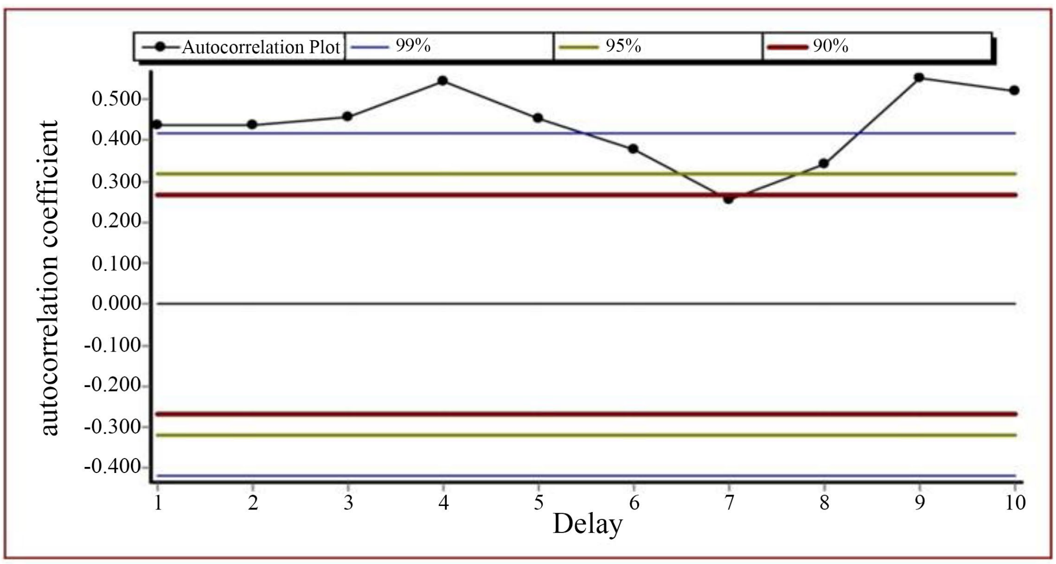

Figure 9. Analysis of the autocorrelation of hydrological discharges at the Bakel station: persistence, cycles, and hydrological memory of the Senegal river.

5. Discussions

The results confirm that the Senegal River basin is subject to complex hydroclimatic variability resulting from the interaction between climatic forcings and anthropogenic pressures. The attribution framework adopted in this study is based on a comparative analysis of hydrological responses observed at stations subjected to different levels of river regulation. The upstream stations of Daka-Saidou and Manantali, which preserve a more natural hydrological regime, were compared with the downstream Bakel station, where streamflow is directly influenced by the operation of the Manantali Dam. Similar temporal trends and breakpoints observed simultaneously at both regulated and unregulated stations were interpreted as evidence of regional climatic forcing, whereas discrepancies mainly identified at Bakel were attributed to the effects of dam regulation. Although climatic variability and hydraulic regulation interact continuously, this comparative framework provides a robust basis for discussing their respective contributions to the observed hydroclimatic changes, without assuming a complete separation of these two driving factors [10].

The marked decline in river flows observed since the 1970s is part of the broader Sahelian drought, which has been extensively documented by [3] [19]. This period corresponds to a major climatic shift that led to a widespread decrease in precipitation and runoff throughout West Africa. The identification of shifts around the years 1990-1993 is a key finding of this study. It indicates a transition to a new hydrological regime, characterized by a partial recovery in river flows, but also by increased variability.

This behavior is consistent with the findings of [17], which highlighted a reconfiguration of hydrological regimes in West Africa following prolonged droughts. The analysis also underscores the crucial role of water infrastructure projects, notably the Manantali Dam, in transforming the river's flow regime. Flow regulation has helped mitigate the magnitude of floods and support certain uses (irrigation, hydroelectricity), but it has also altered the river's natural functioning. This hydrological recovery was also observed by Ndiaye et. al [20], who show that precipitation and discharge in the Senegal River basin have exhibited an increase in the frequency of extreme events since the 2000s, reflecting a partial recovery of the hydroclimatic system but accompanied by greater interannual variability. As highlighted by Nicholson [21], these changes can have significant ecological impacts, particularly on floodplains. Furthermore, the low autocorrelation observed in the discharge time series suggests that hydrological variations are primarily influenced by external factors, especially climatic ones. These observations are consistent with the recent work in [2], which showed that the regulation of the Manantali Dam significantly alters the seasonal flow dynamics by reducing the natural amplitude of floods and increasing low-flow rates in the Senegal River basin.

Finally, the combined use of statistical methods (Mann-Kendall, Pettitt, Bayesian approach) represents a major methodological advantage. It enhances the robustness of the results and provides a complementary perspective on hydrological dynamics. This integrated approach is particularly relevant in a non-stationary context, as highlighted in [22], which emphasizes the need to rethink hydrological analysis methods in the face of climate change.

6. Conclusion

This study highlights a marked non-stationarity in the hydrological regime of the Senegal River along the Daka-Saidou-Manantali-Bakel axis. This regime is characterized by high interannual variability, as well as significant structural breaks, as confirmed by Pettitt's tests and Bayesian analysis. A marked hydrological transition was identified during the early 1990s, corresponding to the major Sahelian drought and the subsequent partial recovery of river flows. This finding highlights the vulnerability of the basin to regional climatic variability and confirms the occurrence of significant hydroclimatic changes during the study period. The low temporal dependence of the data series suggests that flow rates are primarily influenced by precipitation and large-scale climate variability. Furthermore, the impact of the Manantali Dam is crucial, as it mitigates extremes while transforming the river's natural dynamics. These findings highlight the importance of incorporating non-stationarity into hydrological models and call for an interdisciplinary approach that integrates climate, hydrology, and human activities in order to optimize the sustainable management of water resources in the Sahel region. The results confirm recent observations made in several West African basins and underscore the need to incorporate the combined effects of climate change and water infrastructure projects into future water resource management strategies [2].

Conflicts of Interest

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

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