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Rainfall and Discharge Variability in the Senegal River Basin Based on the IHA/RVA

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ABSTRACT

The hydrological regime of a river is a driving force of its ecosystem. The operation of dams and locks has significant impacts on the hydrological situation of rivers. The objective of this study was to study the change and variability of precipitation and hydrological data in the Senegal River basin and to assess the change in the discharge regime of the Senegal River caused by the operation of the Manantali hydroelectric dam. Based on the IHA (Indicators of Hydrologic Alteration), a range of variability of thirty-three hydrological parameters was calculated and the hydrological alteration associated with the functioning of the dam was quantified. Using the RVA (Range of Variability Approach) method, the hydrological alteration at the Bakel site was evaluated and showed the influence of the dam on the hydrological state. The results showed a strong influence of the dam on the hydrological regime. The fluvial eco-hydrological objectives calculated in this study can constitute certain support for the management of water resources and ecosystems of the Senegal River basin.

INTRODUCTION

High concentrations of greenhouse gases cause global temperature increases (Ahmed et al., 2017; Moazenzadeh et al., 2018; Crawford et al., 2019). Temperature increase plays an unfavorable role in modifying the components of the global hydrological cycle (Wang et al., 2017; Iqbal et al., 2019). Precipitation is considered to be the most vigorous component of the global hydrological cycle, which is believed to have changed in several regions of the global world (Saadi et al., 2017; Meshram et al., 2017; Asfaw et al., 2018). Altered rainfall patterns can have serious consequences for society in the form of floods and droughts, which can have a negative impact on the socioeconomic situation of populations (Ezzine et al., 2014). Changes in the discharge of streams or rivers are often associated with changes in rainfall (Rawshan et al., 2019). Cigizoglu et al (2005) reported that changes in river discharge are very sensitive to even small changes in rainfall. It is therefore very important and informative to investigate trends in river discharge.

Faced with a succession of extreme climatological (droughts and floods) and hydrological (floods and low water levels) episodes, numerous studies have been carried out on the Senegal River catchment area (Faye, 2015; Faye et al. 2015). These different studies, therefore, analyzed the data to characterize climate change in this basin. The Senegal River basin has experienced climate variability since the 1970s marked by a decline in rainfall (Sow, 2007) which has resulted in a significant decrease in surface runoff (Faye et al., 2015), as illustrated by the years 1983 and 1984 when runoff even ceased at Bakel. This drop in runoff has had a negative impact on many sectors of activity (agricultural production, industry, drinking water supply, navigation, etc.), placing the basin in an unprecedented ecological crisis (Tropica Environmental Consultants, 2008). However, new studies have highlighted the increase in rainfall and runoff in the area since the 2000s, which augurs well for an improvement in the hydrological regime (Ali et al., 2008; Niang, 2008; Faye et al., 2015) and an increase in flooding.

Faced with the changes in watercourses, numerous structures have been put in place, leading to an alteration in the discharge regimes of the watercourses. River discharge regimes are considered to be the main driving force of their ecosystem (Poff et al., 1997; Yang et al., 2012). The integrity and stability of river ecosystems are largely dependent on the characteristics of natural dynamic changes in river discharge (Poff et al., 1997; Zuo and Liang, 2014). Human development and management of water resources have led to changes in the natural discharge of rivers worldwide (Richter, 1997). Altered discharge regimes in the river system affect water quality, energy sources, physical habitat, and biotic interactions, resulting in damage to the ecological integrity of rivers (Suen, 2011).

To conserve water, many dams have been built along rivers and make it possible to regulate the discharge of a river, thus reducing the differences in discharge and thus the intensity of floods and droughts. This regulation by dams modifies the natural discharge pattern of rivers. The likely increase in the mean downstream discharge during the dry season can permanently flood important ecosystems, while a decrease in discharges during the wet season can harm the biological productivity of small floodplains (Kummu and Varis, 2007). In addition, according to studies on the Amazon by Junk et al (1997), a change in the river regime can lead to delays in the arrival and shorter duration of floods, which would have a negative effect on the productivity of ecosystems.

The natural discharge of a river is subject to great spatial and temporal variability and has ecologically important characteristics. To characterize this natural variability in the discharge of a river, several years of observation at a hydrological station are generally necessary. This characterization of the natural regime can be carried out using different approaches, and its assessment is essential for understanding and predicting, following development, the biological impact of both natural and modified discharge regimes on the environment (Zuo and Liang, 2014). To this end, a number of hydrological indices and methods that take into account not only hydrological but also ecological parameters are being developed and applied by researchers to characterize different components of the hydrological regime (Faye, 2015).

Numerous studies on the relationships between hydrological variables and the integrity of river ecosystems lead to a paradigm on natural discharge that states that the full range of intra- and interannual variations in hydrological regimes, and associated characteristics such as magnitude, seasonality, duration, frequency, and rate of change, are critical for maintaining biodiversity and the integrity of aquatic ecosystems (Hirtt, 2009). It follows that managing an ecosystem with all its ranges of natural variation is an appropriate means of maintaining a diverse, productive, flexible, and healthy system. Therefore, if the conservation of native biodiversity and ecosystem integrity are the objectives of river management, then the manager must take into account the natural discharge paradigm, as proposed by the Indicators of Hydrologic Alteration (IHA) method.

Like all the proposed hydrological indices, the HIA method, with its Range of Variability Approach (RVA), is widely used to characterize the variability of the natural discharge of a river (Richter et al., 1996, 1997, 1998). It identifies annual management objectives based on a comprehensive statistical study of ecologically relevant discharge characteristics. To this end, it first determines a set of 33 hydrological parameters for descriptive statistics and then develops a management method. The IHA/RVA method provides a more quantitative way to assess the degree of alteration and allows the effects of river management on its ecology to be recorded, information that can be used to redefine new management objectives and rules. Current applications of the HIA/RVA method around the world show high degrees of alteration at locations downstream of hydraulic control structures (Yang et al., 2008).

The analysis of the hydrological regime and the determination of reasonable ecological discharge are key elements in water resource management. Water resource problems are becoming increasingly difficult and complex worldwide. The complexity of water resources planning and management is due to the contribution of climate variability, social and environmental considerations, the transboundary nature of rivers, and population growth (Fentaw et al., 2019). The objective of this study was to study the change and variability of long-term historical rainfall and hydrological data in the Senegal River basin and to assess the change in the discharge regime of the Senegal River caused by the operation of the Manantali hydroelectric dam.

MATERIALS AND METHODS

Study Area

The Senegal River, some 1,700 km long, drains a basin of 300,000 km2, straddling four countries: Guinea, Mali, Senegal, and Mauritania from upstream to downstream (Figure 1). It runs from 10°20' to 17°N and from 7° to 12°20' W and is made up of several tributaries, the main ones being the Bafing, Bakoye, and Falémé. These three tributaries have their sources in Guinea and form the upper basin (Michel, 1973) which produces more than 80% of the river's inflow at Bakel. The Senegal River thus formed by the junction between the Bafing and the Bakoye, receives the Kolimbiné then the Karokoro on the right and the Falémé on the left, 50 km upstream from Bakel (Rochette, 1974). The basin is generally divided into three entities: the upper basin, the valley, and the delta.

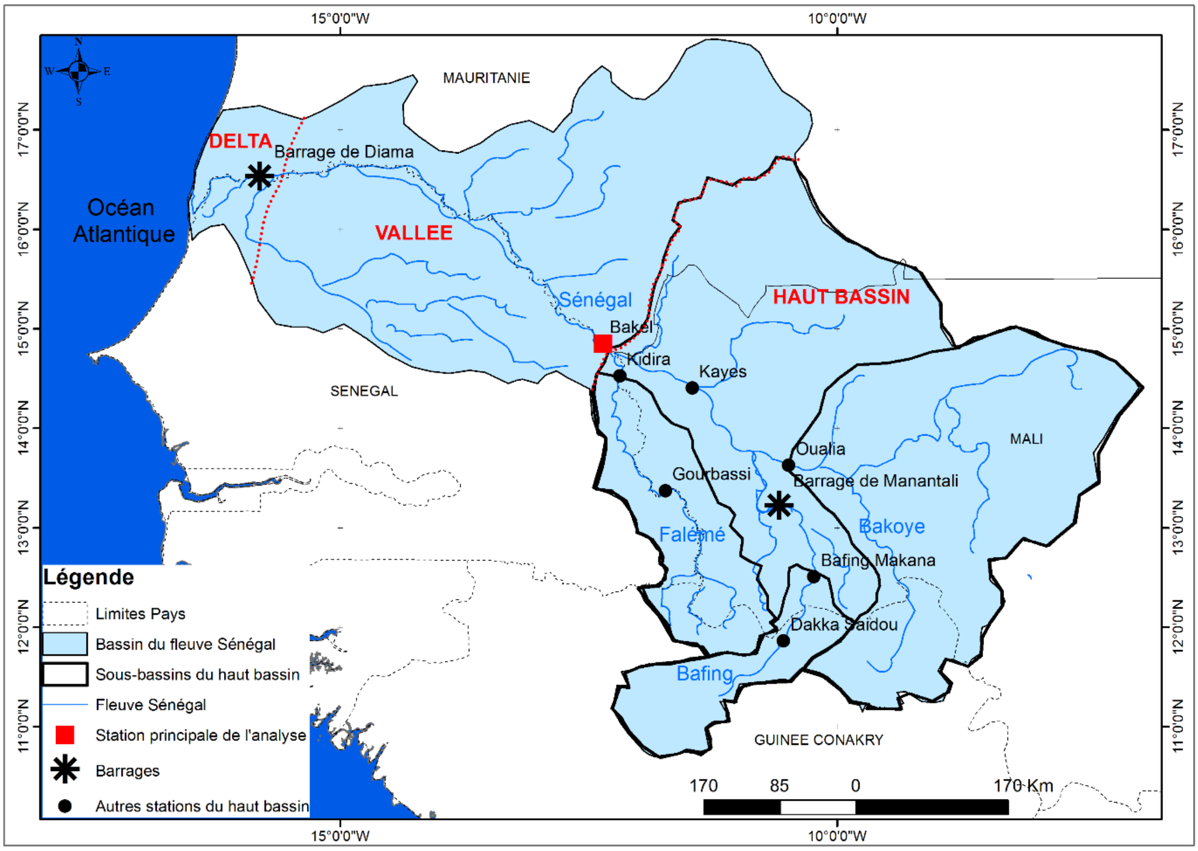

Figure 1. Location of the Senegal River catchment area, the dam and Manantali, and the Bakel hydrometric station

The Senegal River watershed is a hydro system of the humid tropical domain in its southern part and dries in its northern part whose altitudes vary from 15 m (Bakel: middle course) to 1330 m (Fouta Djallon) for an average altitude of about 672 m. In the basin upstream of Senegal and Mali, rainfall is high (> 1800 mm/year in Mamou), with steep slopes and rocks that are generally not very permeable. The downstream and northern part (Bakel area), is oriented north and then west. It has slopes (slope index = 0.022%) and low altitudes (minimum altitude = 15 m). Rainfall is low (≈ 500 mm in Bakel) (Michel, 1973; Rochette, 1974; Faye, 2015).

The Manantali dam is located on the Bafing River, the main tributary of the Senegal River, 90 km upstream from Bafoulabé (Figure 1). Built between 1982 and 1987, the Manantali dam consists of a 1,460 m long dike and is 66 m high at the foundation. At the filling level of 208 meters IGN, its reservoir has a capacity of 11.3 billion m3 and covers an area of 477 km² (International Office for

Water, 2009). At its minimum operating level (187 m IGN), the reservoir has a volume of 3.4 billion m3 and covers an area of 275 km². The Manantali dam regulates the discharge of the Senegal River and makes it possible to irrigate a potential 255,000 ha of land and should eventually allow the river to be navigable over approximately 800 km from its mouth. The management of the dam between the riparian States of the Senegal River is carried out in a concerted manner within a regional cooperation framework under the supervision of the Organisation for the Development of the Senegal River (OMVS), whose construction of the Manantali dam is undoubtedly one of its greatest achievements.

During the 1970s and 1980s, the effects of climate change and drought led to changes in the hydrological regime of the basin (Sow, 2007; Faye et al., 2015). To remedy this, a series of developments, notably the two Diama and Manantali dams, were put in place and have totally transformed the hydrological dynamics of the Senegal River basin. The Bakel hydrological station, which controls the upper basin and whose discharges are influenced by the operation of the Manantali dam, is used, given the availability of hydrological data, to study the influence of the Manantali dam on the hydrological regime of the Senegal River.

The objective of this study was to study the change and variability of precipitation and hydrological data in the Senegal River basin and to assess the change in the discharge regime of the Senegal River caused by the operation of the Manantali hydroelectric dam.

Data

Daily discharge data were used to analyze the variation of the hydrological regime of the upper Senegal River basin with the HIA/VAR method. These observed daily data were made available to us by the Organisation for the Development of the Senegal River (OMVS). These data cover the period 1958-2018. The database used in the Senegal River basin for this study met two important criteria: the length of the chronicles on the one hand (covering the largest possible time), and the quality of the data on the other hand (as few missing data as possible).

Methods of Trend Analysis

The Mann-Kendall test was used to reveal trends in monthly discharge data, modulus, annual maximum discharge, annual minimum discharge, and high and low discharge periods (Cigizoglu et al., 2005; Wang et al., 2013). The Mann-Kendall (MK) test is frequently used to assess trends and is a non-parametric test (Mann, 1945; Kendall, 1975). The World Meteorological Organization (WMO) for hydrometeorological trend assessments also approves the test. The Sen slope method, which is a non-parametric linear slope estimator that works best on monotonic data, is also used. The Sen slope method is used to determine the amplitude of the trend line. Sen's slope calculates the slope as a change in measurement per change in time.

Methods Indicators of Hydrologic Alteration (IHA)/Range of Variability Approach (RVA)

The HIA method established by The Nature Conservancy (Richter et al., 1996) has been used to assess the main hydrological characteristics affected downstream of dams (Magilligan and Nislow, 2005) and the alteration of the hydrological regime of rivers. This model uses mean daily discharges and calculates 33 ecologically relevant hydrological parameters that describe the hydrological regime and are grouped into 5 categories (Richter et al., 1998). : (i) amplitude, (ii) amplitude and duration of annual extreme conditions, (iii) periodicity (timing) of these annual extreme conditions, (iv) frequency and duration of strong and weak pulses, (v) rate and frequency of discharge variations (Table 1). All these indices measured by IHA were defined to take into account most of the hydrological disturbances corresponding to the potential ecological impacts of dams (Erskine et al., 1999).

The IHA method consists of four steps: (1) defining the data series for pre- and post-impact periods; (2) calculating the values of hydrological attributes; (3) calculating interannual statistics; (4) calculating the HIA values. Based on the HIA, the RVA (Range of Variability Approach) method can be used to assess the effects of dam operation on the hydrological regime of a river. The method requires discharge data over about twenty years, before and after changes in the hydrological regime of the river.

Table 1. Summary of the 33 HIA parameters and their hydrological significance (Richter et al., 1998)

Categories	IHA parameter groups	Hydrological parameters
(i) Amplitude	1. Extent of monthly water conditions (1 parameter in total)	Mean or median value for each month
(ii) Extent and duration of annual extreme conditions	2. Extent and duration of annual extreme water conditions (12 parameters in total)	Annual minimums, 1-day average
		Annual minimums, average over 3 days
		Annual minimums, average of 7 days
		Annual minimums, average of 30 days
		Annual minimums, average of 90 days
		Annual maximum, average over 1 day
		Annual maximum, average of 3 days
		Annual maximum, average of 7 days
		Annual maximum, average of 30 days
		Annual maximum, average of 90 days
		Number of days with zero discharge
		Basic discharge rate index: minimum 7-day discharge rate/average discharge rate for the year
(iii) Periodicity of these extreme conditions on an annual basis	3. Timing of annual extreme water conditions (2 parameters in total)	Julian date of each year 1 day maximum
		Julian date of each year 1 day minimum
(iv) Frequency and duration of strong and weak pulses	4. High and low pulse frequency and duration (4 parameters in total)	Number of weak impulses in each hydrological year
		Mean or median duration of weak pulses (days)
		High number of pulses in each hydrological year
		Mean or median duration of high pulses (days)
(v) Rate and frequency of discharge changes	5. Rate and frequency of changes in water status (2 parameters in total)	Rate increase: Mean or median of all positive differences between consecutive daily values
		Falling rate: Mean or median of all negative differences between consecutive daily values.
		Number of hydrological inversions

The HIA-based RVA method is well known for the assessment of hydrological alteration in river ecosystems (Richter et al., 1996). The study replaces the number of elevations and the number of falls of the parameter used in the RVA method with the number of hydrological changes. The "zero discharge" was excluded from the study because no zero discharge is recorded at the station. The HIA values of each indicator for each hydrological year are calculated according to the mathematical formulation (equations 1-12) mentioned in the study from Barbalic and Kuspilic (2014) and the results were used to calculate the hydrological alteration using the histogram comparison approach. The mathematical formulation of the hydrological weathering indices is given below (Huang et al., 2019).

- Group 1 indices: Average monthly water status (magnitude).

$$\mathrm{IHA}_{1,m}=\frac{1}{n}\sum_{i=1}^{n} Q_i \qquad (1)$$

Where $\mathrm{IHA}_{1,m}$ - group 1 indices, m denotes the month (m3/s); m-number of months, $1 \leq m \leq 12$; n - number of days in a month (m); Qi - average daytime discharge (m3/s), ith day of the same month.

- Group 2 indices: Annual extreme water conditions (magnitude and duration).

Case: minimum

$$\mathrm{IHA}_{2,m}=\min\left[\frac{1}{n}\sum_{i=k}^{k-n-1} Q_i\right] \qquad (2)$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\nabla 1 \ll k \ll 365-(n+1)$$

Where $IHA_{2,m}$ -Group 2 indexes (m3/s), m = {1,3,5,7,9}; n-duration of discharge (days), n = {1,3,7,30,90}; Qi - average diurnal discharge (m3/s), ith day of the year.

Case: maximum

$$\mathrm{IHA}_{2,m}=\max\left[\frac{1}{n}\sum_{i=k}^{k-n-1} Q_i\right] \quad (3)$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\nabla 1 \lll k \lll 365-(n+1)$$

Where $\mathrm{IHA}_{2,m}$ -Group 2 indices (m3/s), m = {2,4,6,6,8,10}; n-duration of discharge (days), n = {1,3,7,30,90}; Qi - average diurnal discharge (m3/s), ith day of the year.

- Group 3 indices: Annual extreme water conditions (timing):

$$\mathrm{IHA}_{3,1}=i\left[Q_i=Q_{max}\right] \quad (4)$$

$$\mathrm{IHA}_{3,2}=i\left[Q_i=Q_{min}\right] \quad (5)$$

Where, $\mathrm{IHA}_{3,1}$, $\mathrm{IHA}_{3,2}$ - HIA indices of group 3. i - number of days in the year ($1 \leq i \leq 365$); Qi - average daily discharge (m3/s), ith day of the year; Qmax - maximum daily average discharge (m3/s) during the year; Qmin - minimum daily average discharge (m3/s) during the year.

- Group 4 indices: High and low impulses (frequency and duration):

$$\mathrm{IHA}_{4,1}=\sum_{i=1}^{364}\left[Q_i \leq Q_{25\%} < Q_{i+1}\right] \quad (6)$$

$$\mathrm{IHA}_{4,2}=\sum_{i=1}^{364}\left[Q_i > Q_{75\%} > Q_{i+1}\right] \quad (7)$$

$$\mathrm{IHA}_{4,3}=\frac{1}{\mathrm{IHA}_{4,1}}\sum_{i=1}^{365}\left[Q_i > Q_{75\%}\right] \quad (8)$$

$$\mathrm{IHA}_{4,4}=\frac{1}{\mathrm{IHA}_{4,2}}\sum_{i=1}^{365}\left[Q_i < Q_{25\%}\right] \quad (9)$$

Where, $\mathrm{IHA}_{4,1}$, $\mathrm{IHA}_{4,2}$ - HIA indices of group 4 (number of high and low pulses); $\mathrm{IHA}_{4,3}$, $\mathrm{IHA}_{4,4}$ - IHA indices of group 4 (average duration of high and low pulses); i - number of days in a year ($1 \leq i \leq 365$); Qi - average diurnal discharge rate (m3/s), ith day of the year; Q25% - discharge rate of 25% duration (m3/s); Q75% - discharge rate of 75% duration (m3/s).

- Group 5 indices: Changes in water status (rate and frequency):

$$\mathrm{IHA}_{5,1}=\frac{\sum_{i=1}^{364}(Q_{i+1}-Q_i)\left[Q_i<Q_{i+1}\right]}{\sum_{1}^{364}[\![Q_i<Q_{i+1}]\!]} \quad (10)$$

$$\mathrm{IHA}_{5,2}=\frac{\sum_{i=1}^{364}(Q_{i+1}-Q_i)\left[Q_i>Q_{i+1}\right]}{\sum_{1}^{364}\left[Q_i>Q_{i+1}\right]} \quad (11)$$

$$\mathrm{IHA}_{5,3}=\sum_{i=2}^{364}\left[(Q_{i+1}-Q_i)(Q_i-Q_{i+1})<0\right] \quad (12)$$

Where, $\mathrm{IHA}_{5,1}$, $\mathrm{IHA}_{5,2}$ and $\mathrm{IHA}_{5,3}$ - HIA indices of group 5 (m3/s); i - number of days in the year ($1 \leq i \leq 365$); Q1- average daytime discharge (m3/s), ith day of the year.

Measurements of general trends and dispersion of discharges are taken from the annual series for each of the parameters studied and are used to characterize interannual variations. An objective is chosen for each of the parameters. The basic principle is that the river should be managed in such a way that the annual values of each HIA parameter are included within the range of natural variations of that parameter. Thus, management objectives for each of the parameters are given within a range of acceptable RVA values (Richter et al., 1997), and management objectives defined by the 25th and 75th percentile of the parameter at only 50% of years (Richter et al., 1997). The degree of hydrological alteration (HA), expressed as a percentage, can be calculated as follows:

$$\mathrm{HA}=\frac{N_0-N_e}{N_e}\times 100 \quad (13)$$

$$N_e=pxN_T \quad (14)$$

Where No is the observed number, Ne is the expected number and p is the percentage of post-dam years for which the values of the hydrological parameters are within the target range RVA, and NT is the total number of post-dam years. Hydrological alteration is equal to zero when the observed frequency of annual post-dam values within the RVA range is equal to the expected frequency. A positive difference indicates that annual parameter values have fallen more frequently than expected in the RVA range; negative values indicate that annual values have fallen less frequently than expected in the RVA range (Yang et al., 2008). To quantify this hydrological alteration, Richter et al (1998) divided the alteration ranges into three classes of equal range: (i) 0% -33% (L) represents little or no alteration; (ii) 34% -67% (M) represents moderate alteration; (iii) 68% -100% (H) represents a high degree of alteration. Xue et al (2017) reported improving the categorization and classifying it into five categories: mild impairment (<20%), low (20-40%), moderate (40-60%), high (60-80%), and severe (>80%). The hydrological alteration is analyzed according to the improvement of the categorization.

The coefficient of dispersion (CD) is a commonly used indicator to assess the variability of daily discharge. It is calculated as follows:

$$CD=\frac{Q_3 - Q_1}{Q_2} \qquad (15)$$

Where Q3 is the third quartile (or 75th percentile); Q1 is the first quartile (or 25th percentile) and Q2 is the median (or 50th percentile).

- HCA method (Histogram Comparison Approach)

Huang et al (2017) proposed the HCA method with the degree of similarity as a key parameter to remove some of the limitations of the VAR approach, which takes into account both class and cross-class information in the histograms and reflects how many characteristics of the pre-impact histogram remain in the post-impact histogram. The study used the histogram comparison approach (HCA) to assess the quantitative degree of hydrological alteration. Xue et al (2017) concluded that in the HCA method when calculating the overall degree of alteration, an indicator that is highly (or severely) altered could easily be underestimated among most indicators with a moderate (or low) degree of alteration. With this in mind, he proposed an improved method based on the group average technique to address this limitation. It is set out below:

$$D_j=\sqrt{\frac{D^2_{j\,max}+D^2_{j\,moy}}{2}} \text{ (j=1, 2, 3, 4, 5)} \qquad (16)$$

Where Dj max and Dj moy are the maximum and average values of the degree of impairment for each group of indicators (Xue et al., 2017). The overall degree of impairment is given by:

$$D_{total}=\frac{\sum_1^5 D_j}{5} \qquad (17)$$

Results and Discussion

Trend and variation in rainfall and runoff in the Senegal River basin

Discharge is a very useful indicator of long-term hydroclimatic changes. From a water resource management perspective, identification of the trend and variability of discharge is critical for planning purposes. Trend analysis is useful for understanding the dynamics and behavior of hydrological and climatic variables over a long time (Fentaw et al., 2019). The Mann-Kendall test was applied to annual and seasonal discharge rainfall data at the Bakel station over the period 1958 to 2018 (Figure 2). For the seasonal classification, a segmentation of the data series on a monthly scale was made with the monthly coefficient of monthly discharge, which allowed the series to be divided into two components: a high water period (July-October) and a low water period (November-June). The magnitude of the river discharge trends was assessed using the Sen slope, while its importance was confirmed by the Mann-Kendall trend test.

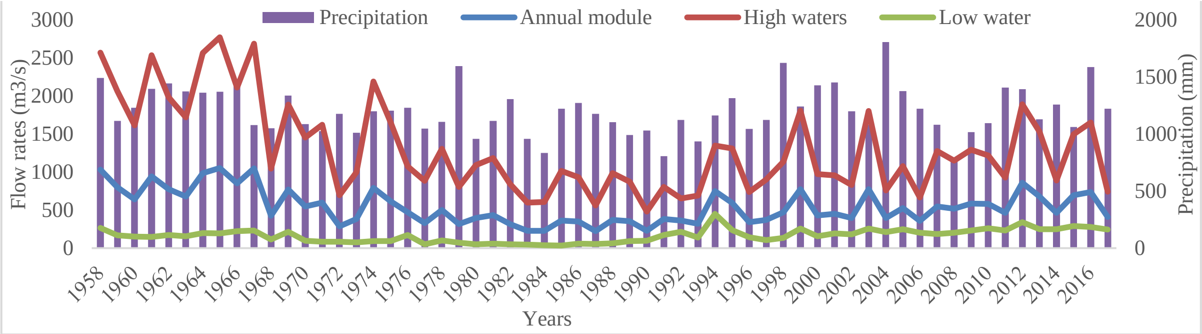

Figure 2. Evolution of rainfall in the Senegal River basin and discharge rate at Bakel station from 1958 to 2018

The study of the climatic framework is fundamental (Faye 2015) and the evolution of rainfall shows great climatic variability in the basin with the presence of two periods: a very rainy period marked by abundant rainfall during the 1950s and 1960s and a dry period characterized by drought during the 1970s and 1980s. On the other hand, during the 2000s, it was noted in the basins that an increase in rainfall predicted an improvement in rainfall patterns compared to the drought period of previous decades (Faye, 2015). However, the persistence and sustainability of the increase have yet to be proven, given that the sufficiently long climatological scale is thirty years (Faye et al., 2015).

On an annual scale, the average modulus is 534 m3/s for a maximum of 1054 m3/s and a minimum of 225 m3/s. For the high water period, the average discharge rate is around 1299 m3/s for a maximum of 2772 m3/s and a minimum of 483 m3/s. As for the low water period, the average discharge rate is around 166 m3/s for a maximum of 452 m3/s and a minimum of 36 m3/s. The discharge in the basin is highly variable (0.41 on an annual scale). This variation is greater in periods of low water (0.52) than in periods of high water (0.45). The Sen slope and the Mann-Kendall trend test applied show opposite trends. If the trends are negative for the modulus (Kendall's tau of -0.12 m3/s and Sen's slope of -2.16) and the discharge in high water periods (Kendall's tau of -0.24 m3/s and Sen's slope of -12.8), they are statistically positive for the discharge in low water periods (Kendall's tau of 0.3 m3/s and Sen's slope of 2.29) at the 99% confidence level. The downward trend of the discharge on an annual scale in periods of high water and the upward trend in periods of low water can be explained respectively by the policy of limiting floods and of supporting the low water levels of the dam.

This study of discharge variability at the Bakel station is important because all the discharges generated from the Fouta Djallon mountainous regions generally reach their maximum value at this station. It should be stressed that the hydrological regime of the basin is strongly affected by human activities such as the Manantali hydroelectric dam and the planned irrigation, hydropower, and water conservation projects. Although annual rainfall has shown an upward trend over the past decades, which should in theory lead to an increase in runoff, discharge, and water availability in the basin, the runoff has shown a downward trend during high water periods. Therefore, human activities, as well as climate change and variability, may all contribute to the discharge trends detected in this study.

Influence of the operation of the Manantali dam on the discharge regime of the Senegal River at the Bakel station

Firstly, the mean value of the 33 hydrological parameters in the pre-impact discharge data series of the Manantali dam over the wet period (1958-1987) and over the post-impact period (1988-2018) was calculated, as well as the range of approaches to the variability of these parameters. Then, the mean value of the same hydrological parameters in the series of discharges after the impact of the dam was calculated. To compare the series of the pre-impact period of the Manantali dam with that of the post-impact period, the differences between the two periods were also calculated. Finally, using the 25th and 75th percentile values of the pre-impact parameters as eco-hydrological targets, the degree of variation of the post-impact parameters compared to the pre-impact parameters (or degree of hydrological alteration) was calculated. (Table 2).

Table 2. Level of alteration of the 33 hydrological parameters between the pre-impact (1958 -1987) and post-impact (1988-2018) periods

	Pre-impact period (1958-1987)		Post-impact period (1988-2018)		RVA limits			
	Median	CD	Median	CD	Minimum	Maximum	Degree of alteration	
							%	Category
IHA Group 1								
May	111	1,75	187	0,68	13	169	22,1	Low
June	192	1,01	240	0,56	132	236	3,33	Light
July	415	0,73	458	0,67	341	546	31,5	Low
August	1577	0,64	1031	0,74	1223	1796	-53,0	Moderate
September	2190	0,76	1750	0,69	1667	2798	31,5	Low
October	1009	0,96	684	0,69	676	1300	40,9	Moderate
November	373	0,99	308	0,64	285	577	12,7	Light
December	187	0,90	187	0,67	143	266	12,7	Light
January	122	0,78	164	0,66	98	168	40,9	Moderate
February	100	0,81	166	0,46	74	130	-43,6	Moderate
March	67	1,17	192	0,54	47	94	-81,2	Severe
April	42	2,74	218	0,56	26	131	-24,9	Low
Group 2 IHA								
Minimum 1 day	15	5,73	122	0,50	0	75	-80,3	Severe
Minimum 3 days	16	5,59	122	0,50	0	76	-80,3	Severe
Minimum 7 days	18	5,39	124	0,50	0	78	-80,3	Severe
Minimum 30 days	27	3,93	136	0,50	1,844	88	-62,4	Forte
Minimum 90 days	54	2,14	153	0,51	19,83	108	-71,8	Forte
Maximum 1 day	3421	0,73	2674	0,55	2664	4207	31,5	Low
Maximum 3 days	3319	0,72	2625	0,52	2582	4139	31,5	Low
Maximum 7 days	3097	0,77	2541	0,50	2312	3948	40,9	Moderate
Maximum 30 days	2507	0,80	1961	0,59	1834	3110	40,9	Moderate
Maximum 90 days	1395	0,85	1126	0,53	1183	1833	-15,5	Light
Zero-rate days	0	0	0	0	0	12	47,6	Moderate
Basic discharge index	0,03	4,01	0,25	0,46	0	0,09	-100	Severe
Group 3 IHA								
Date of the minimum	116	0,20	27,5	0,27	77	137	-43,6	Moderate
Date of maximum	254	0,05	249	0,02	251	257	-43,6	Moderate
Group 4 IHA								
Number of weak pulses	1	0	0	0	1	1	-88,1	Severe
Duration of weak pulses	107	1,22	73,50	2,16	72,02	161	-90,6	Severe
Number of strong impulses	1	0	1	1	1	1	-26,2	Light
Duration of strong pulses	87	0,57	68	0,96	69,36	109	-15,5	Light
Group 5 IHA								
Rise rate	4,87	5,44	3,25	1,35	1,88	16,18	97,3	Severe
Descent rate	-3,72	-1,35	-4,12	-1,04	-5,91	-2,71	12,7	Light
Number of retakes	16	0,38	21	0,49	13	18	-58,7	Moderate

Timing of Annual Change in Extreme Discharges

IHA Group 3 includes the Julian date of the minimum and maximum (Table 2). The Julian median Julian dates of the annual one-day minimum fall from the 116th day of the pre-impact period to the 28th day of the post-impact 1 period (a sharp drop of 88 days), with a moderate change of -43.6%. Julian median dates of the annual one-day maximum also decreased slightly from the 254th day of the pre-impact period to the 249th day of the post-impact period (a slight decrease of only 5 days), with a moderate change of -43.6%.

Strong and Weak Impulses

Of the four indices in this IHA 4 group, the number of weak impulses, the duration of weak impulses, the number of strong impulses, and the duration of strong impulses were modified, with an alteration of -88.1%, -90.6%, -26.2% and -15.5%, respectively (Table 2). While this alteration is severe for the number and duration of weak impulses, it is slight for the number and duration of strong impulses. With the exception of the number of strong impulses (where there is equality), the median number of weak impulses, the duration of weak impulses, and the duration of strong impulses in the post-impact period were lower than in the pre-impact period (Table 2). The coefficient of dispersion for the duration of weak pulses, the number of strong pulses, and the duration of strong pulses were higher in the post-impact period, in contrast to the number of weak pulses where there is no variation in both the pre-impact and post-impact periods. For both high and low pulses, a sharp decrease in duration is noted between the post-impact and pre-impact periods. This indicates that the frequency and duration of low and high discharge pulses in the Senegal River are influenced by the construction of the Manantali hydroelectric dam.

Rate and Frequency of Discharge Variations

A change in the medians of the rise rate, fall rate, and number of recoveries (reversals) over the pre-impact and post-impact periods. is shown in Table 2. The median rise rate increased from 4.87 m3/s per day in the pre-impact period to 3.25 m3/s per day in the post-impact period with a severe hydrological alteration of 97.3%. The median fall rate also decreased from -3.72 m3/s per day in the pre-impact period to -4.12 m3/s per day in the post-impact period with a slight hydrological alteration of 12.7%. These changes indicate that the dam has significantly reduced the rate of hydrological rise due to the storage effects of the reservoir and has led to numerous other inversions between the upward and downward stages of discharge in the river. The median of the number of inversions was also significantly changed from 16 in pre-impact to 21 in post-impact with a moderate hydrological alteration of -58.7%.

Size of the Monthly Flow

The result in Table 2 indicates that the river discharge has become more fluid in the post-impact period through two major changes, a decrease in the high discharge and an increase in the low discharge. The changes in the discharge regime were closely linked to the operation of the Manantali hydroelectric dam, which stores more water during the rainy season (July to October) and releases water downstream for power generation and maintenance of water-related activities during the low-water season. The operation of the Manantali hydropower reservoir has modified the original hydrological process, smoothing the peak discharge and increasing the dry season discharge of the Senegal River (Figure 3).

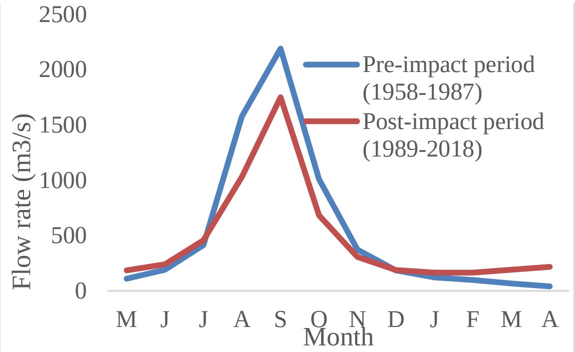

Figure 3. Comparison of the median monthly discharge before and after the construction of the Manantali hydroelectric dam in the Senegal River

The magnitude of the monthly discharge from February to June, the normal low discharge period, increased after 1987 when the reservoir behind the dam stored water. The median discharge for each month after the dam was built differs considerably from the discharges in the period before the dam was built. Thus, during the low discharge period of the year, the operation of the dam increases the median discharges while decreasing the median discharge in the high discharge months. Figure 3 shows an increase in the median discharge in March and a decrease in the median discharge in September. The month of March shows a severe alteration with 81.2% and the month of September, the month of the maximum discharge in the series, has a weak alteration with 31.5% (Figure 3). The positive hydrological alteration for June (3.33%), November, and December (with 12.7%) is slight. The moderate alteration noted there is sometimes negative in August (-53%) and February (-43.6%), and sometimes positive in October and January (49.9%). The positive differences in the low-water months and the negative ones in the high-water months result from the management of the Manantali dam, especially with the action of rolling the floods and supporting the low discharges (Sambou et al., 2009). Nevertheless, positive deviations noted in months of high water are thought to result from climate change and its corollary, the hydrological deficit (Faye et al., 2015).

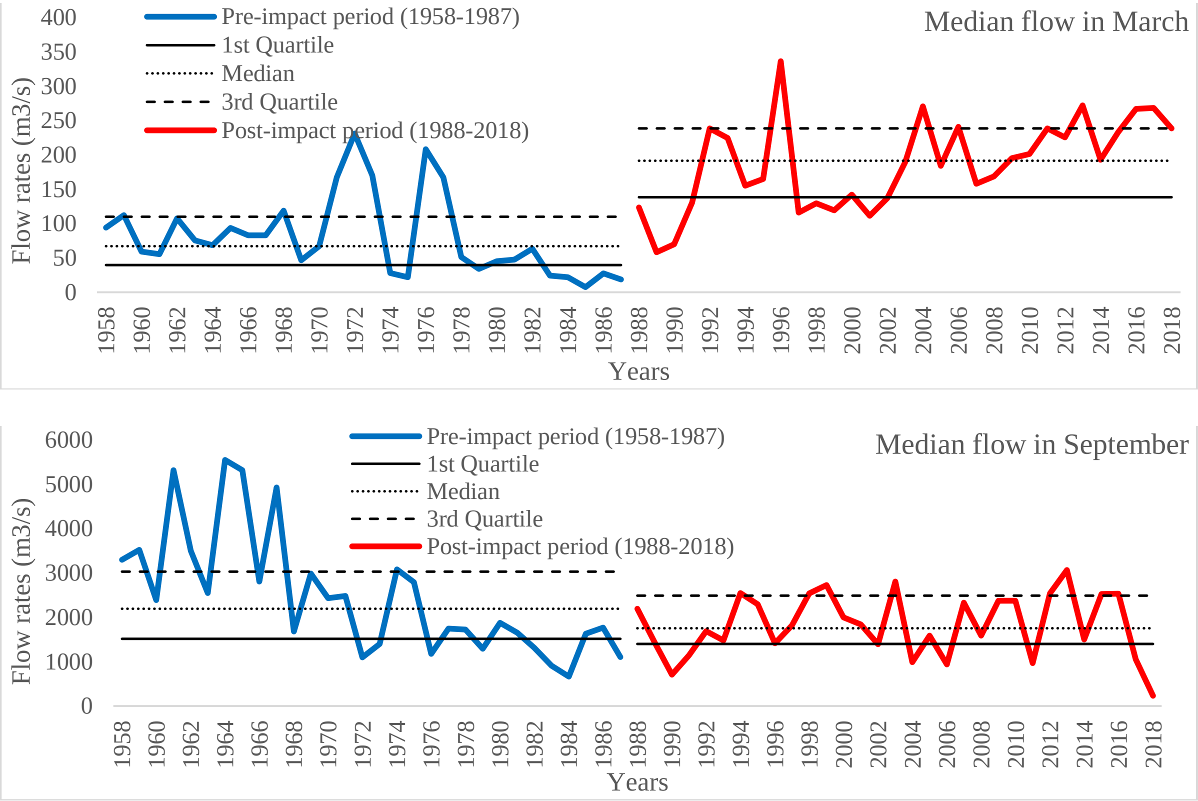

Figure 4. Monthly variation of the median discharge in March and September before and after the construction of the Manantali hydroelectric dam in the Senegal River.

Magnitude and Duration of Extreme Annual Discharges

A hydrological alteration of the Group 2 indices is observed as a high alteration (Table 2). All HIA indices for annual minimum extreme discharges indicate strong and severe alteration, only the annual minimum extreme discharges indicate weak to moderate alteration.

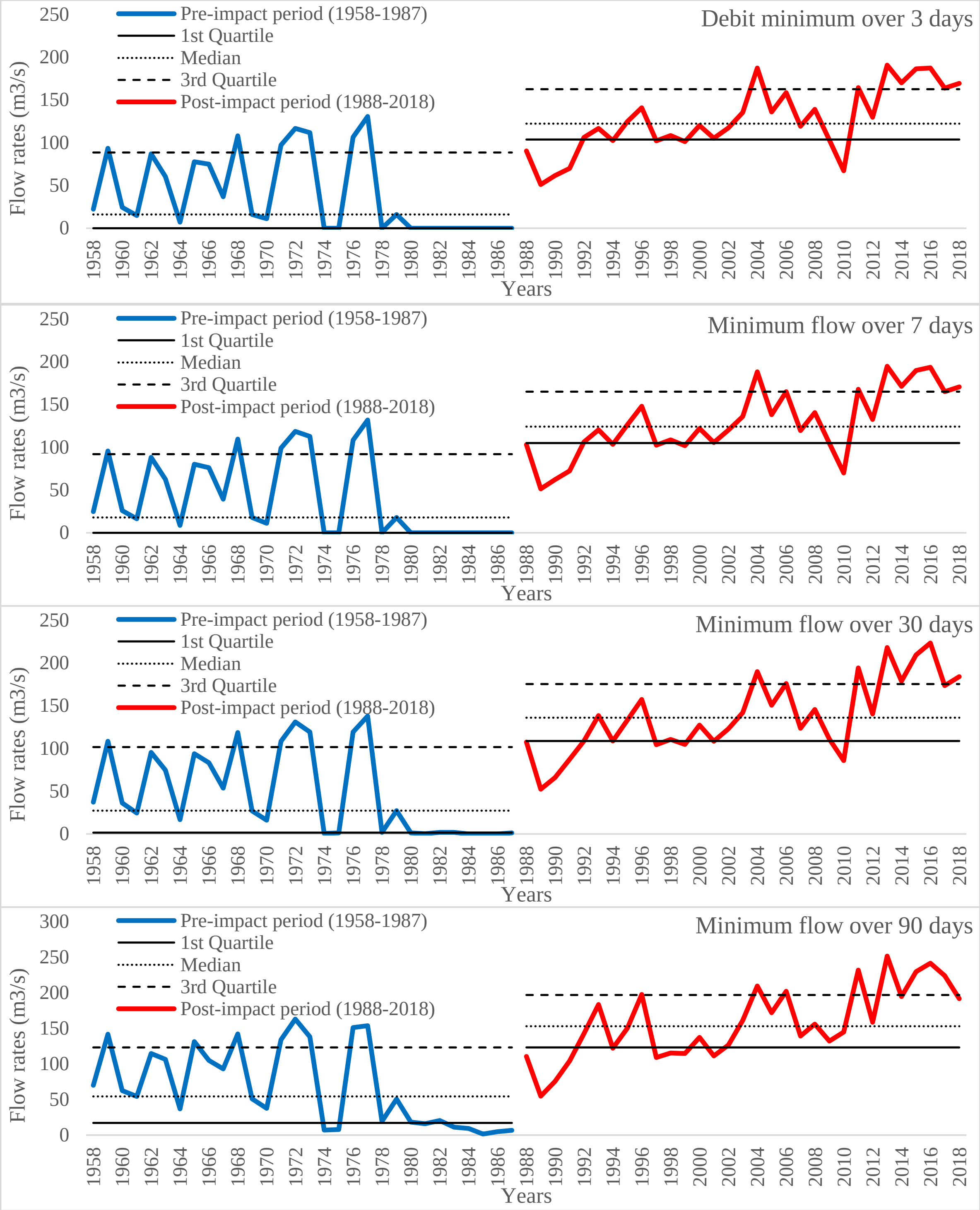

Figure 5. Hydrological modifications of the minimum discharge over 3, 7, 30, and 90 days before and after the construction of the Manantali hydroelectric dam in the Senegal River

These results show that the dam has a greater effect on the magnitude and duration of annual extreme water conditions in the Senegal River. The Senegal River time series of median maximum and minimum 1-day, 3-day, 7-day, 30-day, and 90-day maximum and minimum values for the pre-impact and post-impact periods with the median value and the limits of the mean category (i.e. 1st and 3rd quartile), calculated regarding the pre-impact period, is shown in Figures 5 and 6.

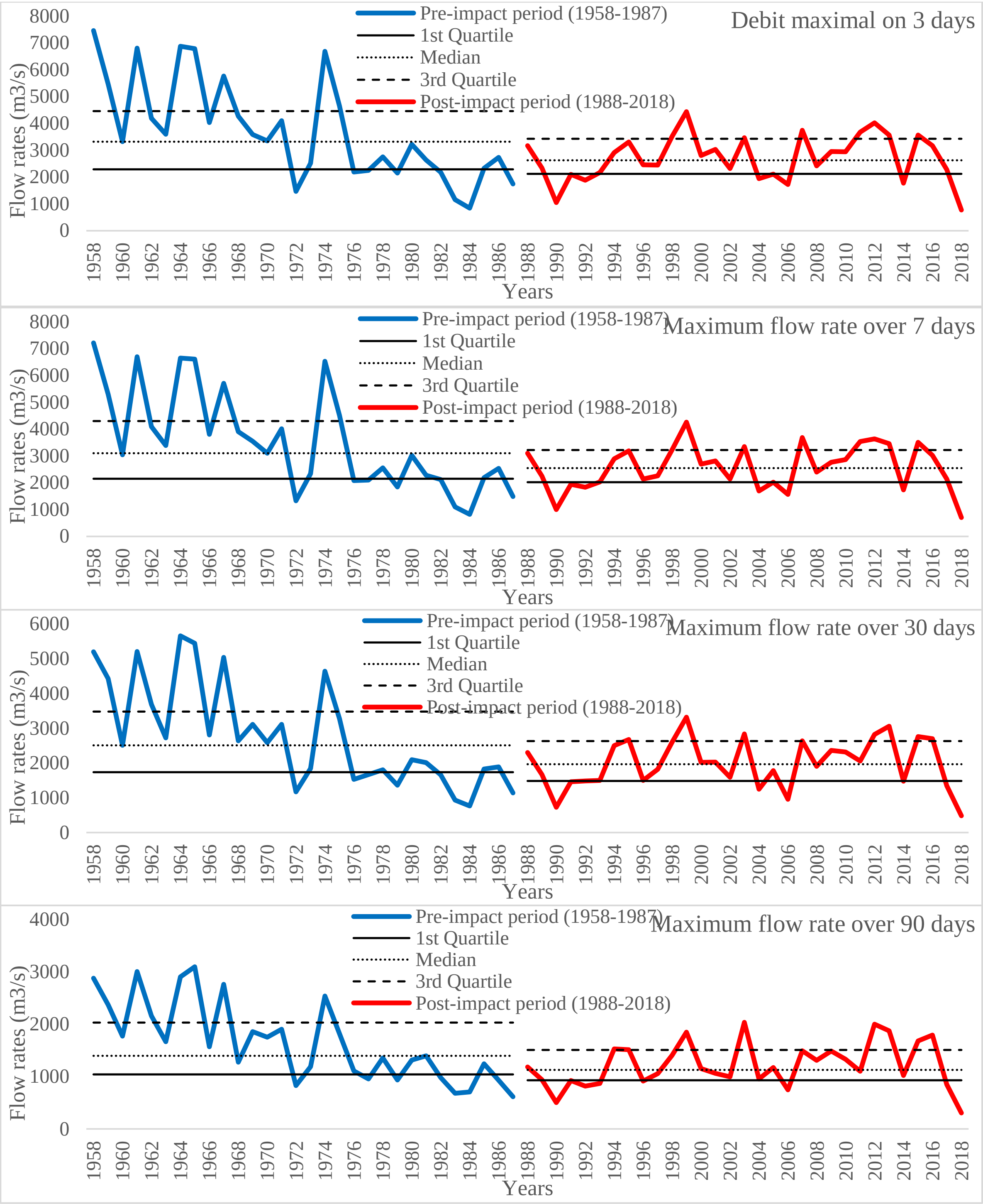

Figure 6. Hydrological modifications of the maximum discharge rate over 3, 7, 30, and 90 days before and after the construction of the Manantali hydroelectric dam in the Senegal River

In the VAR analysis, differences in significance were observed in the maximum and minimum annual discharges in the post-impact periods. Medians of annual minimum discharges over 1, 3, 7, 30, and 90 days for the post-impact period increased due to the dam capturing a high-season flood discharge for subsequent release during the dry season for hydropower generation and dewatering control. On the other hand, the medians of the maximum annual discharge over 1, 3, 7, 30, and 90 days for the post-impact period decreased sharply due to the buffering of large floods by storage in the reservoir (Table 2). In contrast to the medians of the minimum discharges where all RVA values are negative, for the medians of the maximum discharges, only the maximum annual 90-day discharge has a negative RVA value.

Dispersion coefficients for minimum and maximum annual discharges in the post-impact period ranging from 0.51 to 0.55 are generally lower than those in the pre-impact period ranging from 0.72 to 5.73. The base discharge index is higher in the post-impact period (0.25) due to the effect of off-season water released from the reservoir for hydroelectric production when natural discharge is at its minimum. This translates into higher persistence of the annual base discharge index for the upper category and, consequently, lower persistence in the lower and middle categories by a negative index of 0 and 100%, respectively.

As for zero-rate days (likely to cause significant mortality of aquatic organisms, threaten and alter ecological quality and continuity over the long term), they are a maximum of 49 days in the pre-impact period and zero in the post-impact period. This is quite logical because the pre-impact period (1958-1987) was very wet with a permanent discharge (from the 1950s and 1960s) which masked the dry periods of the 1970s and 1980s) and the post-impact period, with the dam, experiencing support of low discharges. This disappearance of zero-discharge days is very beneficial for aquatic ecosystems and can be explained by the support of low discharges by the dam. The results indicate that the daily, weekly, monthly, and quarterly maximum and minimum discharges are influenced both negatively and positively by the Manantali hydroelectric dam and its management.

Global Alteration in the Basin

For the analysis of overall weathering in the Senegal River basin at the Bakel station, statistics are given in Tables 3 and 4 and Figure 7.

Table 3. Categorization of indicators of hydrological alteration

Categories	Positive VAR values		Negative RVA values		Total RVA values	
	Number of indicators	Percentage (%)	Number of indicators	Percentage (%)	Number of indicators	Percentage (%)
Slight alteration	4	12,1	2	6,1	6	18,2
Low alteration	5	15,2	2	6,1	7	21,2
Moderate weathering	5	15,2	5	15,2	10	30,3
Strong alteration	0	0,0	2	6,1	2	6,1
Severe weathering	1	3,0	7	21,2	8	24,2
Total	15	45,5	18	54,5	33	100

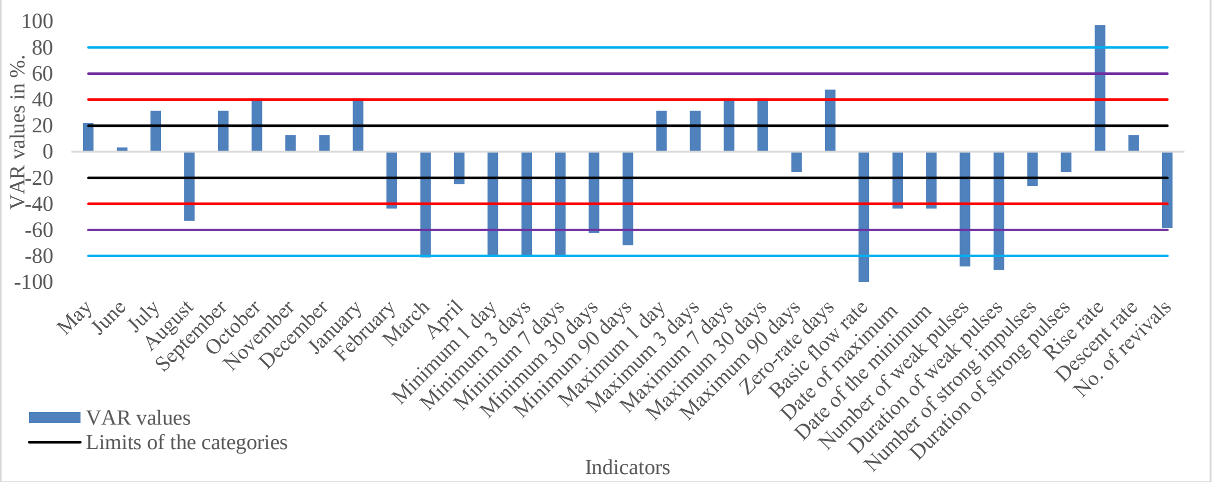

Figure 7. Histogram of the degree of hydrological alteration of each indicator

Of the 33 hydrological weathering parameters (Table 3), 15 had a negative value (i.e. 45.5%) indicating that the annual values fell less often than expected within the RVA range, while 18 had a positive value (i.e. 54.5%) indicating that the values of the annual parameters fell more often than expected within the RVA range. For the range of negative RVA values, 12.1% are slightly impaired, 15.2% weak, 15.2% moderate, and 3% severe. For the range of positive RVA values, 6.1% are slightly impaired, 6.1% weak, 15.2% moderate, 6.1% strong, and 21.2% severe. Overall, the hydrological alteration of the parameters is 18.2% slight, 21.2% weak, 31.3% moderate, 6.1% strong, and 24.2% severe.

Table 4. Degree of hydrological alteration in the basin by group

Groups	Group 1	Group 2	Group 3	Group 4	Group 5	Global alteration
Degree of alteration	28,9	38,0	43,6	40,5	69,8	44,2

The overall degree of hydrological alteration in the basin per group is given in Table 4 and varies from 28.9% to 69.8%. The degree of hydrological alteration (DAH) for Group I (representing amplitude) remains the lowest and is 28.9%, which corresponds to a low alteration. For Group 2 (amplitude and duration of annual extreme conditions), the DAH shows an alteration of 38.0%, which is also a low alteration like Group 1. For group 3 (periodicity of these annual extreme conditions), the DHA reaches a value of 43.6%, which is a moderate alteration. Like group 3, the overall weathering of group 4 (frequency and duration of strong and weak pulses) as mentioned in Table 4 is moderate with a value of 40.4%. Finally, for group 5 (rate and frequency of discharge variations), the hydrological alteration remains the strongest of the groups with a value of 69.8%, which corresponds to a strong alteration. For the overall degree of hydrological alteration in the basin for all groups, it is 44.2%, i.e. a moderate alteration. These results show that the dam has a greater effect on the magnitude and duration of annual extreme water conditions in the Senegal River basin.

CONCLUSION

In this study, Mann-Kendall's non-parametric trend test was used to study spatial and temporal trends and variability in rainfall data in the Senegal River basin and discharge at the Bakel station on annual and seasonal time scales for the period 1958-2018. The non-parametric Mann-Kendall test shows that annual rainfall has an upward trend in the basin. The annual discharge in the Senegal River basin showed a non-significant downward trend on an annual scale. Seasonal discharge showed the opposite evolution with a decreasing trend over the high water period and an increasing trend over the low water period.

Statistical analysis using HIA and RVA at the Bakel station shows an increase in minimum discharge time and a decrease in maximum discharge time, fall, and rise rate. After the construction of the Manantali dam, the hydrology was modified with a significant decrease in high discharges and an increase in low discharges, mainly due to storage during the rainy season and discharge during the dry season.

The results of this research can provide information to the government and the community on rainfall and discharge variability for current and future dams and irrigation projects. This information can also be used by policymakers and managers for water resources management, hydrology, agriculture, and ecosystem management in the Senegal River basin.

The result also shows that the current rules for reservoir exploitation need to be studied in depth and that new reservoir exploitation plans and policies need to be developed, taking into account the ecological needs of the river to minimize the alteration of the hydrological regimes.

The results of this study are indications of the overall impact of climate change and human activities, but it was not able to specify the individual roles of climate change and human activities. Further research should be carried out to distinguish between the effects of climate change and human activities separately.

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