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Evaluation of extreme flow characteristics in the Casamance watershed upstream of Kolda using the IHA/RVA method

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ABSTRACT

Understanding water availability is essential for the development and management of water resources, as well as for designing interventions for river health. Climate change/variability impacts the hydrology of a river system, which subsequently affects human and ecological health by altering the structure and function of the aquatic ecosystem. This study therefore aims to assess water availability and river health according to current and future climate scenarios in the Casamance watershed upstream of Kolda. Climate change is expected to increase hydrologic alterations from low (currently) to high (in the future), as revealed by the Indicators of Hydrologic Alteration (IHA) tool. Average annual water availability decreased, varying seasonally, and seasonal trends followed annual trends under Shared Socioeconomic Pathways (SSP) scenarios. In the basin, negative developments in minimum and maximum annual conditions are generally decreasing over the future period, compared to the reference period (1985-2014), with the exception of the minimum flow rate over 7 and 30 days on SSP 126 and the minimum flow rate over 30 days and the maximum flow rate 1, 3 and 7 days on SSP 585. In this SSP 585 scenario, the Mann Kendall test on the minimum flow rate and the flow rate maximum indicate the most significant downward trend with a risk of error of 0.05, with a Kendall tau varying from -0.45 m3/s/year to - 0.05 m3/s/year. For the minimum flow parameters, Kolda station shows negative Hydrological Alteration (HA) values for the high RVA category, which results in a decrease in low flow.

Contribution/Originality: This study is original in that it addresses the impact of climate change/variability on the hydrology of a river system in the Casamance watershed upstream of Kolda using the IHA/RVA method. Climate change has increased hydrological alterations from low (currently) to high (in the future), as revealed by the Hydrological Alteration Tool (IHA).

1. INTRODUCTION

Freshwater resources are essential for the ecological sustainability and socio-economic development of river basins (Wang, Shrestha, Delavar, Meshesha, & Bhanja, 2021). Healthy rivers are the basis of life. A river is generally considered healthy if it can withstand disturbance and have a greater capacity for resilience to natural and anthropogenic stressors, thereby providing sustainable ecological services to society. River health includes two aspects i) the physical state of the river, including biota, water quality and availability, and ii) the social service functions of the river that support societal needs and livelihoods (Huaibin & Jianping, 2014; Pinto & Maheshwari, 2014). However, in today's industrialized world, river systems have lost their natural integrity. Globally, river ecosystems are widely considered for conservation due to the diverse services they provide (drinking, agriculture and industry, maintenance of biodiversity, power generation, transport and recreational activities) (Rolls, Leigh, & Sheldon, 2012). Climate-induced hydrological changes, when combined with human activities, alter the spatio-temporal variability of river hydrology, affecting water availability (Knouft & Ficklin, 2017; Konapala, Mishra, Wada, & Mann, 2020).

Climate change is the result of changes in climatic conditions that alter the composition of the atmosphere. This trend is accelerating at an alarming rate around the world, with significant implications for water availability and quality (IPCC, 2014). Climate change alters river flow due to changes in annual runoff and seasonal and interannual runoff regimes, which has a significant impact on water resources (IPCC, 2014; Shrestha et al., 2016). Thus, climate change also induces extreme weather events that have a significant negative impact on society and create challenges to cope with climate change (WMO, 2020). Extreme climate events such as heat waves, hot days, floods, droughts and fewer colder days are expected to worsen in the coming decades due to the high unpredictability of hydrological and climatic events (IPCC, 2012; Perkins, Alexander, & Nairn, 2012). This will pose major challenges for agricultural production, biological resources and ecosystem services (Shrestha, Acharya, & Shrestha, 2017).

Understanding how climate change affects water resources is essential because it reflects how it affects other related sectors (Stahl et al., 2010). It is influenced by changes in precipitation and temperature, thereby affecting water quality and flow regimes. Climate change may lead to a change in the quality of water resources (Wang et al., 2021), which may ultimately have a negative impact on river health.

Thus, the availability of water on land must be documented (measured and simulated) at finer temporal and spatial scales to guarantee its availability for various uses in waterways (hydropower, recreation, fishing) and outside (irrigation, domestic, municipal, industrial). Several studies have determined the impacts of climate uncertainty on water availability at global, regional and local scales (Aryal, Shrestha, & Babel, 2018; Pandey, Dhaubanjar, Bharati, & Thapa, 2019).

Hydrological models are important for determining the availability of water resources under a changing climate with realistic estimates of water production and availability in a basin, as well as for understanding its implications (Mapes & Pricope, 2020; Thapa, Ishidaira, Pandey, & Shakya, 2017). They are useful for effective watershed planning, especially with widely available high spatial and temporal resolution data, because they are rapid and inexpensive compared to obtaining physical measurements consisting of large spatial and temporal hydrological processes (Mapes & Pricope, 2020).

Thus, understanding historical climate and projecting future scenarios based on climate variables, in terms of magnitude, trend and significance, is important for planning climate resilient development. Furthermore, understanding the hydrological effects of projected climate change is essential (Devkota & Gyawali, 2015) to ensure irreversible consequences on people, species and ecosystems, as well as for sustainable use and management of water resources, ensuring human security and river health (IPCC, 2012). This study therefore aims to assess the availability of river water in the context of current and future climate scenarios in the Casamance watershed upstream of Kolda.

2. STUDY AREA

The Casamance basin, which extends over three administrative regions (Ziguinchor, Sédhiou and Kolda), in the south of Senegal, is located in latitude between 12°20' and 13°21' North and in longitude between 14°17 1 and 16°47' West. The basin covers approximately an area of 20,150 km2 and stretches from West to East over 270 km, and from North to South over 100 km (Dacosta, 1989). The climate of Casamance, of the Atlantic Sudanese and South Sudanese type (Sané, Sy, & Dieye, 2011), is strongly influenced by geographical and atmospheric factors (Sagna, 2005). From a topographic point of view, the Casamance watershed is characterized by low relief. In fact, all rivers have their source on the Continental Terminal plateau. The weakness of the slopes explains the deep invasion of the sea inside the Casamance basin, thus causing the salinization of agricultural lands (PADERCA, 2008). The Casamance watershed upstream of Kolda has an area of 3,650 km2 for a maximum altitude of 80 m and a minimum altitude of 10 m.

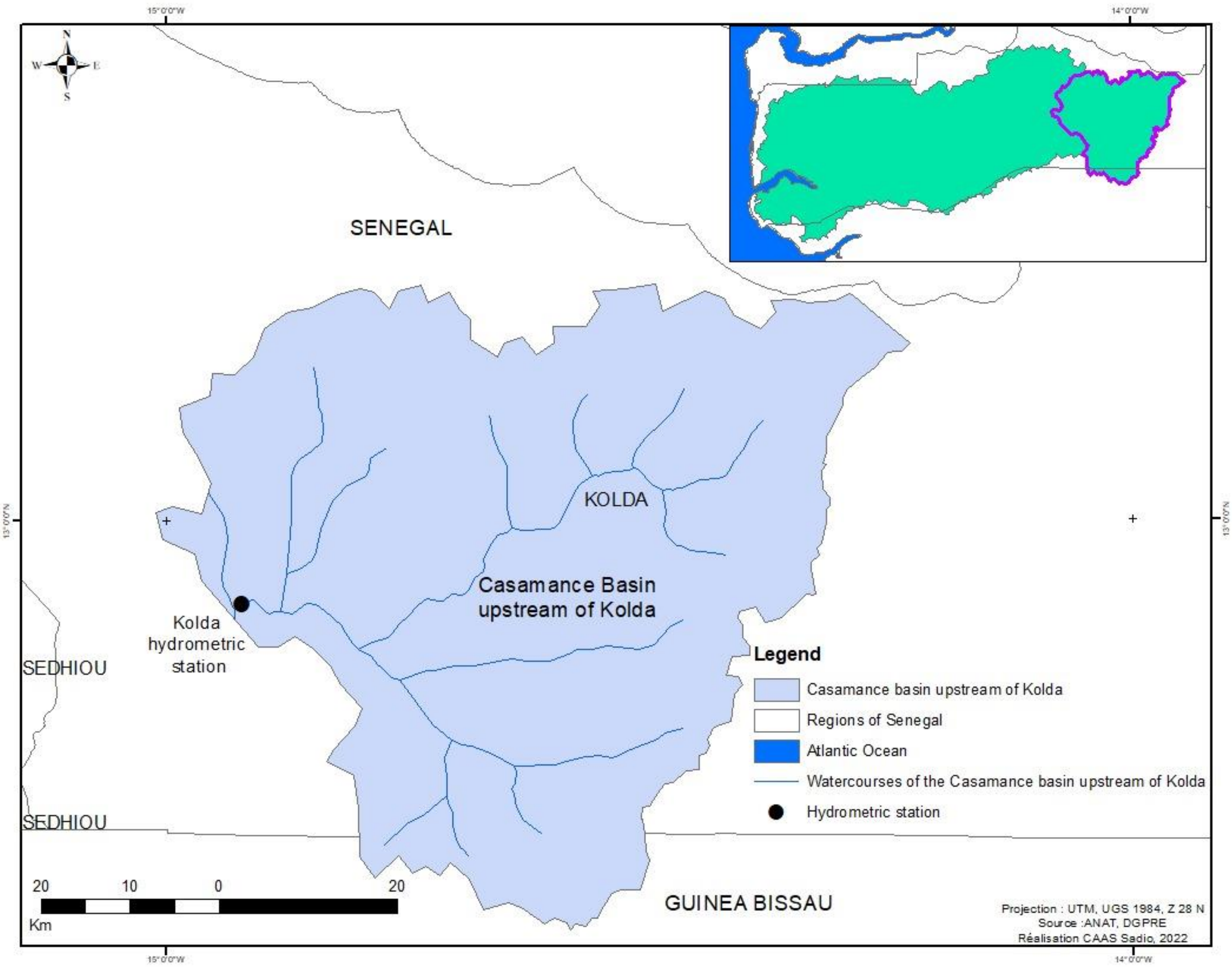

Figure 1. Geographical location of the Casamance basins at the Kolda station.

3. MATERIALS AND METHODS

3.1. Data

The daily data from the Casamance basin upstream of Kolda used here come from the WRA (Women and Resilient Agriculture) project database. These are data simulated by the CHyM model (Cetemps Hydrological Model). CHyM is a distributed hydrological model developed by the Cetemps Center of Excellence at the University of L'Aquila and is used and under development at the International Center for Theoretical Physics in Italy (Tomassetti, Coppola, Verdecchia, & Visconti, 2005). Its use can be done in different geographical areas. To apply this model, the input data are among others rain, temperature, evaporation, flow direction, DEM, drainage network and land use). This model is capable of simulating flows by taking as input runoff data from surface models incorporated into climate models. The simulated flow is obtained by routing the total runoff flow interpolated with a scheme derived from the distributed hydrological model CHyM (Coppola et al., 2014).

3.2. Methods

To assess the main hydrological characteristics affected downstream of dams (Magilligan & Nislow, 2005) and the alteration of the hydrological regime of dams, the Hydrological Alteration Indicators (HAI) method established by The "Nature Conservancy" (Richter, Baumgartner, Powell, & Braun, 1996) was used. From average daily flows, this model calculates 33 ecologically relevant hydrological parameters which describe the hydrological regime and which are grouped into 5 categories (Richter, Baumgartner, Wigington, & Braun, 1997): (i) amplitude, (ii) amplitude and duration of annual conditions extremes, (iii) periodicity (Timing) of these extreme annual conditions, (iv) frequency and duration of strong and weak pulsations, (v) rate and frequency of flow variations (Table 1). All these indices measured by the IHA were defined to take into account most of the hydrological disturbances corresponding to the potential ecological impacts linked to dams (Erskine, Terrazzolo, & Warner, 1999).

The IHA method involves four steps: (1) defining the data series for pre- and post-impact periods; (2) calculate hydrological attribute values; (3) calculate interannual statistics; (4) calculate the IHA values. The method requires having flow data over approximately twenty years, before and after modification of the hydrological regime of the watercourse.

The IHA-based Range of Variability Approach (RVA) method is well known for the assessment of hydrological alteration in river ecosystems (Richter et al., 1996). The study replaces the number of rises and the number of falls of the parameter used in the RVA method with the number of hydrological changes. The IHA values of each indicator for each hydrological year are calculated according to the mathematical formulation mentioned in the study of Barbalin and Kuspilić (2014) and the results were used to calculate the hydrological alteration using the histogram comparison approach. The mathematical formulation of hydrological alteration indices is given below (Huang, Suwal, Fan, Pandey, & Jia, 2019).

Table 1. Summary of the 33 IHA parameters and their hydrological significance.

Categories	HAI parameter groups	Hydrological parameters
(i) Amplitude	1. Magnitude of monthly water conditions (12 parameters in total)	Average or median value for each month
(ii) Amplitude and duration of annual extreme conditions	2. Magnitude and duration of annual extreme water conditions (12 parameters in total)	Annual minimums, 1-day average
		Annual minimums, 3-day average
		Annual minimums, 7-day average
		Annual minimums, 30-day average
		Annual minimums, 90-day average
		Annual maximum, 1-day average
		Annual maximum, 3-day average
		Annual maximum, 7-day average
		Annual maximum, 30-day average
		Annual maximum, 90-day average
		Number of days with zero flow
		Basic flow index: minimum flow over 7 days / Average flow for the year
(iii) Periodicity of these extreme annual conditions	3. Calendar of annual extreme water conditions (2 settings 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. Frequency and duration of high and low pulses (4 settings total)	Number of weak pulses in each hydrological year
		Mean or median duration of weak pulses (Days)
		Number of high pulses in each water year
		Mean or median duration of high pulses (Days)
(v) Rates and frequencies of flow variations	5. Rate and frequency of water state changes (3 settings total)	Rising rates: Average or median of all positive differences between consecutive daily values
		Drop rate: Mean or median of all negative differences between consecutive daily values
		Number of hydrological inversions

Source: Richter et al. (1997).

The measurements of general evolution and dispersion of flow come from annual series of the parameters studied. These make it possible to characterize interannual variations. The basic principle is that the river should be managed such that the annual values of each IHA parameter are included within the range of natural variations of that parameter. Therefore, management objectives for each of the parameters are given within a range of acceptable RVA values (Richter et al., 1997), with management objectives defined by the 25th and 75th percentiles of the parameter in only 50% of years (Richter et al., 1997). The formula for calculating the degree of hydrological alteration (HA), expressed as a percentage, is given as follows:

$$HA = \frac{N_0 - N_e}{N_e} \times 100 \quad (1)$$

$$N_e = pxN_T \quad (2)$$

Where No is the observed number, Ne is the expected number and p is the percentage of post-impact years for which the hydrological parameter values are within the RVA target range, and NT is the total number of post-impact years . Hydrological alteration is equal to zero when the observed frequency of annual post-impact values within the RVA range is equal to the expected frequency. A positive deviation indicates that annual parameter values fell more often than expected within the RVA range; negative values indicate that annual values fell less often than expected within the RVA range (Yang et al., 2008). To quantify this hydrological alteration, Richter et al. (1997) divided the weathering ranges into three classes of equal range: (i) 0% -33% (L) represents little or no weathering; (ii) 34% -67% (M) represents moderate alteration; (iii) 68% -100% (H) represents a high degree of alteration.

The dispersion coefficient (DC) is a commonly used indicator to assess daily flow variability. It is calculated as follows:

$$CD = \frac{Q_3 - Q_1}{Q_2} \quad (3)$$

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).

The analysis was based on hydrological simulation data. RVA is based on a comprehensive statistical characterization of the temporal variability of the hydrological regime quantifying the degree of alteration of 33 ecologically relevant hydrological parameters Table 1 that describe crucial relationships between flow and ecological functions (Richter et al., 2007).

4. RESULTS

IHA version 7.1 is used to calculate extreme fluxes based on CHyM outputs. The IHA calculation is based on daily flow data generated from CHyM simulations. For the projection of the hydrological regime into the future, simulated flows are executed in the Hydrological Alteration Indicators software according to two SSP scenarios. Then, using Xlstat software, the trends of selected hydrological extremes were analyzed using the Mann Kendall and Slope and Sen methods.

4.1. Changes in the Magnitude of Annual Extreme Conditions over Different Durations

Figure 2 and Tables 2 and 3 show the variations in magnitude over different durations of annual extreme situations. Regarding the negative changes in annual minimum and maximum conditions over 1, 3, 7, 30 and 90 days, there are minor or no trends on SSP 126 (between -11.9 and -0.8%) over the future period (2021-2100). These negative trends are a little more significant on SSP 585 (between -23.0 and -1.8 %) over the future period (2021-2100). Regarding positive changes, they range between 3.4 and 6.8 % for SSP 126 and between 4.3 and 16.4 % for SSP 585) over the future period (2021-2100). In the basin, negative changes in annual minimum and maximum conditions over 1, 3, 7, 30 and 90 days are generally decreasing over the future period, compared to the reference period (1985-2014), with the exception of minimum flow rate over 7 and 30 days on SSP 126 and the minimum flow rate over 30 days and the maximum flow rate 1, 3 and 7 days on SSP 585. There is a fairly large gap in the case of extremely high flow at maximums of 1, 3 and 7 days. There is a maximum for the extremely high flow case at maximum flows of 1, 3 and 7 days, flows, showing that the magnitude floods may increase in the near future and droughts may increase in the distant future. The results indicate that maximum and minimum flows are influenced sometimes negatively and sometimes positively by climate change. For the base flow index, a small decrease of -0.7% under SSP 126 and –3.7% under SSP 585 for the distant future period will be noted. This indicates that the future quantity of water available for fresh water supply tends to decrease slightly compared to the current value. As for the number of zero-flow days (likely to cause significant mortality of aquatic organisms, to threaten, to alter ecological quality and continuity in the long term), it is zero over the reference period as well as over the period future under SSP 126 and SSP 585 in the post-impact period (period 2021-2100).

Table 2. Annual average values of the twelve extreme flow indices retained over the reference period and the future period at the Kolda hydrological station following the SSP 126 and SSP 585 scenarios.

Settings	History	SSP 126					SSP 585				
Group 2	**1985–2014**	**2021–2100**	**2021–2040**	**2041–2060**	**2061–2080**	**2081–2100**	**2021–2100**	**2021–2040**	**2041–2060**	**2061–2080**	**2081–2100**
1-day min	1.8	1.7	1.7	1.8	1.5	1.8	1.4	1.8	1.3	1.2	1.5
3-day min	1.8	1.8	1.9	1.8	1.6	1.9	1.6	1.9	1.4	1.4	1.7
7-day min	1.9	2.0	2.1	2.0	1.8	2.0	1.9	2.0	1.5	1.7	2.3
30-day min	2.5	2.7	2.7	2.7	2.6	2.7	2.6	2.7	2.1	2.4	3.3
90-day min	4.3	3.8	3.6	3.8	3.9	3.8	3.8	3.7	3.0	3.8	4.9
1-day max	48.2	47.8	50.5	46.9	47.3	46.8	56.1	59.7	48.7	50.9	65.2
3-day max	44.2	43.5	45.6	42.5	43.2	42.7	49.7	54.5	43.9	45.8	54.5
7-day max	38.9	37.4	39.9	36.7	36.5	36.4	40.7	46.3	38.1	37.3	41.1
30-day max	30.9	30.4	31.5	30.9	29.5	29.6	30.3	35.7	30.0	28.0	27.5
90-day max	23.1	22.5	22.8	23.6	22.0	21.6	21.4	24.6	21.8	20.4	18.9
Zero days	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Base flow	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Group 3	1985–2014	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100
Date min	131	187	163	227	94.5	262.8	188	148	230	114	261
Date max	250	172	139	201	203	143.3	157	140	212	211	64.4
Group 4	1985–2014	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100
Low pulse #	5.5	7.6	7.1	7.4	8.1	8.1	6.4	6.9	7.2	4.7	6.8
Low pulse L	14.0	5.5	5.1	4.8	5.6	6.4	7.3	5.7	7.8	12.0	3.7
High pulse #	5.0	5.8	5.7	5.4	5.7	6.3	7.6	5.5	5.2	8.6	11.3
High pulse L	9.7	5.6	8.8	6.8	3.6	3.3	6.3	6.1	8.7	6.8	3.5
Group 5	1985–2014	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100
Rise rate	1.6	1.4	1.8	1.3	1.4	1.4	1.4	1.5	1.4	1.6	1.2
Fall rate	-1.0	-1.0	-1.1	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.1	-1.1
Reversals	73.0	87.4	84.4	85.6	88.1	91.4	84.4	82.5	83.7	76.8	94.5

Generally, with a decrease in the duration of the maximum extreme parameters, the percentage change increases. It is evident that the changes in the magnitude of maximum flow are greater than those of minimum flow. It therefore clearly appears that the magnitude and duration of extreme annual parameters would vary over the future period.

4.2. Changes in the Timing, Pace and Frequency of Annual Extremes

The third IHA group indicates extreme flow events in terms of timing of occurrence. A water year is defined using the Julian date format where "day 1" refers to January 1 and "day 365" refers to December 31. As shown in Figure 1 and Tables 2 and 3, the timing of occurrence of future minimum and maximum annual events that are projected by CHyM will experience an opposite evolution. If for future minimum annual events, the occurrence schedule will increase by 42.8% under SSP 126 and 44% under SSP 585, on the other hand for future maximum annual events, the occurrence schedule will decrease by -31.2 % under SSP 126 and -37.2% under SSP 585. This decrease is generalized over all sub-periods (near future, medium future and distant future).

Table 3. Percentage of change of the twelve extreme flow indices retained from the future period compared to the reference period at the Kolda hydrological station following the SSP 126 and SSP 585 scenarios.

Settings	SSP 126					SSP 585				
Group 2	**2021–2100**	**2021–2040**	**2041–2060**	**2061–2080**	**2081–2100**	**2021–2100**	**2021–2040**	**2041–2060**	**2061–2080**	**2081–2100**
1-day min	-8.6	-7.3	-4.5	-18.2	-4.5	-23.0	-4.5	-31.8	-34.5	-20.9
3-day min	-1.8	3.6	-1.8	-11.8	2.7	-13.9	3.6	-25.5	-26.4	-7.3
7-day min	3.4	11.4	3.2	-5.7	4.7	-1.7	5.8	-20.9	-12.7	21.0
30-day min	6.8	8.4	8.0	4.0	6.9	4.3	8.9	-17.5	-3.6	29.5
90-day min	-11.9	-17.0	-10.4	-9.4	-10.7	-10.6	-14.7	-30.0	-11.7	13.8
1-day max	-0.8	4.7	-2.7	-2.0	-3.0	16.4	23.9	1.0	5.5	35.3
3-day max	-1.5	3.2	-3.7	-2.2	-3.3	12.4	23.4	-0.7	3.6	23.3
7-day max	-3.9	2.7	-5.7	-6.1	-6.5	4.6	19.0	-2.1	-4.0	5.5
30-day max	-1.6	2.2	0.0	-4.2	-4.1	-1.8	15.7	-2.9	-9.3	-10.8
90-day max	-2.6	-1.4	2.3	-4.7	-6.4	-7.2	6.6	-5.5	-11.6	-18.5
Zero days	---	---	---	---	---	---	---	---	---	---
Base flow	-0.6	2.8	0.7	-7.3	1.3	-3.7	-3.9	-14.6	-11.6	15.3
Group 3	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100
Date min	42.8	24.7	73.7	-27.8	101	44.0	13.4	75.4	-12.6	99.7
Date max	-31.2	-44.1	-19.5	-18.7	-42.6	-37.2	-44.1	-15.0	-15.6	-74.2
Group 4	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100
Low pulse #	39.5	29.0	34.5	47.3	47.3	16.6	26.2	31.7	-14.9	23.5
Low pulse L	-61.0	-63.6	-65.9	-60.2	-54.3	-48.0	-59.7	-44.2	-14.4	-73.6
High pulse #	15.3	14.0	8.0	14.0	25.0	52.5	9.0	4.0	71.0	126.0
High pulse L	-42.2	-9.6	-30.1	-62.8	-66.4	-35.7	-37.3	-11.1	-30.1	-64.3
Group 5	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100	2021–2100	2021–2040	2041–2060	2061–2080	2081–2100
Rise rate	-10.2	11.9	-22.3	-14.5	-16.1	-12.2	-8.3	-16.1	-0.5	-23.8
Fall rate	-0.2	6.5	-3.2	-0.8	-3.2	0.4	-3.2	-3.2	1.6	6.5
Reversals	19.6	15.6	17.1	20.6	25.1	15.5	13.0	14.6	5.2	29.4

The fourth IHA group indicates the number and duration of extreme pulses. The results show that the number of low pulses (39.5% under SSP 126 and 16.6% under SSP 585) and the duration of future low pulses (-61% under SSP 126 and -48% under SSP 585) have also showed substantial changes. At the same time, the number of high pulses is expected to increase significantly by 15.3% and 52.5% under SSP 126 and SSP 585 respectively over the future period 2021-2100. As for the duration of future high pulses, it also tends to decrease sharply compared to the historical period, based on an overall average of -42.2% and -35.7% respectively under SSP 126 and SSP 585 for the future period 2021-2100.

The last IHA group (group 5) contains the rate and frequency of changes in water condition. There is a fairly significant decrease in the rate of climb (-10.2%, under SSP 126 and -12.2% under SSP 585) and a small decrease in the rate of fall (-0.2%) under SSP 126 and a small increase (0.4%) below SSP 585 at the Casamance basin upstream of Kolda, which shows that an increase or decrease in flow could occur in the future. The number of hydrological inversions will increase (with 19.6% under SSP 126 and 15.5% under SSP 585), which sometimes shows an increase in the number of daily flow increases.

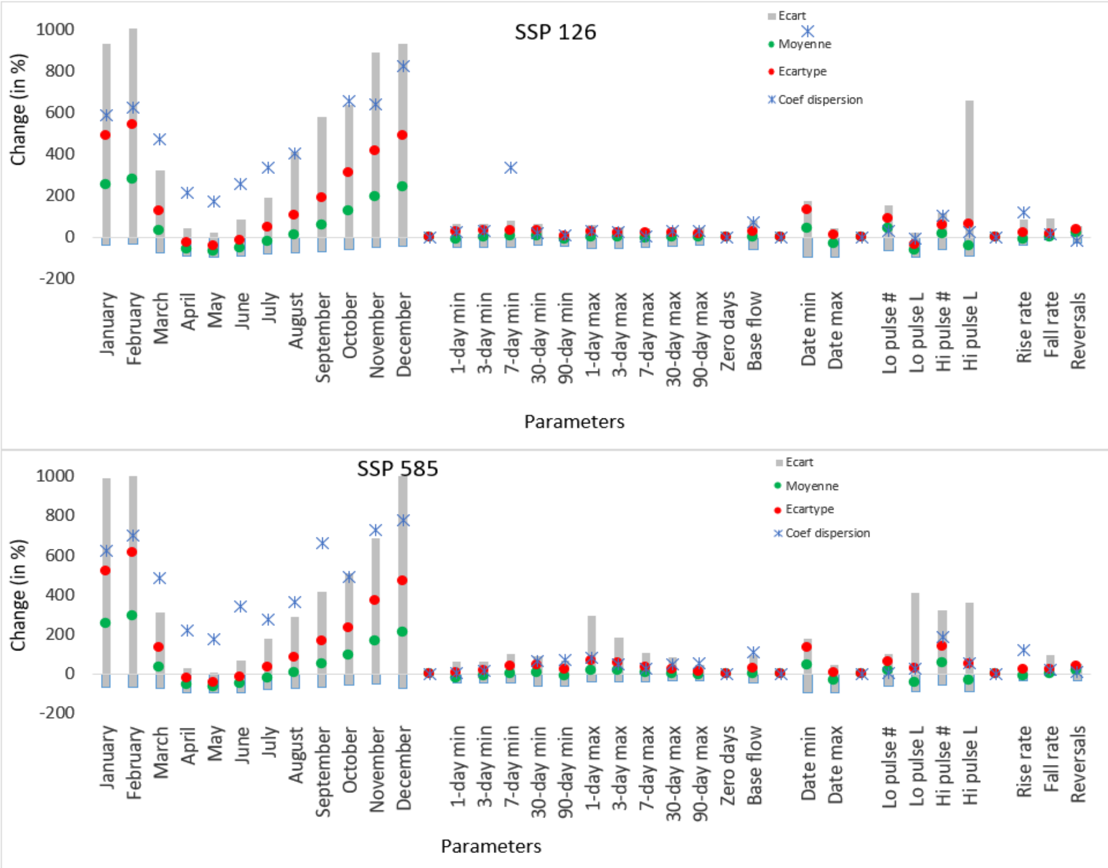

Figure 2. Projected changes in hydrologic extremes as indicated by 33 IHA parameters of (a) monthly runoff, (b) amplitude and duration, (c) timing, (d) frequency and duration, and (e)) the rate and frequency between 1985 to 2014 and 2021-2100 at the Kolda hydrological station following the SSP 126 and SSP 585 scenarios.

Understanding and quantifying the effects of future climate change is currently one of the most pressing scientific challenges of great importance to society. Most future studies of climate change consider changes between arbitrary time periods. The transition of hydrological regimes to an alternative state over the future period is likely to occur as the majority of indicators move out of the current RVA state. We further notice changes dependent on high water period flows and extreme low flow flows decreasing.

4.3. Future Trends in Hydrological Extremes

Future trends were analyzed among the twenty-one (21) extreme hydrological indices that were moderately and highly modified as revealed by the IHA tool and the results are presented (i.e. trends with Kendall's tau, Sen's slope and p-value) in Table 4.

Under the SSP 126 scenario, the Mann Kendall test on the minimum flow and maximum flow at 1, 3, 7, 30 and 90 days indicate a statistically insignificant downward trend at the risk of error of 0.05, with a Kendall tau which varies from -0.14 m3/s/year to -0.03 m3/s/year (with the exception of the minimum flow over 90 days whose trend is positive). Under the SSP 585 scenario, the Mann Kendall test on the minimum flow and maximum flow over 1, 3, 7, 30 and 90 days indicate the most significant decreasing trend at the risk of error of 0.05, with a Kendall t au which varies from -0.45 m3/s/year to -0.05 m3/s/year. Under this scenario, the parameters of minimum flow days (1 and 3 days) and maximum flow days (7, 30 and 90 days) show a statistically significant downward trend. However, three minimum flow parameters show an upward trend (minimum flow over 7, 30 and 90 days). For the base flow, the statistically insignificant trend is downward (-0.02 m3/s/year) under SSP 126 and upward (0.09 m3/s/year) under SSP 585.

Table 4. Average annual changes of the twelve extreme flow indices retained from the future period from the Mann Kendall test at the Kolda hydrological station following the SSP 126 and SSP 585 scenarios at an error risk of 0.05.

Group 2	SSP 126				SSP 585			
	Kendall's Tau	S	p-value	Sen slope	Kendall's Tau	S	p-value	Sen slope
1-day min	-0.03	-81	0.733	0	-0.24	-635	0.006	0
3-day min	-0.03	-77	0.760	0	-0.17	-533	0.037	0
7-day min	-0.08	-262	0.325	0	0.00	16	0.955	0
30-day min	-0.06	-223	0.407	-0.002	0.03	97	0.720	0.001
90-day min	0.03	99	0.715	0.001	0.13	471	0.080	0.011
1-day max	-0.13	-467	0.082	-0.092	-0.05	-179	0.506	-0.045
3-day max	-0.12	-447	0.096	-0.076	-0.07	-265	0.325	-0.057
7-day max	-0.13	-486	0.070	-0.073	-0.16	-578	0.031	-0.094
30-day max	-0.12	-440	0.101	-0.047	-0.35	-1290	< 0.0001	-0.139
90-day max	-0.14	-520	0.053	-0.034	-0.45	-1658	< 0.0001	-0.107
Zero days	x	x	x		x	x	x	
Base flow	-0.02	-79	0.771	-0.0001	0.09	316	0.240	0.0003
Group 3	Kendall's Tau	S	p-value	Sen slope	Kendall's Tau	S	p-value	Sen slope
Date min	0.03	109	0.687	0.2	0.07	244	0.365	0.409
Date max	-0.16	-579	0.031	-1.3	-0.36	-1298	< 0.0001	-2.548
Group 4	Kendall's Tau	S	p-value	Sen slope	Kendall's Tau	S	p-value	Sen slope
Low pulse #	0.12	408	0.125	0.013	-0.07	-237	0.373	0
Low pulse L	0.03	98	0.716	0	-0.13	-454	0.089	-0.019
High pulse #	0.15	516	0.052	0.015	0.39	1351	< 0.0001	0.088
High pulse L	-0.18	-627	0.018	-0.016	-0.07	-245	0.359	0
Group 5	Kendall's Tau	S	p-value	Sen slope	Kendall's Tau	S	p-value	Sen slope
Rise rate	-0.27	-732	0.002	0	-0.16	-435	0.064	0
Fall rate	0.11	103	0.230	0	-0.14	-137	0.110	0
Reversals	0.16	583	0.030	0.094	0.22	783	0.004	0.154

For the third IHA group, the timing of occurrence of future annual minimum and maximum events that are projected by CHyM will experience an opposite trend. If for future minimum annual events, the occurrence calendar will experience an upward trend of 0.03 days/year under SSP 126 and 0.07 days/year under SSP 585, on the other hand for future maximum annual events, the occurrence calendar will experience a downward trend of –0.16 days/year under SSP 126 and –0.36 days/year under SSP 585.

For the fourth IHA group, the results show that the number of low pulses (0.12/year under SSP 126 and -0.07/year under SSP 585) and the duration of future low pulses 0.03 days/year under SSP 126 and -0.13 days/year under SSP 585) also showed positive trends on SSP 126 and negative trends on SSP 585. At the same time, the trends in the number of high pulses are decreasing with 0.15/ year and 0.39 / year respectively under SSP 126 and SSP 585 over the future period 2021-2100, while those of the duration of future high pulses are decreasing by around -0.18 days / year under SSP 126 and -0.07 days/year under SSP 585.

For the fifth IHA group, there is a downward trend in the rate of rise (-0.27/year under SSP 126 and -0.16/year under SSP 585), while for the rate of fall, the trend is increasing under SSP 126 (0.11/year) and decreasing under SSP 585 (-0.14/year). For the number of hydrological inversions, the trend will remain upward everywhere (with 0.16/year under SSP 126 and 0.22/year under SSP 585). Hydrological extremes show interannual variability in the value of the indices. Annual and monthly flows are expected to decrease in the future, respectively, as simulated from CHyM. Additionally, a significant difference in mean flow at 95% confidence level can be found at annual and monthly timescales, which is similar to changes in monthly precipitation.

4.4. Hydrological Alteration of the Basin

The average hydrological alteration (HA), median value, degree of deviation and degree of alteration of IHA parameters characterizing five groups of extreme flow regimes at the Kolda hydrological station in the Casamance watershed are listed in Table 5, and the hydrological alteration values for each indicator are shown in Figure 2.

Table 5. Degree of hydrological alterations of IHA parameters at the Kolda hydrological station for the future between 1985 to 2014 and 2021-2100 following the SSP 126 and SSP 585 scenarios.

Settings	Pre impact		Post impact							
			SSP 126				SSP 585			
	Med	CD	Med	CD	P%	HA%	Med	CD	P%	HA%
Group 1						-78.6 (H)				-77.5 (M)
January	3.0	0.7	9.0	1.3	100.0	-58.0	8.0	1.4	106.3	-59.5
February	3.0	0.7	9.0	1.2	83.3	-91.4	8.0	1.3	87.5	-78.0
March	8.0	0.3	9.0	1.1	344.4	-72.6	9.5	1.1	352.6	-69.1
April	21.0	0.3	8.0	1.1	237.5	-82.6	9.5	1.2	246.8	-83.3
May	27.0	0.3	8.0	0.9	215.0	-79.9	9.0	0.9	219.4	-83.8
June	16.0	0.3	6.0	1.2	273.3	-87.6	7.0	1.0	357.1	-83.3
July	10.0	0.3	6.0	1.2	288.9	-86.7	7.0	0.8	241.3	-77.0
August	8.0	0.3	6.0	1.0	300.0	-85.5	6.0	1.0	283.3	-80.2
September	7.0	0.1	6.0	1.5	950.0	-76.9	7.0	0.9	500.0	-71.1
October	5.0	0.4	7.0	1.8	346.4	-75.1	6.3	1.4	260.0	-79.2
November	4.0	0.5	8.0	1.6	225.0	-72.6	7.0	1.4	357.1	-78.6
December	3.0	0.3	9.0	1.4	333.3	-74.5	7.3	1.4	308.6	-86.6
Group 2						-10.1 (L)				-20.2 (L)
1-day min	2.0	0.0	2.0	0.5	0.0	-31.5	1.0	1.0	0.0	-47.2
3-day min	2.0	0.0	2.0	0.3	0.0	-36.7	1.7	0.6	0.0	-52.9
7-day min	2.0	0.1	2.0	0.3	300.0	-53.9	2.0	0.5	2700	-64.3
30-day min	2.5	0.4	2.6	0.4	9.3	12.1	2.6	0.5	23.3	-3.6
90-day min	4.2	0.3	3.8	0.3	2.2	-8.3	3.7	0.4	50.1	-17.9
1-day max	46.0	0.4	47.0	0.4	3.6	-4.9	52.5	0.4	16.0	-25.0
3-day max	42.0	0.4	42.7	0.4	2.7	-8.3	47.2	0.4	3.4	-10.7
7-day max	38.3	0.4	36.9	0.3	15.7	35.8	40.1	0.4	6.9	21.4
30-day max	31.0	0.3	30.6	0.3	13.5	-15.1	31.3	0.3	28.8	-7.1
90-day max	23.0	0.2	22.6	0.2	18.6	1.9	21.8	0.3	43.6	0.0
Zero days	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Base flow	0.2	0.2	0.2	0.3	47.3	-11.7	0.2	0.4	82.0	-35.7
Group 3						-84.4 (M)				-91.2 (M)
Date min	129.0	0.0	297.0	0.4	864.7	-72.7	289.0	0.5	877.9	-85.7
Date max	248.0	0.0	167.0	0.4	1183.0	-96.1	165.0	0.4	1116.0	-96.8
Group 4						-4.0 (L)				-7.7 (L)
Low pulse #	5.0	1.0	7.0	0.4	57.1	1.9	6.5	0.5	53.9	14.3
Low pulse L	8.0	0.9	4.0	1.1	28.6	-16.0	5.0	1.0	0.6	-25.0
High pulse #	5.0	0.4	5.0	0.6	50.0	-32.8	6.0	0.7	48.2	-45.2
High pulse L	5.0	1.2	3.5	0.7	37.9	30.7	3.5	1.2	5.6	25.0
Group 5						-16.5 (L)				-6.5 (L)
Rise rate	2.0	0.5	1.0	1.0	100.0	2.1	1.0	1.0	100.0	3.4
Fall rate	-1.0	0.0	-1.0	0.0	---	-0.4	-1.0	0.0	---	-0.2
Reversals	78.0	0.2	87.0	0.1	48.1	-51.2	84.5	0.2	24.4	-22.6

Note: Med: Median; CD: Dispersion coefficient; HA: Hydrological alteration; L: Low; M: Moderate; H: High; P: Percentage of deviation.

Significant differences were observed in the maximum and minimum annual flows in the post-impact periods Table 5. The minimum annual average flow of 1, 3, 7, 30 and 90 days for the future period have decreased due to climate change. The same is true for the maximum annual average flow over 1, 3, 7, 30 and 90 days for the future period which also decreased due to the rainfall deficit. If the dispersion coefficients of the minimum annual flows vary between 0.3 and 0.5 under SSP 126 and 0.5 and 1 under SSP 585, those of the maximum annual flows over the future period range from 0.04 to 0.4 under SSP 126 and from 0.3 to 0.4 under SSP 585, and are generally higher than those of the reference period with values ranging from 0 to 0.4. The dispersion coefficients of the base flow index are higher in the future period due to the effect of climate change.

Generally, among the five group parameters, hydrological alteration was found to be high in the future for both scenarios compared to the baseline. The overall degree of hydrological alterations (HA) in the flow regime was observed to be high for SSP 126 and SSP 585, with different magnitudes in the future (Table 5) based on 33 hydrological indices. For low flows, almost all minimum and maximum flow parameters for the medium RVA category have negative HA values and most alterations are of low and sometimes medium degree. For the minimum flow parameters (minimum flow over 1 day, 3 days, 7 days, 30 days and 90 days), the Kolda station shows negative HA values for the high RVA category, which results in a decrease in flow weak. For low high, the trend of high flow HA values for Kolda station is similar to that of low flow, i.e. negative high and medium RVA categories are observed when low RVA category is positive. Although these trends are not statistically significant, they provide information on the decline in flow in the basin in the short, medium and long term.

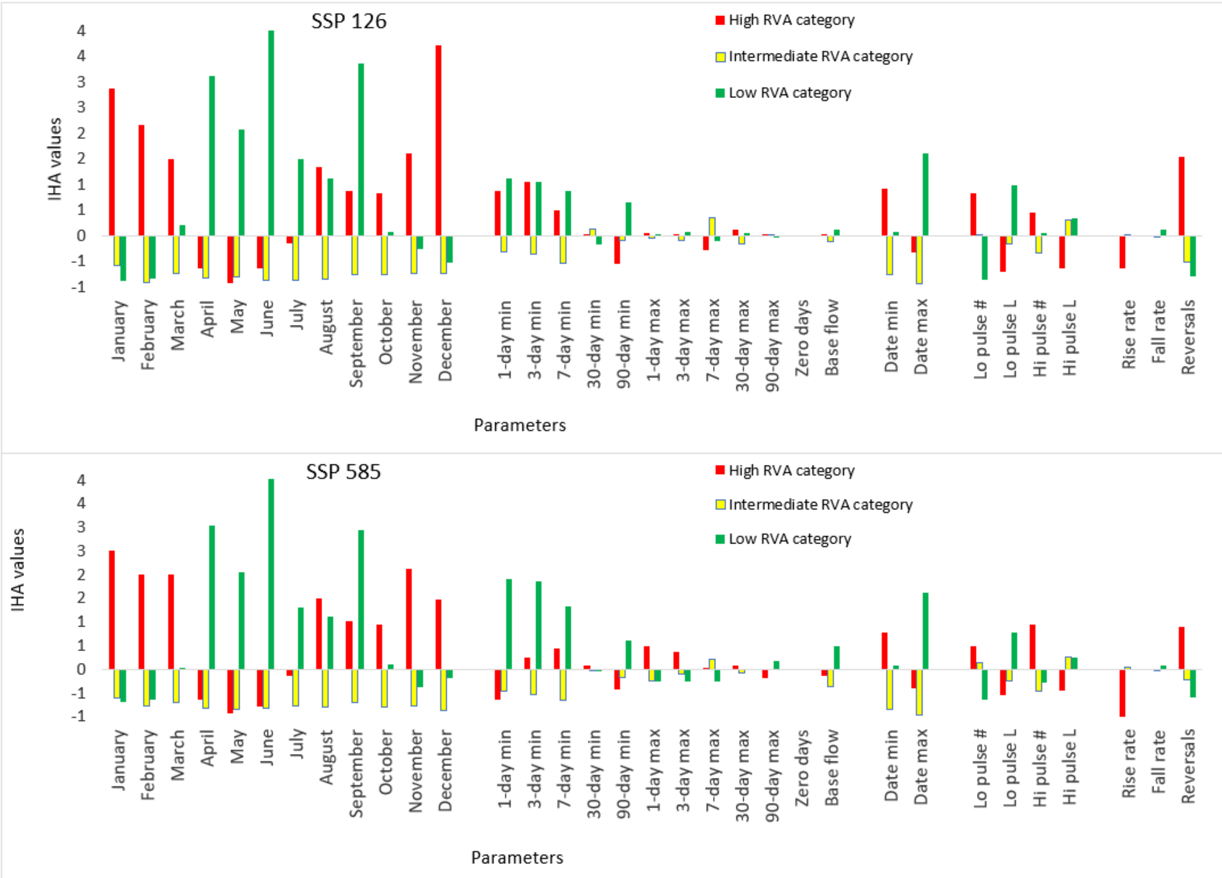

Figure 3. Hydrological modifications for all 33 IHA parameters at the Kolda hydrological station following the SSP 126 and SSP 585 scenarios.

From the pre-impact period to the post-impact period, analysis of median values, degree of deviation and degree of hydrological alteration for extreme annual flow conditions reveals that the degree of deviation (P %) is positive and shows a high deviation for the minimum daily flow. in the extreme hydrological parameters, while the deviation (P%) was less in all the extreme hydrological parameters of minimum daily flow, except the minimum 7-day flow Table 5. However, under the SSP 585 scenarios, the situation was more or less reversed. In the Casamance basin upstream of Kolda, we therefore note significant decreasing variations in the minimum flow. Additionally, a decrease in 1-, 3-, 7-, and 90-day maximum flow for both SSPs in the future suggests changes in streamflow. The base flow index decreases between the period before and after the impact, suggesting that periods of low flow will affect, even if only slightly, water availability. If the hydrological alteration (HA) indicates a light level of alteration at the level of the parameters of group 2 (-10.1% under SSP 126 and -20.2% under SSP 585), of group 4 (-4.0 % under SSP 126 and -7.7% under SSP 585) and group 5 (-16.5% under SSP 126 and -6.5% under SSP 585), on the other hand, it indicates a high level of alteration at level of group 3 parameters (-84.4% under SSP 126 and -91.2% under SSP 585). Overall, the degree of hydrological change for Group 2 parameters is less than 33%, suggesting little hydrological change. In the case of the timing of extreme annual minimums (i.e. group 3 indicators), the degree of deviations (P%) is also positive and very high in the future, i.e. that the timing of the one-day minimum advances from the 131st day to the 187th under SSP 126 and to the 188th under SSP 585, while the one-day maximum moves back from the 249th day to the 172nd under SSP 126 and to the 157th day under SSP 585, respectively, from the pre-impact period to the post-impact period. Thus, the delay in the Julian date of minimum flow indicates that annual minimum values will appear at the beginning of the year, which will have a negative impact on river ecology (Xue, Zhang, Yang, Zhang, & Sun, 2017). However, the hydrological alterations for the timing of the one-day minimum (Min Date) and the one-day maximum (Max Date) are identified as high categories for both scenarios Table 5. Group 3 IHA parameters have a high degree of hydrological modification (D > 67%).

Among the group 4 parameters, from the pre-impact period to the post-impact period, the frequency and duration of low pulse number (25th percentile), as well as high pulse number (75th percentile), sometimes increase, sometimes decrease insignificantly Table 5. The degree of deviation for low and high pulse numbers is high, indicating an increased frequency of low and high flow during the post-impact period Figure 3. However, all four parameters in this group show a low degree of hydrological alteration, with the exception of a high pulse number (i.e., frequency of high flow peaks) which shows moderate HA. The change in group 4 parameters influences bedload transport and channel sediments (Yuqin, Pandey, Huang, Suwal, & Bhattarai, 2019).

All group 5 parameters show little hydrological modification, except for the number of hydrological inversions which was moderately modified. The number of reversals increases insignificantly (from 73 to 87.4 under SSP 126 and 84.4 under SSP 585) between the pre- and post-impact period Table 5, indicating small intra-impact changes, annuals under downstream channel water conditions (Zhang, Shen, Han, & Jia, 2019).

It is important to note that the future scenario of both SSPs shows low alteration of the hydrological regime, but during the baseline, only the group 3 parameter shows high HA.

5. DISCUSSION

Freshwater resources are crucial for the ecological, economic, social and environmental development and sustainability of the basin. However, climate change has had an impact on these resources and is expected to increase in the coming days. Climate change, coupled with an ever-increasing population and limited availability of fresh water, has exacerbated water security concerns around the world. Such climate changes due to the variability of its parameters (precipitation, temperature) have direct or indirect hydrological effects in terms of quantity, quality and duration of flows. Thus, impacts in various sectors primarily result in changes in stream flow and associated changes in water availability and river health. Thus, a widely used hydrological model was used to assess the hydrological and water availability conditions in the Casamance watershed upstream of Kolda. Hydrological alteration indicators were used to assess climatic and hydrological extremes in the watershed.

The impacts of climate change on the flow regime in the Casamance watershed upstream of Kolda are analyzed using several CMIP6 datasets. The CHyM was used for this purpose and the variations in the flow regime are evaluated using the 33 IHA parameters. The results indicate that changes in the flow regime would occur in the future period. The indicated high flow magnitudes would be decreased and the low flow magnitudes would be intensified. Likewise, all 33 IHA parameters indicate that substantial variations would be caused by climate change. Numerous studies have highlighted the fact that West African watersheds would experience more severe and more frequent droughts (Faye, Sow, & Ndong, 2015; Santé, N'Go, Soro, Meledje, & Goula, 2019). The increase in air temperature under climate change will increase evapotranspiration and the decrease in precipitation would decrease flow (Abtew & Melesse, 2013). The GCMs show a decreasing trend in monthly flow, with the exception of the months of October and December indicated by the IHA method in the 2050s and 2090s. The magnitude of extreme annual conditions over different durations showed a tendency to decline under both scenarios. The timing of annual extremes, duration of high pulse, number of low pulses, and rate of increase showed a decreasing trend toward the end of the century.

6. CONCLUSION

This study assessed the availability of river water in future scenarios for two scenarios SSP 126 and SSP 585 in one of the watersheds that drains the Senegalese territory, the Casamance basin upstream of Kolda. A set of 18 global climate models was used to project future climatic and hydroclimatic extremes and evaluate projected trends in future temperatures and precipitation, from the flow are simulated by the CHyM model (Cetemps Hydrological Model) . The main findings show that in the future, for both SSP scenarios (126 and 585), the maximum (Tmax) and minimum (Tmin) temperatures are expected to increase in the watershed. Such temperature increases and associated temperature extremes suggest that the watershed climate will continue to be warm in the future. At the same time, average annual precipitation is expected to decrease for all scenarios and future periods considered. Additionally, increasing trends in the number of consecutive dry days were observed, suggesting that the watershed would be drier in the future. Water availability in terms of river flow is likely to decrease in the future, with a sharp decrease in volume compared to the baseline scenario. In the basin, negative changes in annual minimum and maximum conditions over 1, 3, 7, 30 and 90 days are generally decreasing over the future period, compared to the reference period (1985-2014), with the exception of 7 and 30 day minimum flow on SSP 126 and 30 day minimum flow and 1, 3 and 7 day maximum flow on SSP 585. Significant strong alteration in the base flow index for both SSP scenarios also suggests that low water periods will be affected, thus reducing the conditions of water availability in the watershed. Furthermore, the flow regime based on 33 extreme hydrological indices calculated from the IHA tool reveals a strong alteration during the future period. Thus, the increase in the trend of indices such as 1-day and 3-day flow in the future scenario and its strong alteration of the natural flow regime reveal a variation in flow for the two SSPs considered, leading to serious ecological consequences in the future.

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REFERENCES

Abtew, W., & Melesse, A. (2013). *Climate change and evapotranspiration in: Evaporation and evapotranspiration*. Dordrecht: Springer.

Aryal, A., Shrestha, S., & Babel, M. S. (2018). Quantifying the sources of uncertainty in an ensemble of hydrological climate-impact projections. *Theoretical and Applied Climatology, 135*(1-2), 193-209. https://doi.org/10.1007/s00704-017-2359-3

Barbalin, D., & Kuspilić, N. (2014). Trends of indicators of hydrological alterations. *Journal of the Croatian Association of Civil Engineers, 66*(7), 613-624. https://doi.org/10.14256/jce.1003.2014

Coppola, E., Verdecchia, M., Giorgi, F., Colaiuda, V., Tomassetti, B., & Lombardi, A. (2014). Changing hydrological conditions in the Po basin under global warming. *Science of the Total Environment*, *493*, 1183-1196. https://doi.org/10.1016/j.scitotenv.2014.03.003

Dacosta, H. (1989). *Precipitation and runoff in the casamance basin*. Doctoral Thesis, University of Cheikh Anta Diop, Dakar, faculty of Letters and Human Sciences, Department of Geography.

Devkota, L. P., & Gyawali, D. R. (2015). Impacts of climate change on hydrological regime and water resources management of the Koshi River Basin, Nepal. *Journal of Hydrology: Regional Studies*, *4*, 502-515. https://doi.org/10.1016/j.ejrh.2015.06.023

Erskine, W. D., Terrazzolo, N., & Warner, R. (1999). River rehabilitation from the hydrogeomorphic impacts of a large hydro-electric power project: Snowy River, Australia. *Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management*, *15*(1-3), 3-24. https://doi.org/10.1002/(sici)1099-1646(199901/06)15:1/3%3C3::aid-rrr532%3E3.0.co;2-r

Faye, C., Sow, A. A., & Ndong, J. B. (2015). Study of rainfall and hydrological droughts in tropical Africa: Characterization and mapping of drought by indices in the upper Senegal River basin. *Physio-Géo*, *9*, 17-35. https://doi.org/10.3390/hydrology3020015

Huaibin, W., & Jianping, Y. (2014). Research on theory and method of river health assessment. *The Open Cybernetics & Systemics Journal*, *8*(1), 1-9. https://doi.org/10.2174/1874110x01408011166

Huang, X., Suwal, N., Fan, J., Pandey, K. P., & Jia, Y. (2019). Hydrological alteration assessment by histogram comparison approach: A case study of Erdu River Basin, China. *Journal of Coastal Research*, *93*(SI), 139-145. https://doi.org/10.2112/si93-020.1

IPCC. (2012). Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of Working Groups I and II of the Intergovernmental Panel on Climate Change. [Field, C. B., Barros, V., Stocker, T. F., Qin, D., Dokken, D. J., Ebi, K.L., Mastrabdrea, M.D., Mach, K.J., Plattner, G.K., Allen, S.K., Tignor, M., Midgley, P.M. (eds). In (pp. 582). Cambridge: Cambrudge Univeristy Press.

IPCC. (2014). *Climate change 2014- synthesis report*. New York, USA: IPCC.

Knouft, J. H., & Ficklin, D. L. (2017). The potential impacts of climate change on biodiversity in flowing freshwater systems. *Annual Review of Ecology, Evolution, and Systematics*, *48*, 111-133. https://doi.org/10.1146/annurev-ecolsys-110316-022803

Konapala, G., Mishra, A. K., Wada, Y., & Mann, M. E. (2020). Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation. *Nature Communications*, *11*(1), 1-10. https://doi.org/10.1038/s41467-020-16757-w

Magilligan, F. J., & Nislow, K. H. (2005). Changes in hydrologic regime by dams. *Geomorphology*, *71*(1-2), 61-78.

Mapes, K. L., & Pricope, N. G. (2020). Evaluating SWAT model performance for runoff, percolation, and sediment loss estimation in low-gradient watersheds of the Atlantic coastal plain. *Hydrology*, *7*(2), 1-22. https://doi.org/10.3390/hydrology7020021

PADERCA. (2008). *Establishment of the reference situation of the natural environment in lower and middle Casamance*. Republic of Senegal Ministry of Agriculture Final report, No. 201.

Pandey, V. P., Dhaubanjar, S., Bharati, L., & Thapa, B. R. (2019). Hydrological response of Chamelia watershed in Mahakali Basin to climate change. *Science of the Total Environment*, *650*, 365-383. https://doi.org/10.1016/j.scitotenv.2018.09.053

Perkins, S. E., Alexander, L. V., & Nairn, J. R. (2012). Increasing frequency, intensity and duration of observed global heatwaves and warm spells. *Geophysical Research Letters*, *39*(20), 1–5. https://doi.org/10.1029/2012gl053361

Pinto, U., & Maheshwari, B. (2014). A framework for assessing river health in peri-urban landscapes. *Ecohydrology & Hydrobiology*, *14*(2), 121-131. https://doi.org/10.1016/j.ecohyd.2014.04.001

Richter, B., Baumgartner, J., Wigington, R., & Braun, D. (1997). How much water does a river need? *Freshwater Biology*, *37*(1), 231-249. https://doi.org/10.1046/j.1365-2427.1997.00153.x

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology, 10*(4), 1163-1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x

Richter, E., Tortoli, E., Fischer, A., Hendricks, O., Engel, R., Hillemann, D., . . . Kristiansen, J. E. (2007). Mycobacterium alsiense, a novel, slowly growing species isolated from two patients with pulmonary disease. *Journal of Clinical Microbiology, 45*(11), 3837-3839.

Rolls, R. J., Leigh, C., & Sheldon, F. (2012). Mechanistic effects of low-flow hydrology on riverine ecosystems: Ecological principles and consequences of alteration. *Freshwater Science, 31*(4), 1163-1186.

Sagna, P. (2005). *Climate dynamics and its recent evolution in the western part of West Africa*. State Doctorate Thesis, Cheikh Anta Diop University of Dakar.

Sané, T., Sy, O., & Dieye, E. H. B. (2011). *Climate change and vulnerability of the city of Ziguinchor*. Paper presented at the Proceedings of the conference "Strengthening Cities' Resilience to Climate Change: from Spatial Diagnosis to Adaptation Measures" (2R2CV) July 7 and 8, 2011, Paul Verlaine University - Metz, France.

Santé, N., N'Go, Y., Soro, G., Meledje, N., & Goula, B. (2019). Characterization of meteorological droughts occurrences in Côte D'Ivoire: Case of the sassandra watershed. *Climate, 7*(4), 60. https://doi.org/10.3390/cli7040060

Shrestha, H., Bhattarai, U., Dulal, K. N., Adhikari, S., Marahatta, S., & Devkota, L. P. (2016). Impact of climate change in the Karnali Basin, Nepal. *Journal of Hydrology and Meteorology, 10*(1), 1-19. https://doi.org/10.3390/cli4020017

Shrestha, M., Acharya, S. C., & Shrestha, P. K. (2017). Bias correction of climate models for hydrological modelling – are simple methods still useful? *Meteorological Application, 24*(3), 531–539.

Stahl, K., Hisdal, H., Hannaford, J., Tallaksen, L., Van Lanen, H., Sauquet, E., . . . Jódar, J. (2010). Streamflow trends in Europe: Evidence from a dataset of near-natural catchments. *Hydrology and Earth System Sciences, 14*(12), 2367-2382. https://doi.org/10.5194/hess-14-2367-2010

Thapa, B. R., Ishidaira, H., Pandey, V. P., & Shakya, N. M. (2017). A multi-model approach for analyzing water balance dynamics in Kathmandu Valley, Nepal. *Journal of Hydrology: Regional Studies, 9*, 149-162. https://doi.org/10.1016/j.ejrh.2016.12.080

Tomassetti, B., Coppola, E., Verdecchia, M., & Visconti, G. (2005). Coupling a distributed grid based hydrological model and MM5 meteorological model for flooding alert mapping. *Advances in Geosciences, 2*, 59-63. https://doi.org/10.5194/adgeo-2-59-2005

Wang, J., Shrestha, N. K., Delavar, M. A., Meshesha, T. W., & Bhanja, S. N. (2021). Modelling watershed and river basin processes in cold climate regions: A review. *Water, 13*(4), 1-19. https://doi.org/10.3390/w13040518

WMO. (2020). *Multi-agency report highlights increasing signs and impacts of climate change in atmosphere, land and oceans world meteorological organization*. Retrieved from https://public.wmo.int/en/media/pressrelease/multi-agency-report-highlights-increasing-signs-and-impacts-ofclimate-change

Xue, L., Zhang, H., Yang, C., Zhang, L., & Sun, C. (2017). Quantitative assessment of hydrological alteration caused by irrigation projects in the Tarim River basin. *China. Scientific Reports, 7*(1), 1-13. https://doi.org/10.1038/s41598-017-04583-y

Yang, T., Zhang, Q., Chen, Y. D., Tao, X., Xu, C. y., & Chen, X. (2008). A spatial assessment of hydrologic alteration caused by dam construction in the middle and lower Yellow River, China. *Hydrological Processes: An International Journal, 22*(18), 3829-3843.

Yuqin, G., Pandey, K. P., Huang, X., Suwal, N., & Bhattarai, K. P. (2019). Estimation of hydrologic alteration in Kaligandaki River using representative hydrologic indices. *Water (Switzerland), 11*(4), 11–14. https://doi.org/10.3390/w11040688

Zhang, K., Shen, J., Han, H., & Jia, Y. (2019). Urban River health analysis of the Jialu River in Zhengzhou City using the improved fuzzy matter-element extension model. *Water, 11*(6), 1190. https://doi.org/10.3390/w11061190