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Komlan Koudahe

Koffi Djaman

Ansoumana Bodian

Suat Irkmaq

Mamadou Sall

See next page for additional authors

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Authors

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Trend Analysis in Rainfall, Reference Evapotranspiration and Aridity Index in Southern Senegal: Adaptation to the Vulnerability of Rainfed Rice Cultivation to Climate Change

Komlan Koudahe¹, Koffi Djaman², Ansoumana Bodian³, Suat Irmak⁴, Mamadou Sall⁵, Lamine Diop⁶, Alpha B. Balde⁷, Daran R. Rudnick⁴

¹Direction des Filières Végétales (DFV), MAEH, Lomé, Togo

²Department of Plant and Environmental Sciences, New Mexico State University, Agricultural Science Center at Farmington, Farmington, NM, USA

³Laboratoire Leïdi “Dynamique des territoires et développement”, Université Gaston Berger (UGB), Saint Louis, Sénégal

⁴Department of Biological Systems Engineering, University of Nebraska-Lincoln, Chase Hall, Lincoln, NE, USA

⁵Research Scientist, Institut Sénégalais de Recherches Agricoles, Centre de Saint Louis, Saint Louis, Sénégal

⁶UFR S2ATA, Université Gaston Berger (UGB), Saint Louis, Sénégal

⁷Institut Sénégalais de Recherches Agricoles, Bambey, Sénégal

Email: komlankoudahe@gmail.com

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Abstract

Rainfall and evapotranspiration are two vital elements for food production under rainfed agriculture. This study aims at investigating the combined changes in these variables in the form of aridity index in the southern Senegal. The temporal trends in annual and monthly (from May to October) aridity index, rainfall and evapotranspiration are examined and adaptation strategies to the vulnerability of rainfed rice cultivation to the changes are developed. The results show a significant decreasing trend in annual rainfall at all study locations for the period 1922-2015. When analyzing the trends in sub-periods, there are two clear patterns in the annual rainfall series: a decreasing trend for the period 1922-1979 and a reversal increasing trend for the period 1980-2015. An increasing trend is also observed in annual reference evapotranspiration. The results reveal that the region will be drier with a significant increase in aridity at the annual and most monthly series. Appropriate adaptation strategies should be implemented to diminish the adverse influence of the increasing aridity on rice productivity for a sustaina-

ble agriculture.

Keywords

Variation, Evapotranspiration, Rainfall, Aridity Index, Senegal, Rainfed Rice

1. Introduction

Rainfall and evapotranspiration are the most important components of the hydrological cycle and govern food production under rainfed agriculture. Several studies across the globe reported decreasing trends in annual rainfall with more frequent extreme events causing disaster in terms of severe droughts, production destruction, flooding, death and other catastrophes [1]. Drastic reduction in rainfall across Africa is reported by [2]. West African Sahel is becoming drier with inter-annual variability of total rainfall [3] under the influence of the north-south migration of the Inter-Tropical Convergence Zone [4]. [5] reported a significant decreasing trend in annual precipitation across the Senegal River Basin from 1950 to 2000 similar to the results obtained for a longer period of 1900-2002 [6]. [7] observed a decrease in total annual rainfall over Burkina Faso from 1950 to 2013. Climatic variables and reference evapotranspiration showed a strong spatial and temporal variability in Senegal. [8] reported annual rainfall variation from 247 mm at Podor in the northern Senegal within the Senegal River Basin to 1325 mm at Ziguinchor in the south East Senegal. [5] indicated significant temporal variation in climate across the Senegal River Basin for the 1950-2000 period. [9] showed high temporal and spatial variability in rainfall across Senegal for the 1979-1998 period. [10] indicated the decreasing trend in total rainfall and the persistence of drought.

Reference evapotranspiration (ET_o) is a key parameter used to estimate actual crop water use through the two step approach by multiplying ET_o by stage specific crop coefficients [11] [12]. Under the changing climate, the analysis of ET_o is recommended for food production sustainability regarding water deficit or flooding conditions, relative to the total rainfall. Knowledge of the dynamics in ET_o is therefore critical for water resources management under rainfed conditions and development of adaptation strategies to reduce the vulnerability of food production to the climatic changes in arid and semiarid regions. Increasing trend in ET_o was observed in South Taiwan [13], in Iran [14] and Southern Russia [15]. [16] found a significant increase in ET_o across the southern Togo. In contrast, a decreasing trend in ET_o was reported in some locations. [17] indicated a decreasing trend in ET_o due to a decrease in net total radiation and a significant decrease in wind speed over the Changjiang (Yangtze River) catchment in China for the period 1960-2000. [18] reported an increasing trend in annual rainfall at the rate of 1.17 mm/year followed by a decreasing trend in annual rainfall at the rate of 20.51 mm/year in Eastern Mississippi (USA) for the period 1894-2014. In North America, a decreasing trend in ET_o was reported by

[19]. A decline in ETo over all India was reported by [20]. Increasing trend in annual ETo for the 1980 to 2010 period was observed in Serbia by [21]. Similarly, [22] reported a significant decline in ETo during the 1893-2008 period in the Platte river basin in central Nebraska (USA) due to a significant increase in precipitation, and reduction in solar radiation and net radiation.

The ratio of rainfall to ETo known as aridity index (AI) [16] can be used as an indicator of the severity of drought related to crop production under good watering conditions. It expresses the compensability of potential evapotranspiration by rainfall. AI greater than unity implies availability of rainfall to cover the potential crop water requirement and otherwise, there is a water deficit which can cause damages to crop production. [16] found a significant declining trend in annual aridity index across the southern Togo. [23] reported annual aridity ranging from 0.2 to 0.4 at Podor, Matam, and St-Louis and the maximum monthly aridity index of 0.54, 0.93 and 0.64 in August at the respective locations in the Northern Senegal along the Senegal River. In other arid regions of the world also an aridity increase was observed. [24] found an increase in aridity synonym of a decreasing trend in the aridity index in Iran during the 1966-2005 period.

There is a close relationship between socioeconomic activities and climate in West Africa and rainfall is the most influencing variable on these activities [25]. In the Southern Senegal with a humid climate, rainfed upland and lowland rice production is expanding under the objective of rice self-sufficiency by the Senegalese government. The rainy season covers only five month basically from June to October. Whenever resource mobilizations and effort to improve rice production generally in Senegal and particularly in the southern Senegal is increasing, water, land, and crop management inadequacy is detrimental for paddy yield. The rice production is threatened by variability in annual rainfall and the onset of the growing season. The existing information on quantifying the change in the local climatic variables and impact on agriculture is extremely limited. The objective of this study is to investigate the change in annual and monthly rainfall, reference evapotranspiration and aridity index in the southern Senegal and the development of adaptation strategies to the vulnerability of rainfed rice cultivation to climate change.

2. Materials and Methods

2.1. Study Area and Data Used

Datasets of daily rainfall were obtained from 4 meteorological stations in the Southern Senegal for the period of 1922-2015 and reference evapotranspiration were calculated for the same weather stations for the 1950-2000 period. Senegal is the westernmost country in Africa; the North Atlantic Ocean is to its western border. The country is located between latitudes 12°30' and 16°30' N and longitudes 11°30' and 17°30'W. The sites and their coordinates are as follows: Ziguinchor (13°33'00"N; 16°16'00"W), Kolda (12°53'0"; 14°58'00"W), Kedougou

(12°34'00"N, 12°13'00"W), and Tambacounda (13°46'00"N; 13°42'00"W). Annual mean of rainfall, reference evapotranspiration, and aridity index was calculated and used in trend analysis.

2.2. Reference Evapotranspiration Estimation Method

The aridity index, defined as the ratio of annual or monthly precipitation to annual or monthly ET_o , was used to characterize the severity of the aridity at Ziguinchor, Kolda, Kedougou, and Tambacounda. Daily climate data at Ziguinchor, Kolda, Kedougou, and Tambacounda were used to estimate daily grass reference ET_o by the Penman-Monteith equation [11]. The Penman-Monteith reference ET_o equation with fixed stomatal resistance values for grass surface is:

$$ET_o = \frac{0.408\Delta(Rn - G) + (\gamma C_n u_2 / (T + 273))(e_s - e_a)}{\Delta + \gamma(1 + C_d u_2)} \quad (1)$$

where: ET_o is the reference evapotranspiration ($\text{mm}\cdot\text{day}^{-1}$), Δ is the slope of saturation vapor pressure versus air temperature curve ($\text{kPa}\cdot^\circ\text{C}^{-1}$), Rn is the net radiation at the crop surface ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), G is the soil heat flux density at the soil surface ($\text{MJ}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$), T is the mean daily air temperature at 1.5 - 2.5 m height ($^\circ\text{C}$), u_2 is the mean daily wind speed at 2 m height ($\text{m}\cdot\text{s}^{-1}$), e_s is the saturation vapor pressure at 1.5 - 2.5 m height (kPa), e_a is the actual vapor pressure at 1.5 - 2.5 m height (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), γ is the psychrometric constant ($\text{kPa}\cdot^\circ\text{C}^{-1}$), C_n and C_d are constants with values of $900^\circ\text{C mm s}^3 \text{Mg}^{-1}\cdot\text{d}^{-1}$ and $0.34 \text{s}\cdot\text{m}^{-1}$, respectively. All parameters necessary for computing ET_o were computed according to the procedure developed in FAO-56 by [11].

2.3. Temporal Trend Analysis

The Mann-Kendall test [26] [27], a nonparametric method for trend analysis, was used for the analysis of temporal trend in annual and monthly rainfall, annual ET_o , and annual aridity index. It should be noted that the Mann-Kendall test is a statistical test widely used for the analysis of trends in climatologic [28] [23], and hydrologic time series [16]. There are two advantages of using this test: it is a nonparametric test and does not require the data to be normally distributed and the test has low sensitivity to abrupt breaks due to inhomogeneous time series [29]. According to this test, the null hypothesis (H_0) assumes that there is no trend (the data is independent and randomly ordered) and this is tested against the alternative hypothesis (H_1), which assumes that there is a trend. The Mann-Kendall test statistic S is given as follows:

$$S = \sum_{j=1}^{n-1} \sum_{i=j+1}^n \text{sign}(x_i - x_j) \quad (2)$$

where x_i and x_j are the data values at time i and j , n is the length of the dataset and $\text{sign}()$ is the sign function which can be computed as:

$$\text{sign}(xi - xj) = \begin{cases} 1 & \text{if } (xi - xj) > 0 \\ 0 & \text{if } (xi - xj) = 0 \\ -1 & \text{if } (xi - xj) < 0 \end{cases} \quad (3)$$

For $n > 10$, the test statistic Z approximately follows a standard normal distribution:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (4)$$

in which $\text{Var}(S)$ is the variance of statistic S .

A positive value of Z indicates that there is an increasing trend, and a negative value indicates a decreasing trend. The null hypothesis, H_0 , that there is no trend in the records is either accepted or rejected depending on whether the computed Z statistics is less than or more than the critical value of Z statistics obtained from the normal distribution table at the 5% significance level [30]. If $|Z| > Z_{(1-\alpha/2)}$, the null hypothesis of no autocorrelation and trend in time series is rejected, in which $Z_{(1-\alpha/2)}$ is corresponding to the normal distribution with α being the significance level.

If a time series has a trend, the magnitude of the trend can be denoted by the trend slope β [31] [32]:

$$\beta = \text{Median} \left(\frac{xi - xj}{i - j} \right) \quad \forall j < i \quad (5)$$

where xi and xj are data values at the time ti and tj ($i > j$), respectively.

Linear regression analysis was applied for analyzing trends in the time series. The main statistical parameter drawn from regression analysis is the slope which indicates the mean temporal change in the variable under study. A positive slope indicates an increasing trend, while a negative slope indicates a decreasing trend. The total change during a decade was obtained by multiplying the slope by 10 years.

3. Results and Discussion

3.1. Trend in Annual and Monthly Rainfall

Inter-annual and spatial variation in annual rainfall was observed for the 1922-2015 period in the southern region of Senegal. Annual rainfall varied from 696 to 2183 mm at Ziguinchor, from 566 to 1929 mm at Kolda, from 765 to 1898 mm at Kedougou, and from 408 to 1246 mm at Tambacounda (Figure 1). For the 1922-2015 period, the driest year was 1980 at Ziguinchor and Kolda, 2002 at Tambacounda and 2007 at Kedougou, while the wettest year was 1924 at Ziguinchor, 1958 at Kolda, 1954 at Kedougou and 1935 at Tambacounda. The long-term average annual rainfall was 1373 ± 321 mm, 1129 ± 251 mm, $1248 \pm$

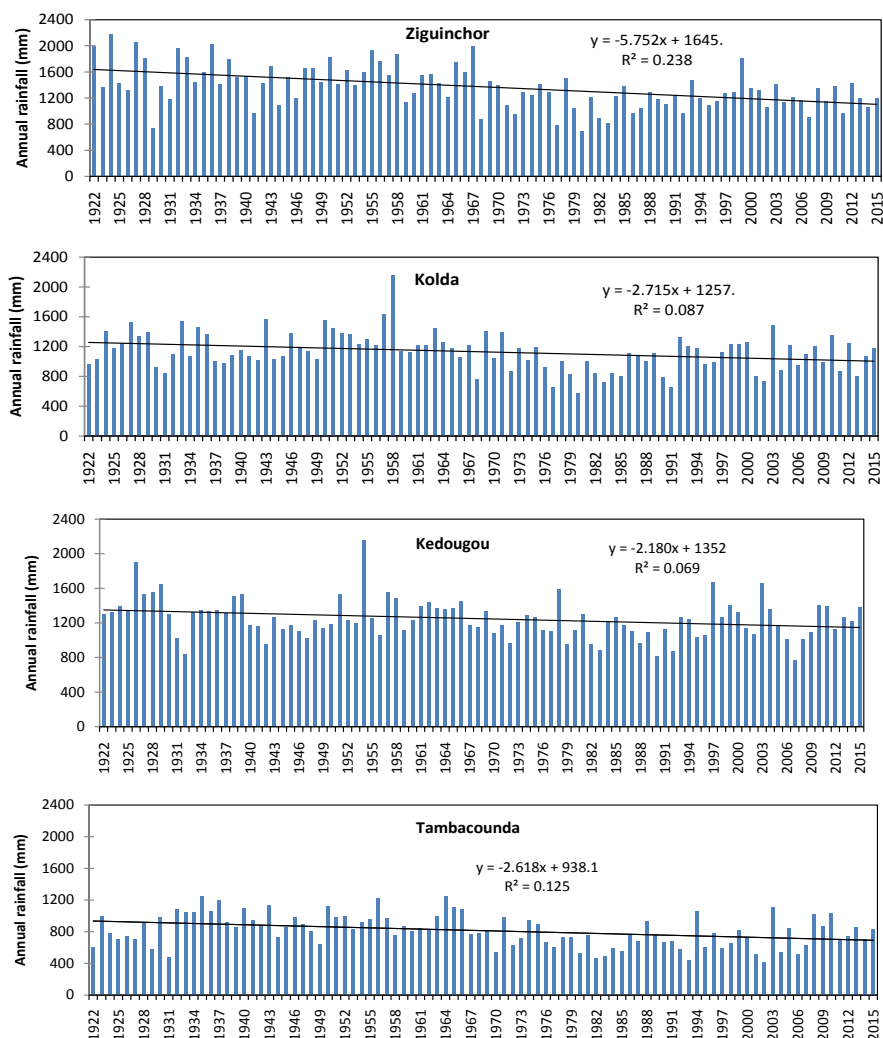


Figure 1. Variation in annual total rainfall at Ziguinchor, Kolda, Kedougou and Tambacounda during the 1922-2015 period.

225 mm, and 814 ± 201 mm at the respective locations. Extremely wet year was observed at Kolda and Kedougou with total rainfall of 2152 mm in 1958 at Kolda and 2160 mm in 1954 at Kedougou. There was a significant decreasing trend in annual rainfall at all locations for the 1922-2015 period at the rate of 5.78, 2.46, 2.18 and 3.15 mm/year (Table 1). Over the study period, total reduction in rainfall was 541, 255, 205, and 246 mm at the respective stations. In terms of geographical spatial variation in rainfall (East-West) there was no pattern in annual rainfall. For the period 1980 to 2015, the trend is slightly upward and this reflects a slight resumption of rainfall after known droughts in the 1970s and 1980s. The linear regression also showed a decline in annual rainfall as presented in Figure 1. However, there are two patterns in the rainfall series as shown in Figure 1. A significant decreasing trend in rainfall was observed from 1922 to 1979 at Ziguinchor and Kolda (Table 1) and a reversal increasing trend from 1980 to 2015 at all locations but only significant at Kolda and Tambacounda (Table 1). Similar results were reported by [33] who indicated persistent drought in the 1970

Table 1. Summary of the Mann-Kendall trend test for annual rainfall.

Locations	First year	Last year	n	Z	Significance	Sen's slope Q	B
Ziguinchor	1922	2015	94	-4.83	***	-5.781	1648.87
Kolda	1922	2015	94	-2.62	**	-2.463	1241.45
Kedougou	1922	2015	94	-2.66	**	-2.181	1323.68
Tambacounda	1922	2015	94	-3.59	***	-3.246	961.68
Ziguinchor	1922	1979	58	-2.48	*	-7.433	1700.07
Kolda	1922	1979	58	-1.11	n.s.	-2.108	1247.47
Kedougou	1922	1979	58	-1.84	+	-3.357	1357.50
Tambacounda	1922	1979	58	-1.19	n.s.	-2.181	940.21
Ziguinchor	1980	2015	36	1.38	n.s.	5.466	1075.30
Kolda	1980	2015	36	2.03	*	7.850	890.95
Kedougou	1980	2015	36	1.46	n.s.	5.128	1066.75
Tambacounda	1980	2015	36	1.98	*	5.963	583.51

n: Number of years, Z: Mann-Kendall test statistic $f(\text{year}) = Q * (\text{year} - \text{firstDataYear}) + B$ where Q is the sen's slope and B is the constant. n.s. Non-significant. +Significant at 5%. *Significant at 1%. **Significant at 0.1%. ***Significant at 0.01%.

and the 1980s and increasing trend in recent rainfall in Senegal. Similarly, [34] found significant increasing and decreasing annual rainfall in sub periods within the 1910-2004 period in South Africa. A general decreasing trend in rainfall across the West African Sahel for the 1960-2010 period as shown in **Figure 2** with negative Standardized Precipitation Index as reported by [10].

In the Southern Senegal, the rainy season starts in May with rainfall effectiveness in June and stops in October. August has been received the highest amount of rainfall for the period of 1922-2015 with rainfall amount equal to 460, 344, 322, and 245 mm at Zigninchor, Kolda, Kedougou and Tambacounda, respectively. A downward trend in monthly rainfall was achieved for the months of June to October at the Ziguinchor station for the period 1922-2015 (**Table 2**). At Kolda station, the downward trend is observed from August to October, while a non-significant increasing trend was observed in June and July rainfall (**Table 2**). For the stations of Kedougou and Tambacounda, a decreasing trend in monthly rainfall was observed from June to October (negative Z statistics), while May rainfall showed non-significant increasing trend (**Table 2**). A decreasing trend observed in monthly rainfall at Kedougou and Tambacounda was significant for June and September at both stations. The decreasing rate of monthly rainfall ranged from 0.08 to 0.89 mm/year (**Table 2**). These results indicated an increase in early season rainfall, while a shortage of rainfall might be observed toward the end of the rainy season when the crops may need supplementary irrigation to reach maturity. The trends in monthly rainfall enhance the drought risk already observed in the study area. This entails implementing strategies for resilience and adaptation to the changing climate to maintain and/or increase

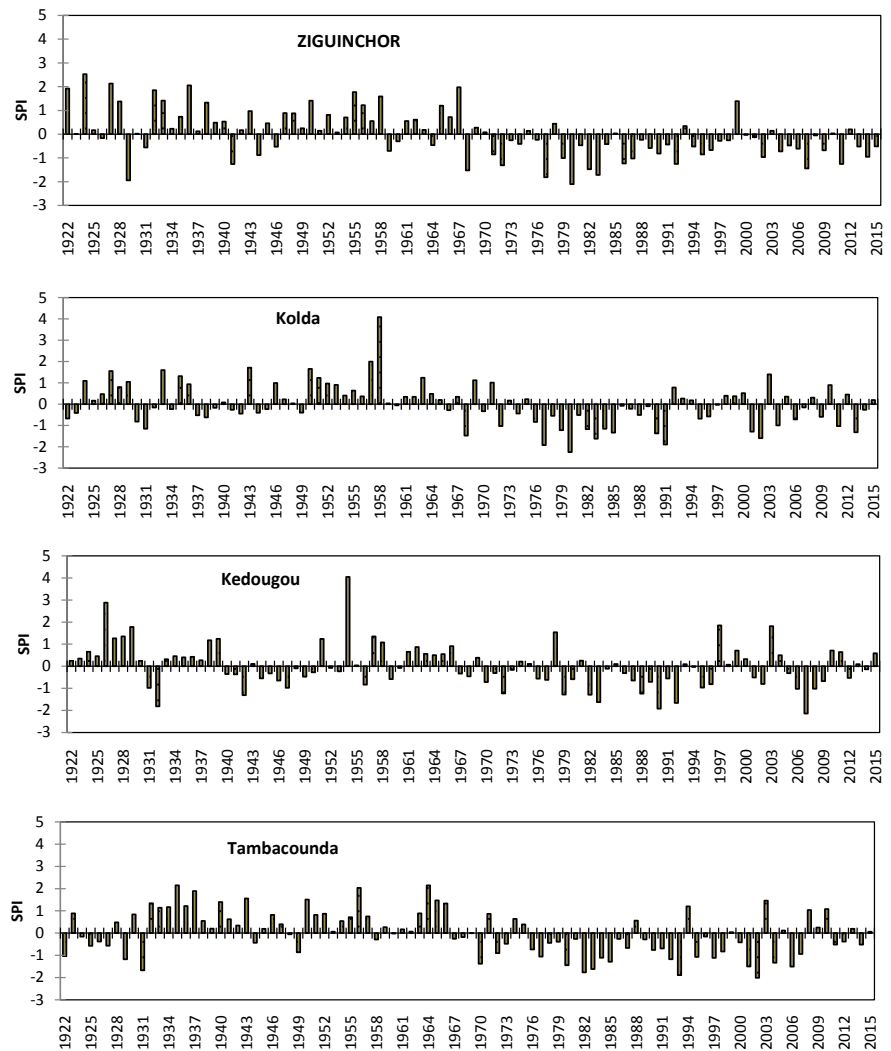


Figure 2. Variation in Standardized Precipitation Index (SPI) at Ziguinchor, Kolda, Kedougou and Tambacounda during the 1922-2015 period.

food production for the increasing need for food and fed for the growing population and livestock. Similar results were reported by [35] who indicated that the smaller rate of rainfall events from June to September the main cause of the change in rainfall patterns in the western Sahel.

3.2. Trend in Annual Reference Evapotranspiration

Annual reference evapotranspiration varied with locations across the southern Senegal and ranged from 1549 to 1887 mm at Ziguinchor, from 1638 to 2041 mm at Kolda, from 1692 to 2238 mm at Kedougou, and from 1821 to 2260 at Tambacounda for the 1950-2000 period. Linear regression between annual reference evapotranspiration and the corresponding year showed an increasing trend in annual reference evapotranspiration at the rate of 1.4, 1.2, 4.4 and 2.6 mm/year at Ziguinchor, Kolda, Kedougou and Tambacounda, respectively (**Figure 3**). The trend in annual reference evapotranspiration is highly significant

Table 2. Summary of the Mann-Kendall trend test for monthly rainfall.

Locations	Months	First year	Last year	n	Test Z	Significance	Sen's slope Q	B
Ziguinchor	June	1922	2015	94	-1.78	+	-0.43	126.05
	July	1922	2015	94	-2.14	*	-1.02	360.99
	August	1922	2015	94	-4.26	***	-2.74	582.06
	September	1922	2015	94	-2.26	*	-0.72	354.70
	October	1922	2015	94	-2.84	**	-0.73	153.53
Kolda	May	1922	2015	94	2.44	*	0.08	5.62
	June	1922	2015	94	0.61	n.s.	0.15	116.80
	July	1922	2015	94	0.54	n.s.	0.19	231.58
	August	1922	2015	94	-1.82	+	-0.78	388.12
	September	1922	2015	94	-1.36	n.s.	-0.41	291.36
Kedougou	October	1922	2015	94	-1.76	+	-0.37	111.39
	May	1922	2015	94	1.07	n.s.	0.14	32.46
	June	1922	2015	94	-2.27	*	-0.56	193.09
	July	1922	2015	94	-0.71	n.s.	-0.20	264.44
	August	1922	2015	94	-0.20	n.s.	-0.08	336.72
Tambacounda	September	1922	2015	94	-2.61	**	-0.89	342.03
	October	1922	2015	94	-0.56	n.s.	-0.15	108.47
	May	1922	2015	94	0.64	n.s.	0.02	8.97
	June	1922	2015	94	-1.84	+	-0.39	123.99
	July	1922	2015	94	-0.50	n.s.	-0.11	178.63
Tambacounda	August	1922	2015	94	-0.54	n.s.	-0.21	252.47
	September	1922	2015	94	-2.37	*	-0.72	236.62
Tambacounda	October	1922	2015	94	-1.08	n.s.	-0.16	65.09

$f(\text{year}) = Q * (\text{year} - \text{firstdatayear}) + B$ where Q is the sen's slope and B is the constant. n.s. Non-significant. +Significant at 5%. *Significant at 1%. **Significant at 0.1%. ***Significant at 0.01%.

at Kedougou (Test Z = 3.48), significant at Ziguinchor and Tambacounda while not significant at Kolda (Table 3). Sen's slope estimates were 1.19, 0.55, 4.09, and 2.43 mm/year at Ziguinchor, Kolda, Kedougou and Tambacounda, respectively.

3.3. Trend in Annual and Monthly Aridity Index

The calculated annual aridity index is generally lower than unity showing the insufficiency of annual rainfall vs annual reference evapotranspiration. It varied from 0.40 to 1.25 at Ziguinchor, from 0.26 to 0.88 with sole high value of 1.20 in 1958 at Kolda, from 0.41 to 0.91 with sole high value of 1.20 in 1954 at Kedougou, and from 0.20 to 0.63 at Tambacounda (Figure 4). The Figure 4 showed two patterns in annual aridity index at all stations. A decreasing tendency is observed from 1950 to 1982 and an increasing tendency from 1983 to 2000.

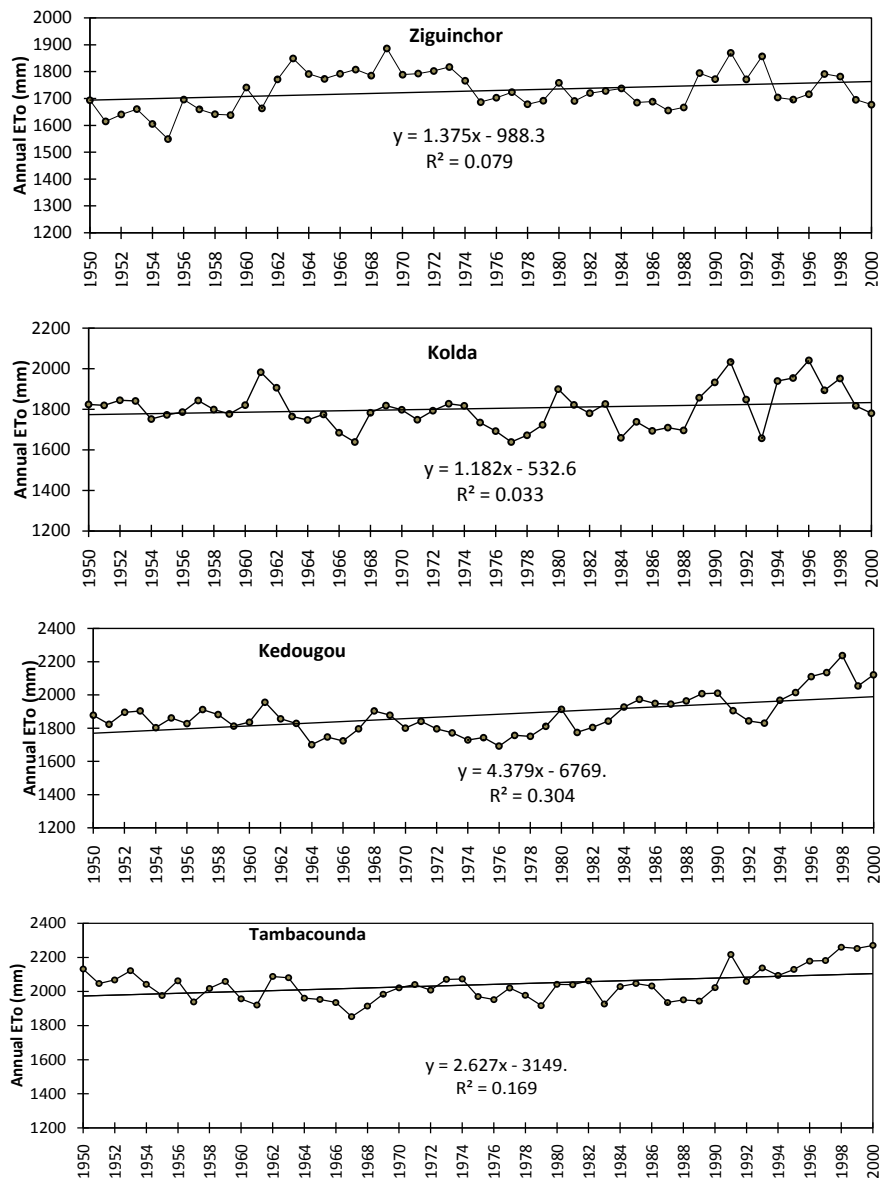


Figure 3. Variation in annual total reference evapotranspiration at Ziguinchor, Kolda, Kedougou and Tambacounda during the 1950-2000 period.

However, the trend analysis of the aridity index for the entire period 1950-2000 showed a significant decrease in the annual aridity index, implying an increasing aridity or severity of drought across the region (Table 3). Our results are in agreement with [29] who reported an increase in aridity across Iran. Similar results were reported by [5] for the Senegal River Valley. The increasing trend in annual reference evapotranspiration and the decreasing trend in annual rainfall and the increasing severity of drought (increasing aridity index) need real consideration in terms of water management under rainfed agriculture mostly practiced in the southern regions of Senegal for cereal and legume production.

Monthly aridity index study is focused on the period of June to October: the rainy season in the southern Senegal. During the period from 1950 to 2000,

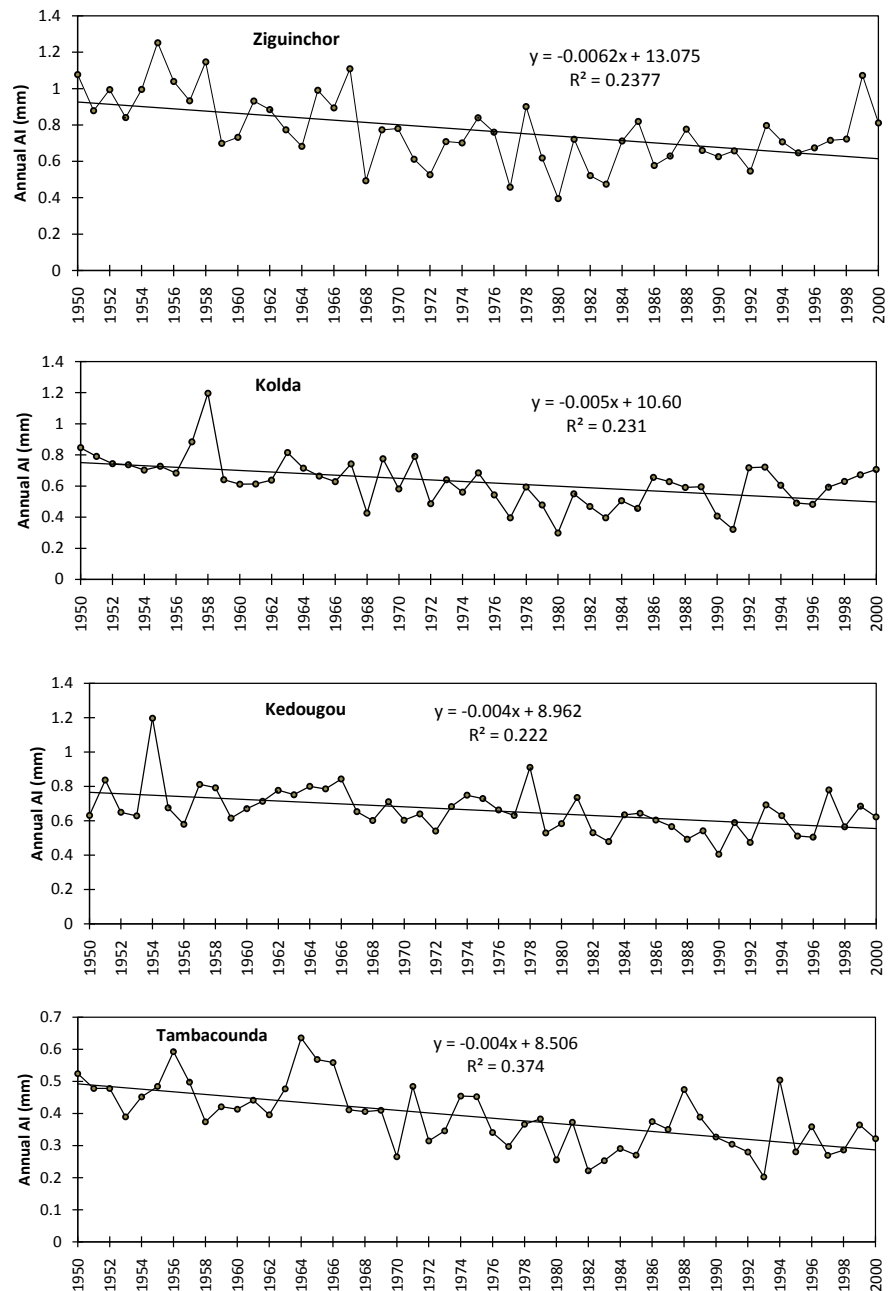


Figure 4. Variation in annual aridity index at Ziguinchor, Kolda, Kedougou and Tambacounda during the 1950-2000 period.

monthly aridity of June varied from 0.04 to 8.18 at Ziguinchor, from 0.06 to 8.12 at Kolda, from 0.16 to 3.93 at Kedougou and 0.01 to 3.52 at Tambacounda. The highest value of the monthly aridity was registered in August, the lowest one in the last month of the rainy season (October) as the rainiest month. At Ziguinchor, the long-term average monthly aridity varied from 0.72 in June to 0.93 in October and peaked 3.61 in August. It varied from 0.80 in June to 0.78 in October at Kolda, from 1.03 in June to 0.85 in October at Kedougou, and from 0.53 in June to 0.45 in October at Tambacounda, and peaked 2.54, 2.22, and 1.73 in

Table 3. Summary of the Mann-Kendall trend test for annual reference evapotranspiration and aridity index.

Parameters	Locations	First year	Last year	n	Z	Significance	Sen's slope Q	B
ETo	Ziguinchor	1950	2000	51	1.67	+	1.185	1689.39
	Kolda	1950	2000	51	0.58	n.s.	0.552	1786.85
	Kedougou	1950	2000	51	3.48	***	4.085	1791.14
	Tambacounda	1950	2000	51	2.11	*	2.431	1964.45
Aridity index	Ziguinchor	1950	2000	51	-3.23	**	-0.006	0.91
	Kolda	1950	2000	51	-3.53	***	-0.005	0.73
	Kedougou	1950	2000	51	-3.46	***	-0.004	0.74
	Tambacounda	1950	2000	51	-4.61	***	-0.004	0.48

$f(\text{year}) = Q * (\text{year} - \text{firstDataYear}) + B$ where Q is the sen's slope and B is the constant. n.s. Non-significant. +Significant at 5%. *Significant at 1%. **Significant at 0.1%. ***Significant at 0.01%.

August at the respective stations. Long-term average aridity of May was 0, 0.07, 0.21, and 0.07 at Ziguinchor, Kolda, Kedougou, and Tambacounda, respectively, while November long-term average aridity index was 0.06, 0.07, 0.06 and 0.00 at the respective stations (Figure 5). In the light of these results, the period of June–October is appropriate for crop growth and development. The statistical analysis revealed a significant decreasing trend in the monthly aridity index for June, August, September and October at Ziguinchor. A significant decreasing trend in monthly aridity index was observed from August to October at Kolda, while the decline was not significant for May, June and July implying rainfall shortage toward the end of the rainy season at this station. At Kedougou, a reversal situation is observed with a significant increasing trend in monthly aridity except for October (Table 4). At Tambacounda, the monthly aridity index showed a significant declining trend in July, August, September and October, while the decline was not significant in June (Table 4). The monthly aridity index can help in decision making regarding adoption of adaptation strategies or resilience to climate change.

3.4. Adaptation to the Vulnerability of Rainfed Rice Cultivation to Climate Change

In the study zone, two rice production systems are practiced as flooded lowlands and rainfed uplands. Food insecurity was shown to be more prevalent in the southern and central Senegal, especially in the regions of Ziguinchor, Kolda and Kedougou which are under the present study [33]. Rainfed rice yields varied from 1 to 2 tons/ha in the region. The causes of low yield are low input use, no water management and the use of low yielding traditional varieties which are medium and long duration ones. [33] reported a strong correlation between rainfall and cereal production in Ziguinchor. [36] indicated that the promotion of resilience and change are the natural resources management strategies under the decreasing trend in rainfall. The short rainy season presented in Figure 6

Table 4. Summary of the Mann-Kendall trend test for monthly aridity index.

Locations	Months	First year	Last year	n	Z	Significance	Sen's slope Q	B
Ziguinchor	June	1950	2000	51	-2.10	*	-0.0072	0.75
	July	1950	2000	51	-1.04	n.s.	-0.0096	2.52
	August	1950	2000	51	-3.17	**	-0.0378	4.43
	September	1950	2000	51	-1.66	+	-0.0158	2.97
	October	1950	2000	51	-1.67	+	-0.0111	1.17
Kolda	May	1950	2000	50	-1.16	n.s.	-0.0003	0.05
	June	1950	2000	51	-1.28	n.s.	-0.0062	0.86
	July	1950	2000	51	-1.07	n.s.	-0.0070	1.99
	August	1950	2000	51	-2.18	*	-0.0217	2.96
	September	1950	2000	51	-2.23	*	-0.0181	2.46
Kedougou	October	1950	2000	51	-2.97	**	-0.0127	1.04
	May	1950	2000	51	-0.33	n.s.	0.1997	0.31
	June	1950	2000	51	-3.88	***	1.3727	1.56
	July	1950	2000	51	-1.92	+	2.0897	2.45
	August	1950	2000	51	-3.15	**	2.7697	3.17
Tambacounda	September	1950	2000	51	-2.11	*	2.5235	2.98
	October	1950	2000	51	-1.58	n.s.	0.8524	1.29
	May	1950	2000	51	-0.70	n.s.	-0.0002	0.03
	June	1950	2000	51	-1.58	n.s.	-0.0041	0.59
	July	1950	2000	51	-2.96	**	-0.0117	1.52
Tambacounda	August	1950	2000	51	-2.27	*	-0.0180	2.12
	September	1950	2000	51	-2.24	*	-0.0154	1.70
	October	1950	2000	51	-1.66	+	-0.0056	0.57

$f(\text{year}) = Q * (\text{year} - \text{firstDataYear}) + B$ where Q is the sen's slope and B is the constant. n.s. Non-significant. +Significant at 5%. *Significant at 1%. **Significant at 0.1%. ***Significant at 0.01%.

corresponding to the period with acceptable aridity index greater than unity that covers the period from July to September (Figure 5) imposes the adoption of short to medium duration rice varieties as adaptation strategy to the vulnerability of crop production to climate change. The *Oryzaberrima* varieties traditionally grown were replaced by the more yield *Oryza sativa* varieties as shown in Figure 7 [37]. The development of the New Rice for Africa (NERICA) varieties by [38] through interspecific breeding between *Oryza sativa* and *Oryzaberrima* [39] [40], contributes to mitigating the impact of climate change on upland rice production. The 18 high yielding upland NERICA varieties can produce from 4000 to 5000 kg/ha with relatively short duration about 95 to 100 days, even less for some of the NERICAS as NERICA 8 with cycle duration of 75 - 85 days [38]. Moreover, AfricaRice had developed 60 lowland NERICA

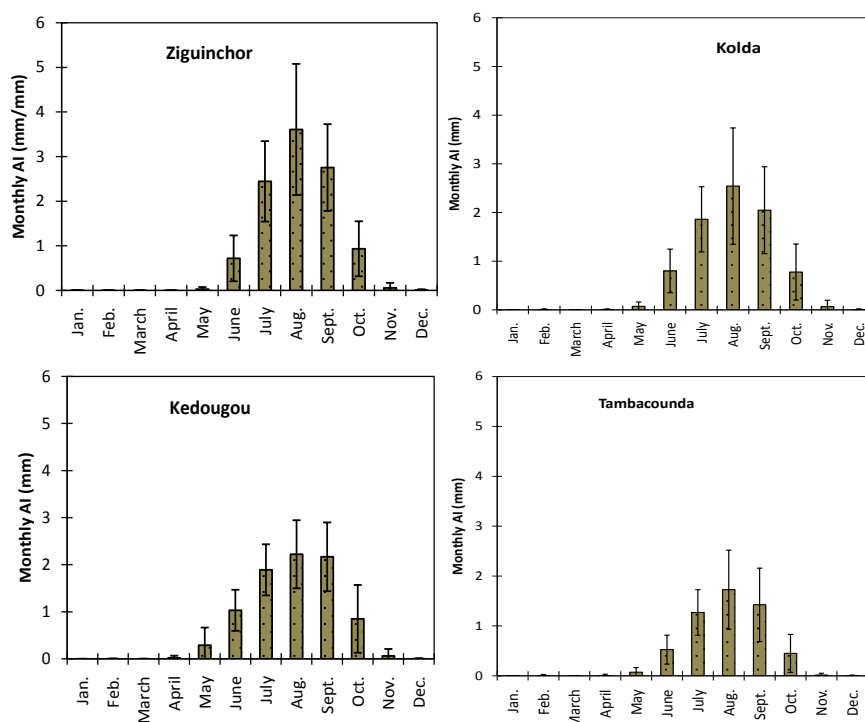


Figure 5. Long-term average monthly aridity index (AI) at Ziguinchor, Kolda, Kedougou and Tambacounda during the 1950-2000 period.

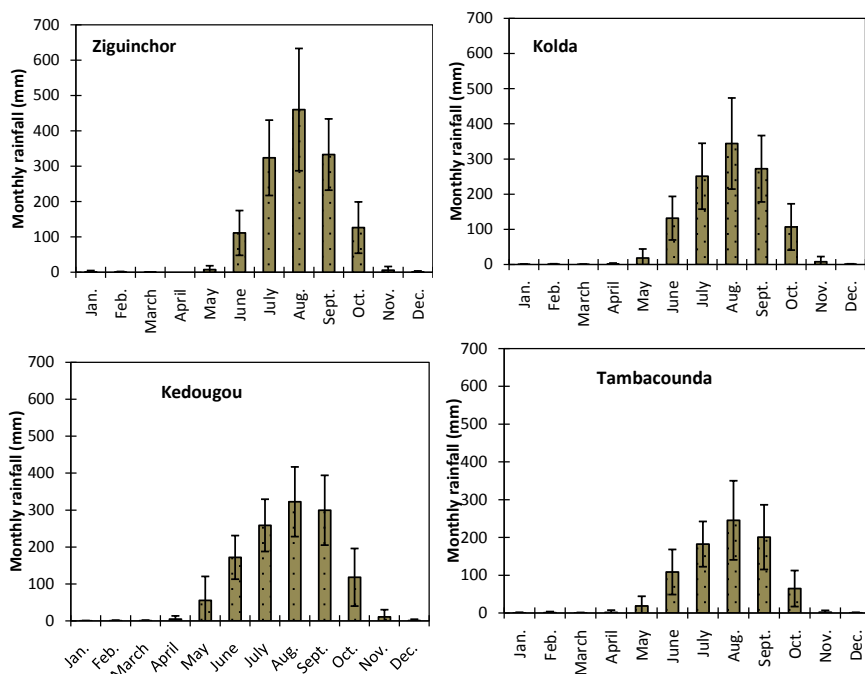


Figure 6. Long-term average monthly rainfall and Standard Error of the Mean (SEM) at Ziguinchor, Kolda, Kedougou and Tambacounda during the 1922-2015 period.

(NERICA-L) varieties adapted to rainfed and irrigated conditions. [41] indicated that the improved varieties performed better than the local varieties under good agricultural practices in the Casamance area. Since 2012, through the Feed the

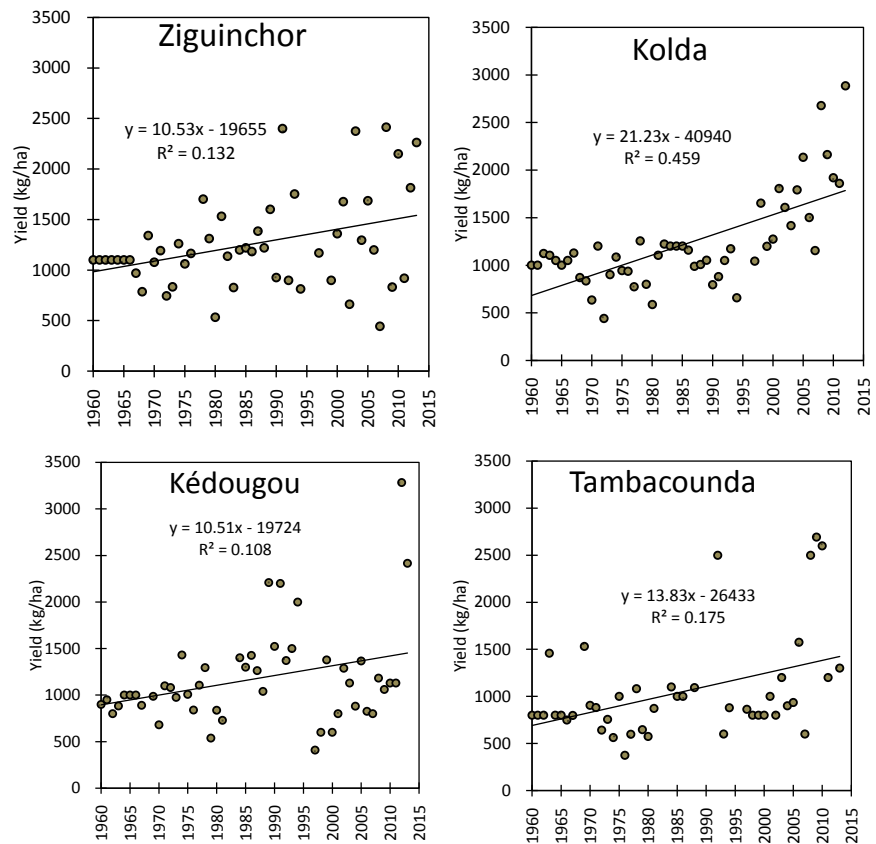


Figure 7. Evolution of paddy rice yield in the delegation of Ziguinchor, Kolda, Kedougou, and Tambacounda.

Future project funded by USAID, AfricaRice has been providing quality seed of the high yielding NERICAs to rice producers in the southern Senegal (<https://feedthefuture.gov/article/new-rice-variety-boosts-yields-senegal>). Some changes in practices have been adopted to control water under rainfed production as bonding the plots. Rainfall water can be harvested by collecting run-off, improving the infiltration capacity of the soil to increase water storage in soils, wetlands and the water table [42]. Small-scale water harvesting methods include terracing, using dams and ditches to channel run-off into fields, creating ponds, tanks and sub-surface storage in sand and soil [43]. Conservation tillage, and mulch or residue cover management are other strategies to reduce soil water evaporation. The adoption of these strategic systems can hold the equivalent of a few rainy-season deluges, enough to bridge month-long dry spells [44]. Dry spell within the crop growth and development period can be mitigated by in situ water harvesting. [45] indicated an increase in rice yield in the Mbarali and Kyela districts in Tanzania. [44] reported that doubling crop yields would be agro-hydrologically possible with relatively small manipulations of rainwater partitioning in the water balance or improvement in crop yield from 1 ton to 3 - 4 tons/ ha. Introduction of cover crop between two rice growing seasons can improve soil water storage and soil physical and chemical properties. These

management practices are summarized as climate-smart agriculture that increases resilience to climate change [46] [47]. Finally, a combination of different methods of determining the onset of the growing season [48] [49] with the estimated monthly aridity index should be used to determine the sowing window to minimize the effect of the dry spell on rice productivity and maximize rice yield under sustainable agriculture.

4. Conclusions

As rainfall and evapotranspiration are the most important variables for rice production under rainfed agriculture in the southern Senegal, this study investigated temporal trends in rainfall, evapotranspiration and aridity index. The trends in the annual and monthly (from May to October) time series were detected using the nonparametric Mann-Kendall tests, while the trend magnitude was estimated using nonparametric Theil-Sen and parametric regression methods. Adaptation strategies for the vulnerability of rainfed upland rice cultivation to the climatic changes were developed. For the full period 1922-2015, the results indicated a significant decreasing trend in annual rainfall at the rate of 5.78, 2.46, 2.18 and 3.15 mm/year at Zigninchor, Kolda, Kedougou and Tambacounda stations, respectively. This decreasing trend was also observed for monthly rainfall. While the sub-series of annual rainfall for the period 1922-1979 had the same decreasing trend as that for the full time series, annual rainfall in recent decades (1980-2015) shows an increasing trend.

The trend analysis of annual ETo revealed a significant increasing trend at three out of the four study stations during 1950-2000. The amount of the significant ETo trends varied from 1.19 mm/year at Zigninchor to 4.09 mm/year at Kedougou station. The trend analysis of aridity index for the period 1950-2000 showed a significant decrease in the annual aridity index, implying an increasing aridity in the region. This increasing tendency towards a drier climate was also observed in most months.

Appropriate adaptation strategies should be implemented to diminish the adverse influence of the increasing aridity on rice productivity for a sustainable agriculture. This includes adoption of short to medium duration rice varieties that can withstand the increasing aridity conditions under climatic change. Change of rice cropping pattern is another option to escape the peak of aridity and water demand. For instance, rice cropping period (or at least, the more sensitive growing stages of rice) can be limited to the July-September period with the lowest aridity based on our results. Proper water management strategies can be accomplished for harvesting rainfall water and reducing soil water evaporation.

The results of this study are practical however; new study should be conducted with broad coverage of the entire region. Moreover, projection of future climate is recommended to better understand the future climate and adopt new adaptation strategies to the climate change to mitigate the effects of the severity

of the aridity regarding water resources management for the sustainability of rainfed rice production under the Sahelian environment.

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