

Estimation of Current Agricultural Drought in the District des Savanes (Northern Côte d'Ivoire)

Léréyaha Coulibaly¹, Kouadio Assemien François Yao¹, Ismaïla Ouattara¹, Moussa Ouedraogo¹, Seydou Diallo², Amidou Dao², Emile Gneneyougo Soro², Bamory Kamagate²

¹Department of Mines and Reservoirs, Training and Research Unit in Geological and Mining Sciences, University of Man, Man, Côte d'Ivoire

²Geosciences and Environment Laboratory, Training and Research Unit in Environmental Sciences and Management, Nangui Abrogoua University, Abidjan, Côte d'Ivoire
Email: lereyaha.coulibaly@univ-man.edu.ci

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Abstract

This study investigates the spatio-temporal variability of soil moisture in relation to drought estimation over the period 1981-2022 in the District des Savanes of Côte d'Ivoire. Hydro-climatic data were used to compute the Standardised Soil Water Index (SSWI) at a six-month cumulative time scale (SSWI-6). Stationarity and trend tests were applied to identify breakpoints (Pettitt test), monotonic trends (Mann-Kendall test), and the magnitude of these trends (Sen's Slope) in the SSWI-6 series. In addition, the Inverse Distance Weighting (IDW) interpolation method was employed to assess the spatial variability of drought. Overall, the results reveal predominantly negative trends, indicating an intensification of agricultural drought since 1991. The period from 1995 to 2001 was characterized by particularly high rainfall across much of the district. However, a significant drought episode emerged in 1994 and became widespread across the district by 2010, except in the Korhogo region. The duration of the most frequent agricultural droughts exceeded five months, with prolonged episodes particularly affecting Boundiali, Ferkessédougou, and Kong. The findings highlight that the district has been highly exposed to recurrent droughts, although a slight recovery in soil moisture was observed between 1995 and 2001. Interannual variations of the index further revealed alternating dry and wet periods across the District des Savanes.

Keywords

Agricultural Drought, SSWI, Soil Moisture, Trend, District des Savanes, Côte d'Ivoire

1. Introduction

Across the world, populations are acutely experiencing the impacts of climate and environmental crises through water. Land desiccation, degradation of fertile soils, and the recurrence of drought episodes illustrate the growing vulnerability of ecosystems and human societies. According to the World Meteorological Organization [1], since 1970, weather-, climate-, and water-related hazards have accounted for nearly 50% of all recorded disasters and 45% of associated deaths, 90% of which occurred in developing countries. Among these hazards, drought stands out as one of the most severe threats to sustainable development, with a 29% increase in both frequency and duration since 2000 compared with the previous two decades [1]. More recently, the 8th Lancet Countdown Report on Health and Climate Change, published in 2023, highlighted that 48% of the world's land surface experienced at least one month of extreme drought in 2022, compared with an average of 15% during the 1980s, confirming the acceleration of a now global phenomenon [2] [3]. West Africa is a striking illustration of this trend, with marked decreases in rainfall and regional warming since the 1970s [4] [5]. Several studies have shown that the frequency, intensity, and spatial extent of droughts have become exceptional in this region [4] [6], leading to severe impacts on agriculture, livestock, and natural resources—sectors that are critical to both the economy and food security [7]. In Côte d'Ivoire, these changes are reflected in a significant decline in rainfall [8], an abnormal lengthening of the dry season [9], and growing pressure on an economy that relies heavily on rainfed agriculture, employing more than 60% of the workforce and contributing on average over 22% of GDP [10]. Against this backdrop, monitoring and anticipating drought conditions appear essential to strengthen the resilience of agricultural systems. Various climatic and hydrological indices have been developed for this purpose [11]. However, soil moisture stands out as an integrated indicator, directly linked to the hydrological cycle (evapotranspiration, infiltration, runoff) and critical for both plant growth and water availability in agroecosystems [12] [13]. The District des Savanes, in northern Côte d'Ivoire, is a strategic region for the national economy, with more than 661,000 hectares of agricultural land, of which 62% is devoted to food and horticultural crops (maize, rice, sorghum) and 38% to cash crops (cotton, cashew, mango) [14]. In this context, the analysis of soil moisture provides a relevant pathway to better understand and estimate current agricultural drought. The present study therefore aims to analyze, based on soil moisture data, the recent dynamics of agricultural drought in the District des Savanes.

2. Material and Methods

2.1. Study Area

The District des Savanes is located in the northern part of Côte d'Ivoire, bordering Mali and Burkina Faso (**Figure 1**). This area covers a surface of 40,323 km² and includes major cities such as Korhogo, Boundiali, and Ferkessédougou. With an

estimated population of approximately 2.16 million inhabitants and a demographic density of 53.72 inhabitants/km² [15], the district was created during the administrative reorganization of 2021. It is subdivided into three (3) regions—Bagoué, Poro, and Tchologo—comprising ten (10) departments: Boundiali, Kouto, Tingrela, Korhogo, Sinématiali, Dikodougou, M'Bengué, Kong, Ferkessédougou, and Ouangolodougou.

The Ivorian territory is influenced by several hydrological regimes: the transitional tropical regime (Sudanian climate), the transitional equatorial regime (Attiéen climate), the attenuated transitional equatorial regime (Baouléen climate), and the mountain regime. The District des Savanes is characterized by the transitional tropical regime (Sudanian climate). Specifically, the northern part of the country experiences a single rainy season, with peak intensity occurring in August, followed by a very long and distinct dry season marked by the Harmattan (dry wind, high temperatures, and low rainfall).

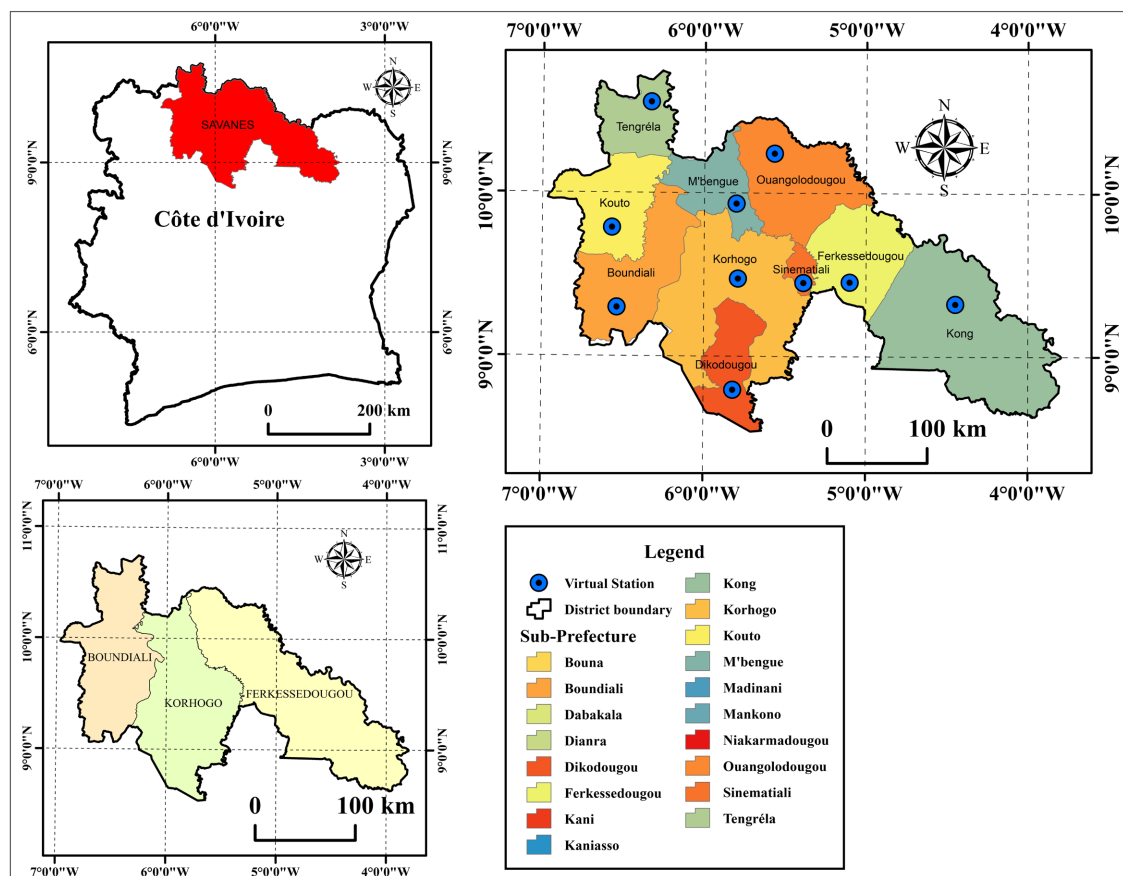


Figure 1. Administrative boundaries of the District des Savanes (Côte d'Ivoire).

2.2. Data Collection

This study is primarily based on the analysis of soil moisture data covering the entire study area. These hydro-climatic data, derived from satellite observations, were collected through virtual stations distributed across the District des Savanes

over the period 1981-2022 (**Table 1**). The satellite data originate from the NASA POWER Climate Data Access database, which provides monthly information on the global water balance and climate. This database constitutes an important source of information for hydrological studies at the global scale. All data have a spatial resolution of 0.5×0.625 . The dataset is accessible at:

<http://power.larc.nasa.gov/data-access-viewer/>. For the purposes of this study, the time series available from 1981 to 2022 was selected. The processing of these hydro-climatic data enabled the calculation of the Soil Moisture Index and the assessment of soil moisture dynamics across the study area.

The analyses were conducted using software tools adapted for climatic, statistical, and spatial processing. The Standardized Soil Water Index (SSWI) was computed in RStudio using the SPEI 1.8.1 package (CRAN, <https://cran.r-project.org>), which allows the calculation of standardized indices from precipitation and evapotranspiration series for the period 1981-2022. Trend and break detection in the SSWI series was performed using the Trend 1.1.5 package, applying Sen's slope test to quantify trends, Pettitt's test to identify breakpoints, and the Mann-Kendall test to evaluate statistical significance. Spatial analysis was carried out with QGIS 3.4.12 and ArcGIS, enabling the production of thematic maps of the District des Savanes, including the administrative map, the hydrographic network derived from a digital elevation model, and the spatial distribution of the drought index. The latter was obtained through interpolation using the Inverse Distance Weighting (IDW) method, in order to represent the spatial variability of drought at the regional scale.

Table 1. List of virtual stations.

Stations	Localities	X	Y
S1	Boundiali	-6.49	9.52
S2	Dikodougou	-5.77	9.07
S3	Ferke	-5.08	9.62
S4	Kong	-4.61	9.15
S5	Korhogo	-5.63	9.46
S6	Kouto	-6.41	9.90
S7	M'bengué	-5.91	10.01
S8	Ouangolo	-5.14	9.97
S9	Sinematiali	-5.38	9.58
S10	Tingrela	-6.41	10.48

2.3. Methods

2.3.1. Calculation and Interpretation of the Standardized Soil Moisture Index

The available soil moisture is calculated as a monthly average to obtain the soil moisture for each department. The soil moisture data were used to derive the Standardized Soil Moisture Index (SSWI) in order to account for drought. This

index requires soil moisture data recorded at different ground stations as input. The SSWI for a given location is calculated, for the selected period, from long-term soil moisture records. The standardized soil moisture index is statistically similar to other commonly used standardized precipitation indices. The index for a monthly period is defined as the difference in soil moisture between the monthly mean and the standard deviation calculated on a monthly basis.

$$SSWI_t = \frac{SW_{vt} - \overline{SW}_t}{\sigma_t} \quad (1)$$

With

$$\overline{SW}_t = \frac{1}{n} \sum_{v=1}^n F_{v,t} \quad (2)$$

$$\sigma_t = \sqrt{\frac{1}{n-1} \sum_{v=1}^n (SW_{v,t} - \overline{SW}_t)^2} \quad (3)$$

where t denotes the interval within the year and v denotes the year;

F and σ_t are the mean and standard deviation of month t , which ranges from 1 to 12 for monthly calculations. Negative SSWI values can be used as threshold levels to classify the intensity of agricultural drought. Here, we apply the classification system suggested by [16] to categorize the onset, intensity, and cessation of agricultural activities (Table 2). This system was used by [17] to monitor drought conditions and their uncertainty in Africa, and it has also been applied worldwide in many different contexts by other authors.

In the classification system proposed by [16], a “moderate” drought episode begins when the value of the SSWI or SSMI is less than or equal to -1 and ends when its value becomes positive. The Standardized Soil Moisture Index (SSWI) was chosen for the characterization of agricultural drought. The SSWI calculation procedure includes the estimation of soil moisture at different time scales and fitting to a given parametric distribution. For the present study, a 6-month time step was applied because the 6-month and 9-month timescales are the periods required for the characterization of agricultural drought according to the WMO. Soil moisture (agriculture) responds relatively quickly to precipitation anomalies, over a timescale that can extend up to 9 months (agricultural drought: SPI-6, SPI-9) (WMO, 2012).

Table 2. Drought classification by value according to [16].

Valeurs SSWI	Drought class
$SSWI \geq 2.0$	Extremely wet
$1.5 \leq SSWI < 2.0$	Very wet
$1.0 \leq SSWI < 1.5$	Moderately wet
$1.0 \leq SSWI < 0$	Slightly wet
$-1.0 < SSWI \leq 0$	Slightly dry
$-1.5 < SSWI \leq -1.0$	Moderately dry
$-2.0 < SSWI \leq -1.5$	Severe drought

2.3.2. Methods for Analyzing the Temporal Variability of the SSWI

The analysis of the temporal variability of the SSWI is structured around the different stations in the District des Savanes in order to capture the distribution of drought within each station based on the SSWI values obtained. The SSWI is considered an improved drought index, particularly well-suited for climate change analysis [18]. The SSWI is based on a water balance determined by the difference between precipitation (P) and evapotranspiration (ETP) for month i :

$$P_i = P_i - ETP_i \quad (4)$$

D_i provides a simple measure of the water surplus or deficit for the month under analysis.

▪ Trend and break tests in standardized soil moisture index series

The purpose of these tests in the SSWI series is to assess the temporal distribution of the records in the District des Savanes. For our case study, we used the Pettitt test developed by [19], the Mann-Kendall test developed by [20] and [21], as well as Sen's slope proposed by [22]. These procedures were designed to facilitate statistical testing. They also allow the detection of breakpoints in measurement series, and the assessment of the magnitude and significance of increasing or decreasing trends over time [23]. The Pettitt test allows us to identify a change point by checking whether the means of two different periods are significantly different. The Mann-Kendall test was applied to detect a drying or wetting trend in the area. To determine the magnitude of the change, Sen's slope method was applied. It should be noted that when the assumption of normality is not satisfied and the sample size is small, a set of so-called non-parametric tests is used, while parametric tests are applied in the opposite case. **Table 3** summarizes all the tests used in this study.

Table 3. Tests selected for the study.

Test	Break detection	Trend detection	Amplitude detection
Non-parametric	Pettitt test	Mann-Kendall	Sen's slope

▪ Sen's slope

If a linear trend is present in the time series, the true slope can be estimated using a simple non-parametric test known as Sen's slope estimator. Reference [22] developed a non-parametric procedure to estimate the trend slope from a sample of N data pairs:

$$T_i = \frac{X_j - X_k}{j - k}, \quad i = 1, 2, 3, \dots, N \quad (5)$$

where X_j and X_k represent the data values at time steps " j " and " k " respectively, with " j " being greater than " k ". The median of these " N " T_i values is called the Sen's slope estimator and is calculated using the following formulas:

If N is even:

$$\beta = \frac{1}{2} \left(\frac{T_N}{2} + \frac{T_{N+2}}{2} \right) \quad (6)$$

If N is odd:

$$\beta = \frac{T_{N+1}}{2} \quad (7)$$

▪ Mann-Kendall test

This method tests whether there is a trend in the time series data. It is a non-parametric test. The n values of the time series ($X_1, X_2, X_3, \dots, X_n$) are replaced by their relative ranks ($R_1, R_2, R_3, \dots, R_n$) (from 1 for the lowest up to n). The test statistic S is:

$$S = \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^n \text{sgn}(R_j - R_i) \right) \quad (8)$$

where $\text{sgn}(x) = 1$ for $x > 0$; $\text{sgn}(x) = 0$ for $x = 0$; $\text{sgn}(x) = -1$ for $x < 0$.

If the null hypothesis H_0 is true, then S is approximately normally distributed with:

$$\mu = 0; \quad \sigma = n(n-1)(2n+5)/18$$

The z statistic is therefore (the critical test statistic values for various significance levels can be obtained from the standard normal probability tables):

$$z = |S|/\sigma^{0.5}$$

A positive value of S indicates an upward trend, and vice versa.

2.3.3. Method of Analysis of the Spatial Variability of the SSWI

Spatialization was carried out using Inverse Distance Weighting (IDW) interpolation, which estimates unknown values from available observations. This method is simple, fast, and well-suited to irregularly distributed data. According to Lloyd and [24], IDW provides reliable estimates with minimal parameterization. It allows for the assessment of the spatial distribution of the studied variables, in this case soil moisture. The SSWI indices, calculated over different time scales (1981-2022), were thus interpolated. This approach enabled the mapping of the spatial variability of drought within the study area.

The inverse distance method (commonly referred to by the acronym IDW: Inverse Distance Weighting) is an interpolation technique based on the distances between the location where a value is to be estimated and neighboring points with known measurements. IDW interpolation explicitly applies the assumption that entities closer to each other are more similar than those further apart. To predict a value at an unmeasured location, IDW uses the measured values surrounding the prediction site. Measured values closer to the prediction location have greater influence on the predicted value than those further away. Thus, the IDW function assumes that each measured point has a local influence that decreases with distance. The IDW function should be used when the set of points is sufficiently dense to capture the extent of local variation across the surface required for anal-

ysis. IDW determines cell values using a set of sample points combined with a linear weighting scheme. It assigns higher weights to points nearer to the prediction location than to those farther away, hence the name inverse distance weighting.

The predicted value for a spatial point is calculated as the weighted mean of surrounding observation points (virtual stations, in this case), with greater weight assigned to the nearest points. The predicted value at a given location is expressed as:

$$\left[\sum_{i=1}^N \frac{Z_i}{d_i^k} \right] / \left[\sum_{i=1}^N \frac{1}{d_i^k} \right] \quad (9)$$

With,

Z = the estimated variable;

Z_i = the observed value at the measurement points i ;

d = the distance between the prediction point and the observation point i ;

N = represents the number of stations used in the interpolation process;

k = the power to which the distance is raised.

In most cases, $k = 2$. However, it may be relevant to use other values of k depending on the time step under consideration. For rainfall in particular, the optimal value of k for annual totals appears to be less than 1.5 [25].

3. Results and Discussion

3.1. Results

3.1.1. Interannual Elevation of SSWI-6 Time Series for the 1981-2022 Records

Figure 2 and **Figure 3** illustrate the interannual evolution of the SSWI-6 indices computed over the period 1981-2022. The blue areas represent positive values (moisture) of SSWI-6, while the red areas indicate negative values (drought). For the District des Savanes, all stations begin with short humid periods alternating with drought between 1981 and 1995, with drought conditions being predominant. From 1996 to 2010, a more pronounced alternation is observed, with drought episodes sometimes ranging between -0.1 and -2.2 , reflecting conditions from mild to extreme drought, but also occasional moist incursions. From 2011 onwards, a significant increase in the index is recorded across all stations, indicating wetter periods, particularly between 2015 and 2020. However, from 2021, negative SSWI-6 values reappear, pointing to an episode of extreme drought.

3.1.2. Stationarity Breaks and Trend Analysis in SSWI Series

Table 4 presents the results of the Pettitt test applied to the SSWI-6 indices, which identifies breakpoints in the time series for ten stations in the District des Savanes, along with the trend analysis associated with these breaks using Sen's slope and the Mann-Kendall test. The results show that three years dominate as break periods in the series: 1991, 1992, and 2009, reflecting significant climatic disturbances at the regional level during these periods.

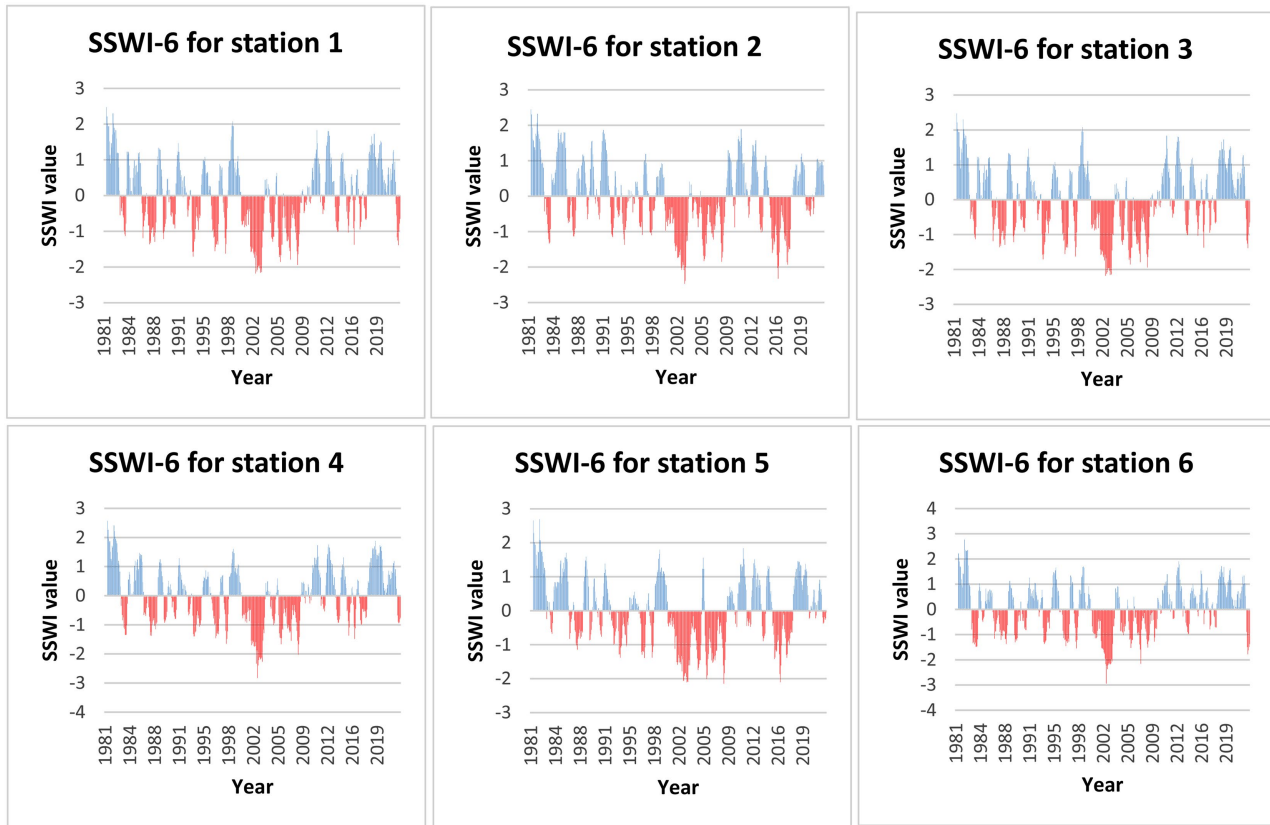


Figure 2. Interannual variability of SSWI-6 indices recorded from stations 1 through station 6.

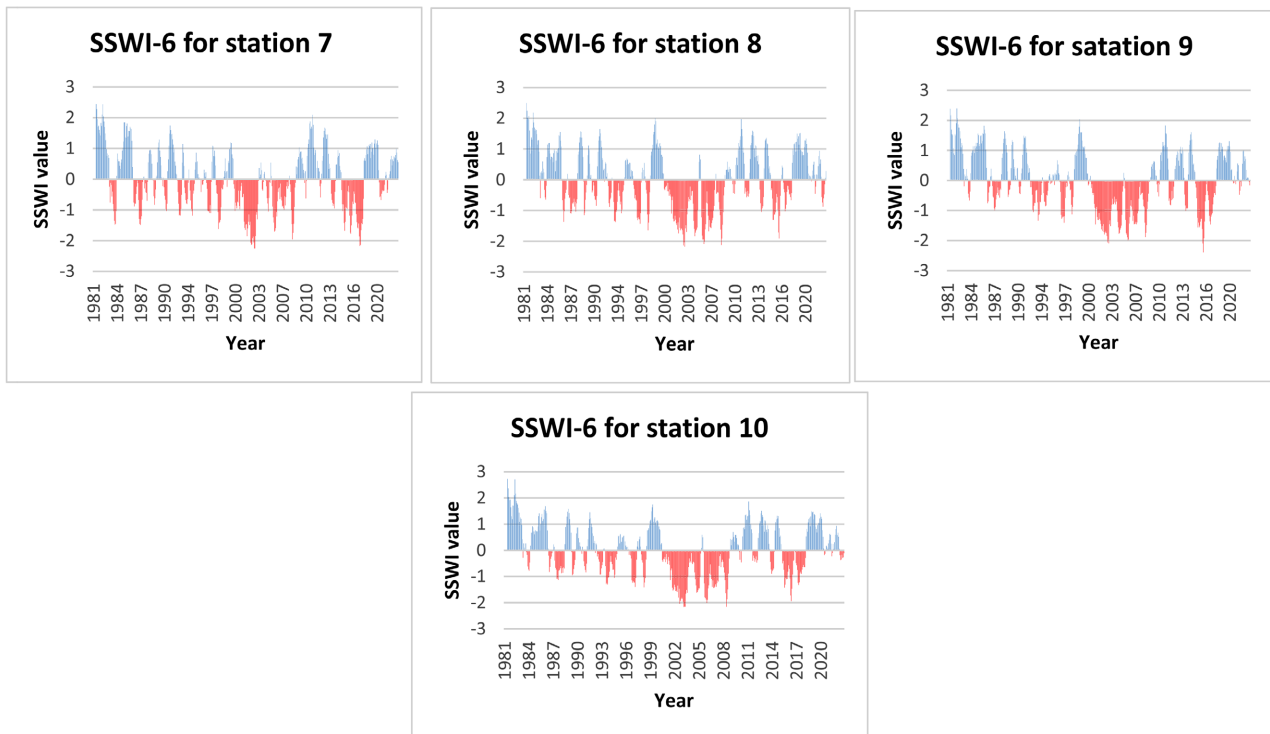


Figure 3. Interannual variability of SSWI-6 indices recorded from stations 7 through station 10.

The Pettitt test shows broadly similar results for most of the studied stations, with the exception of Station 4 (S4) (Table 4). Breaks were detected in 1991 for Stations 5, 9, and 10 (S5, S9, and S10), with precise dates in December 1991. For Stations 2, 7, and 8 (S2, S7, and S8), the break dates occurred in 1992, specifically in January and February. Subsequently, new breaks appeared in 2009 for Stations 1, 3, and 6 (S1, S3, and S6), precisely in April 2009.

With respect to the trend test (Mann-Kendall), the SSWI-6 values are generally negative. However, Stations 1, 3, and 6 (S1, S3, and S6) show positive values. Based on these results, Stations 7, 8, and 10 (S7, S8, and S10) remain the areas where drought progression is most pronounced, with slopes of 9.35×10^{-4} , 8.63×10^{-4} , and 9.88×10^{-4} in absolute terms, respectively. The magnitude of the trend was estimated using Sen's slope. Slopes remain negative and weak from one station to another, except for Stations 1, 3, and 6 (S1, S3, and S6), which present positive slopes (Table 4). According to these results, Stations 2, 5, and 10 (S2, S5, and S10) also show accelerated drought progression with respective slopes of 8.13×10^{-5} and 8.31×10^{-5} in absolute terms. Finally, the rate of drought progression remains relatively weak at Station 5 (S5), compared with other stations in the District des Savanes, with a slope of 5.62×10^{-5} in absolute terms.

The Mann-Kendall test shows result consistent with those of Sen's slope, thereby confirming the observed trends.

Table 4. Break and trend tests of the SSWI-6 indices for stations in the District des Savanes.

Stations	Change-point Test	Trend Test	Trend Magnitude
	Pettitt. Test	Mann-Kendal (.10 ⁴)	Sen's slope (.10 ⁻⁵)
S1	Apr-2009	0.59	6.20
S2	Jan-1992	-1.62	-7.92
S3	Apr-2009	0.59	6.20
S4	Apr-2008	2.45	2.49
S5	Dec-1991	-1.10	-8.13
S6	Apr-2009	7.70	9.45
S7	Jan-1992	-9.35	-5.62
S8	Feb-1992	-8.63	-7.18
S9	Dec-1991	-1.60	-7.64
S10	Dec-1991	-9.88	-8.31

3.1.3. Spatial Variations of the Standardized Soil Moisture Index (SSWI)

▪ Seven-year temporal variability of the SSWI

Figure 4 illustrates the seven-year variation of the Standardized Soil Moisture Index (SSWI-6) in the District des Savanes over the period 1981-2022. The SSWI-6 values allow the assessment of soil water status: positive SSWI-6 values indicate a soil moisture surplus, whereas negative values indicate a water deficit, reflecting soil drying and potentially different types of droughts (meteorological, agricultural, etc.).

The first seven-year period (1981-1987) generally shows a situation of moderate drought, affecting the western areas (Kong and Ferké) and the eastern areas (Boundiali and Kouto), while other parts of the district remain relatively wet. In the following seven-year period (1988-1994), this drying trend intensifies, extending across almost the entire district except for Dikodougou, where the index values remain positive.

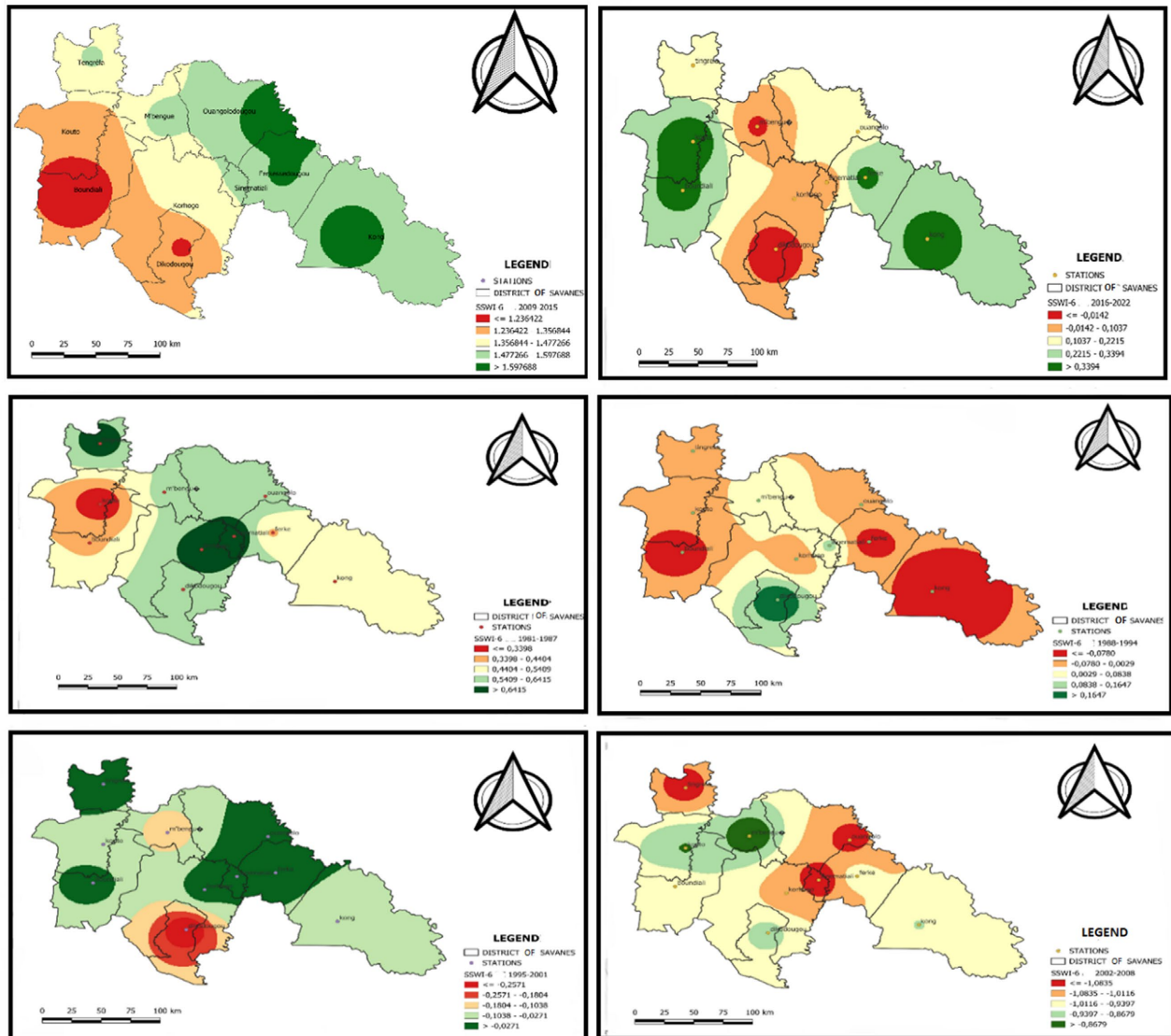


Figure 4. Seven-year variation of the SSWI-6 indices in the District des Savanes over the period 1981-2022.

A reversal of the trend is observed in the 1995-2001 seven-year period, with the index rising toward positive values, particularly in the central-west, central-east, and northern zones. However, this improvement was temporary. Between 2002 and 2008, a gradual return to drought conditions was observed throughout the District des Savanes, except in M'bengué, Kouto, and Dikodougou. The 2009-2015 period presents a contrast between areas of water deficit and wet areas: the eastern

zone is dominated by drought, while the western zone remains wet.

Finally, the last seven-year period (2016-2022) shows an alternation between dry and wet periods, directly opposing the first seven-year period. Indeed, towns such as Tingrela, M'bengué, Ouangolo,

▪ **Spatialization of SSWI-6 slopes before and after the breakpoint**

The spatial distribution of the amplitude of SSWI-6 trends reveals a marked heterogeneity between the pre- and post-breakpoint periods. Before the breakpoint (**Figure 5(a)**), most localities exhibit significant negative trends, indicating a gradual decline in soil moisture across the district, with the exception of Dikodougou, which shows positive Sen's slope values (dark green). This pattern reflects an intensification of dry conditions during the 1980s-1990s.

By contrast, after the breakpoint (**Figure 5(b)**), the intensity of negative trends weakens considerably, and several areas even display reversals towards positive trends. This shift suggests a relative recovery of soil moisture conditions from the 2000s onwards, supporting the hypothesis of improved rainfall and a more favourable seasonal variability.

Overall, the comparison between the two periods highlights the existence of a climatic cycle characterized by a pronounced deficit phase followed by a relative replenishment of soil moisture. These dynamic underlines the role of regional and global climatic oscillations (ENSO, NAO, PDO) in modulating water availability. It also confirms the usefulness of soil-moisture-based drought indices (SSWI) in assessing hydroclimatic transitions at the regional scale.

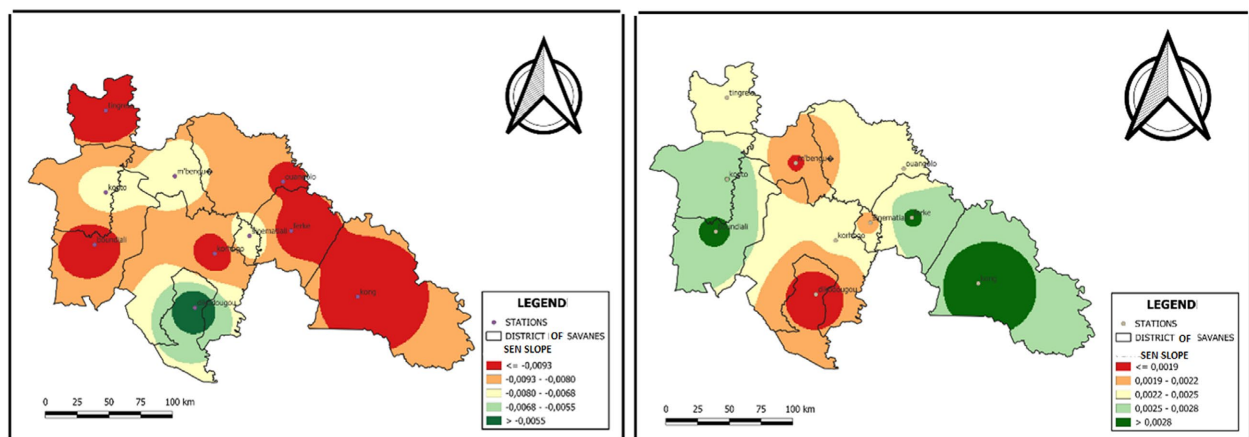


Figure 5. Spatial distribution of the amplitude of SSWI-6 trend indices over the period 1981-2022 ((a) Trend before breakpoint; (b) Trend after breakpoint).

3.1.4. Frequency Distribution of Drought Intensities for the Period 1981-2022

Figure 6 illustrates the distribution of frequencies of the different drought intensities (mild, moderate, severe, and extreme) observed across ten stations in the District des Savanes, based on the Standardised Soil Moisture Index (SSWI-6).

The analysis of drought frequency and intensity highlights relatively homogeneous patterns across the stations, with total drought proportions ranging from

49% to 51%. The dominant component consists of mild droughts, representing between 32% and 35% depending on the station. This predominance reflects a significant recurrence of moderate rainfall anomalies that are likely to affect agricultural yields without necessarily leading to extreme crisis conditions.

Moderate droughts are less frequent (10% - 11%), while severe (3% - 5%) and extreme (2%) droughts remain relatively rare. Nevertheless, their occurrence across all stations underscores that, even though such events are infrequent, they may exert a disproportionate impact on ecosystems and food security. From a spatial perspective, Station 2 records the highest overall frequency (51%), reflecting slightly greater vulnerability, whereas Station 1 and Station 3 show the lowest values (49%). Station 4 occupies an intermediate position (50%), though with a more pronounced proportion of mild droughts (35%). These differences, albeit modest, may be linked to local contrasts in climatic, topographic, or land-use conditions.

Identifying this frequency structure is crucial for guiding adaptation strategies, particularly in the agricultural and water sectors, where managing recurrent but low-intensity droughts must be complemented by resilience mechanisms against rarer but potentially devastating severe episodes.

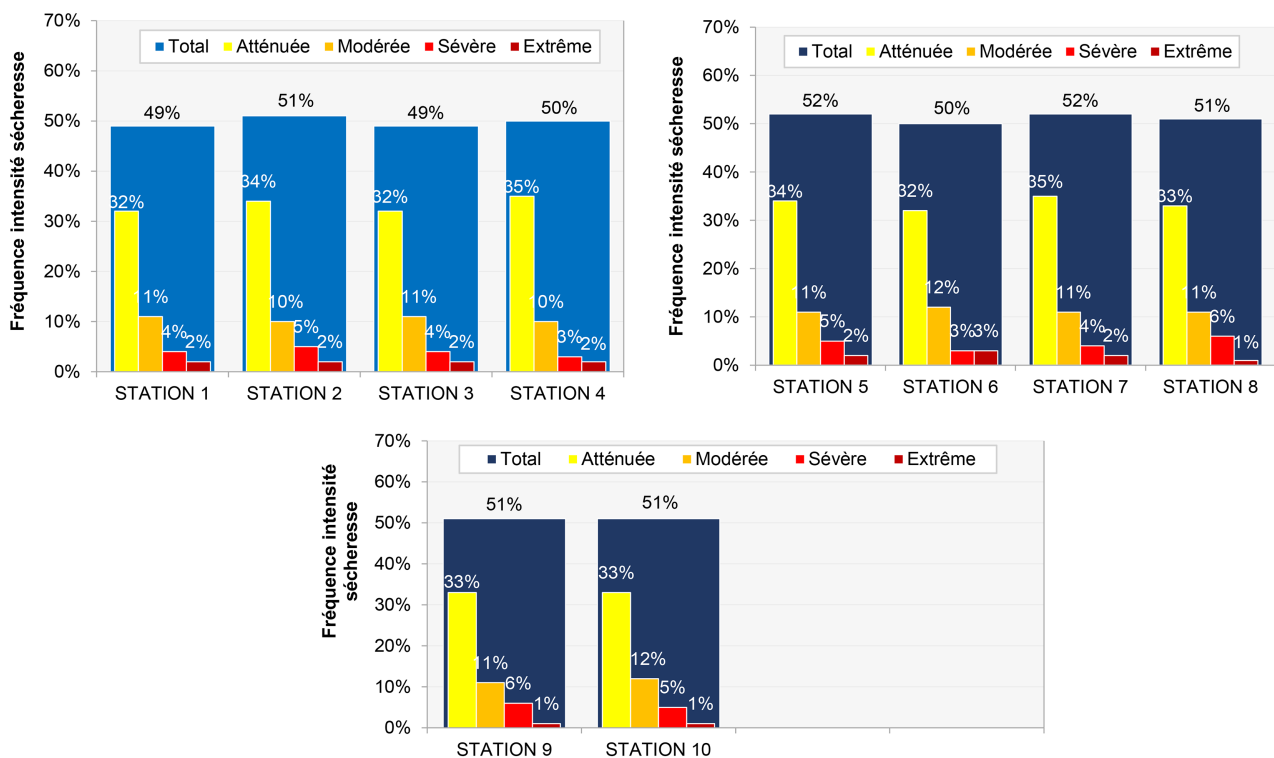


Figure 6. Frequency distribution of drought intensities for the period 1981-2022.

3.2. Discussion

The time series analysis of the SSWI-6 in the District des Savanes reveals marked climatic variability, with drought episodes ranging from mild to severe, according

to the classification of [16]. The most critical periods were observed between 1981 and 1995, and again from 2021 onwards, indicating a trend towards drier conditions. These episodes coincide with regional climatic anomalies, such as the severe droughts of the 1980s and 1990s, attributed to ENSO (El Niño-Southern Oscillation) events that affected West Africa and Brazil between 1993 and 1998 [26]. This observation is corroborated by the findings of [27], which demonstrated that warming of the Indian and Atlantic Oceans induced atmospheric circulation anomalies influencing the climate during that period. Large-scale climatic oscillations such as ENSO, the North Atlantic Oscillation (NAO), and the Pacific Decadal Oscillation (PDO) are known to influence the West African monsoon system through their effects on atmospheric circulation and sea surface temperature gradients. Specifically, warm ENSO phases (El Niño) tend to weaken the monsoon by displacing the Intertropical Convergence Zone (ITCZ) southward, thereby reducing rainfall over northern Côte d'Ivoire. Conversely, positive NAO phases can enhance subtropical high-pressure systems over the Atlantic, limiting moisture advection from the Gulf of Guinea, while PDO-related anomalies can modulate these effects over longer timescales.

The tests applied to the analysis of trends and breakpoints in the SSWI-6 indices confirm significant changes between 1981 and 2022 across all localities of the District des Savanes. The temporal analysis highlights a slight downward trend, reflecting a shift towards drier conditions.

This tendency is linked to declining rainfall since the 1970s, combined with rising temperatures. Research by [28] on Côte d'Ivoire as a whole, based on rainfall series from 1961 to 2016, revealed a decrease in precipitation alongside an increase in temperatures. These downward trends persisted until the 1991-2009 period. Reference [29] also emphasized the establishment of drought conditions beginning in the 1970s, which extended through to the late 1990s. The most significant breakpoints were recorded between 1991 and 2009, with a peak in 1991, considered a major rupture period across sub-Saharan Africa [30]. These findings are consistent with studies by [31], who documented declining rainfall between 1940 and 2010 across the four agroclimatic regions of Côte d'Ivoire, partly attributed to the disruption of the seasonal northward migration of the Intertropical Front (ITF) [32].

From 2009 onwards, however, an increase in soil moisture was observed in most stations. This improvement could be linked to a recovery in rainfall, which enhances soil water recharge. Several studies conducted in Côte d'Ivoire have confirmed a rainfall recovery during the 2000s, indicating a trend towards soil rehumidification [33] [34].

Drought assessment using the SSWI over a six-month period reveals significant variations according to drought type. While intensity remains relatively homogeneous across stations, the duration of episodes shows considerable disparities. Mild drought emerges as the most frequent and dominant category, with variable durations. Furthermore, the six-month period chosen for this characterization is

deemed sufficiently long to capture fluctuations associated with agricultural drought, in line with the recommendations of the World Meteorological Organization [34]. These results are consistent with [35], who demonstrated that extended analysis periods enriched with historical data reduce index variability and better define drought episodes. The mild droughts identified appear to be mainly driven by rainfall deficits, resulting in reduced soil moisture during the study period. This situation poses risks for local agriculture. Reference [36] also reported declining rainfall in the Sahelian region. According to [37], this decline intensified during the 1980s and 1990s, before showing a slight recovery in the 2000s, reflecting the mild drought conditions recorded in the district.

The spatial variability of the SSWI-6 was examined to assess drought using the IDW interpolation method over the period 1981-2022. Results reveal that drought affected the district throughout this period, with particularly pronounced spatial extension during the intervals 1988-1994 (a) and 2002-2008 (b), where 60% - 90% of localities were impacted. It is noteworthy that the most affected periods coincide with the most intense drought phases. Moreover, the analysis of amplitudes before and after the 1991 breakpoint shows negative values prior to the rupture, followed by positive amplitudes thereafter. This suggests that before 1991, the district experienced a widespread water deficit affecting almost the entire District des Savanes, whereas after the breakpoint, a trend towards increasing soil moisture became apparent. These results confirm the observations of [38], who reported that the decades 1970-1979, 1980-1989, and 1990-1999 were characterized by recurrent drought episodes in Côte d'Ivoire, associated with profound regional climatic changes since the 1970s.

4. Conclusions

The spatiotemporal analysis of the six-month Standardized Soil Water Index (SSWI-6) reveals that the District des Savanes was recurrently affected by drought episodes between 1981 and 2022, showing pronounced temporal and spatial variability. Overall, the SSWI-6 time series manifests a long-term declining tendency, suggesting an increasing predisposition to dry conditions. However, this general trend is punctuated by intermittent periods of partial recovery, particularly following the major climatic shift identified in December 1991 by Pettitt's change-point test. This breakpoint corresponds to a widespread drought episode, after which several localities experienced a temporary rebound in soil moisture, reflecting short-lived improvements in hydrological conditions rather than a reversal of the overall drying trend. Spatially, the steepest negative slopes are observed at Dikodougou (S2), Korhogo (S5), and Tingrela (S10) (-7.92×10^{-5} , -8.13×10^{-5} , and -8.31×10^{-5} , respectively), closely followed by M'Bengué (S7), Ouangolodougou (S8), and Sinématiali (S9). In contrast, Kong (S4) shows a more moderate trend (-2.49×10^{-5}), while a few stations, notably Ferkessédougou (S3) and Niellé (S6), display weakly positive slopes, indicating localized resilience or recovery in soil moisture. This spatial heterogeneity underscores the influence of both re-

gional climatic forcing—particularly declining rainfall and rising temperatures—and local factors such as land cover, soil properties, and water management practices.

The assessment of drought frequency and duration confirms that, although most events were of low to moderate intensity, particularly severe periods occurred between 1988-1994 and 2002-2008. Taken together, these findings suggest that the District des Savanes is undergoing a long-term drying process with short-term fluctuations and localized improvements. Identifying both the most vulnerable areas and the relatively resilient ones provides a crucial foundation for designing targeted, sustainable water resource management and agricultural planning strategies aimed at mitigating the impacts of future droughts on production systems and rural livelihoods.

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Conflicts of Interest

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

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