GSC Advanced Research and Reviews
eISSN: 2582-4597 CODEN (USA): GARRC2
Cross Ref DOI: 10.30574/gscarr
Journal homepage: https://gscarr.gsconlinepress.com/

(Research Article)

Check for updates

CHARACTERIZING DROUGHT AT MALANVILLE USING A MULTISCALE STANDARDIZED WATER-BALANCE INDEX (NIGER BASIN, BENIN)

Jean SODJI [1, 2, *] and Hervé Dégla KOUMASSI [1, 2]

[1] Institut du Cadre de Vie (ICaV), University of Abomey-Calavi, Benin.
[2] Laboratoire Pierre Pagney – Climate, Water, Ecosystem and Development, University of Abomey-Calavi, Benin.
* Corresponding Author; Email: kharidad1@gmail.fr

ORCID Details
Hervé Dégla KOUMASSI: https://orcid.org/0000-0003-0798-181X

GSC Advanced Research and Reviews, 2026, 28(03), 075–086

Publication history: Received on 27 July 2026; revised on 02 September 2026; accepted on 05 September 2026

Article DOI: https://doi.org/10.30574/gscarr.2026.28.3.0221

ABSTRACT

The rainfall regime at Malanville (northern Benin, Niger River basin) shows strong intra- and inter-annual variability typical of the Sudano-Sahelian domain, yet drought diagnostics based on rainfall alone do not account for evaporative demand. This study builds and consolidates a standardized water-balance index (SWBI) that integrates potential evapotranspiration (PET) to characterize drought episodes at Malanville over 1995-2024.

In the absence of a temperature record at Malanville itself, PET is estimated with the Hargreaves-Samani method from the 1991-2020 climatological normals of the nearby Kandi station (~100 km away), applied as a fixed seasonal cycle. The monthly water balance (P − PET) is standardized by calendar month at four time scales (1, 3, 6, 12 months), and dry episodes are extracted with run theory (threshold −1). Robustness is tested with seven independent indices: the Rainfall Anomaly Index, a gamma-fitted SPI, the decile method, the ETCCDI daily climate indices, the De Martonne aridity index, the Bagnouls-Gaussen xerothermic index, and the length of the wet period.

Cumulative annual PET (1,949.4 mm) far exceeds mean annual rainfall (823.9 mm), yielding an annual aridity index of 0.42. At the 3-month scale (77% data coverage), 15 dry episodes are identified, the most severe being May-July 2018 (peak −2.10). Four statistically independent methods agree perfectly in flagging 1995, 2013, 2021 and 2023 as robust deficit years, and 2003, 2019 and 2024 as surplus years. Gamma fitting (SPI-Gamma), better suited to the skewness of rainfall series, systematically increases the estimated severity of the driest years relative to a normal approximation. Indices targeting the intra-annual distribution of rainfall (dry months, wet months), nearly independent of the annual total ($r < 0.2$), reveal distinct information: 2024, classified wet on annual total alone, has as many dry months as 2023, a confirmed deficit year.

The convergence of seven methodologically independent indices around the same critical years (1995, 2013, 2021, 2023) gives substantial robustness to the drought diagnosis at Malanville, despite the limitations inherent in using a regional temperature climatology as a proxy. The multi-index approach proposed here, combining water balance, classical rainfall indices and standardized daily climate indices, offers a transferable framework for other Sahelian stations facing comparable data constraints.

Keywords: Drought; Standardized Water-Balance Index; SPI; Sahel; Niger Basin; Benin.

1 INTRODUCTION

Among the climatic hazards weighing on Sahelian agropastoral societies, drought occupies a special place, yet its definition remains disputed. Wilhite and Glantz [1] already distinguished four meanings of the term: meteorological, when rainfall falls short of a norm; agricultural, when this shortfall deprives crops of usable water; hydrological, when it affects streamflow or water reserves; and, finally, socio-economic, when its effects touch human activity. These categories are not interchangeable, and choosing one over another often changes the diagnosis reached for a given territory. In the Sahel, this choice matters doubly, because drought there is not simply a matter of the annual total: Nicholson [2], after several decades of observation, describes a rainfall regime of exceptional inter-annual and intra-seasonal variability, in which the rainfall recovery that began in the mid-1990s, after the major droughts of 1970-1980, does not restore the earlier regime and in fact masks a redistribution of rainfall intensity.

Lebel and Ali [3] documented this redistribution at the sub-seasonal scale: since 1990, the recovery in annual totals has been accompanied, depending on the region, by contrasting trends in the number of rain days and their intensity, which argues for a finer reading of the regime than the total alone. Panthou, Vischel and Lebel [4] go further, showing, over the central Sahel, an intensification of extreme rainfall since the 1990s even as the total number of rainy days remains stable, or even declines slightly. Some have described this as a “Sahelian paradox”: streamflow and runoff increase locally even though annual rainfall does not exceed its level before the major droughts [5]. It is this evolution in rainfall structure, more than the total alone, that justifies turning to indices able to capture other dimensions of the rainfall regime the standardized daily climate indices and the intra-annual distribution indices used in the present study are part of this effort.

The rainy season itself is changing. Drawing on observations from several Sahelian stations, Salack et al. [6] describe the emergence of “hybrid” seasons: late onsets, more frequent early-season breaks, and useful rainfall concentrated into a shorter window traits that bear directly on rainfed agriculture in the study area. Climate projections extend these observed trends. Sylla et al. [7], using regional CORDEX-Africa simulations, project a robust shift of West African climate zones toward warmer, drier regimes by the end of the century; Klutse et al. [8] show, for global warming levels of 1.5 °C and 2 °C, an intensification of consecutive dry spells across much of West Africa, with a clear differential between the two thresholds. The IPCC reaches the same conclusion at the continental scale: as early as its fourth assessment report, Africa was identified as one of the continents most vulnerable to climate variability and change, owing to a combination of multiple stresses and low adaptive capacity [9]; the sixth assessment report, in turn, stresses the urgency of fine-scale local characterization of hydroclimatic extremes to support adaptation strategies in sub-Saharan Africa [10].

It is against this backdrop that a reference rainfall study recently characterized daily dry spells at Malanville [11]. Its main finding was that, in the absence of a significant trend in the annual total, drought there is expressed above all through rainless intra-seasonal sequences, potentially critical for rainfed crops. That approach, however, based on precipitation alone, does not capture the evaporative demand of the atmosphere, which is nonetheless decisive for the water actually available to crops and ecosystems. The present study extends that work by introducing potential evapotranspiration (PET), in order to build a standardized water-balance index (SWBI) for Malanville. It pursues five objectives: to estimate a mean monthly climatological PET cycle in the absence of a local temperature record; to build an SWBI at several time scales (1, 3, 6 and 12 months); to extract and characterize drought episodes using run theory; to compare these results with those already obtained from rainfall alone; and, finally, to consolidate the whole with seven statistically independent indices, including standardized daily climate indices (ETCCDI) and indices targeting the intra-annual distribution of rainfall.

1.1 Study Area

Malanville is a municipality in northern Benin, in the Alibori department, on the right bank of the Niger River and on the border with the Republic of Niger. It lies at the transition between the Sudano-Sahelian domain and the strict Sahel, with a unimodal rainy season (June to September-October) and a long dry season; mean annual rainfall over the study period (1995-2024) is close to 820 mm. The local economy relies heavily on rainfed agriculture and flood-recession market gardening practiced along the river two activities strongly exposed to rainfall variability, whether intra- or inter-annual.

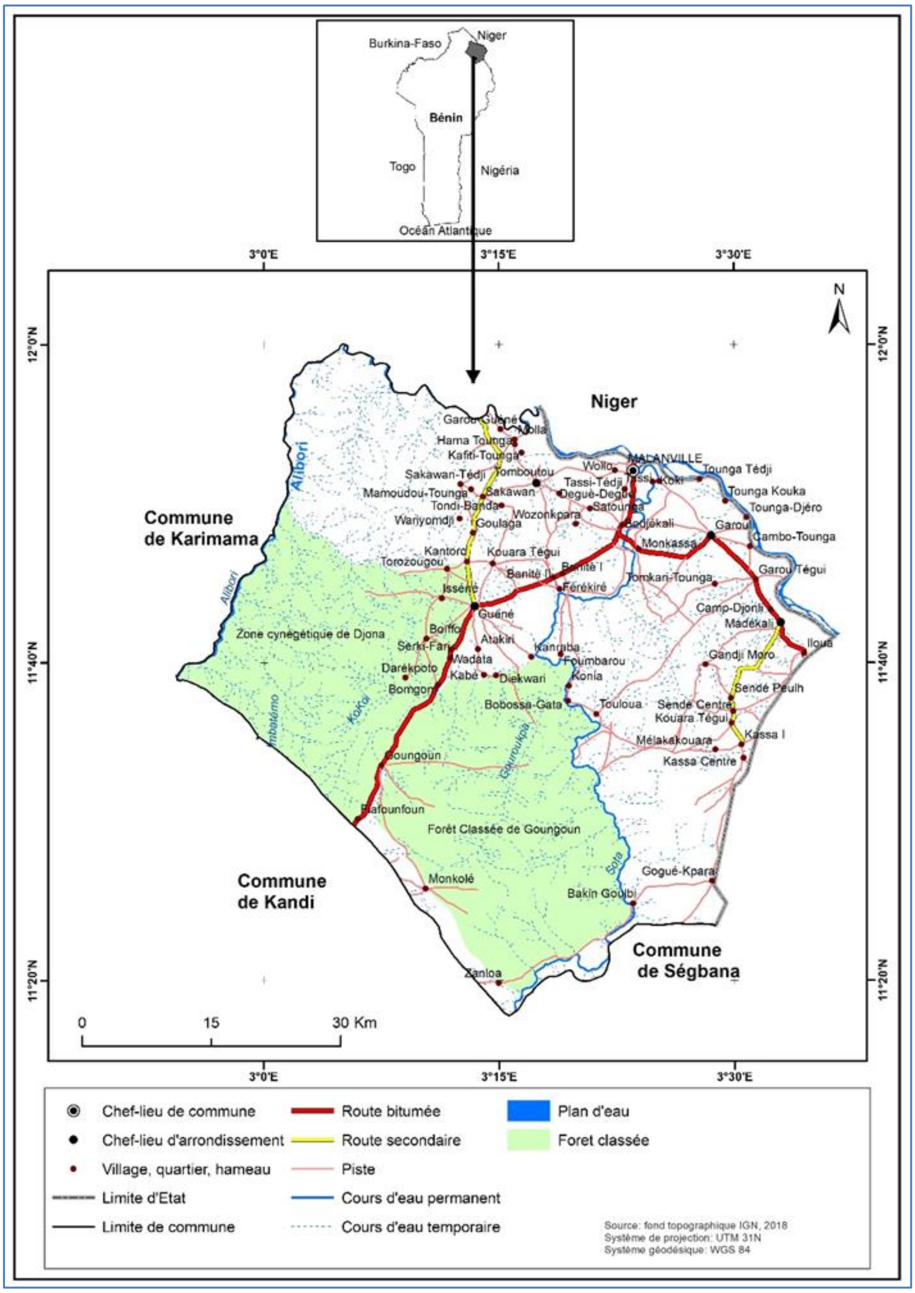

Figure 1: Location of the Malanville Municipality.

2 MATERIALS AND METHODS

2.1 Rainfall Data

The daily rainfall series for Malanville, supplied by the Red Cross for the period 1995-2025, is aggregated into monthly totals. A month is retained as usable only if at least 90% of its days are recorded; below this threshold it is treated as missing rather than underestimated, so as to avoid biasing totals downward. Three years are excluded under the same criteria as the reference rainfall study: 1999, for which only January to May are recorded; 2025, whose record, although complete, is entirely zero a result incompatible with an actual observation; and 2007, entirely absent from the series. The retained series thus spans 28 years, from 1995 to 2024, but still contains around thirty isolated missing months, scattered throughout the period, which reduce the availability of the indices computed at the multi-month scales (section 3.3).

2.2 Temperature and Evapotranspiration: The Kandi Station as a Regional Proxy

Malanville itself has no temperature data. The only usable source is a file of climatological normals (Tmax, Tmin, Tmean) for the period 1991-2020, from the Kandi station, about a hundred kilometers to the south. The two stations share the same Alibori department and the same Sudano-Sahelian climate zone, without being identical: Malanville, farther north, already borders the strict Sahel. Relying on this regional proxy is thus a deliberate assumption of the study. It has a direct consequence: these are normals, not an inter-annual series, so the PET derived from them forms a fixed seasonal cycle, identical from one year to the next the inter-annual signal of the water-balance index therefore comes exclusively from the variability of rainfall. This simplification is common in agro-climatic studies in the Sudano-Sahelian zone, where PET varies markedly less from year to year than rainfall does; it nonetheless remains an approximation, to be distinguished from a true SPEI computed from an inter-annual climate series [12].

2.3 Data Coverage by Time Scale

Computing the SWBI at a k-month scale requires that all k months of the window be recorded: a single missing month invalidates the entire window. Mechanically, the longer the scale, the greater the risk of encountering a missing month, and coverage suffers accordingly: 88% at the monthly scale (SWBI-1), 77% at 3 months (SWBI-3), 63% at 6 months (SWBI-6), and only 41% at the annual scale (SWBI-12). The 3-month scale, the best documented after the monthly step, serves as the reference for characterizing episodes it also corresponds to a time step relevant to agricultural drought, that of a deficit over one phase of the cropping cycle.

2.4 Climatological Potential Evapotranspiration (Hargreaves-Samani Method)

In the absence of radiation, wind, or relative-humidity data, the Hargreaves-Samani method is used here; it requires only extreme temperatures and nonetheless provides a robust estimate of reference PET. It is precisely this modest data requirement that makes it a method often validated, and used as a substitute for Penman-Monteith, in West African contexts where measurements are limited [13]. For each month m, the daily reference PET, ETo (mm/day), is computed as follows:

$$ETo = 0.0023 \times (Tmean + 17.8) \times (Tmax - Tmin)^{0.5} \times Ra$$

where Tmax, Tmin and Tmean are the normal monthly maximum, minimum and mean temperatures (°C, Kandi normals, section 3.2), and Ra is extraterrestrial radiation (converted to an mm/day equivalent), computed with the standard FAO-56 formula for the 15th of each month and the latitude of Malanville (11.87° N):

$$Ra = (24\times60/\pi) \times Gsc \times dr \times [\omega s\cdot\sin(\varphi)\cdot\sin(\delta) + \cos(\varphi)\cdot\cos(\delta)\cdot\sin(\omega s)]$$

where Gsc is the solar constant ($0.0820\ MJ\cdot m^{-2}\cdot min^{-1}$), dr is the inverse relative Earth-Sun distance, δ is the solar declination, φ is latitude in radians, and ωs is the sunset-hour angle, all functions of the day of the year alone. Monthly PET (mm/month) is obtained by multiplying ETo by the number of days in the month. Combining the two data sources raises no consistency issue: Ra is computed for the latitude of Malanville, the site of interest, while the temperatures come from the Kandi normals, and Ra depends only on latitude and date, never on the observing station.

2.5 Monthly Water Balance and the Multiscale Standardized Water-Balance Index (SWBI)

For each year i and each month m, the climatic water balance is defined as:

$$B(i,m) = P(i,m) - PET(m)$$

where P(i,m) is the observed rainfall total for month m of year i, and PET(m) is the climatological PET for the same calendar month, fixed from one year to the next. The balance is accumulated over sliding windows of k = 1, 3, 6 and 12 months, then standardized separately for each calendar end-month, so as to remove seasonality:

$$SWBI\_k(i,m) = [\ B\_k(i,m) - \mu\_k(m)\ ] / \sigma\_k(m)$$

where B_k(i,m) is the balance accumulated over the k months ending in month m of year i, and μ_k(m), σ_k(m) are the mean and standard deviation of B_k computed over all available years for that same end-month m. This standardization approach, rather than a fit to a gamma or log-logistic distribution, follows the principle of the standardized anomaly index already used in the reference rainfall study applied here to the water balance, and extended to several time scales rather than a single one. The usual classification thresholds are retained: severe drought (SWBI ≤ −1.5), moderate (−1.5 < SWBI ≤ −1), normal (−1 < SWBI < 1), wet (1 ≤ SWBI < 1.5), very wet (SWBI ≥ 1.5).

2.6 Episode Characterization Using Run Theory

Run theory [14] — already used for daily dry spells in the reference study is applied here to the continuous time series of the SWBI_k index. A drought episode is defined as a run of consecutive months below the threshold SWBI_k ≤ −1, with a data gap interrupting the count. Each episode is then characterized by four quantities: its duration (D, the number of consecutive months below the threshold), its magnitude (S, the sign-reversed sum of the index values over the episode), its intensity (I = S/D, the mean magnitude per month), and its peak, the most negative value reached.

2.7 Consolidation Indices Based on Precipitation Alone

Three complementary indices test this robustness independently of the regional-proxy limitation, since they are computed from rainfall alone, without recourse to the Kandi climatology. The first, the Rainfall Anomaly Index (RAI) [15], assigns each year a score based on its rank among annual rainfall totals, relative to the mean of the ten wettest years (M) or the ten driest years (X):

$$RAI = 3 \times (P - Pmean) / (M - Pmean) \text{ if } P \geq Pmean; \; RAI = -3 \times (P - Pmean) / (X - Pmean) \text{ if } P < Pmean$$

The second, the SPI-Gamma, follows the same principle as the reference study's standardized anomaly index, but fits a gamma distribution to the rainfall series rather than assuming a normal distribution, a distribution generally better suited to rainfall series, which are naturally skewed [16,17]. It is computed at two scales: the annual scale, to test the robustness of the inter-annual classification, and the 3-month scale, standardized by calendar end-month exactly as for the SWBI-3, allowing the two episode chronologies to be compared directly. The third, the decile method [18], classifies each year solely by its position in the empirical distribution of the 28 years of the series, without any statistical fitting: five usual classes suffice, from deciles 1-2 well below normal to deciles 9-10, well above.

2.8 Standardized Daily Climate Indices (ETCCDI)

A final set of indices reformulates some of the reference study's results using internationally recognized definitions: those of the Expert Team on Climate Change Detection and Indices, computed directly from the daily series at the calendar-year scale. These include CDD (maximum number of consecutive dry days, RR < 1 mm), CWD (its counterpart for wet days, RR ≥ 1 mm), R10mm and R20mm (number of days with at least 10 and 20 mm, respectively), SDII (mean daily intensity on rain days), and PCI (precipitation concentration index [19], computed from a year's monthly totals). As with the SWBI, a day with no recorded data interrupts the CDD and CWD count rather than being counted as dry.

2.9 Additional Indices of Intra-Annual Distribution

Three final indices address how the water balance is distributed within the year, rather than its annual total alone. The first, the De Martonne aridity index [20], relies only on mean annual temperature: $I\_dM(i) = P\_annual(i) / (Tmean\_annual + 10)$, with Tmean_annual = 28.4 °C here, the fixed value derived from the Kandi normals. The usual classes range from arid (< 10) to humid (≥ 28), passing through semi-arid (10-20), semi-humid or Mediterranean (20-24), and sub-humid (24-28). At Malanville, however, since temperature is fixed from one year to the next, this index is by construction merely a linear transformation of the annual rainfall total: it can therefore add nothing to the classification already obtained with the RAI, the SPI-Gamma, or the deciles. Its value lies instead in offering an internationally recognized climate classification system useful for interpretation. The next two indices, by contrast, genuinely depend on how rainfall is distributed within the year, not merely on its total: the Bagnouls-Gaussen xerothermic index [21] counts, for each year, the number of months in which the monthly rainfall total does not exceed twice the mean monthly temperature ($P(i,m) \leq 2 \times Tmean(m)$); symmetrically, the length of the wet period counts the number of months in which the monthly water balance is positive ($B(i,m) \geq 0$). Two years with an identical total can thus show very different counts, depending on whether their rainfall is concentrated in a few very wet months or spread more evenly.

3 RESULTS

3.1 Mean Climatic Cycle: Precipitation and Potential Evapotranspiration

Figure 2 presents the mean monthly cycle of observed precipitation at Malanville (1995-2024) and of climatological potential evapotranspiration estimated with the Hargreaves method (section 3.4) from the Kandi temperature normals (section 3.2).

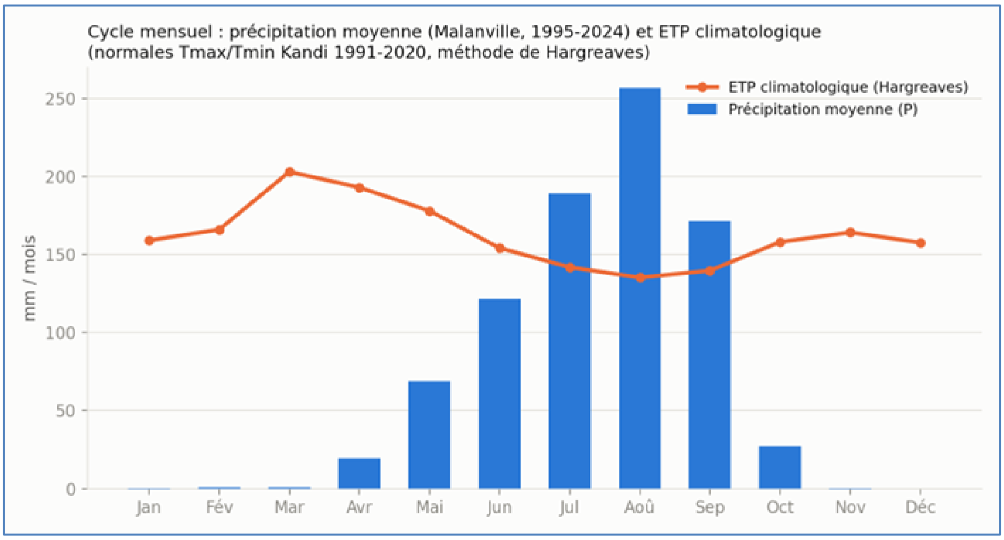

Figure 2: Mean monthly cycle of precipitation at Malanville (1995-2024) and of climatological potential evapotranspiration (Hargreaves method, Kandi normals 1991-2020).

Cumulative annual PET, computed with the method described in section 3.4, reaches 1,949.4 mm — more than double Malanville's mean annual rainfall total (823.9 mm). The resulting annual aridity index (P/PET = 0.423) is that of a climate structurally deficient in water, as is common in the Sudano-Sahelian zone. Figure 2 shows this clearly: precipitation exceeds monthly PET only at the height of the rainy season, from July to September, and only with a slight surplus in August. The rest of the year, including a good part of the rainy season itself, unfolds under a structural climatic water deficit.

3.2 Dry Episodes at the 3-Month Scale and Consistency with the Reference Rainfall Analysis

Figure 3 presents the complete chronology of the standardized water-balance index at the 3-month scale (SWBI-3) over 1995-2024, with the moderate (−1) and severe (−1.5) drought thresholds; Table 1 details the characteristics of the dry episodes extracted from it using run theory (section 3.6).

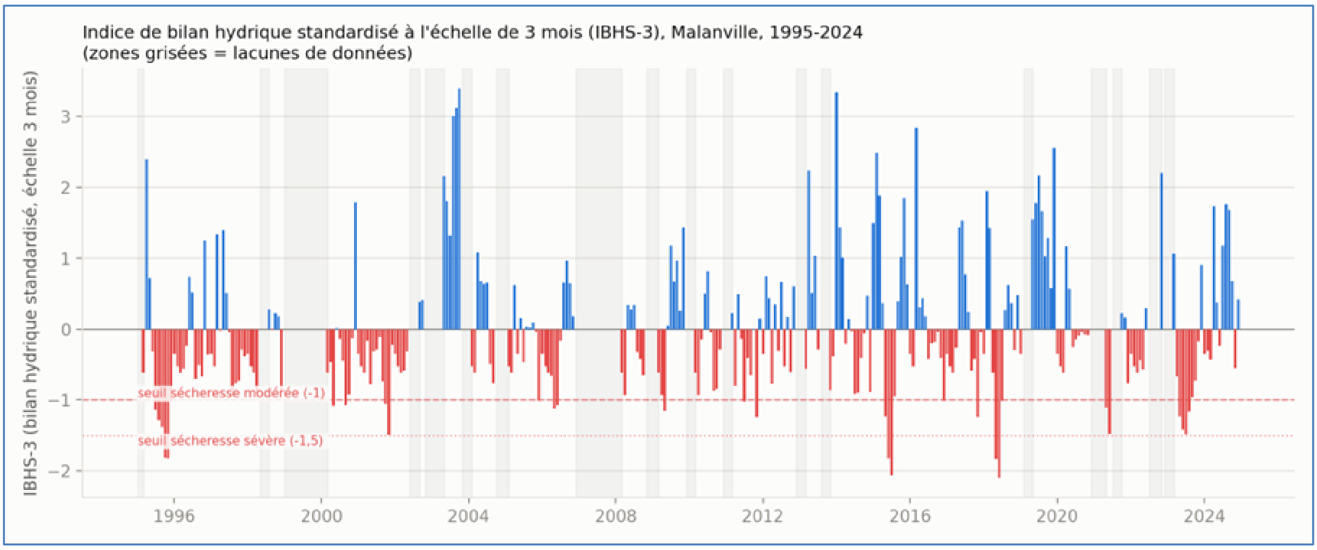

Figure 3: Standardized water-balance index at the 3-month scale (SWBI-3), Malanville, 1995-2024. Shaded areas correspond to data gaps.

At the 3-month scale, the most robust after the monthly step, with 77% coverage, no fewer than 15 episodes of at least moderate drought stand out over 1995-2024, with a mean duration of two months and a mean intensity of 1.24 (the longest, six months, running from July to December 1995). Three of them cross the severe threshold: July-December 1995 (peak −1.82), May-July 2015 (peak −2.07), and, above all, May-July 2018, whose peak of −2.10 makes it the most severe episode of the entire series (Table 1).

Table 1: Drought episodes at the SWBI-3 scale (threshold −1), Malanville, 1995-2024.

Start	End	Duration (months)	Intensity	Peak
1995-07	1995-12	6	1.4	-1.8
2000-05	2000-05	1	1.1	-1.1
2000-09	2000-09	1	1.1	-1.1
2001-10	2001-11	2	1.3	-1.5
2005-12	2005-12	1	1.0	-1.0
2006-05	2006-06	2	1.1	-1.1
2009-05	2009-05	1	1.2	-1.2
2011-07	2011-07	1	1.0	-1.0
2011-11	2011-11	1	1.2	-1.2
2015-05	2015-07	3	1.7	-2.1
2016-12	2016-12	1	1.0	-1.0
2017-11	2017-11	1	1.2	-1.2
2018-05	2018-07	3	1.6	-2.1
2021-05	2021-06	2	1.3	-1.5
2023-05	2023-08	4	1.3	-1.5

Most of these episodes overlap with the years already flagged as deficient in the reference rainfall study, which supports the validity of the water-balance approach. May-July 2018 corresponds to the year of the record daily dry spell (53 consecutive rainless days, at the start of the season); May-June 2021 (peak −1.48) and May-August 2023 (peak −1.48) overlap with the two other years classified as moderate drought on rainfall alone. The 1995 episode stands out as an exception: it emerges here as the longest of the series and crosses the severe threshold, whereas the annual analysis on rainfall alone had classified it as only moderate drought. Accounting for PET therefore reveals, for that year, a severity that the rainfall total alone underestimated. The reverse occurs for 2013, otherwise the driest year of the series based on its annual total (563.9 mm): it does not appear in any SWBI-3 episode, simply because August 2013 is missing from the series and invalidates the three 3-month windows that include it. The most severe episode of that year has therefore most likely gone unnoticed a concrete limitation of data coverage at the sub-annual scale.

3.3 Robustness of the Inter-Annual Classification (RAI, SPI-Gamma, Deciles)

Figure 4 illustrates the agreement between the four annual classification methods the reference standardized anomaly index, RAI, SPI-Gamma and deciles year by year, with a box marking the years of total agreement; Table 2 details the numerical values for these years.

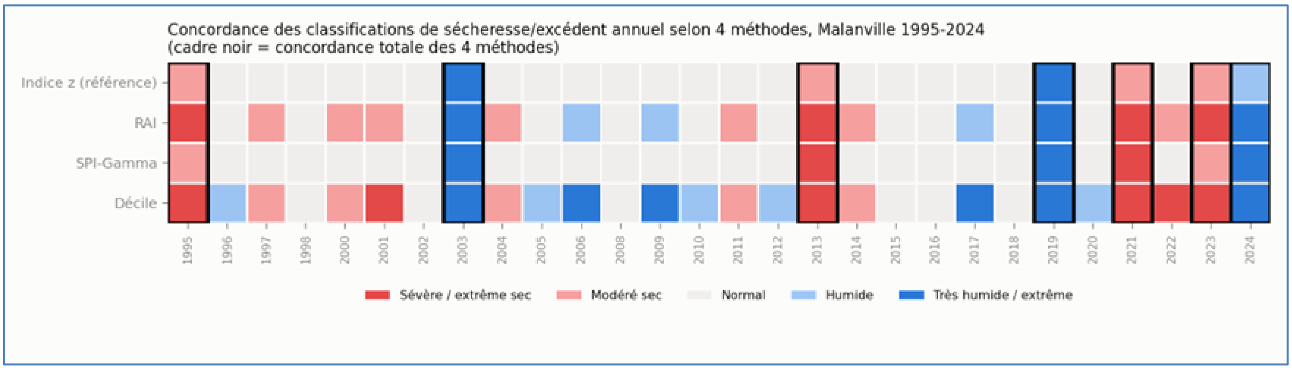

Figure 4: Agreement between annual drought and rainfall-surplus classifications from four independent methods, Malanville, 1995-2024.

Applied at the annual scale, the three indices defined in section 3.7 join the reference study's standardized anomaly index on a striking point: the four methods agree perfectly on four deficit years — 1995, 2013, 2021 and 2023 and on three surplus years, 2003, 2019 and 2024. These are exactly the years already highlighted by the reference study. Such a degree of agreement between statistically independent methods one rank-based, another based on a gamma distribution, the third on the empirical distribution gives these seven years the status of robust benchmarks for Malanville's rainfall regime.

Table 2: Years of rainfall deficit and surplus in full agreement (4/4) across four independent methods, Malanville, 1995-2024.

Year	P (mm)	z (reference)	RAI	SPI-Gamma	Decile	Diagnosis
1995	590	-1.3	-4.8	-1.5	1	Deficit (4/4)
2013	564	-1.4	-5.3	-1.6	1	Deficit (4/4)
2021	574	-1.3	-5.1	-1.6	1	Deficit (4/4)
2023	616	-1.1	-4.2	-1.3	2	Deficit (4/4)
2003	1,450	3.4	11.3	3.1	10	Surplus (4/4)
2019	1,209	2.1	7.0	2.0	10	Surplus (4/4)
2024	1,095	1.4	4.9	1.5	10	Surplus (4/4)

The SPI-Gamma, however, introduces a nuance worth pausing on: it reclassifies 2013 (SPI = −1.65) and 2021 (SPI = −1.57) as severe drought, whereas the reference study's standardized anomaly index, based on a normal approximation, had classified both as moderate. This echoes what was already observed for 1995 with the SWBI (section 4.2): a gamma distribution, better suited to the skewness of rainfall series, tends to assign greater severity to the driest years than a simple normal approximation does.

3.4 Robustness of Intra-Seasonal Episodes (SPI-3 Gamma vs SWBI-3) and Daily Climate Indices (ETCCDI)

Comparing the SPI-3 Gamma to the SWBI-3 month by month makes it possible to verify that the identified episodes do not depend on the choice to integrate PET. Over the 72% of months common to both series, the correlation reaches $r = 0.93$, a very close agreement between a water-balance-based approach and a rainfall-only approach. The SPI-3 Gamma indeed recovers the same major episodes as the SWBI-3: May-July 2018 (peak −2.77), May-June 2021 (peak −1.51), May-September 2023 (peak −1.61), July-November 1995 (peak −2.29). Its peaks are consistently more negative than those of the SWBI-3, confirming once again that gamma fitting increases the estimated severity of the driest events.

The ETCCDI indices, computed directly from the daily series, confirm these results using internationally standardized definitions. Annual CDD ranges from 53 days in 2003, the wettest year, to 125 days in 2010, and correlates only weakly with the annual rainfall total ($r = -0.30$) — a near-independence that echoes, this time with a standardized metric, what the reference study had already established with its own method ($r = -0.13$ between the annual total and the longest dry spell of the rainy season). R10mm and R20mm unsurprisingly identify 2013 as the year poorest in significant rain days (16 and 9 days, respectively) and 2003 as the richest (41 and 32 days). As for SDII, it places 2023 as the year with the lowest mean intensity on rainy days (12.3 mm/day), a sign that that year's deficit reflects both fewer rain days and individually weaker rainfall.

3.5 Intra-Annual Distribution: De Martonne Index, Dry Months and Wet Months

The three indices defined in section 3.9 are computed for the 28 years of the series. Unsurprisingly since this is a mechanical result of the fixed temperature used the De Martonne index shows a near-perfect correlation with the annual rainfall total ($r > 0.999$): it logically places the four already-identified deficit years in a “semi-arid” climate (De Martonne between 14.7 and 16.1), and the three surplus years in a “humid” climate (De Martonne ≥ 28.5), as shown in Table 3.

This correspondence, however clear, confirms the overall consistency without constituting a statistically independent validation: with a fixed temperature, the De Martonne index can by definition add nothing to the classification already obtained with the RAI, the SPI-Gamma and the deciles.

Figure 5 presents, for each year of the series, the number of dry months (Bagnouls-Gaussen xerothermic index) and the number of wet months ($P \geq PET$), with lighter shades flagging years with incomplete monthly coverage.

Table 3: De Martonne index and intra-annual distribution (dry months, wet months) for the robust deficit and surplus years, Malanville, 1995-2024.

Year	Annual P (mm)	De Martonne Index	De Martonne Class	Dry months	Wet months
1995	590	15.4	semi-arid	7/12	2/12
2003	1,450	37.8	humid	4/10	4/10
2013	564	14.7	semi-arid	7/11	1/11
2019	1,209	31.5	humid	5/11	4/11
2021	574	15.0	semi-arid	8/10	2/10
2023	616	16.1	semi-arid	8/12	2/12
2024	1,095	28.5	humid	8/12	2/12

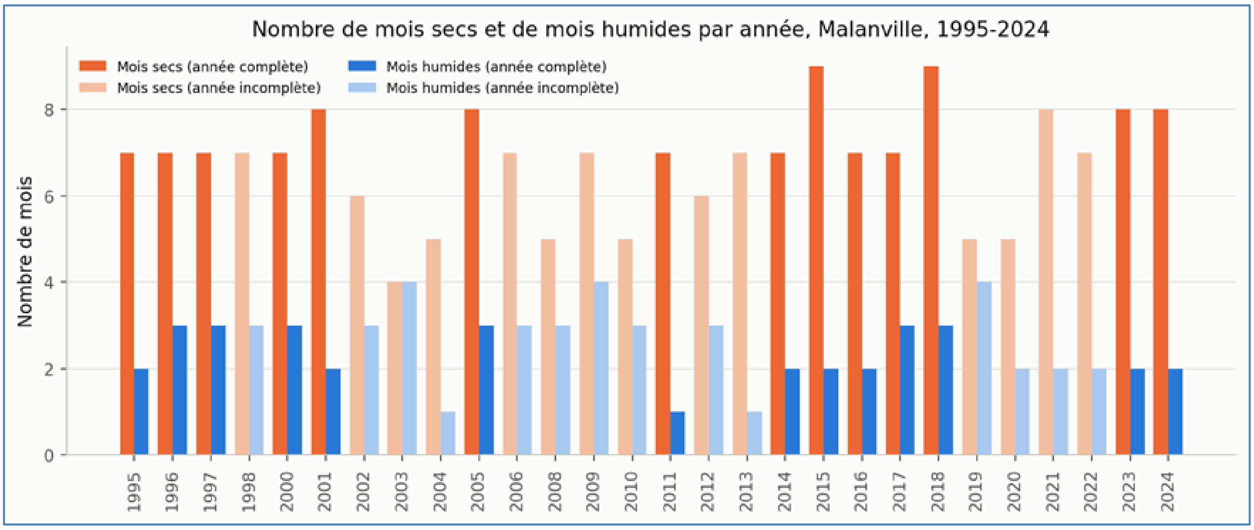

Figure 5: Number of dry months (Bagnouls-Gaussen) and wet months (P ≥ PET) per year, Malanville, 1995-2024.

The number of dry months and the number of wet months tell a very different story: they correlate only weakly with the annual rainfall total (r = 0.12 and r = 0.18, respectively), and not at all with each other (r = 0.02). These two indices therefore capture a dimension of drought that the total does not reveal the distribution of rainfall within the year. The case of 2024 is telling: classified “wet” by its annual total (1,094.5 mm, De Martonne 28.5), that year nonetheless has 8 dry months out of 12, as many as 2023, a confirmed deficit year. Its rainfall surplus was thus concentrated into a small number of very wet months, rather than spread across the whole rainy season. Conversely, 2013 and 2011 stand out for having the fewest wet months of the entire series (1/11 and 1/12, respectively), consistent with their status as deficit years.

4 DISCUSSION

4.1 Internal Consistency and Contribution of the Multi-Index Approach

Integrating PET by means of a fixed climatology borrowed from a neighboring station makes it possible, overall, to recover the results obtained from rainfall alone, and sometimes to refine them: the years and episodes already identified as deficient 2018, 2021, 2023 remain so, and 1995 even appears more severe than initially estimated. Consolidation using seven statistically independent indices reinforces this confidence: 1995, 2013, 2021 and 2023 stand out as robust deficit years regardless of the method used, and the 0.93 correlation between the SWBI-3 and an SPI-3 computed without any recourse to temperature shows that the intra-seasonal episodes, too, do not depend on the choice to integrate PET. This convergence among indices of very different statistical nature standardized anomaly, parametric fitting, empirical rank, water balance is nothing new in the methodological literature on drought indices. In proposing the Standardized Precipitation Index, McKee, Doesken and Kleist [17] had already emphasized the value of statistically transforming the precipitation distribution into a metric comparable across stations and time scales, a principle the present study simply extends to the water balance. Vicente-Serrano, Beguería and López-Moreno [12], in developing the SPEI, went further by showing that integrating evaporative demand into an SPI-type standardized index makes it possible to capture droughts that rainfall alone misses, especially in a warming context. Our results partially corroborate this finding for 1995, whose severity is revised upward once PET is taken into account, even though the absence of inter-annual PET variability in our proxy limits the scope of this comparison.

The choice of standardization (centering and scaling) rather than a gamma fit also finds an echo in the literature. Stagge et al. [16], in a systematic evaluation of candidate distributions for drought indices (SPI and SPEI), show that the choice of statistical distribution weighs substantially on the estimated severity of extreme events, especially when series are short or incomplete. Our results point the same way: gamma fitting systematically increases the estimated severity of the driest years and episodes (1995, 2013, 2021) relative to the normal approximation. The same study also notes the difficulty of fitting a parametric distribution when series contain many zero or missing values exactly the case here, where the SPI-3 Gamma loses coverage (72%) relative to the SWBI-3 (77%) during the dry season. Ali and Lebel [22], in revisiting the Sahelian standardized rainfall index, had already warned against the mechanical application, to Sahelian rainfall regimes, of indices designed for other climates — strongly seasonal ones marked by a long dry season. Our choice to standardize by calendar end-month, rather than by a continuous moving normal, directly addresses this warning.

4.2 Comparison with the Regional Literature on the Niger Basin and the Sahel

The Hargreaves-Samani method, chosen for lack of radiation and wind data, has been specifically validated under Sahelian conditions. Comparing sixteen reference-evapotranspiration estimation methods in the Senegal River valley, Djaman et al. [13] conclude that Hargreaves-Samani, given local coefficient calibration, compares well with the FAO Penman-Monteith reference method under limited-data conditions comparable to those encountered here. This result supports the methodological choice made, without ruling out a systematic bias that our study, lacking calibration, could not correct. At the scale of the Niger basin, in which Malanville is directly situated, Oyerinde et al. [23] cross-check hydro-climatic observations against local perceptions and find genuine consistency between measured trends and riverine populations' sense of worsening rainfall variability and growing pressure on water resources, particularly since the 2000s. This trend is at least qualitatively consistent with the recurrence of severe dry episodes observed at Malanville in 2018, 2021 and 2023.

The classical indices used for consolidation also have a long history in drought climatology. Van Rooy's Rainfall Anomaly Index [15], designed to compare rainfall anomalies independently of time and space scale, remains, despite its age, a reference for this type of multi-method exercise. The decile method of Gibbs and Maher [18], older still, has the advantage of relying on no distributional assumption, which makes it a robustness test particularly independent of the parametric choices made for the SWBI and the SPI-Gamma. That these two indices, developed more than half a century ago, converge with much more recent methods SPI-Gamma, SWBI, ETCCDI on the same critical years amounts, in effect, to a cross-validation of several decades of methodological development.

4.3 Methodological Limitations

These results nonetheless call for three caveats, to be kept in mind before any operational use. The first concerns the regional proxy: temperature comes from Kandi, about a hundred kilometers away, and a systematic bias between this estimate and Malanville's actual PET cannot be ruled out, particularly if the wind or humidity regime differs between the two sites. The second concerns the absence of inter-annual PET variability: by construction, the SWBI captures only rainfall variability and therefore cannot detect any effect of local warming on evaporative demand which was nonetheless one of the initial motivations for introducing temperature, and what distinguishes our index from a true SPEI [12]. The third concerns data coverage, which decreases with scale: a single gap, such as the one in August 2013, can mask a genuine episode, particularly at the 6- and 12-month scales, where coverage falls to 63% and then 41%. The SPI-Gamma suffers from a comparable problem, since fitting a gamma distribution requires a minimum number of non-zero values per calendar month, a condition the full dry season does not always meet. Finally, it should be noted that, among the seven consolidation indices used, the De Martonne index, computed with a fixed temperature, is mathematically redundant with the classification already obtained from the rainfall total alone: its value therefore lies in interpretation rather than statistics, unlike the number of dry months and the number of wet months, which provide classification information genuinely independent of the annual total.

4.4 Implications and Perspectives

At the local scale of Malanville, these results ultimately confirm the broad trends already reported for the Sahel: rainfall variability dominated by extremes rather than by a monotonic trend in the annual total [2], an intensification of the most intense rainfall events that goes hand in hand with more contrasted trends in the number of rain days [4], and rainy seasons whose internal structure onset, breaks, distribution matters for rainfed agriculture as much as the seasonal total does [6]. Two avenues would help address the limitations identified here: obtaining an inter-annual temperature series, even a monthly one, specific to Malanville or to a closer station, which would finally allow a full-fledged SPEI to be computed; and filling or interpolating the isolated gaps in the rainfall series, for instance from neighboring stations or satellite rainfall products, to limit coverage losses at the multi-month scales. In the longer term, downscaled CMIP6 climate projections could also be incorporated, to place these observational diagnostics within the warming and drying trajectory that models project for West Africa [7,8].

5 CONCLUSION

This study offers a first characterization of drought at Malanville based on the climatic water balance rather than on rainfall alone, making the best use of the available data despite their limitations foremost among them the Kandi temperature, used as a proxy in the form of fixed normals. The standardized water-balance index (SWBI), built on a centering-and-scaling principle and computed at several time scales, then coupled with episode characterization using run theory, confirms and refines the results already obtained from rainfall alone: it recovers the most severe episodes of the series (1995, 2018) as well as the years recently flagged as deficient (2021, 2023), with 1995 showing a more pronounced severity than initially estimated. Consolidation using seven complementary indices reinforces this confidence: 1995, 2013, 2021 and 2023 stand out as robust deficit years regardless of the statistical method used, and gamma fitting even suggests that their severity may have been slightly underestimated by the normal approximation used until now. The indices targeting the intra-annual distribution of rainfall add a useful nuance: a year with a high total can very well have an unfavorable rainfall distribution, an aspect of the rainfall regime that the annual total alone never reveals. Beyond the case of Malanville, this multi-index approach water balance, classical rainfall indices, standardized daily climate indices offers a methodological framework transferable to other Sahelian stations facing the same data constraints: the absence of a local temperature series and isolated rainfall gaps, two realities common in the region's observation networks. Acquiring a temperature series specific to Malanville, even at monthly resolution, would remain the most direct improvement for refining this analysis and finally opening the way to a full-fledged SPEI-type index.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest regarding this manuscript.

Statement of Ethical Approval

This study relies exclusively on historical climatic data and involves neither human nor animal subjects. Therefore, no specific ethical approval was required.

REFERENCES

[1] Wilhite, D.A., Glantz, M.H. (1985). Understanding: the drought phenomenon: the role of definitions. Water International, 10(3), 111-120.

[2] Nicholson, S.E. (2013). The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. ISRN Meteorology, 2013, 453521.

[3] Lebel, T., Ali, A. (2009). Recent trends in the Central and Western Sahel rainfall regime (1990-2007). Journal of Hydrology, 375(1-2), 52-64.

[4] Panthou, G., Vischel, T., Lebel, T. (2014). Recent trends in the regime of extreme rainfall in the Central Sahel. International Journal of Climatology, 34(15), 3998-4006.

[5] Descroix, L., Guichard, F., Grippa, M., Lambert, L.A., Panthou, G., Mahé, G., Gal, L., Dardel, C., Quantin, G., Kergoat, L., et al. (2018). Evolution of surface hydrology in the Sahelo-Sudanian strip: an updated review. Water, 10(6), 748.

[6] Salack, S., Klein, C., Giannini, A., Sarr, B., Worou, O.N., Belko, N., Bliefernicht, J., Kunstman, H. (2016). Global warming induced hybrid rainy seasons in the Sahel. Environmental Research Letters, 11(10), 104008.

[7] Sylla, M.B., Giorgi, F., Pal, J.S., Gibba, P., Kebe, I., Nikiema, M. (2016). Projected robust shift of climate zones over West Africa in response to anthropogenic climate change. Climatic Change, 134(1-2), 241-253.

[8] Klutse, N.A.B., Ajayi, V.O., Gbobaniyi, E.O., Egbebiyi, T.S., Kouadio, K., Nkrumah, F., Quagraine, K.A., Olusegun, C., Diasso, U., Abiodun, B.J., Lawal, K., Nikulin, G., Lennard, C., Dosio, A. (2018). Potential impact of 1.5 °C and 2 °C global warming on consecutive dry and wet days over West Africa. Environmental Research Letters, 13(5), 055013.

[9] Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., Yanda, P. (2007). Africa. In: Parry, M.L. et al. (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge University Press, 433-467.

[10] Trisos, C.H., Adelekan, I.O., Totin, E., Ayanlade, A., Efitre, J., Gemeda, A., Kalaba, K., Lennard, C., Masao, C., Mgaya, Y., et al. (2022). Africa. In: Pörtner, H.-O. et al. (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the IPCC. Cambridge University Press, 1285-1455.

[11] Koumassi, H. (2026). Caractérisation des séquences sèches journalières à Malanville : analyse pluviométrique de référence (1995-2024). Note technique.

[12] Vicente-Serrano, S.M., Beguería, S., López-Moreno, J.I. (2010). A multiscalar drought index sensitive to global warming: the Standardized Precipitation Evapotranspiration Index. Journal of Climate, 23(7), 1696-1718.

[13] Djaman, K., Balde, A.B., Sow, A., Muller, B., Irmak, S., N'Diaye, M.K., Manneh, B., Moukoumbi, Y.D., Futakuchi, K., Saito, K. (2015). Evaluation of sixteen reference evapotranspiration methods under sahelian conditions in the Senegal River Valley. Journal of Hydrology: Regional Studies, 3, 139-159.

[14] Yevjevich, V. (1967). An objective approach to definitions and investigations of continental hydrologic droughts. Hydrology Papers No. 23. Colorado State University, Fort Collins.

[15] Van Rooy, M.P. (1965). A rainfall anomaly index independent of time and space. Notos, 14, 43-48.

[16] Stagge, J.H., Tallaksen, L.M., Gudmundsson, L., Van Loon, A.F., Stahl, K. (2015). Candidate distributions for climatological drought indices (SPI and SPEI). International Journal of Climatology, 35(13), 4027-4040.

[17] McKee, T.B., Doesken, N.J., Kleist, J. (1993). The relationship of drought frequency and duration to time scales. In: Proceedings of the 8th Conference on Applied Climatology, Anaheim, California. American Meteorological Society, 179-184.

[18] Gibbs, W.J., Maher, J.V. (1967). Rainfall deciles as drought indicators. Bureau of Meteorology Bulletin No. 48. Commonwealth of Australia, Melbourne.

[19] Oliver, J.E. (1980). Monthly precipitation distribution: a comparative index. The Professional Geographer, 32(3), 300-309.

[20] De Martonne, E. (1926). Une nouvelle fonction climatologique : l'indice d'aridité. La Météorologie, 2, 449-458.

[21] Bagnouls, F., Gaussen, H. (1957). Les climats biologiques et leur classification. Annales de Géographie, 66(355), 193-220.

[22] Ali, A., Lebel, T. (2009). The Sahelian standardized rainfall index revisited. International Journal of Climatology, 29(12), 1705-1714.

[23] Oyerinde, G.T., Wisser, D., Hountondji, F.C.C., Odofin, A.J., Lawin, A.E., Afouda, A., Diekkrüger, B. (2014). Hydro-climatic changes in the Niger basin and consistency of local perceptions. Regional Environmental Change, 15(8), 1627-1637.