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Spatiotemporal analysis of meteorological and hydrological droughts across the Beninese part of the Niger River Basin (West Africa)

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Abstract. Understanding hydroclimatic variability and climate teleconnections in a warming world is crucial for drought-prone regions like West Africa, where economies heavily depend on rain-fed agriculture. This study investigates the spatiotemporal dynamics of hydrological and meteorological droughts in the Beninese Part of the Niger River Basin (BPNRB). Using the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), the Consecutive Dry Days Index (CDD), and the Streamflow Drought Index (SDI), the study assessed drought variability on 3- and 12-month timescales. Statistical methods were employed to explore drought patterns. The findings reveal a recovery phase in the 1990s following severe droughts in the 1970s and 1980s. Significant trends include an increase in CDD values during the rainy season, with an average of 18 dry spell days, and a pronounced upward trend in SDI, indicating intensifying hydrological droughts. These changes suggest growing pressure on both surface and groundwater resources. These findings provide critical guidance for water resource management, promoting efficient irrigation practices and developing preparedness plans. This research offers a robust scientific foundation for designing proactive drought management strategies and enhancing water and food security in Northern Benin.

1 Introduction

Droughts are natural phenomena with harsh consequences for livelihoods and ecosystems. They are defined as a "deficiency of precipitation that results in a water shortage for some activity or for some group", or a "period of abnormally dry weather sufficiently prolonged for the lack of precipitation to cause a serious hydrological imbalance" (Trenberth et al., 2014). Generally, four types are differentiated: meteorological, agricultural, hydrological, and socio-economic drought (Van Loon et al., 2022) . Droughts occur in most parts of the world, both in arid and humid regions (Dai, 2011). West Africa experienced its worst droughts between 1968 to 1993; the most severe occurred in 1983 and affected nearly 18 million people (UNDP and AGRHYMET Regional Centre, 2022). This drought was exceptionally long and widespread, affecting more than 5 million km^2. With the deficit becoming increasingly pronounced towards the north, the naturally semi-arid Sahel zone was the most heavily hit area. The impacts of droughts increased dramatically over the past two decades and were expected to worsen in the future. According to the sixth report of the Intergovernmental Panel on Climate Change (IPCC), West Africa could be exposed to a temperature increase of 1.5 to 3 °C by 2050 (Trisos et al., 2022).

The Beninese Part of the Niger River Basin (BPNRB), is particularly vulnerable to droughts. Located in a semi-arid zone, it undergoes significant population growth. This demographic increase intensifies the pressure on fragile resources whose degradation is increasingly worrying (Badou et al., 2017). The demand for agricultural "cotton land" in Benin, for example, has drastically increased from 137 085 ha in 2010 to 665 703 ha in 2019, implying an annual demand of 6494 ha (INStaD-Benin, 2020).

Some parts of the country have received little attention so far, such as northern Benin, where the study area for the present paper is located. Studies conducted in the area focused on blue and green water availability (Badou et al., 2018), on assessing water resources (Gaba, 2015; Badou et al., 2017) and on climate variability and change impacts on water (Vissin, 2007; Obada, 2017; Halissou et al., 2021). However, there has been little work on droughts, Alamou et al. (2022) addressed the historical and projected meteorological droughts across the study area. Understanding the spatiotemporal variations of drought is of primary importance for freshwater planning and management (Mishra and Singh, 2010). This study aims to fill this gap by analyzing the spatiotemporal variations of meteorological and hydrological droughts across this region.

2 Study area and data

The Beninese Part of the Niger River Basin is located in the extreme north of Benin. Located between 1°32′ and 3°50′ E and 10° and 12°30′ N, it covers an area of about 48 000 km^2, i.e., 42 % of the total area of Benin (Halissou et al., 2021). It is shared by 17 municipalities and includes the Mekrou (10 552 km^2), Alibori (13 684 km^2) and Sota (13 449 km^2) sub-basins (Fig. 1).

The study area has two distinct seasons. The rainy season lasts from April to October, – having its maximum rain in August while the dry season extends from November to March (Vissin, 2007). The annual rainfall ranges from 780 to 1200 mm over the period 1970–2020. The average daily potential evapotranspiration (PET) varies between 1.6 (min) and 10 mm (max) and the average monthly maximum temperature is 33.8 °C over the same period. This value sometimes rises to around 40 °C. Unlike the main Niger River, all three rivers have their high flows during the rainy season and their low flows during the dry season. The Sota River has a permanent flow regime with low streamflow during the dry season evaluated at around 3.6 $\mathrm{m}^3\,\mathrm{s}^{-1}$; the Alibori and Mekrou Rivers are characterized by seasonal flow regimes (Vissin, 2007).

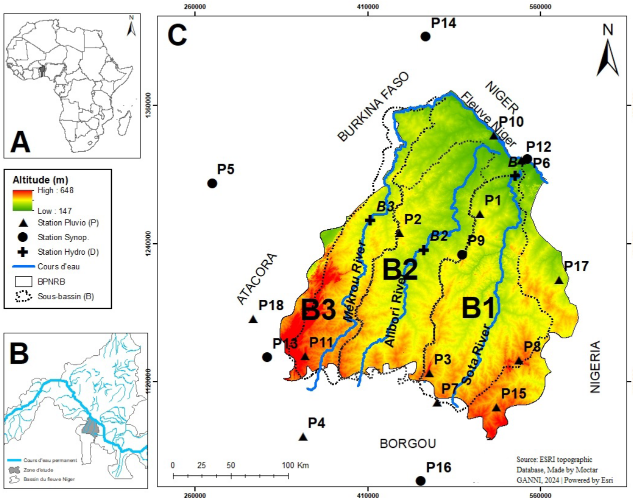

Figure 1. Study area, Beninese Part of the Niger River Basin: (A) Location of Benin in West Africa. (B) Niger River Basin including the study area. (C) Study area BPNRB: topography, location of climate and discharge stations, and the three catchments (Sota River, B1; Alibori River, B2; Mekrou River, B3).

Daily rainfall data from 21 climate stations for the period 1970–2020 were acquired from the Benin Meteorological Agency and neighbouring countries, i.e., the National Meteorological Service of Niger and the Burkina Faso Meteorological Agency. After quality control (see Secti. 3.1), 18 stations were used for the analysis (Fig. 1 and Table S1 in the Supplement). Daily discharge data from three hydrometric stations (Couberi, Yankin, and Kompongou for the three catchments were obtained from the Hydrological Service of Benin (Table S1) for the same period.

Prior to the analysis of droughts, the precipitation and discharge time series were quality-controlled. For each station, years with more than 5 % missing data during the rainy season and those with more than 10 % missing records in any season were excluded.

For all three streamflow stations, substantial gaps occurred during the period 1993–2004 due to delays between the breakdown of the gauging instruments and their repair or replacement (Badou et al., 2017). The hydrological model ModHyPMA (Hydrological Model based on the Least Action Principle) was used to model river flows and to fill the missing discharge data (Table S2).

3 Methods

3.1 Drought indices used

Four indicators were used to determine droughts: the Standardized Precipitation Index (SPI), the Standardized Precipitation Evapotranspiration Index (SPEI), the Streamflow

Drought Index (SDI), and the Consecutive Dry Days Index (CDD). In addition, we calculated the drought duration and intensity to understand the space-time variation of droughts across the study area.

The Standardized Precipitation Index (SPI) is one of the most frequently used indicators of meteorological drought and was developed on the basis of the normalization of precipitation probabilities (Mckee et al., 1993). This indicator defines a precipitation deficit and allows the monitoring of droughts in different time frames. The SPI is recommended by the World Meteorological Organization (WMO) for determining the phenomenon of drought (World Meteorological Organization (WMO) and Global Water Partnership (GWP), 2016). For more information on the formulation of SPI, its advantages and limitations, readers can refer to Fang et al. (2020).

The SPI was calculated on the basis of daily precipitation for the spatial average of the BPNRB. The daily precipitation data were aggregated into 3-, 6-, and 12-month timescales, and a two-parameter gamma distribution function was fitted to these aggregated data. In this study, we considered meteorological and hydrological droughts, thus aggregating precipitation data to timescales of 3-, 6- and 12-months. SPI values define the deviation from the mean expressed in units of standard deviation:

$$\mathrm{SPI} = \frac{f(x) - u}{\sigma} \tag{1}$$

where $f(x)$ is the transformed sum of precipitation, u is the mean value of the normalized variable x, and σ is the standard deviation of variable x.

Based on the value of SPI, a period is classified as normal or dry, from moderately dry to extremely dry (Table 1).

The Standardized Precipitation Evapotranspiration Index (SPEI), which also includes the evapotranspiration besides precipitation, was calculated for the same timescales (3-, 6-, and 12-months). Different methods are used to calculate PET (potential evapotranspiration), like the Penman-Monteith, Hargreaves or Thornthwaite's equations. The Penman-Monteith method requires observations of climate variables which are not available at most meteorological stations in many countries (Krishnan et al., 2019). Hence, we calculated the SPEI by applying the Hargreaves method which uses only radiation and minimum and maximum temperature at a particular location (Vicente-Serrano et al., 2010). Daily PET was estimated based on Hargreaves' equation as:

$$\mathrm{PET} = 0.0023\, R_\mathrm{a} \left(\frac{T_\mathrm{max} + T_\mathrm{min}}{2} + 17.8 \right) (T_\mathrm{max} - T_\mathrm{min})^{0.5} \tag{2}$$

where R_a is the extra-terrestrial radiation and T_max and T_min are the maximum and minimum temperature values, respectively. 0.0023 is the original empirical coefficient proposed by Hargreaves and Samani (Hargreaves and Samani, 1985). SPEI is based on the normalization of a simple water balance equation stated as follows:

Table 1. Drought classification using SPI, SPEI, and SDI values (Mckee et al., 1993; Nalbantis and Tsakiris, 2008).

SPI and SDI Values	Category
−0.99 to 0.99	Near normal
−1.49 to −1.0	Moderately dry
−1.99 to −1.5	Severely dry
−2.0 or less	Extremely dry

$$D_i = P_i - \mathrm{PET}_i$$

D_i indicates whether there is a water surplus or a deficit. The D_i values were aggregated to 3, 6, and 12 months as in the case of SPI. As recommended by Krishnan et al. (2019), a three-parameter log-logistic distribution was used to fit a distribution to the SPEI values. Drought classification based on SPEI values uses the same scheme as for SPI (Table 1). Mean temperature of the rainy season at Kandi station (P9, see Figs. 1 and S2) for the period 1970–2020 was used in the PET calculation. PET and SPEI were calculated using the R software package SPEI (Vicente-Serrano et al., 2010).

The Streamflow Drought Index (SDI), developed by Nalbantis and Tsakiris (2008), is calculated in the same way as SPI by using discharge instead of precipitation (Lorenzo-Lacruz et al., 2013). Classification of dry periods is the same as for SPI and SPEI (values smaller than −1.0), while wet periods are identified for values larger than 1.0.

The Consecutive Dry Days index (CDD), i.e., the maximum period of consecutive dry days (with rainfall ≤ 1 mm), is another useful drought indicator (Frich et al., 2002). In contrast to the other indicators that represent water fluxes, CDD quantifies the variations of dry spells in a given region. To account for the distinct seasonality of rainfall, we calculated the CDD for the rainy season (April to September) and the entire year.

Drought duration (D) is the time between the onset and the end of a drought. Onset and end are defined as the points in time when SPI falls below −1 (drought onset) and rises above −1 (drought end), respectively

Drought intensity (I) is estimated as a ratio of drought magnitude and drought duration (Eq. 4). It is presented in Eq. (6) (Wang et al., 2018; Haile et al., 2020).

Drought magnitude is the sum of all SPI values smaller than −1 during the drought period (Mckee et al., 1993).

3.2 Statistical analysis

Basic statistical parameters, i.e., maximum, minimum and mean, were used to represent the monthly and annual distribution trends of the original precipitation data at these 18 selected meteorological stations.

The traditional nonparametric Mann–Kendall test is the most widely applied trend test all over the world (Hamed

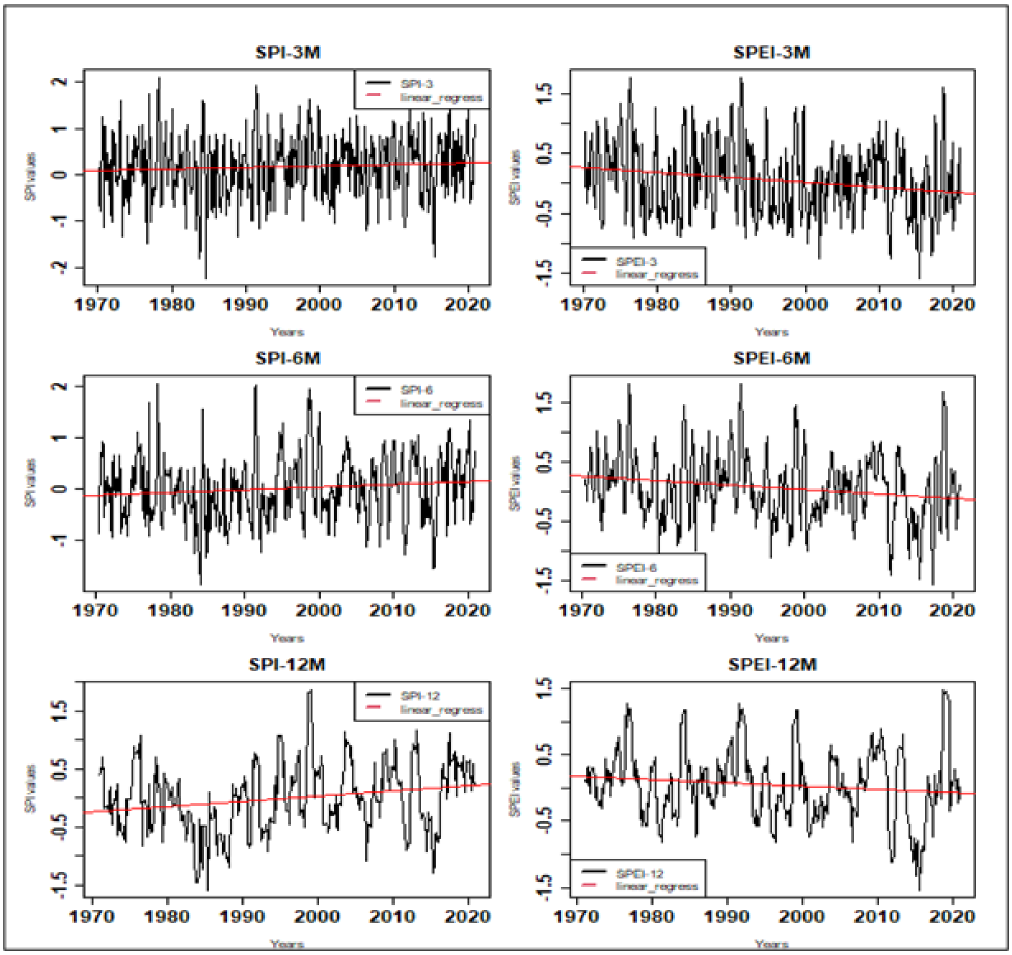

Figure 2. The temporal evolution of the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) at 3-, 6-, and 12-month timescales over the BPNRB during 1970–2020.

and Rao, 1998). However, the persistence of the hydrometeorological dataset will affect the Mann–Kendall test results. Therefore, (Hamed and Rao, 1998) proposed a Modified Mann–Kendall test (MMK) for removing the autocorrelation. This test is consistent and robust in terms of research on the trends of the hydro-meteorological series (Huang et al., 2014). This study implemented the MMK trend test to evaluate the spatial drought trend characteristics across the BPNRB (see the Supplement for the MMK result). The significance level $\alpha = 0.05$ was used in this study. At the 5 % significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$ (Mann, 1945).

4 Results

4.1 Analysis of meteorological droughts

4.1.1 Temporal Distribution of SPI and SPEI

Figure 2 illustrates the temporal evolution of the spatial mean of SPI and SPEI for the different timescales over the basin. An upward trend was noted for the SPI while a downward for the SPEI. Both the SPI and SPEI fluctuated frequently around the value of 0, with a large range. The longer the timescale was, the more obvious the drought trend. The variations of the SPI and SPEI were similar at various timescales, but there were still slight differences in the fluctuation value.

4.1.2 Spatial variation of Drought's occurrence

Figure 3 shows the spatial variability of drought occurrence using the SPI values. The SPI values obtained at each station were classified based on Table 1 and then spatialized.

Spatially, during moderate drought, the extreme southeast and southwest of the basin show the highest values of drought occurrence (Fig. 3). These values vary between 6 %–14 %. Severe drought, on the other hand, has its highest values in the centre of the basin on a diagonal and varies between 2 %–7 % (Fig. 3). Finally, extreme drought is only felt in the northernmost of the basin, with values varying between 2 %–5 % (Fig. 3).

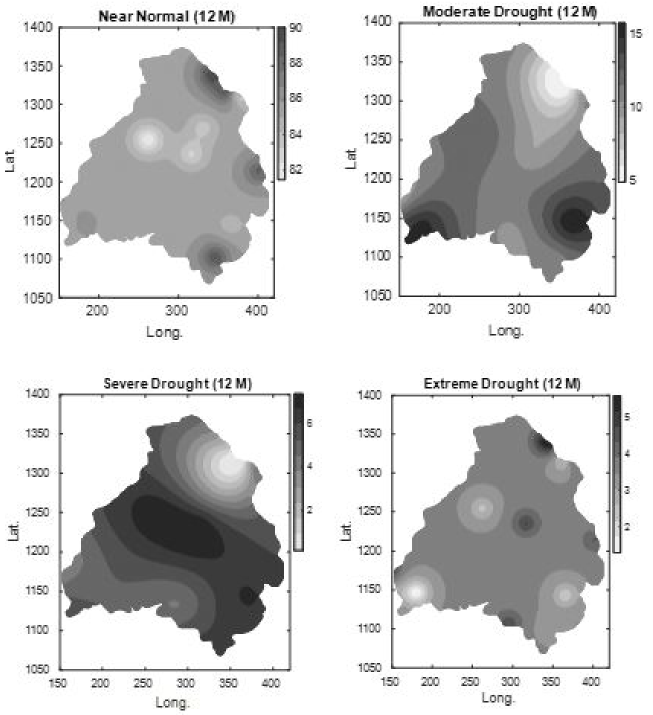

Figure 3. Spatialization of drought-type percentage of occurrence using the SPI values.

4.1.3 Drought's Duration and Intensity

Figure 4 illustrates the spatialization of droughts duration and intensity at 6 and 12 month timescales. We note a decrease in the durations of the 12 month SPI with increasing latitude. The durations are more pronounced in the south than in the north of the basin with long durations (maximum) (Fig. 4).

The average intensity of SPI-6 and 12 months are −1.69 and −1.73 respectively. All these average values plunge the basin into a severe drought situation. This situation is noticeably recorded in the extreme areas of the north and southeast of the basin (Fig. 4).

4.2 Analysis of Consecutive Dry Days (CDD) Index

The CDD values obtained for each station during the study period were kriged and then spatialized over the entire study area. Figure 6 shows the spatialized mean CDD values (plots a and b) and the trend results (plots c and d).

In the rainy season, the CDD, which corresponds to dry spells varies from 9 to 18 d. Its maximum was recorded in the northern part of the basin (plots b and d).

4.3 Analysis of the hydrological drought in the Beninese Part of the Niger River Basin

Figure 6 shows the fluctuations in the wet and dry periods for the whole hydrometric stations of BPNRB during 1970–2020. A significant (level = 5 %) upward trend was noted for the SDI at the various timescales except for 3-month at Couberi and Kompongou stations and 12-month at Yankin station. Duration and intensity of drought were comparatively higher at longer time scales of 6- and 12-month and they seemed to increase as the time scale increased (Fig. 6).

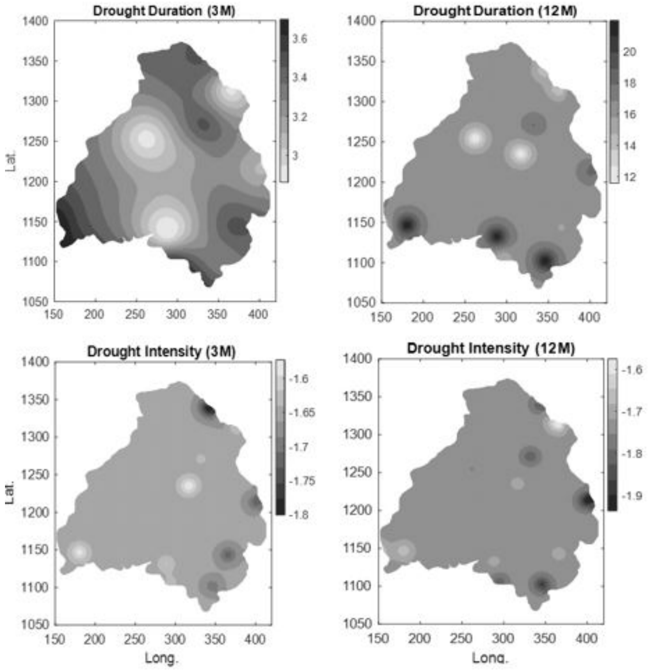

Figure 4. Spatiotemporal variations of drought duration and intensity using SPI values.

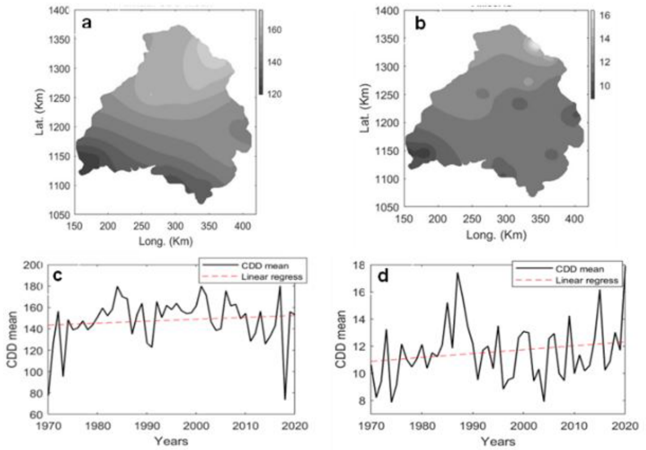

Figure 5. Spatialization and trends of averaged CDD annually and in the rainy season.

5 Discussion

Spatiotemporal distributions of the SPI and SPEI revealed that from 1970–2020, the basin experienced both wet and dry

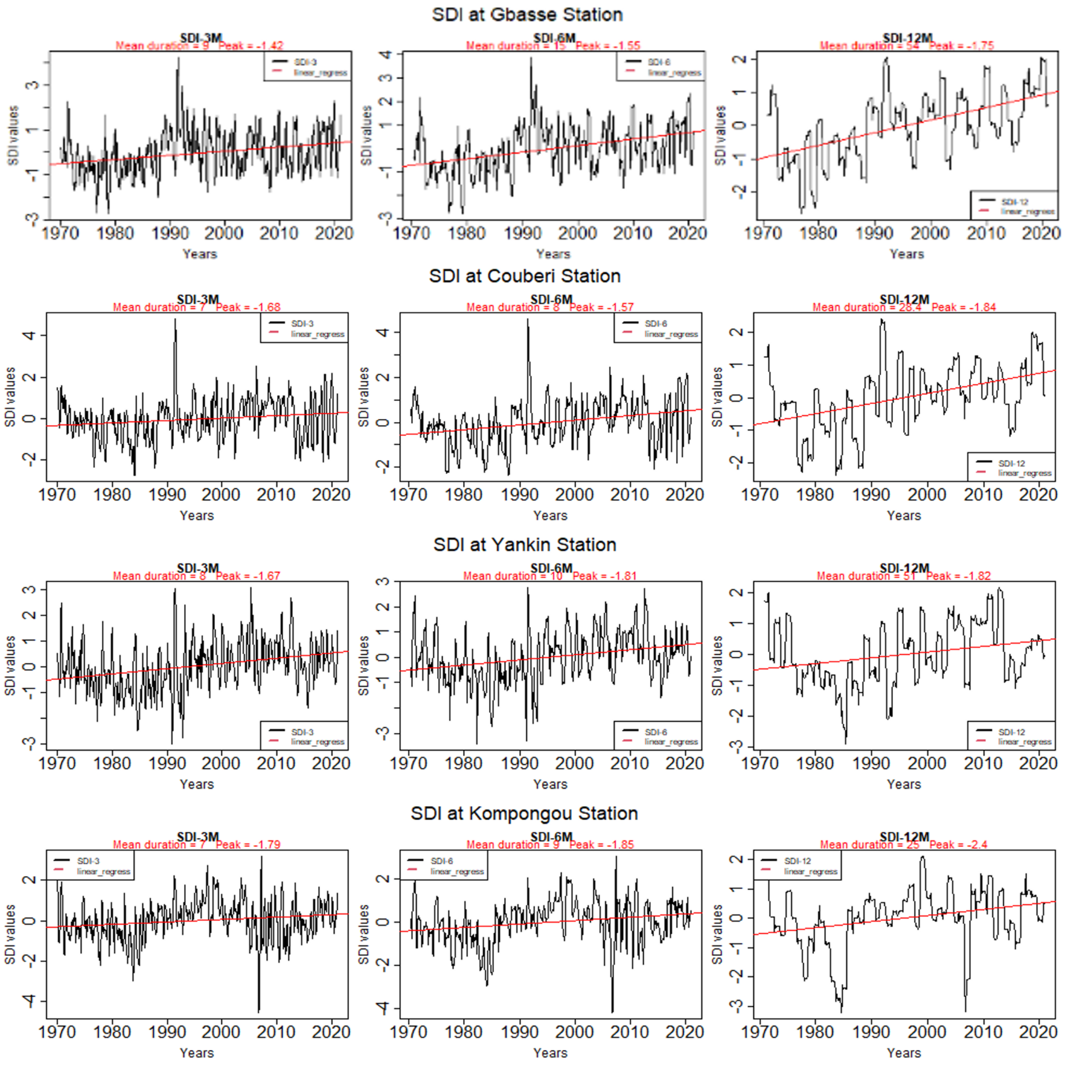

Figure 6. The temporal evolution of the SDI, Duration, and Peak values at each hydrological station at 3-, 6-, and 12-month timescales in BPNRB during 1970–2020.

sequences. There was a substantial spatiotemporal variability in the distribution of drought in BPNRB. An upward trend was observed for the SPI while a downward for the SPEI. The latter indicated an increase in the intensity of drought. These findings were partially consistent with (Katchele et al., 2017), which obtained a downward trend for the SPEI from 1901 to 2010 in Sub-Sahara Africa. Drought durations were more pronounced in the south than in the north of the basin while the peak values of SPI and SPEI were recorded in the extreme areas of the north and south-east of the basin. Those situations plunged the basin into a severe and extreme drought situation. This phenomenon in the basin confirms what is happening in Africa in general, where the number of rainy days and wet sequences has been decreasing chronologically since the 1970s, as shown by (Balliet et al., 2016; New et al., 2006).

A cross-analysis of the time series of the three indices (SPI, SPEI, and SDI) shows an upward trend for the SPI and SDI and a downward trend for the SPEI. This divergence between the SPI and SPEI can be attributed to the growing influence of temperature-driven evapotranspiration in the region. While the SPI is solely based on precipitation, the SPEI accounts for the atmospheric evaporative demand, which increases with rising temperatures. Thus, even in cases where precipitation shows a slight recovery, enhanced evapotranspiration due to warming can intensify drought severity and duration, leading to contrasting trends between the two indices. This suggests that temperature increases are becoming a dominant factor shaping drought dynamics in the basin. These results were consistent with other related studies reported by Hulme et al. (2001) in the Niger River Basin; Sun et al. (2023) in China and Mohammed et al. (2022) and Alsafadi et al. (2022) in other regions.

Combining the findings on the temporal and spatial patterns of drought in BPNRB in this study, and taking different actions in each sub-basin, can improve the overall level of drought response. However, the study acknowledges certain limitations. Some potential drought drivers were not explicitly considered, including land-use and land-cover changes, groundwater abstraction, and large-scale atmospheric circulation patterns that influence regional hydroclimatic variability. In addition, uncertainties related to data quality and the choice of PET estimation method may have influenced the magnitude of the detected trends. Future research should integrate remote sensing observations, hydrological modeling, and teleconnection analyses to better capture the combined effects of climatic and anthropogenic factors on drought evolution (Wang et al., 2018).

6 Conclusions

This study examined the spatiotemporal patterns of meteorological and hydrological droughts in the Beninese part of the Niger River Basin (1970–2020). Meteorological droughts were identified using SPI and SPEI from 18 climate stations, while hydrological droughts were assessed via SDI using discharge data from four stations. Consecutive dry days (CDD) were also analyzed. Key findings include:

- Significant spatiotemporal variability in drought distribution, with both meteorological and hydrological droughts observed between 1970 and 1990.
- Short-duration droughts occurred throughout the basin, while long-duration droughts were more frequent near the Sahelian borders (Niger and Burkina Faso).
- A significant increasing trend in CDD (5 % level), with up to 180 dry days annually and 18 d dry spells.
- SDI results indicated increasing drought duration and intensity across sub-basins since the 1970s.

Overall, the results of this study are important for a better understanding of drought, which could be used as a baseline for designing drought management strategies to reduce impacts on agricultural communities and other water-related sectors in Northern Benin.

Code and data availability. The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Author contributions. OMGM: Data curation, Formal analysis, Investigation, Methodology, Conceptualization, Resources, Software, Writing – original draft, Writing – review & editing. KFG: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. BM: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing. EO: Conceptualization, Methodology, Supervision, Writing – review & editing. RKG: Conceptualization, Methodology, Supervision, Writing – review & editing. HY: Conceptualization, Methodology, Supervision, Writing – review & editing. JH: Conceptualization, Methodology, Supervision, Writing – review & editing. AEA: Conceptualization, Methodology, Supervision, Validation, Writing – review & editing.

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