

## RESEARCH ARTICLE

# Over a century evidence of historical and recent dryness/wetness in sub-humid areas: A Uganda, East African case

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## Abstract

Many regions globally are grappling with the challenge of recurrent extreme weather events. Whereas attempts are being undertaken to understand their characteristics as a first step to guide targeted mitigation measures, these are focused on dryness and not wetness, which is also a challenge in sub-humid areas. This study investigates dryness and wetness characteristics using the standardized precipitation evaporation index (SPEI) at timescales of 3, 6, 12 and 24 months for a period of 1901–2018 across Uganda's drainage basins. Trends in the dryness and wetness evolutions were conducted using the Mann-Kendall (MK) statistic to establish the effects of global warming on the study area. A step change analysis reveals 1961 as a change point year from cool to warm periods. Results also reveal that warming mainly occurred in the recent period (1962–2018), with a temperature rise of over 2°C being recorded in 2009. Severe dryness events occurred in the recent period as opposed to wetness events that dominated the earlier period (1901–1961). Dryness and wetness varied among drainage basins, with the Aswa basin being more susceptible to severe dryness while the Lake Kyoga basin to severe wetness. Lira and Kitgum were identified as drought hotspots at timescales of 3, 6 and 12 months. SPEI was able to reveal 60% of historical dryness events and 75% of wetness events on record, making it an adequate tool for monitoring humid events as opposed to droughts in sub-humid climates. It is hoped that this evidence can guide targeted mitigation measures towards climatic shocks within the region.

## KEYWORDS

climate variability, disaster risk, drought hotspot, drought severity, global warming, standardized precipitation evaporation index

## 1 | INTRODUCTION

The world is currently grappling with increasing incidences of extreme weather events that have heightened

after the 1950s (Conforti et al., 2018; Seneviratne et al., 2012). These events have manifested through disasters such as floods, droughts, wild fires and landslides as some of the examples. The degree of impact of these

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disasters varies from region to region but is particularly more devastating in developing countries where infrastructure development and adaptability options are still slow and at low levels (Byakatonda et al., 2020; Stocker et al., 2013). For example, in developing countries alone, weather-related extremes have caused an estimated combined damage in excess of \$95 BN just over the last 10 years (2004–2014) (Below & Wallemacq, 2018; Zhang & Huang, 2018). It is further anticipated that in Africa alone 20% of agricultural productivity may be lost as a result of recurrent droughts only (Byakatonda et al., 2020; FAO, 2016). With evidence of climate variability and change, projections continue to show a sustained temperature rise until the end of the 21st century (Akisanola et al., 2018; Dyderski et al., 2018; Galarneau et al., 2008). Warming of the earth is not only anticipated to lead to further drying of arid and semi-arid regions, but also more precipitation in humid locations (IPCC, 2012; Stocker et al., 2013). From the foregoing, it is clear that the globe is likely to experience droughts and floods as alternating events if these projections are to be realized. Natural disasters have a tendency of causing damage to infrastructure and the entire agricultural value chain. For the developing countries whose populations are mainly engaged in agriculture, these extreme weather events may disrupt economic growth. Regionally in East Africa, warming of above 2°C is already being experienced in some locations surpassing the 2015 Paris agreement limits (Gebrechorkos et al., 2019). This calls for identification of disaster hotspots for targeted intervention options tailor-made at a regional scale.

Extreme weather events generally occur due to the occurrence of precipitation either below or above the normal range over a region. The impact of these extreme events is known to vary in space and build up over time (Adnan et al., 2018). Understanding the spatial and temporal variability of extreme events at a regional scale is key to developing targeted drought preparedness and mitigation interventions (Jain et al., 2015). As a result, analysis of trends in meteorological variables has recently gained wide acceptance in providing vital information on disaster monitoring, management and mitigation in general (Adnan et al., 2018; Byakatonda et al., 2020). As a starting point, drought indices that can provide temporal evolutions of both wet and dry episodes have been applied in most cases. Some of these indices that have been applied include the palmar drought severity index (PDSI), the standardized precipitation index (SPI), evaporative demand drought index (EDDI), soil moisture drought index (SMDI), normalized ecosystem drought index (NEDI) and most recently the standardized precipitation evaporation index (SPEI) (Ayantobo et al., 2017; Byakatonda, Parida, Moalafhi, & Kenabatho, 2018c; Faiz et al., 2020; Homdee et al., 2016;

Lloyd-Hughes & Saunders, 2002; Nalbantis & Tsakiris, 2009; Vicente-Serrano et al., 2010).

Several studies have applied these drought indices in different regions such as globally (Spinoni et al., 2014), Brazil (Gozzo et al., 2019), South Korea (Bae et al. (2018), Pakistan (Adnan et al., 2018), China (Yao et al., 2018), India (Das et al., 2016), Niger river basin (Oloruntade et al., 2017), Nile Basins, (Elkollaly et al., 2018) and Botswana (Byakatonda, Parida, Kenabatho, & Moalafhi, 2018b). These studies investigated the spatial and temporal variability of drought. However, they are largely limited to extreme dryness, and do not consider humid events. Studies to understand drought effects on Uganda's population are also limited to dryness and with little or no attention to humid events. For example, whereas Ojara et al. (2020) studied the occurrence of dry spells in the Lake Kyoga basin, the study is criticized for combining periods with inter-decadal variations, which cannot be assumed homogeneous for purposes of analysis. In another study, Nakalembe (2018) characterized droughts using SPI over the Karamoja region located in the northeast. However, with the ongoing global warming, SPI is not robust enough to effectively track dryness events (Byakatonda, Parida, & Kenabatho, 2018a; Oloruntade et al., 2017). Additionally, both these Ugandan studies are limited to dryness events and specific drainage basins and hence not representative of the entire country. Whereas the complete scope of extreme weather events should cover both dryness and wetness, existing studies have been limited to mostly dryness events.

This paper, therefore, addresses the aforementioned research gap and builds on the prior studies by undertaking a comprehensive analysis that takes into consideration both dryness and wetness events over different time horizons to try and understand their characteristics at a country scale and, in the end, identify drought/humid hotspots. This study extends the application of SPEI in the monitoring of humid events and establishes its performance in sub-humid climates such as Uganda. To achieve this, the study characterizes dryness and wetness events for a period between 1901 and 2018. The specific objectives of this study are therefore as follows:

- i. Establish effects of global warming on the local climatic variables and identify possible change point years;
- ii. Characterize dryness and wetness events using standardized precipitation and evaporation index (SPEI) at timescales of 3, 6, 12 and 24 months;
- iii. Identify drought/humid hotspots that require targeted interventions across the study area.

It is envisaged that the results from this study will present an evidence-based strategy towards disaster risk reduction as proposed in the 2030 SDG agenda. Conducting a long-term and comprehensive characterization of dryness and wetness events is an important step in the formulation and implementation of more appropriate drought mitigation strategies aimed at reducing drought impacts and accelerating progress towards the achievement of SDG 13. Accordingly, regional governments can build on this information to enhance their dryness/wetness monitoring capabilities as well as in the development of robust drought mitigation strategies.

## 2 | DATA AND METHODS

The data and methods used in this study are described in this section. The description and justification of the study area are also presented here.

### 2.1 | Study area

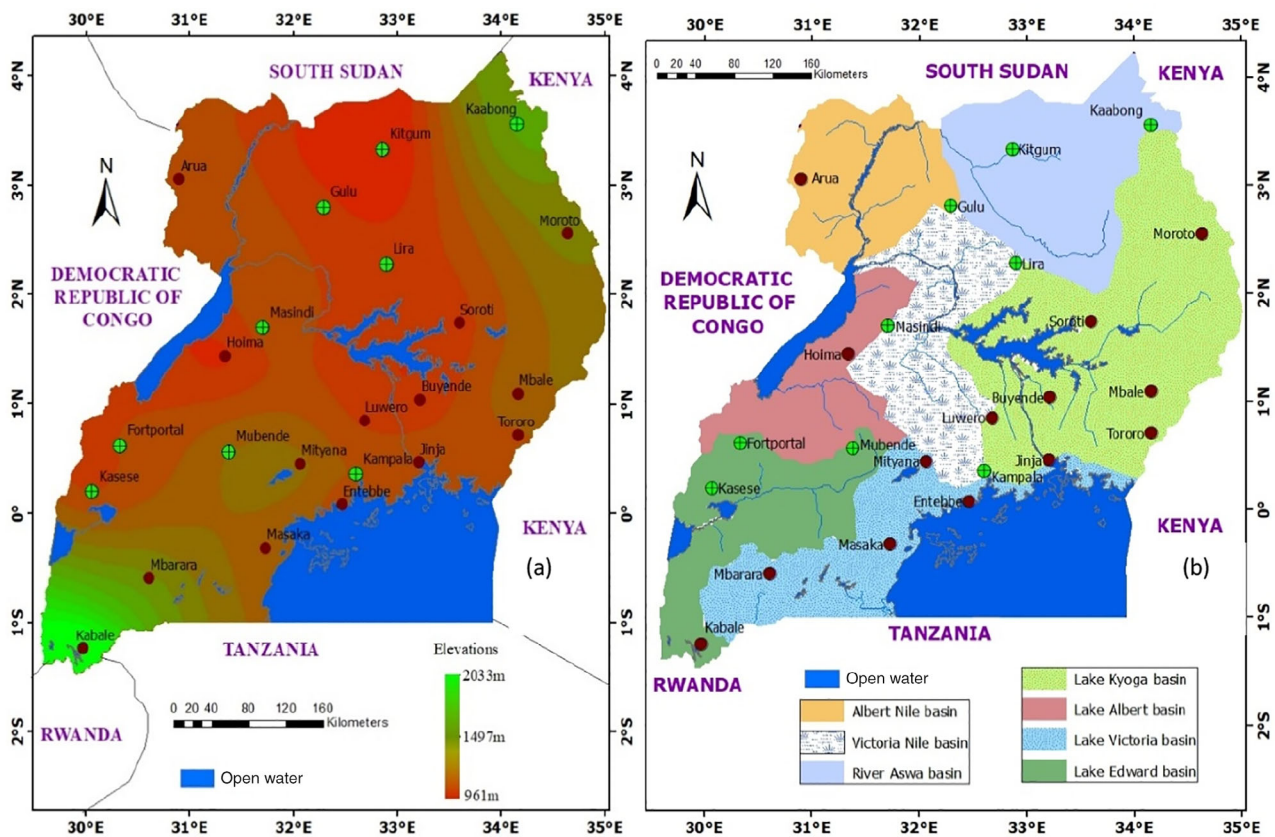
Uganda in Eastern Africa is characterized by a sub-humid to tropical savanna climate according to the Köppen's climate classification (Nsubuga, Olwoch, & Rautenbach, 2014b). It is bounded between Latitudes of  $-1^{\circ}$  S and  $4^{\circ}$  N as well as longitudes of  $29^{\circ}$  E and  $35^{\circ}$  E. It shares a border with the Democratic Republic of Congo (DRC) in the west and South Sudan in the north. In the east, it borders Kenya, while in the south, Rwanda and Tanzania. The study area is divided by the equator leading it to experience a bimodal type of rainfall. The long rains ranging from 800 to 1700 mm are experienced between March and May (Nsubuga, Botai, et al., 2014a; Ojara et al., 2020). This rain season is mainly attributed to the shifting of the Inter-Tropical Convergence Zone (ITCZ) to the north of the equator. The shorter rains that occur between September and November are also associated with the retreating of ITCZ to the southern hemisphere (Kizza et al., 2009; Ojara et al., 2020). However, the rainfall patterns are also moderated by ENSO events of the equatorial Pacific and the Indian Ocean Dipole (IOD) (Kisembe et al., 2019; Ntale & Gan, 2004). There also exist other complex weather mechanisms such as the interaction between tropical air masses and flows from the Congo tropical rain forest that contributes to seasonal rainfall variations (Gebrehiwot et al., 2019; Ojara et al., 2020). Uganda is characterized by an angulating topography as shown in Figure 1a. This alone contributes to none uniformity in rainfall distribution within the study area. The mountainous regions such as the Rwenzori, Muhavura ranges located in the Lake Edward

basin and Elgon in the Lake Kyoga basin receive the highest amount of rainfall in excess of 1500 mm/year. The Lake Victoria being the largest fresh water lake on the African continent also moderates the climate across the study area (Olaka et al., 2019). The north to the northeast is relatively flat and receives low rainfall amount of less than 1000 mm/year, especially in the northeast of the Lake Kyoga basin. The lowest rainfall is received in the cattle corridor that stretches from the northeast at Kaabong and Moroto through Soroti and Luwero sub-basins. This corridor continues through the sub-basins of Mubende winding up in Mbarara and Rakai districts at the border of Uganda and Tanzania (Nimusiima et al., 2013) covering Aswa, Victoria Nile and Lake Edward drainage basins. This region is the most susceptible to recurrent drought.

Uganda has experienced twice as many droughts between 1970 and 2010 compared with the earlier period of 1920–1970 (GOU, 2012). The most recent dryness events on record are those of 1992–1994, 1998–1999, 2002–2003 and 2005–2008, and mild ones of 2010–2011 and 2014–2015. These dryness events were experienced at different severity levels across the study area. In particular, the dryness event of 2005–2008 was devastating in that, it resulted in a drastic drop in Lake Victoria water levels by 1.2 m below the 1951–2006 average (Awange et al., 2008; Kull, 2006). This makes it then necessary to identify drought hotspots at a country scale, which this study attempts to address. Wet episodes have equally been experienced across the study area, which in most cases have led to flooding in the low lands and landslides in the mountainous regions, especially in the Elgon and Rwenzori. The historical landslide disasters on record in Uganda are those of 1900, 1918, 1920, 1927, 1947, 1997, 2012, 2016, 2018, 2019 and most recently 2020 (UNESCO, 2020). This demonstrates that these extreme events have occurred every other year in the last 10 years. In a nutshell, the study area could already be experiencing effects of climate variability and change that are manifesting in form of these climate-related disasters.

### 2.2 | Data description

The data used in this study were gridded climatological datasets obtained from Climate Research Unit Time Series, version 4.0 release (CRU TS v4). The study area is divided into seven drainage basins, namely Lake Edward, Lake albert, Albert Nile, Victoria Nile, river Aswa, Lake Kyoga and Lake Victoria, as shown in Figure 1b (MWE, 2016). These drainage basins were further subdivided into 23 drainage sub-basins using a digital elevation model (DEM) to take care of location-specific spatial



**FIGURE 1** Study area map showing (a) elevations and locations of observation stations and (b) drainage basins from which sub-drainage basins were created. Green dots show stations with recorded long-term data that were compared with CRU-gridded data while the red dots are stations with insufficient observation data

attributes. CRU data were then obtained for each drainage sub-basin as the average of the CRU  $0.5^{\circ} \times 0.5^{\circ}$  grid cells covering each of the sub-basins. The CRU TS v4 is one of the latest releases of the gridded climatic dataset from the climate research unit with a global coverage except for Antarctica regions. Details of the methods used in the construction of CRU TS v4 and the interpolation techniques are found in the study by Harris et al. (2020). Due to scarcity of station data, CRU-gridded datasets have recently been widely used in climate change and drought studies in Africa and found adequate in representing historical patterns on the continent (Haile et al., 2020; Mahmood et al., 2019; Shiru et al., 2019). The advantage of CRU datasets over other gridded climatic data is that it compares with local meteorological stations that are used in the interpolation of the climatic variables over the half-degree cell grids (Dai & Zhao, 2017). Across the 23 drainage sub-basins, only 9 had recorded station data of reasonable length that were used to evaluate the suitability of CRU-gridded data for climatological analysis across the study area. The remaining stations had data with a number of temporal breaks and missing values that would not allow any meaningful comparison. The only

reliable data at the remaining stations were the CRU-gridded dataset that was used in this study. Table 1 shows the available record of the nine station data, the percentage of missing climatic data and their degree of association with CRU-gridded data of monthly rainfall at the nine locations. The gridded CRU TS v4 datasets used contained monthly temporal resolution of climatological data of rainfall, minimum and maximum temperature, cloud cover and vapour pressure covering over 100 years from 1901 to 2018.

Correlations between CRU-gridded data and available station data were all significant at  $p < 0.05$ . Based on this significant association and low bias between recorded and gridded datasets, this study used the CRU-gridded data that had a long record length and covered the entire study area for the analysis. Normally the assumption in derivation of the gridded datasets is that quality checks of the contributing stations' data, such as checks for homogeneity and consistency, are done by the individual meteorological authorities of the contributing stations. Since this information was not available, some of these quality checks, such as a test for normality, homogeneity and consistency of the rainfall and temperature datasets, were conducted in this study.

**TABLE 1** Correlation coefficients and bias between available station's rainfall data and the corresponding CRU-TS gridded data where these stations are located

SN	Station	Latitude	Longitude	Correlation coefficient ( <i>r</i> )	Bias (mm/year)	Start	End	Years with data	Percentage of missing values (%)
1	Fortportal	0.677	30.088	0.80	15.7	1940	2013	73	9
2	Gulu	2.822	32.295	0.86	11.6	1911	2011	100	1
3	Kaabong	3.535	33.978	0.74	24.7	1940	2011	71	11
4	Kampala	0.3286	32.592	0.62	52.5	1932	2015	83	35
5	Kasese	0.191	30.088	0.72	23.4	1951	2013	50	3
6	Kitgum	3.298	32.883	0.70	32.4	1914	2011	87	10
7	Lira	2.255	32.893	0.81	18.6	1914	2013	87	4
8	Masindi	1.688	31.714	0.79	21.4	1922	2015	93	4
9	Mubende	0.592	31.534	0.74	22.9	1960	2014	54	21

## 2.3 | Methods used in the study

### 2.3.1 | Step change analysis in the meteorological time series

With undeniable evidence of climate variability and change, climatic data can no longer be assumed to be stationary. Accordingly, a homogeneity test was carried out on the temperature and rainfall time series to determine any possibility of a significant shift. In this study, we applied the standard normal homogeneity test (SNHT), Buishand range and Pettit homogeneity test to try and locate any possible change point year. All these tests are non-parametric and recommended over parametric ones. These absolute homogeneity tests have been used in a number of hydro-climatic studies such as in Europe (Costa & Soares, 2009; Wijngaard et al., 2003), in southern Africa (Byakatonda, Parida, Kenabatho, & Moalafhi, 2018b) and in West Africa (Akinsanola & Ogunjobi, 2015). In spite of the good performance of relative techniques over absolute ones, they require reliable reference stations, which are largely missing across the study area (Byakatonda, Parida, Kenabatho, & Moalafhi, 2018b; Yozgatligil & Yazici, 2016). For this reason, the absolute tests are preferred over relative tests in this study. All the three techniques selected are statistical tests whose null hypothesis assumes no significant shift in the meteorological time series exists. The alternative hypothesis is that there is a shift in the meteorological time series, and in this case, a change point exists. The significance of the shift was tested at  $p < 0.01$  in this study. Once the change year is identified, the dataset is split at that point into two distinct time periods. Formulation details of the SNHT, Buishand range and Pettit tests can be found in Wijngaard et al. (2003) and Byakatonda, Parida, Kenabatho, and Moalafhi (2018b).

### 2.3.2 | Determination of the dryness index and classification

Drought indices that are proxies of effects of droughts on the hydrological cycle (Byakatonda et al., 2016; Nalbantis & Tsakiris, 2009) have been applied in many hydro-climatic studies across the globe. Their suitability stems from their ability to represent both wetness and dryness events at the same time. Over time, a number of drought indices have been developed; however, most of them are specific for a particular drought category; a case in point is the standardized flow index (SFI) (Byakatonda, Parida, & Kenabatho, 2018a; Lloyd-Hughes, 2012; Nalbantis & Tsakiris, 2009), which is specific for stream flow drought, the SMDI (Homdee et al., 2016; Narasimhan & Srinivasan, 2005) for agricultural droughts. There is also a number of drought indices that use meteorological variables to determine drought magnitude and duration at multiple time-scales. These have been found applicable in a wide range of drought studies since the same index can be used to quantify dryness/wetness across the entire hydrological cycle. Two of these indices that have been recommended by the World Meteorological Organization (WMO) are the SPI and SPEI (Hayes et al., 2011; WMO & GWP, 2016). SPI developed by McKee et al. (1993) uses only precipitation and has been found to be ineffective in respect to the ongoing global warming phenomena (Byakatonda, Parida, Moalafhi, & Kenabatho, 2018c). For this reason, SPEI, which uses both precipitation and temperature, has been preferred over SPI for this study. At short time scales of 1 and 2 months, the SPEI is able to quantify meteorological droughts, equally at 3–6-months, the index has the capability of monitoring agricultural droughts, whereas

at longer timescales of 12 and 24 months, the index is associated with hydrological droughts (Byakatonda, Parida, Moalafhi, & Kenabatho, 2018c; Vicente-Serrano & López-Moreno, 2005). In this study, the drought index was determined for 3-, 6-, 12- and 24-month timescales to identify the influence of dryness/wetness on the entire hydrological cycle. The 1-month timescale was not analysed because it basically reports monthly variations, which may not be long enough to reveal significant changes in the hydrological cycle.

To determine the drought index, the moisture deficit/surplus, which is the difference between precipitation and potential evapotranspiration ( $ET_0$ ), is accumulated over a period equivalent to the preferred timescale. The potential evapotranspiration was determined using the Penman–Monteith technique, which is a physically based model (Allen et al., 1998; Song et al., 2019).

The accumulated deficit/surplus time series were then fitted on a probability density function (pdf) of best fit. There are various candidate distributions from which the best fit was carefully selected. In this study, we used L-moments, which have been applied in a number of similar studies and identified to have the least bias (Byakatonda et al., 2020; Hosking & Wallis, 2005). The pdf identified to fit the deficit/surplus time series was the three-parameter generalized extreme value (GEV) distribution function. The GEV representing the accumulated series denoted by  $R$  is given by:

$$f(R) = \alpha^{-1} \exp[-(1-k)y - \exp(-y)], \quad (1)$$

where

$$y = \begin{cases} -k^{-1} \ln \left[ 1 - \frac{k(s-\xi)}{\alpha} \right], & k \neq 0 \\ \frac{(s-\xi)}{\alpha}, & k = 0 \end{cases}, \quad (2)$$

The cumulative density function (CDF) of the GEV above is also given by:

$$F(R) = \exp[-\exp(-y)], \quad (3)$$

where  $\xi$ ,  $\alpha$  and  $k$  are location, scale and shape parameters, respectively, for  $R$  ranging from:

$$R: \begin{cases} -\infty < s \leq \xi + \frac{\alpha}{k} & \text{if } k > 0 \\ -\infty < s < \infty & \text{if } k = 0 \end{cases} \quad (4)$$

The parameters were computed as a function of L-moment ratios whose details can be found in the study by Byakatonda et al. (2016).

The CDF in Equation (3) was taken through a Gaussian transformation to obtain an index with a mean zero and standard deviation 1. The  $F(R)$  values for a normal variate are approximated as follows:

$$S = M - \frac{A_0 + A_1M + A_2M^2}{1 + B_1M + B_2M^2 + B_3M^3}, \quad (5)$$

where

$$M = \left( \text{Ln} \left( \frac{1}{P^2} \right) \right)^{\frac{1}{2}}, \quad (6)$$

$P$  is the probability of exceedance for a given quantile of dryness/wetness time series, while  $A$  and  $B$  are constants given by  $A_0 = 2.515517$ ,  $A_1 = 0.802853$ ,  $A_2 = 0.010328$ ,  $B_1 = 1.432788$ ,  $B_2 = 0.189269$ ,  $B_3 = 0.001308$ .

The standardized values of the index contain both negative (dryness) and positive (wetness) events. The departure from the mean measures the severity of either dryness (negative departure) or wetness (positive departure). Based on the magnitude, the dryness/wetness events can be classified according to Table 2.

### 2.3.3 | Mann-Kendall trend analysis tests in the dryness/wetness evolutions

The Mann-Kendall (MK) statistic is a common non-parametric method used to detect a trend in time series (Byakatonda, Parida, Kenabatho, & Moalafhi, 2018b; Das et al., 2016; Shifteh Some'e et al., 2012; Tabari et al., 2011). It is preferred because it performs well even with time series containing outliers and does not necessarily require data to be normally distributed. The MK test statistic  $S$  for a given variable  $Y_1, Y_2, \dots, Y_k, Y_j, \dots, Y_n$  is expressed as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{Sgn}(Y_j - Y_k), \quad (7)$$

where  $j \geq k$  and the  $\text{Sgn}(Y_j - Y_k)$  is given by:

$$\text{Sgn}(Y_j - Y_k) = \begin{cases} +1 & \text{if } (Y_j - Y_k) > 0 \\ 0 & \text{if } (Y_j - Y_k) = 0 \\ -1 & \text{if } (Y_j - Y_k) < 0 \end{cases}. \quad (8)$$

The alternative hypothesis of this test statistic assumes there is a trend in the dryness/wetness severity time series. The statistical significance of the trend was tested

**TABLE 2** Dryness/wetness classification (Bae et al., 2018; Byakatonda et al., 2016)

SPEI	Classes
<−2	Extreme dryness
−1.99 to −1.50	Severe dryness
−1.49 to 1.00	Moderate dryness
−1.00 to 1.00	Near normal
1.00 to 1.49	Moderate wetness
1.50 to 1.99	Severe wetness
>2.00	Extreme wetness

at  $p < 0.05$  significance level. Trend analysis in the first instance was subjected to serially independent drought index time series at time scales of 3, 6, 12 and 24 months. The serial correlation effect on the time series increases the chances of missing the trend when it actually exists. To achieve this, time series that were found to be serially correlated were pre-whitened until random series were realized. Details of the pre-whitening technique can be found in (Byakatonda, Parida, Kenabatho, & Moalafhi, 2018b; Gocic & Trajkovic, 2013; Yue et al., 2002).

### 2.3.4 | Trend magnitude

Since the MK test statistic can only reveal the trend direction, it was necessary to also determine the rate of change over a period of time. In this study, a decadal rate of change denoted as  $S/10$  years has been used. To achieve this, Sen's slope estimator was applied to determine this trend magnitude. It is obtained from the slope of a dataset of  $N$  ordered pairs given by:

$$Q_i = \frac{(Y_j - Y_k)}{j - k} \text{ for } i = 1, 2, 3, \dots, N. \quad (9)$$

The midpoint of the  $Q_i$  series arranged in ascending order results in the Sen's slope estimate.

The methodology is summarized in Figure 2.

## 3 | RESULTS AND DISCUSSIONS

Due to the angulating topography and complex landscape across the study area, there are inherent spatial variations in both rainfall and temperature, the main climatic variables. This alone could lead to different responses towards dryness and wetness events. A case in point is the mountainous regions that receive high rainfall

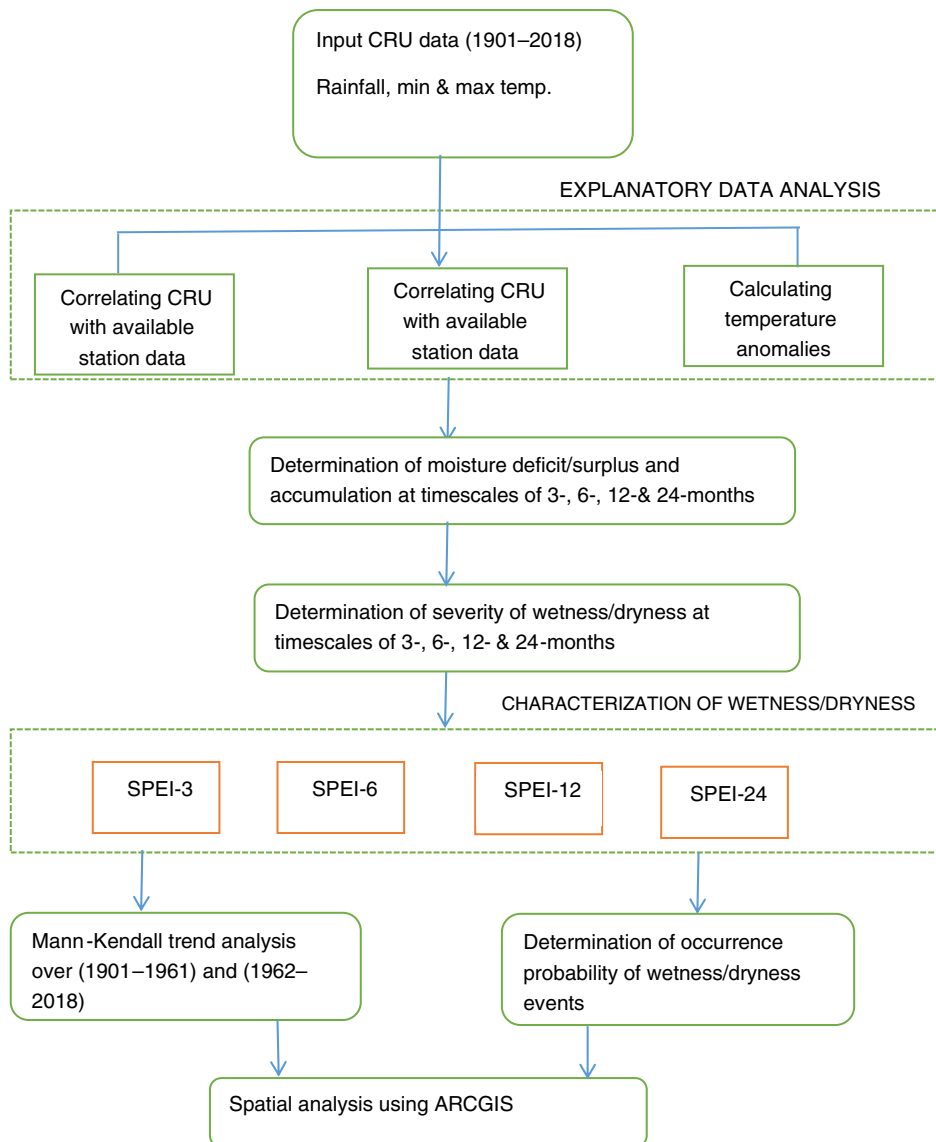
compared with the relatively flat cattle corridor. For this reason, the results are presented at the drainage basin scale instead of taking an areal average over the study area, as is normally the case in related studies.

### 3.1 | Temporal analysis of local temperature anomalies in relation to global warming trends

To understand the possible influence of climate variability and change, in effect global warming on the local climate, temperature anomalies were determined using the 1961–1990 normal period as a reference. The results from this analysis are plotted as shown in Figure 3. Locations in the plots are selected to represent drainage basins across the study area. Kampala and Entebbe, although all located in the Lake Victoria basin, represent urbanized settlements and the lake region, respectively.

Figure 3a,b,f represents temperature anomalies across the Lake Victoria basin, while Figure 3c represents Victoria Nile basin. Figure 3d,e presents anomalies for the Lake Kyoga basin. From Figure 3, it is evident that generally the 20th century was cool, characterized by negative anomalies relative to the reference mean regardless of the drainage basin across the study area. These negative anomalies ceased in 1970. During this period, only three distinct warm episodes occurred. The first episode occurred in 1901 persisting for 3 years. The next episode occurred between 1924 and 1928, and the final warm episode occurred between 1953 and 1958. From the above anomalies, a 20-year inter-annual variation was visible until 1961. From 1961 to 1970, the patterns of cool and warm episode are undefined from region to region. From 1970 to the end of the study period (2018), the temporal variations are only reporting positive anomalies (warm period) relative to the 1961–1990 reference mean. The period between 1960 and 1970 can be regarded as transitional from a cool to a warmer climate. These results also reveal that across the study area, more than 2°C temperature rise was recorded above the 1961–1990 average in 2009. This increment is well above the 1.5°C target stated in the Paris agreement of 2015 (Rogelj et al., 2016). This finding corroborates those of Gebrechorkos et al. (2019) who reported warming beyond 2°C in some locations of East Africa. This analysis demonstrates that despite of Uganda being classified as sub-humid, global warming tendencies are already being experienced. It has already been observed that during the period 1960–1970, Uganda experienced a number of intermittent dry and wet years, this could have been partly attributed to perturbations as a result of climate variability and change. The temperature trends across the

FIGURE 2 Methodology flow diagram

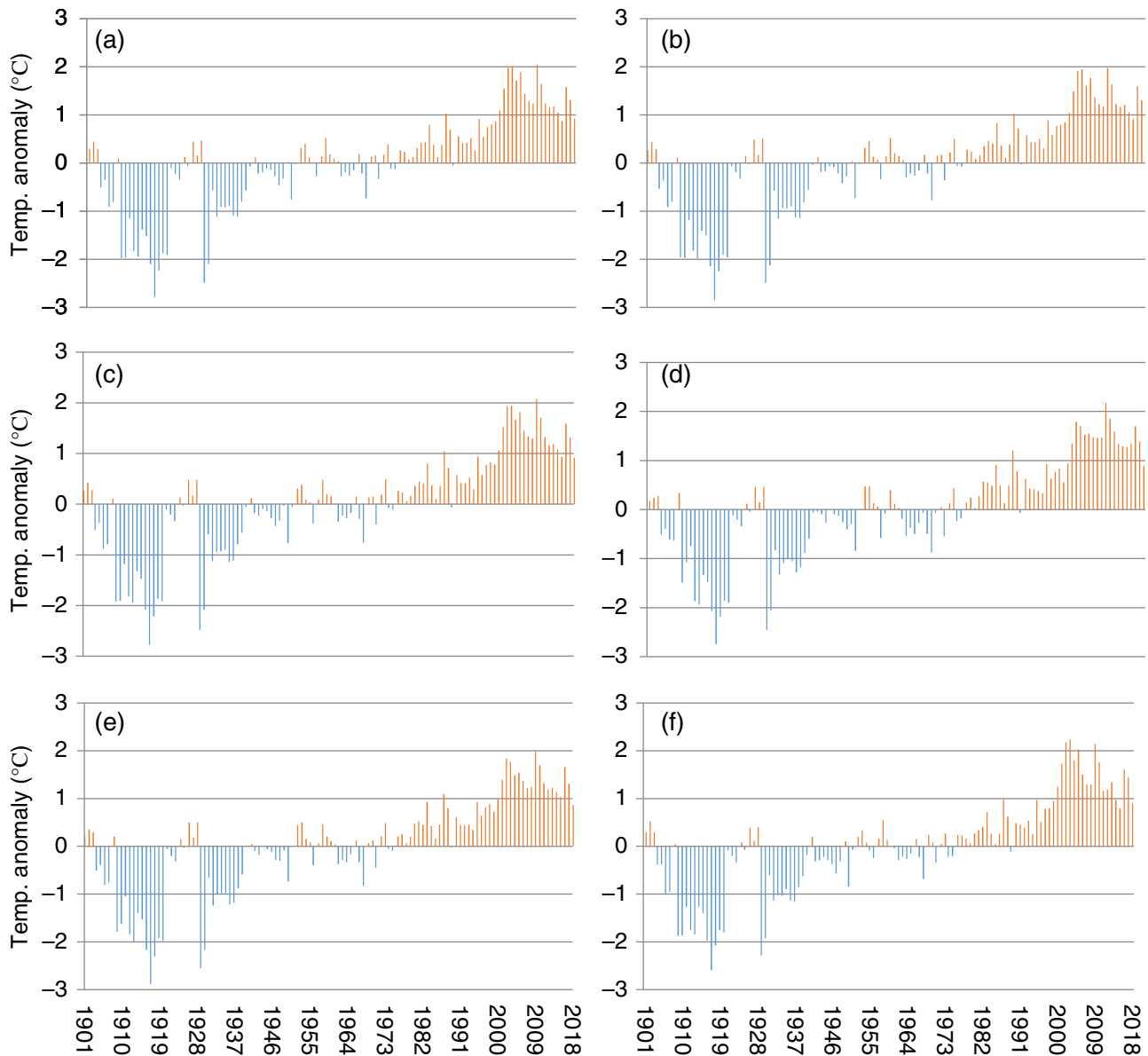


study area are not different from the global warming levels, which show that the highest rate of warming of the Earth occurred after 1960 attributed to warmer surrounding oceans (NOAA, 2021). Just as was with the case in the study area, during the period between 1940 and 1970, global temperature trends were intermittent with warm and cold episodes. This finding demonstrates that the study area is already experiencing the effects of global warming. Further still, the years of 2008, 2009, 2010 and 2011 that recorded the highest positive anomalies are categorized as La Niña years (Golden Gate Weather Services, 2021). This alone may underscore the possibility of an ENSO-driven climate variability over the study area. Our findings also agree with those of Ojara et al. (2020) who recently reported increased incidences of dry spells that have intensified since 1960 to the current period in some of the lake regions of Uganda. Nsubuga, Botai, et al. (2014a) have also reported

decreasing trends in rainfall between 1940 and 2009. From these findings, it was therefore clear that the dataset could have experienced breaks as a result of these climatic changes with a possibility of the data being non-homogenous (Byakatonda, Parida, Kenabatho, & Moalafhi, 2018b; Wijngaard et al., 2003). For this reason, it was then necessary to identify any possible significant shifts in the meteorological time series.

### 3.2 | Step change analysis in meteorological time series

From the temporal analysis of temperature anomalies over the study period (1901–2018), it was revealed that negative anomalies were mainly experienced before 1960 at most locations across the study area. This was an indication of the possibility of the existence of a change



**FIGURE 3** Century long temperature anomalies across Uganda. (a) Entebbe, (b) Kampala (Lake Victoria basin), (c) Luwero (Victoria Nile basin), (d) Moroto (Lake Kyoga Basin and semi-arid), (e) Mbale (Lake Kyoga Basin) and (f) Mbarara (Lake Victoria basin)

point year and hence inhomogeneities in the dataset. For this reason, a homogeneity test was conducted on rainfall and temperature time series, the major meteorological variables. The results from this analysis are presented in Table 3.

For the rainfall time series, significant shifts were identified by both Buishand and Petit tests in the lake basins of Victoria, Edward and Kyoga. These locations are Entebbe, Kampala and Mityana for the Lake Victoria basin, with Kabale and Tororo for Lake Edward and Kyoga basins, respectively. The significant shifts occurred in 1949, 1950, 1953, 1959 and 1961. Further still, for the rainfall time series, the SNHT also showed significant shifts in the Lake Victoria and Kyoga basins at Jinja,

Mityana, Buyende, Soroti, Mbale and Tororo. The temperature time series, on the other hand, were largely homogenous, with only the Lake Victoria basin showing a significant shift in 1950 and 1959 for the Petit and SNHT tests, respectively. The other significant shifts were recorded in the Lake Kyoga at Buyende and Tororo in 1960 and 1950, respectively. The Lake Edward basin had only one station at Kasese that registered a significant shift in 1946. From these results, it is evident that the Aswa River basin, Albert Nile, Lake Albert and Victoria Nile all have homogenous series for both rainfall and temperature. Lake Victoria basin is observed to be the region with the most inhomogeneities. At locations where significant shifts have been recorded, they can be

SN	Station	Rainfall			Temperature		
		Petit	Buishand	SNH	Petit	Buishand	SNH
1	Arua	1945	1945	1943	1950	1945	1943
2	Buyende	1959	1997	1961*	1958	1971	1960*
3	Entebbe	1950*	1950*	1950	1955	1971	1979
4	Fortportal	1946	1946*	1946	1963	1946	1946
6	Gulu	1945	1945	1944	1945	1945	1945
6	Hoima	1946	1946	1946	1955	1955	1946
7	Jinja	1955	1959*	1959*	1950*	1950	1959*
8	Kabale	1953*	1950*	1950	1953	1950	1946
9	Kaabong	2003	2003	2000	2000	2000	2000
10	Kampala	1949*	1949*	1949	1949	1971	1949
11	Kasese	1946	1946*	1946	1943	1946*	1950
12	Kitgum	1988	1988	1959	1976	1976	1979
13	Lira	1959	1959	1959	1961	1961	1959
14	Luwero	1949	1950*	1950	1950	1971	1950
15	Masaka	1959	1950	1950	1961	1951	1950
16	Masindi	1945	1945	1945	1945	1959	1945
17	Mbale	1961	1961	1960*	1961	1961	1959
18	Mbarara	1946	1946*	1946	1950	1946	1946
19	Mityana	1950*	1950*	1950*	1959	1971	1979
20	Moroto	2003	2003	2003	1976	1998	2000
21	Mubende	1961	1961	1961	1960	1959	1962
22	Soroti	1959	2006	2007*	1954	2001	2007
23	Tororo	1961*	1961*	1961*	1971	1950*	1939

\*Significant intervention at  $p < 0.01$ .

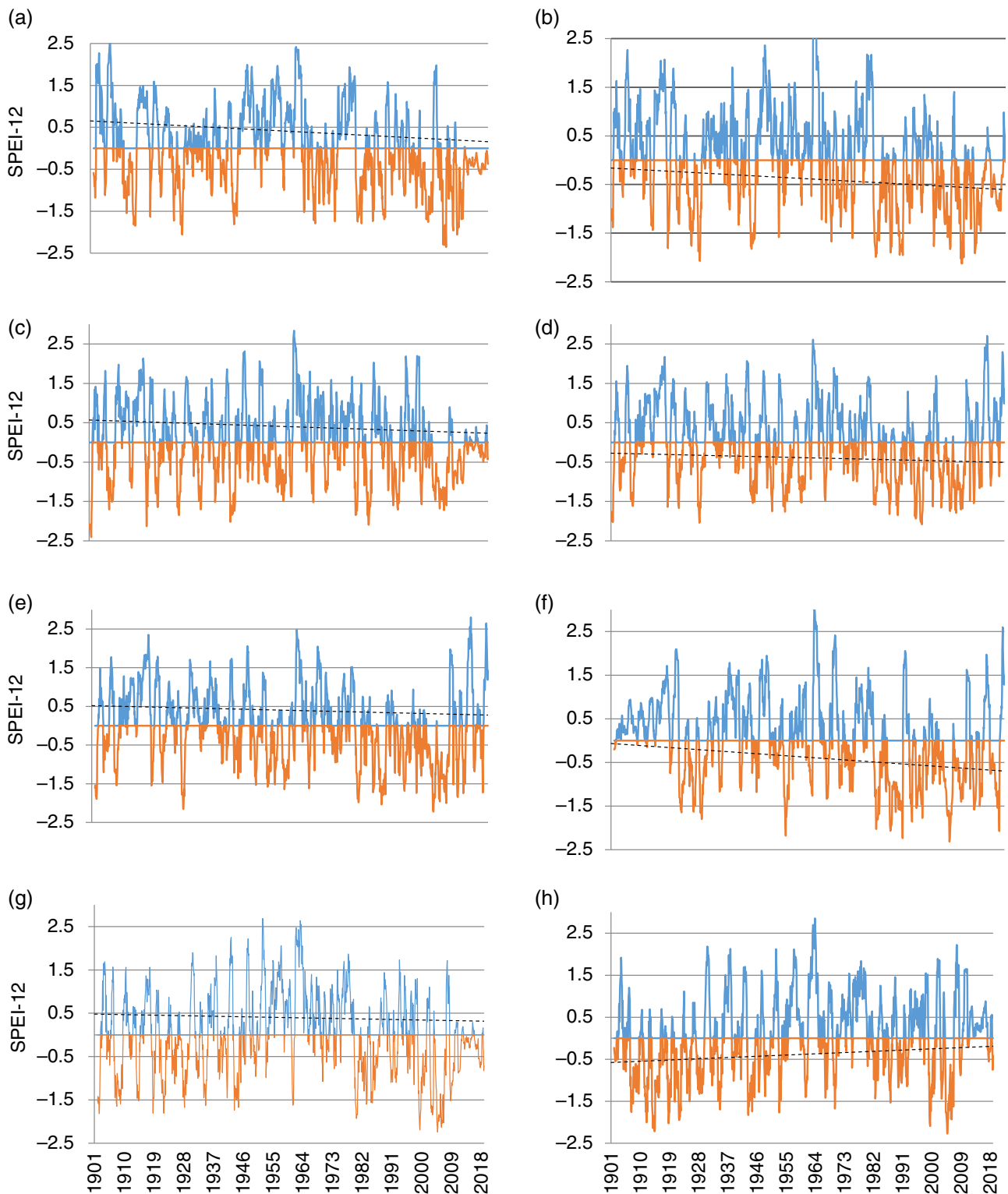
TABLE 3 Years of intervention from three homogeneity tests for rainfall and temperature time series

regarded as non-homogenous, and hence a change point year exists. In similar studies of step change analysis, Kampata et al. (2008) and Byakatonda, Parida, Kenabatho, and Moalafhi (2018b) indicated that once a significant shift is identified, then the dataset can no longer be treated as one long-term time series. Considering the years of significant change presented in Table 3, these years occurred between 1946 and 1961. This implies that the time series between 1962 and 2018 can be considered homogenous. Based on these results, it was then necessary to split the study period into two segments using the latest year of intervention (1961) to be the change year and applied across the study area for purposes of this analysis. The later period (1962–2018) is more important to this analysis because several studies have reported it as the warmest period ever on record mainly attributed to anthropogenic activities (Byakatonda et al., 2020; Gebrechorkos et al., 2019; Hänsel et al., 2016). This study finding agrees with other studies where a significant shift in the rainfall time series has also been identified such as

in southern Africa by Parida and Moalafhi (2008) who identified a change year of 1979/80. Also in other studies in Europe by Wijngaard et al. (2003) and Costa and Soares (2009), significant shifts in meteorological time series were reported. These results demonstrate that indeed a shift in meteorological variables has occurred, which could be attributed to climate variability and change that have caused perturbations in atmospheric air circulation (IPCC, 2012).

### 3.3 | Analysis of dryness and wetness characteristics over the study period

The evolutions of both dryness (negative departures) and wetness (positive departures) episodes are presented in Figure 4. Of interest to this study is the severe and extreme events represented by a cut-off of SPEI =  $-1.5$  for severe dryness and SPEI =  $+1.5$  designating severe wetness. At lower timescales of 3 and 6 months, the



**FIGURE 4** SPEI-12-temporal evolutions across drainage basins (red line = drought and blue line = wet episodes). (a) Arua (Albert Nile basin), (b) Gulu (Aswa basin), (c) Mubende (Lake Edward Basin), (d) Buyende (Lake Kyoga Basin), (e) Soroti (Lake Kyoga Basin), (f) Kaabong (Aswa Basin), (g) Kasese and (h) Kabale (Lake Edward basin)

frequency between wetness and dryness events is high in that it is difficult to identify a distinct event. At higher timescales of 12 and 24 months, both wetness and

dryness are visible with a lower frequency and higher duration. However, the patterns at lower and higher timescales are the same. This behavioural patterns of

SPEI is not exclusive to this study, in similar studies conducted in Botswana, Nigeria, Bolivia, Spain and China where SPEI has been applied to study drought characteristics, the index equally exhibited high frequencies at lower timescales (Byakatonda, Parida, Moalafhi, & Kenabatho, 2018c; Liu et al., 2016; Oloruntade et al., 2017; Vicente-Serrano et al., 2015; Yao et al., 2018).

Different locations across the seven drainage basins (as presented in Figure 1b) are used to try and understand the wetness/dryness evolution characteristics. In this study, we demonstrate the behaviour of these events using the 12-month timescale. Events at other timescales exhibit similar temporal characteristics only differing in frequency. The 12-month timescale evolutions are preferred because of their lower frequency with distinct signals. The results of these evolutions are presented in Figure 4, with both wetness (blue lines) and dryness (red lines) shown in the same figure.

### 3.3.1 | Temporal and spatial analysis of dryness events

The results in this subsection are equally presented per drainage basin, in the Albert Nile at Arua (Figure 4a), the first 2 years of 1901–1902 were registered as dry years, although not severe. In the neighbouring drainage basin of Aswa (Figure 4b), this particular dryness event presented with more severity compared with the Albert Nile. However, this event was not registered in the semi-arid northeastern part of Aswa River basin (Figure 4f). The next event on record in these drainage basins was a long drought that lasted 4 years, starting in 1910 and ending in 1913 but was shorter by 1 year in the Aswa basin. The next severe dryness event in Albert Nile and Aswa was that of 1917. The years from 1924 to 1926 were equally characterized by severe dryness in these basins. Following this dryness event were mainly moderate droughts until the 1942/43 severe dryness. The years 1950–51 were also recorded to have experienced a severe drought in the Aswa River basin, although moderate in the Albert Nile basin. Immediately after the change point year in 1961, another long drought that lasted 10 years from 1964 to 1973 commenced registering three severe droughts in the Aswa basin. It is observed that from 1961, droughts take longer durations compared with the previous period. The longest drought in the Aswa basin lasted 13 years, occurring between 1979 and 1992. Following this event was that of 1996–2000, which also recorded a severe drought in this basin while in the Albert Nile this event was only severe in 2000. The period from 2004 until the end of the study period was characterized by dryness events. In total, six severe dryness events occurred between 1901

and 1961, whereas twice the number were registered in the subsequent period.

In the Lake Kyoga basin as shown in Figure 4d,e at Buyende and Soroti respectively, the situation is not any different from the Aswa and Albert Nile basins, with 1902, 1908, 1918, 1921 and 1927 registering severe droughts at Soroti. The next severe dryness was registered from 1949, lasting 10 years. After 1961, the frequency of severe droughts increased and was characterized with a longer duration. During the period after 1961, a severe dryness event was recorded in 1965 in the north of this basin at Soroti though with less magnitude in other locations within this lake basin. The longest common severe dryness event in this basin was that from 1980 to 1997 at Soroti. This event persisted until 2005 in the southern part of the basin at Buyende, as shown in Figure 4d. The proceeding period until 2018 was characterized by dryness events with a higher severity in the northern part of the basin. As was the case with the Albert Nile and Aswa basins, the period before 1961 recorded eight severe dryness events while the recent period recorded 12 in the Lake Kyoga basin.

For the Lake Edward basin in Figure 4c,g,h at Mubende, Kasese and Kabale, respectively, up to 10 severe dryness events were recorded between 1901 and 1961. The dry years recorded in other basins also coincided with those that occurred in the Lake Edward basin. Exceptionally, 1960 was recorded as a drought year unlike the other regions across the study area. In the south of this basin at Kabale (Figure 4h), the longest dryness event was that of 1982–1991. This event started earlier, though in 1980 in the west of the basin at Kasese (Figure 4g), but interrupted in 1986, which was a wet year. This dryness event resumed in 1989 and persisted until 1992. The next long severe drought was experienced between 1999 and 2008 in the Lake Edward basin. The southern part of this basin is the only location in the entire study area that experienced wet conditions for a 10-year period between 2008 and 2018. However, for the rest of the locations, this period was characterized by near-normal climatic conditions where the drought index was converging to the normal line.

To evaluate the performance of SPEI in detecting drought across the study area, we compared the dryness events on record with those revealed by SPEI evolutions. Unfortunately, the drought recording commenced in 1992 (GOU, 2012), hence the earlier SPEI evolutions were not corroborated with the historical record. The dryness events of 1992–1994 were well captured in all regions and showed it started earlier in 1989 in the Lakes Kyoga and Edward basins. This particular event was moderate in the Albert Nile basin. It was most severe in the northeast of Aswa River basin, a semi-arid region.

The dryness events of 1998–1999, 2002–2003 and 2005–2008 were all revealed by SPEI evolutions. The latest events of 2010–2011 and that of 2014–2015 were not well pronounced except for the northeast, as shown in Figure 4f. In the Lake Edward, this event was missed by the SPEI evolutions. The SPEI has been reported by Vicente-Serrano et al. (2015), Byakatonda, Parida, Moalafhi, and Kenabatho (2018c) and Yao et al. (2018) to perform well in arid and semi-arid regions where the temperature contribution is pronounced. In sub-humid regions, where sufficient rainfall amounts are received, the temperature effect may be dampened. It could then be possible that SPEI may not be the best drought index to be applied in humid to sub-humid locations for monitoring dryness events. This line of argument is corroborated with the high performance of SPEI reported in the northeast semi-arid region just as it was the case in studies conducted in other semi-arid regions.

### 3.3.2 | Temporal and spatial analyses of wetness events

Equally, the wetness events, which are represented by positive SPEI values, are shown in Figure 4 (blue lines). In the Albert Nile and Aswa River basins (Figure 4a,b), the years from 1903 to 1906 were characterized by severe wetness. The next wetness event was registered between 1914 and 1915. The period from 1919 to 1937 was mainly dry with below normal rainfall. Equally, the period 1946–1961 was characterized by a wet spell in Aswa River basin, with 1947, 1954, 1956 and 1960/61 all recording severe wetness. During the period between 1961 and 1972, there was reduced rainfall with a prolonged drought which was eased between 1974 and 1978. During the 1974–1978 period, severe wetness conditions were again realized. In the subsequent period, severely wet years reduced with only 1988 and 2002 recording severe wetness. However, this was only in the Albert Nile basin as shown in Figure 4a. During the same period, the Aswa basin at Gulu (Figure 4b) recorded no severely wet years after 1976. In effect there were only two severely wet years on record in the Aswa basin after 1961 compared with 10 in the earlier period.

The Lake Kyoga basin is presented in Figure 4d,e. Just as was the case with other drainage basins, the years 1903 and 1906 were also characterized by severe wetness. The period moving forward starting from 1910 until 1920 was characterized by severe wetness, with 1917 and 1920 recording the highest severity in the north of this basin at Soroti (Figure 4e). In this lake basin during the period of analysis, 1930, 1936, 1942, 1947 and 1963 all recorded severely wet years. These occurrences were common to the entire lake basin. The next severely wet period was

registered in 1968, oscillating between moderate and near-normal conditions mainly in the north of the basin (Figure 4e) until 2008. During the same period, the southern part of the basin recorded three severely wet events in 1975, 1979 and 1990, as shown in Figure 4d. The next period until the end of the study period recorded also three severely wet events in 2007, 2010–2014 and 2018. These events were recorded both in the east and northeast. This demonstrates that despite the increase in temperature, the rainfall amounts have not been significantly affected in the Lake Kyoga basin.

For the Lake Edward basin represented in Figure 4c, g,h by Mubende, Kasese and Kabale, respectively, the years of 1903, 1904 and 1906 were characterized by severe wetness. The period moving forward shows moderately wet events, especially in the south of the basin at Kabale (Figure 4h). In this basin, the next severely wet years were registered in 1930, 1937, 1942, 1947, 1952, 1957 and 1962/63, exhibiting a 5-year interval between severe wetness events. The period after 1963 was characterized by decreasing severe wetness. The only notable events during this period in the region were those of 1977, 1993 and that of 2008. In the west of this basin, as shown in Figure 4g, no more severely wet years were recorded. However, in the south of the basin at Kabale as shown in Figure 3h, the period after 2008 still recorded severe wetness events in the 2010–2011 period. Equally the most recent period is characterized by near-normal conditions.

To test the capability of SPEI in detecting wetness events just as the case with dryness events, we compared the severe events reported here with landslide disasters that mainly occurred in the Lakes Edward and Kyoga basins during severe to extreme rainfall events. SPEI was able to detect severely wet years that coincided with landslide events of 1918, 1920, 1947, 1997, 2012 and 2018 missing only those of 1927 and 2016. This is rather a better performance compared with the dryness events. This might imply that probably SPEI is a better tool in monitoring humid events compared with drought. This could be attributed to the fact that in the sub-humid climates, the accumulated time steps are more of surplus than deficit, minimizing temperature contribution as compared with arid and semi-arid environments where SPEI has been found to perform well in drought monitoring.

### 3.4 | Occurrence probability and spatial distribution of dryness/wetness events over two time periods (1901–1961 and 1962–2018)

Following the split of the study period, it was then necessary to understand the occurrence probability from the

earlier (1901–1961) to the recent (1961–2018) period. The occurrence probabilities of dryness/wetness, as classified in Table 2, are deduced from the ratio of the frequency of a particular drought category to the total number of events on record. This is essential because, with this information, we are in a position to determine the degree of susceptibility of a particular drainage basin against a given dryness/wetness category to enable planning for mitigation measures. From previous studies, it has been shown that for moderate conditions, users of agricultural and water resources are in a position to develop coping mechanisms. However, challenges usually arise from severe and extreme weather events that in most cases result in disaster relief response (Mubiru et al., 2018; Opiyo et al., 2015; Tolo et al., 2014). In this study, extreme dryness/wetness events were rare, presenting with very low probabilities of occurrence of less than 1%. For this reason, extreme events were analysed but not discussed in this paper. Only severe dryness/wetness over two time periods referred to as the ‘earlier’ and ‘recent’ periods are discussed here. The results from this analysis are presented in Table 4.

### 3.4.1 | Probability of occurrence of severe dryness over the two time periods

The results presented in Table 4 show that there is increasing susceptibility from the earlier (1901–1961) period to the recent time step (1962–2018) across all timescales of 3, 6, 12 and 24 months. This is particularly evident in the Albert Nile, Aswa and Lake Kyoga basins. Also increasing dryness is observed in the east of the Lake Edward basin and the cattle corridor. In contrast, the western part of the Lake Edward basin around Kasese is also showing warming in the recent period with increased susceptibility towards this dryness category. However, it is observed from Table 4 that in the Lake Victoria basin, the degree of vulnerability is decreasing towards the recent period. The east of the Lake Kyoga basin is also observed to be less susceptible in the recent period. The highest probability of 9.5% was recorded in the Aswa River basin at Kitgum during the recent period for the 6-months timescale (SPEI-6). SPEI-6, which is associated with agricultural drought, could lead to a reduction in crop yields at the above-listed locations. Still, at most of these locations, the degree of susceptibility more than doubles from the earlier to the recent period at all the timescales. For illustration purposes in the Aswa basin at Kaabong, the probability increased from 1.9% in 1901–1961 to 8.0% between 1962 and 2018 at SPEI-3. For dryness at SPEI-6, the probability of experiencing a severe drought, which was 2.5% in the

earlier period, increased to 9.6% in the recent period still in the Aswa basin at Kitgum. For SPEI-12 at Soroti, the probability of experiencing this dryness category in the earlier period was 3.1%. During the later period it increased to 9.3%. From this analysis, it can be observed that the study area is more susceptible to severe dryness at timescales of 3, 6 and 12-month timescale. At 24 months, the study area presents with lower probabilities towards severe dryness. From this analysis results, areas such as Kaabong in the Aswa basin, Moroto and Soroti in the Lake Kyoga all classified as semi-arid are showing high susceptibility towards severe dryness. This high susceptibility could be related to findings of Seneviratne et al. (2012), Stocker et al. (2013) and Byakatonda et al. (2020) who reported that global warming will make arid and semi-arid region even hyper-arid. The generally decreasing probabilities across timescales could be an indication of slow response of hydrological systems towards severe dryness (Byakatonda, Parida, & Kenabatho, 2018a; Nalbantis & Tsakiris, 2009) but high susceptibility to agricultural drought (Homdee et al., 2016).

The spatial analysis of the probabilities of occurrence was also conducted, these results are presented in Figure 5 over the two time periods. The spatial distribution further confirms that indeed probabilities increased from the earlier to the recent period. This is revealed by spatial patterns of the probability of occurrence shown on the maps over the two time periods. At SPEI-3, the earlier period shown in Figure 5a indicates that the Albert Nile and Aswa basins were less susceptible. However, the susceptibility was relatively high in the Lake Kyoga basin during this period. The west of Lake Edward basin also shows a high degree of susceptibility in the earlier period compared with the Aswa basin. In the recent period, it is evident from Figure 5b that the Aswa basin and especially the northeast, which was less susceptible in the earlier period, is now highly vulnerable in the recent time step. The east of Lake Kyoga basin interestingly indicates recovery from severe dryness at a 3-month timescale moving into the recent period. The Lake Edward basin is also showing less susceptibility in the recent period at SPEI-3. For SPEI-6 (Figure 5c,d), the spatial pattern is not different from that of SPEI-3, with the only notable difference being higher probabilities at this timescale. The Albert Nile and Aswa basins are again exhibiting high susceptibility during the recent period at SPEI-6.

At SPEI-12 (Figure 5e,f), the most susceptible areas that were confined in the Albert Nile and Aswa basins during the earlier period have now spread southward to the Lake Victoria and Victoria Nile basins in the next time step. Also at this timescale, the Lake Kyoga is more susceptible around Mbale in the recent period. At SPEI-12, the

**TABLE 4** Occurrence probability of severe dryness/wetness events over two time periods 1901–1961 and 1962–2018

SN	Location name	Probability of severe dryness occurrence (%)								Probability of severe wetness occurrence (%)							
		1901–1961				1962–2018				1901–1961				1962–2018			
		SPEI-3-	6-	12-	24-	3-	6-	12-	24-	SPEI-3	6-	12-	24-	3-	6-	12-	24-
1	Arua	3.0	3.7	3.7	2.5	6.4	7.4	7.6	4.1	6.8	5.6	5.6	11.1	2.8	4.7	4.7	1.4
2	Buyende	5.2	4.7	4.4	2.8	5.9	6.4	6.7	3.9	4.9	5.9	6.1	4.1	5.9	6.4	4.4	1.7
3	Entebbe	4.9	5.5	3.9	4.4	4.1	4.2	4.1	3.7	5.2	6.8	3.6	4.2	4.2	3.9	4.8	4.3
4	Fortportal	4.2	4.1	5.5	3.2	5.4	5.7	5.9	3.1	6.4	7.4	5.5	6.6	3.4	3.7	2.0	1.4
5	Gulu	2.7	2.9	3.2	2.8	6.1	7.6	9.0	4.9	5.7	5.9	5.8	7.7	4.8	3.7	2.8	0.9
6	Hoima	4.1	4.4	4.6	2.1	5.2	4.4	2.0	3.1	5.4	5.9	5.9	4.8	4.5	5.4	3.2	1.3
7	Jinja	4.5	4.4	4.6	4.1	5.1	6.2	5.7	3.6	4.8	4.8	3.3	3.2	6.2	4.8	5.2	5.3
8	Kabale	3.7	6.3	5.4	6.7	4.7	3.4	3.2	1.7	5.6	3.3	5.6	5.5	3.8	4.8	7.4	1.9
9	Kaabong	1.9	2.8	2.9	1.0	8.0	9.2	7.3	4.7	4.4	4.5	3.9	6.9	5.2	4.8	4.1	2.2
10	Kampala	4.5	4.8	5.2	3.9	5.4	6.2	4.7	3.7	5.9	6.0	4.9	4.4	4.5	3.4	2.9	2.4
11	Kasese	4.2	4.1	3.7	3.2	5.2	5.4	6.2	3.0	5.9	6.8	6.2	5.7	4.8	4.1	2.9	1.5
12	Kitgum	2.7	2.5	2.6	0.4	6.2	9.6	7.3	5.8	6.1	5.5	7.0	8.7	5.5	2.8	2.9	0.9
13	Lira	2.7	3.3	4.9	2.1	6.2	7.1	7.3	3.8	6.1	5.6	6.3	4.5	5.5	5.7	4.5	1.9
14	Luwero	4.1	3.9	4.3	2.1	5.1	6.2	4.7	4.4	4.8	6.6	4.0	4.4	5.7	4.4	6.7	2.9
15	Masaka	3.0	4.4	3.9	5.6	4.7	4.2	4.4	3.4	4.5	4.7	4.2	2.8	5.9	5.4	6.1	3.6
16	Masindi	2.9	3.9	5.6	2.4	5.8	4.8	3.9	3.9	6.0	7.0	8.6	6.3	3.7	4.2	3.7	1.4
17	Mbale	4.9	3.7	3.6	2.5	5.4	6.2	7.3	2.7	3.6	4.0	3.3	2.0	6.4	5.5	5.1	3.4
18	Mbarara	4.2	4.1	4.3	4.7	5.9	5.9	3.8	2.2	3.7	3.2	4.0	2.4	5.5	5.5	6.8	2.8
19	Mityana	4.9	5.5	3.9	4.4	4.1	4.2	4.1	3.7	5.2	6.8	3.6	4.2	4.2	3.9	4.8	4.3
20	Moroto	2.7	3.2	2.6	0.8	6.4	7.8	7.0	4.1	5.3	5.5	3.9	6.3	4.5	4.5	4.1	1.3
21	Mubende	4.0	3.9	4.6	3.9	4.4	4.8	5.4	3.9	5.2	6.8	6.3	6.4	5.1	4.7	3.8	1.7
22	Soroti	4.1	3.7	3.1	1.8	6.5	7.1	9.3	5.3	5.4	5.2	5.6	3.5	4.8	4.8	5.4	2.6
23	Tororo	5.3	7.7	5.1	6.4	4.2	5.8	3.1	1.0	3.8	4.7	3.5	2.1	6.2	8.0	6.7	3.9

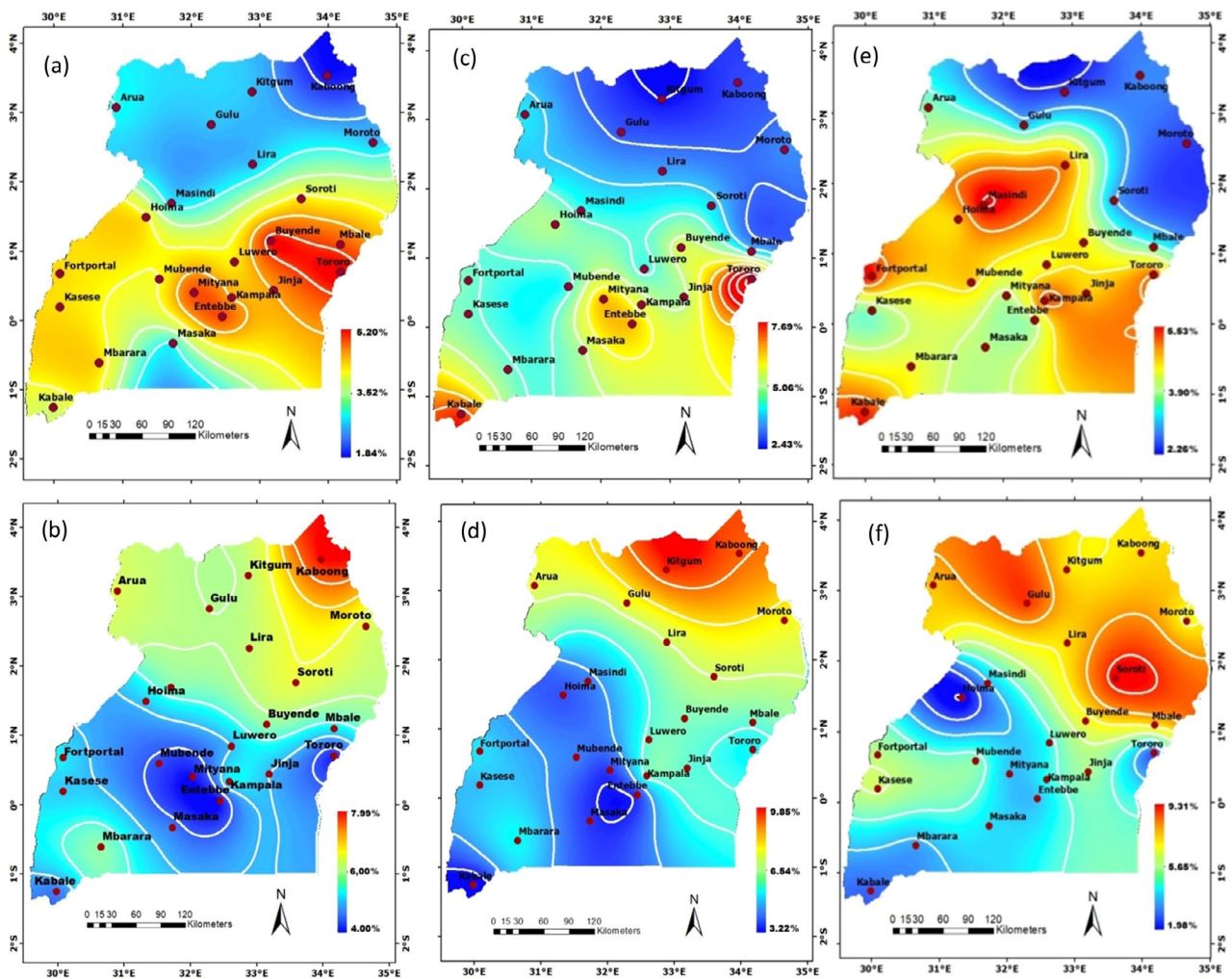
Lake Edward basin around Kasese at the foothills of Rwenzori mountain ranges does not show any recovery during the recent period.

### 3.4.2 | Probability of occurrence of severe wetness over the two time periods

The results from analysis of probability of occurrence of severe wetness at timescales of 3, 6, 12 and 24 months are also presented in Table 4. From these results, it is revealed that 52% of the locations across the study area are experiencing higher probabilities of severe wetness in the earlier period compared with the recent one. Some locations in the Lake Kyoga, Aswa and Lake Edward basins such as Buyende, Kaabong and Kabale, respectively, do not show any significant changes over the two time periods except at 24-month timescale. At this timescale, these locations show a decreasing probability towards the recent period. The highest decrease in the occurrence of

severely wet events from the earlier to the recent period is recorded in the Albert Nile at Arua. The probability, which was 11.1% in the earlier period, dropped to 1.4% in the recent period in this drainage basin. Equally, in the Aswa basin at Kitgum and Gulu also a drastic reduction from 8.7% to 0.9% and 7.7% to 0.9%, respectively, were registered. All these reductions occurred at a 24-month timescale. This implies that this drainage basin is getting dry in the recent period. This could be the reason the basin is presenting with more severe droughts episodes compared with the rest of the study area. Also, the reduction at the 24-month timescale may be an indicator that multi-year wet episodes could be reducing for the future climate. Interestingly, in the northeast at Kaabong (Aswa basin) that registered high susceptibility towards severe droughts, no notable changes in severely wet events were recorded except at the 24-month timescale.

The spatial distribution of severe wetness was conducted, and these results are presented in Figure 6. From Figure 6a,b (SPEI-3), it can be observed that significant



**FIGURE 5** Spatial representation severe dryness occurrence probability. (a) SPEI-3 dryness (1901–1961), (b) SPEI-3 dryness (1962–2018), (c) SPEI-6 dryness (1901–1961), (d) SPEI-6 dryness (1962–2018), (e) SPEI-12 dryness (1901–1961) and (f) SPEI-12 dryness (1962–2018)

changes occurred in the Albert Nile and Lake Victoria basins over the two time periods. Figure 6 also shows the Albert Nile, which was severely wet in the earlier period now records fewer wetness events in the recent period. On the contrary, the Lakes Kyoga and Victoria basins are indicating increased severely wet episodes recorded in the recent period. At SPEI-6 (Figure 6c,d), changes over the two time periods occurred in most regions of the study area. The spatial distribution indicates that the Lake Edward basin experienced a reduction in wet spells from the earlier to the recent period. To the contrary, the east of Lake Kyoga around Mbale and Tororo registered wetter conditions in the recent period than the former. At the 12-month timescale shown in Figure 6e,f, the eastern axis show recovery from a low wet spell count in the early to the recent periods. Conversely, the west to the northwest of the study area is showing decreasing severely wet events in the recent period.

Spatial patterns of occurrence probability of severe dryness and wetness events at 24-month timescale are presented in Figure 7. Probabilities of occurrence of severe dryness (Figure 7a,b) show high susceptibility to drought in the Lake Victoria and Edward basins during the earlier period. However, the Albert Nile and Aswa basins that had been observed to be susceptible to severe dryness at lower timescales, now report low dry spell counts during the earlier period. During the recent period (Figure 7b), the patterns are completely reversed with the Albert Nile, Aswa and parts of the Lake Kyoga basin highly susceptible to severe dryness at a 24-month timescale. The Lakes Victoria and Edward basins are generally less susceptible in the recent period. The low susceptibility in the Lake Victoria basin could be attributed to the presence of the largest fresh water lake on the African continent that occupies an area of approximately 68,000 km<sup>2</sup>. Lake Victoria has been reported to moderate

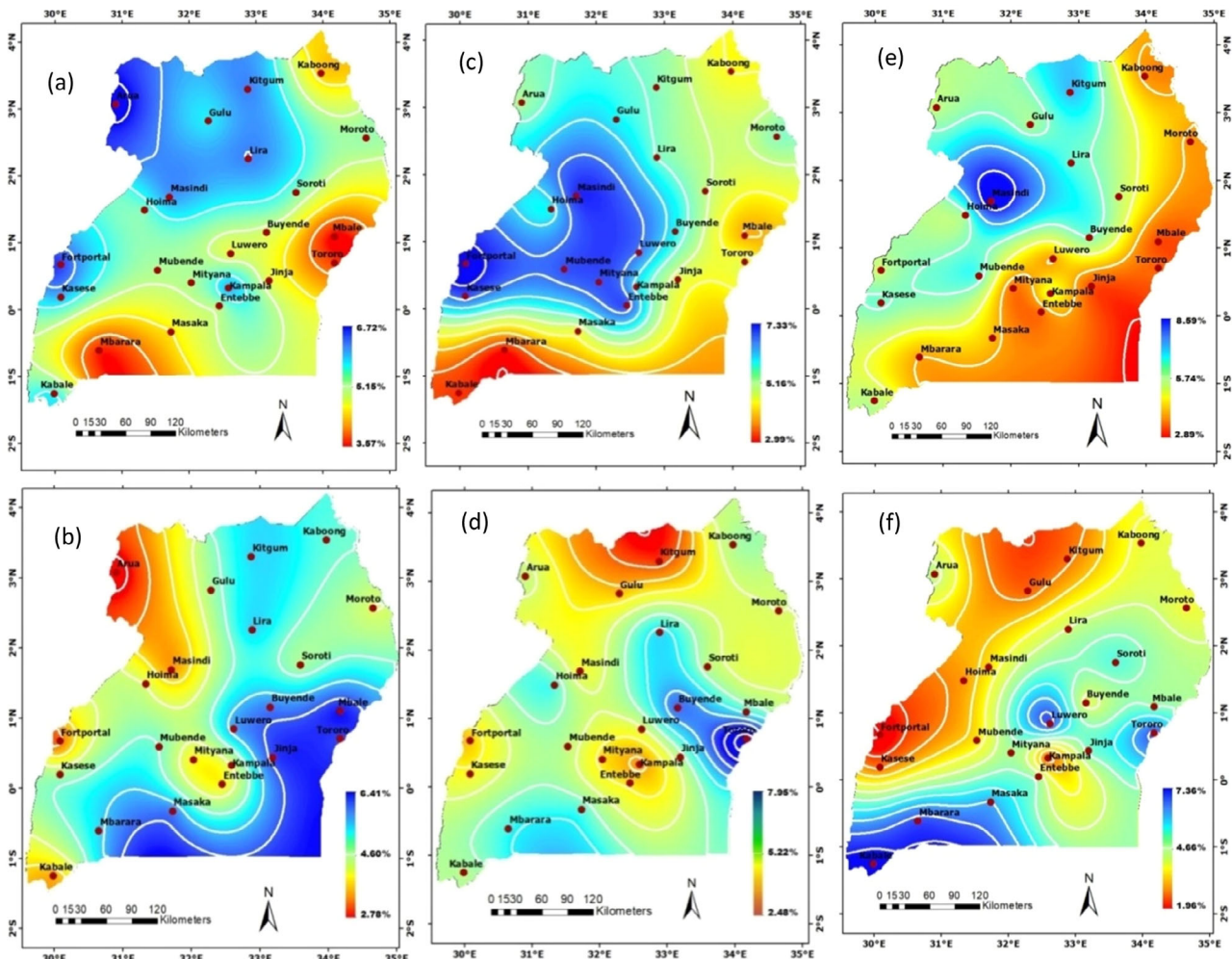


FIGURE 6 Spatial representation of occurrence of severe wetness. (a) SPEI-3 wetness (1901–1961), (b) SPEI-3 wetness (1962–1962), (c) SPEI-6 wetness (1901–1961), (d) SPEI-6 wetness (1962–2018), (e) SPEI-12 wetness (1901–1961) and (f) SPEI-12 wetness (1962–2018)

the local and regional climate of East Africa (Olaka et al., 2019; Tolo et al., 2014).

The spatial distribution of occurrence probabilities of severe wetness at a SPEI-24 is also shown in Figure 7c,d. The earlier period, as presented in Figure 7c, shows that only the Albert Nile has higher episodes of severely wet spells. On the other hand, the spatial patterns shown in Figure 7d indicate that a large percentage of the study area is experiencing reduced severely wet events in the recent period with an exception of the Lake Victoria basin and southeast of Lake Kyoga basin. This could further confirm low chances of multi-year severely wet events that had been alluded to earlier. The Lake Victoria basin and part of Lake Kyoga basin have shown increased wet spells in the recent period across the time-scales, this could also explain the increased incidences of landslides around Mount Elgon in the Lake Kyoga basin. The areas in the Lake Victoria basin, mainly the southern

region, have shown increased incidences of severely wet events in the recent period as well. This also may explain the reason for the unprecedented rise in the Lake Victoria level that displaced surrounding communities in the year 2020 (NBI, 2020).

### 3.5 | MK trend analysis results

After conducting temporal and spatial analysis of dryness/wetness evolutions and understanding their occurrence characteristics, it was then necessary to also investigate their trend behaviour. The trend analysis was conducted over the two time periods (1901–1961 and 1962–2018) using the MK statistic. This was done to try and present more evidence that can guide intervention strategies geared towards weather-related extremes.

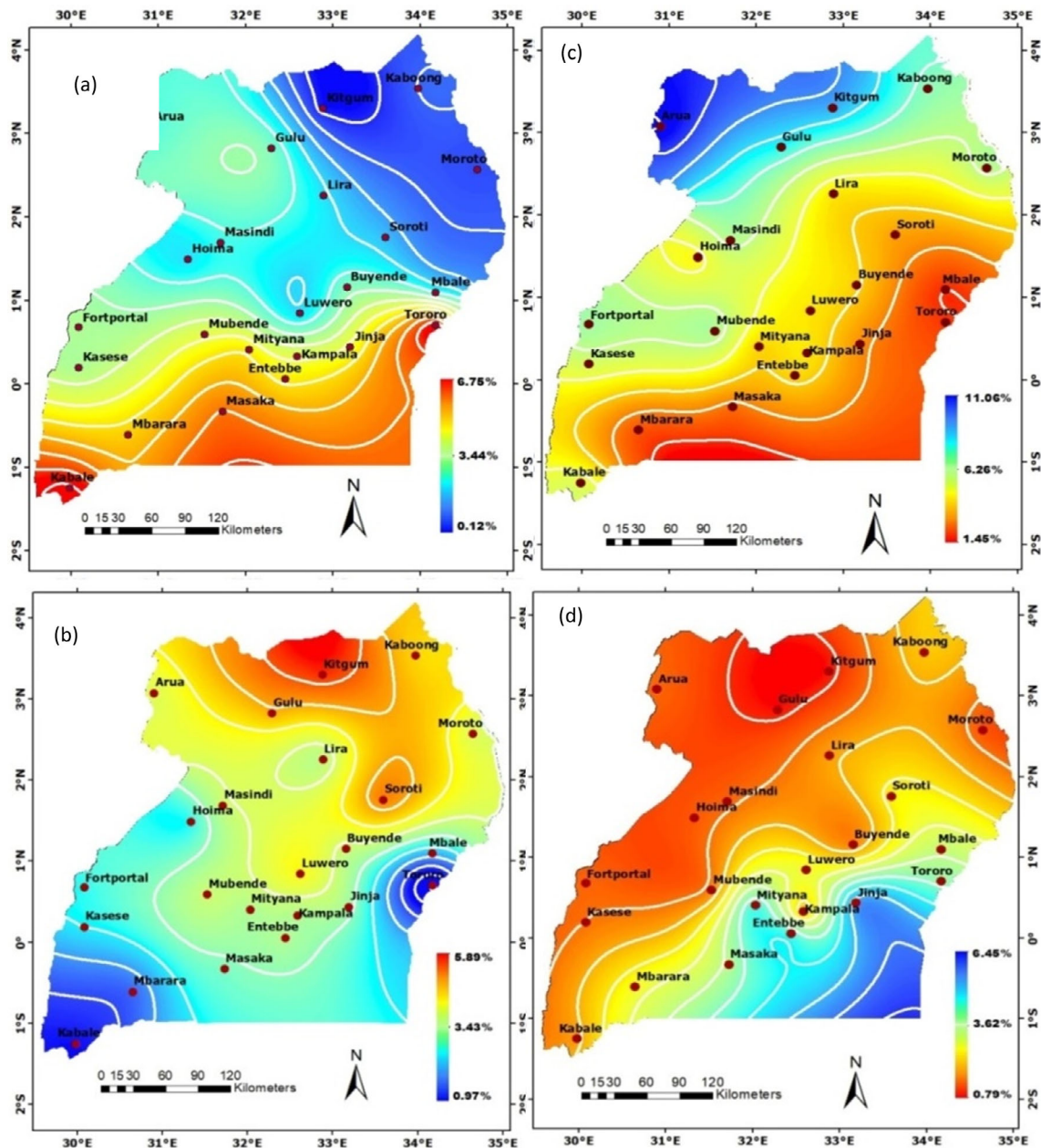


FIGURE 7 Spatial representation of severe dryness and wetness at 24-month timescale. (a) SPEI-24 dryness (1901–1961), (b) SPEI-24 dryness (1962–2018), (c) SPEI-24 wetness (1901–1961) and (d) SPEI-24 wetness (1962–2018)

### 3.5.1 | Results from the MK trend statistic

MK trend results over the two time periods are presented in Table 5. These results show that at SPEI-3, the only negative trends during the earlier period (1901–1961) were registered in the Aswa River basin at Kaabong, Kitgum, Lira. Other negative trends were registered in the Lake Kyoga basin at Mbale and Moroto, although none of them were significant at  $p < 0.05$ . At 78% of the sub-basins, positive trends were realized in the earlier period at a 3-month timescale. In the recent period (1961–2018) at 3-month timescale, it

was a complete reversal with only 17% of the sub-basins showing positive trends (decreasing dryness). Significantly drying trends were recorded in the Aswa River basin at Lira and Kitgum during the later period. The magnitude of the change according to Sen's slope estimator at these locations was  $-0.030$  SPEI units/10 years at both locations. Two of the locations with positive trends during the recent period even though not significant were Mbale and Tororo all located in the Lake Kyoga drainage basin.

At SPEI-6, only Hoima in the Lake Albert basin and Moroto in the Lake Kyoga basin are showing negative

TABLE 5 Mann-Kendal trend and Sen's slope estimator over 1901–1961 and 1962–2018 at timescales of 3, 6, 12 and 24 months

SN Name	SPEI-3			SPEI-6			SPEI-12			SPEI-24						
	1901–1961		1962–2018		1901–1961		1962–2018		1901–1961		1962–2018					
	S/10 years	MK-Z	S/10 years	MK-Z	S/10 years	MK-Z	S/10 years	MK-Z	S/10 years	MK-Z	S/10 years	MK-Z				
1 Arua	0.227	0.114	-0.092	-0.279	0.113	0.072	-0.054	-0.296	0.084	0.100	-0.035	-0.294	0.062	0.125	-0.042	-0.040
2 Buyende	0.053	0.166	-0.103	-0.033	0.031	0.270	-0.058	-0.069	-0.012	-1.688	0.089	0.073	0.003	0.704	0.045	0.043
3 Entebbe	0.421	0.180	-0.018	-0.682	0.270	0.169	0.022	0.336	0.111	0.110	0.028	0.163	0.061	0.071	-0.017	-0.204
4 Fortportal	0.409	0.181	-0.230	-0.346	0.326	0.183	-0.156	-0.336	0.174	0.151	-0.063	-0.467	0.094	0.126	-0.082	-0.323
5 Gulu	0.133	0.045	-0.060	-0.894	0.090	0.018	-0.065	-0.601	0.044	0.048	-0.013	-1.370	0.024	0.093	-0.002	-1.285
6 Hoima	0.233	0.102	-0.153	-0.393	-0.051	-1.083	0.323	0.089	0.007	1.408	-0.015	-0.993	0.004	0.553	-0.077	-0.341
7 Jinja	0.222	0.107	0.144	0.026	0.131	0.080	-0.074	-0.021	0.061	0.046	0.083	0.062	0.037	0.007	0.071	0.101
8 Kabale	0.483	0.170	-0.322	-0.333	0.347	0.205	-0.041	-0.820	0.165	0.160	0.016	0.374	0.106	0.154	-0.005	-1.822
9 Kaabong	-0.052	-0.728	-0.004	-1.224	0.011	0.412	-0.004	-0.747	-0.019	-0.160	-0.024	-0.187	0.014	0.114	-0.001	-4.781*
10 Kampala	0.415	0.189	0.097	0.045	0.254	0.171	-0.068	-0.034	0.118	0.129	0.077	0.058	0.068	0.104	0.060	0.094
11 Kasese	0.411	0.187	-0.260	-0.337	0.334	0.194	-0.134	-0.352	0.174	0.164	-0.056	-0.517	0.082	0.114	-0.056	-0.364
12 Kitgum	-0.001	-0.966	-0.031	-3.518*	0.001	1.107	-0.063	-0.651	-0.181	-0.346	-0.705	-0.398	0.019	0.142	-0.032	-0.572
13 Lira	-0.001	-0.966	-0.030	-2.978*	0.009	0.899	-0.026	-3.632*	-0.029	-1.254	-0.003	-1.512	-0.012	-1.142	-0.002	-4.863*
14 Luwero	0.318	0.155	-0.050	-0.251	0.576	0.236	-0.112	-0.482	0.080	0.078	0.077	0.068	0.063	0.092	0.061	0.093
15 Masaka	0.258	0.114	-0.014	-0.976	0.181	0.119	-0.031	-0.292	0.085	0.081	-0.018	-0.464	0.042	0.009	-0.023	-0.152
16 Masindi	0.239	0.112	-0.097	-0.574	0.158	0.090	-0.100	-0.399	0.067	0.045	-0.017	-0.861	0.039	0.011	-0.012	-1.131
17 Mbale	-0.077	-0.933	0.149	0.048	0.039	0.183	-0.056	-0.073	0.011	0.452	0.119	0.125	-0.001	-1.217	0.048	0.048
18 Mbarara	0.407	0.177	-0.101	-0.608	0.288	0.172	-0.028	-1.226	0.145	0.148	-0.021	-0.303	0.080	0.102	-0.009	-0.763
19 Mityana	0.416	0.174	-0.023	-0.567	0.270	0.169	-0.022	-0.336	0.111	0.110	-0.028	-0.163	0.061	0.071	-0.017	-0.204
20 Moroto	-0.067	-0.649	-0.017	-1.284	-0.087	-0.489	-0.359	-0.325	<b>-0.008</b>	<b>-2.104*</b>	-0.017	-0.269	-0.010	-0.898	-0.010	-0.350
21 Mubende	0.151	0.052	-0.207	-0.345	0.120	0.051	-0.073	-0.442	0.006	0.985	-0.002	-2.415*	-0.021	-0.651	-0.045	-0.446
22 Soroti	0.001	1.243	-0.036	-0.596	0.009	-0.870	-0.034	-0.257	-0.014	-1.136	0.069	0.044	-0.016	-1.092	0.032	-0.032
23 Tororo	0.038	0.347	0.156	0.055	0.013	0.585	0.161	0.082	-0.061	-0.552	0.104	0.048	-0.435	-0.399	-0.038	-0.254

Note: Italicized and bolded values indicate significant trends at 5% significant level.

\*Significant trends at  $p < 0.05$ .

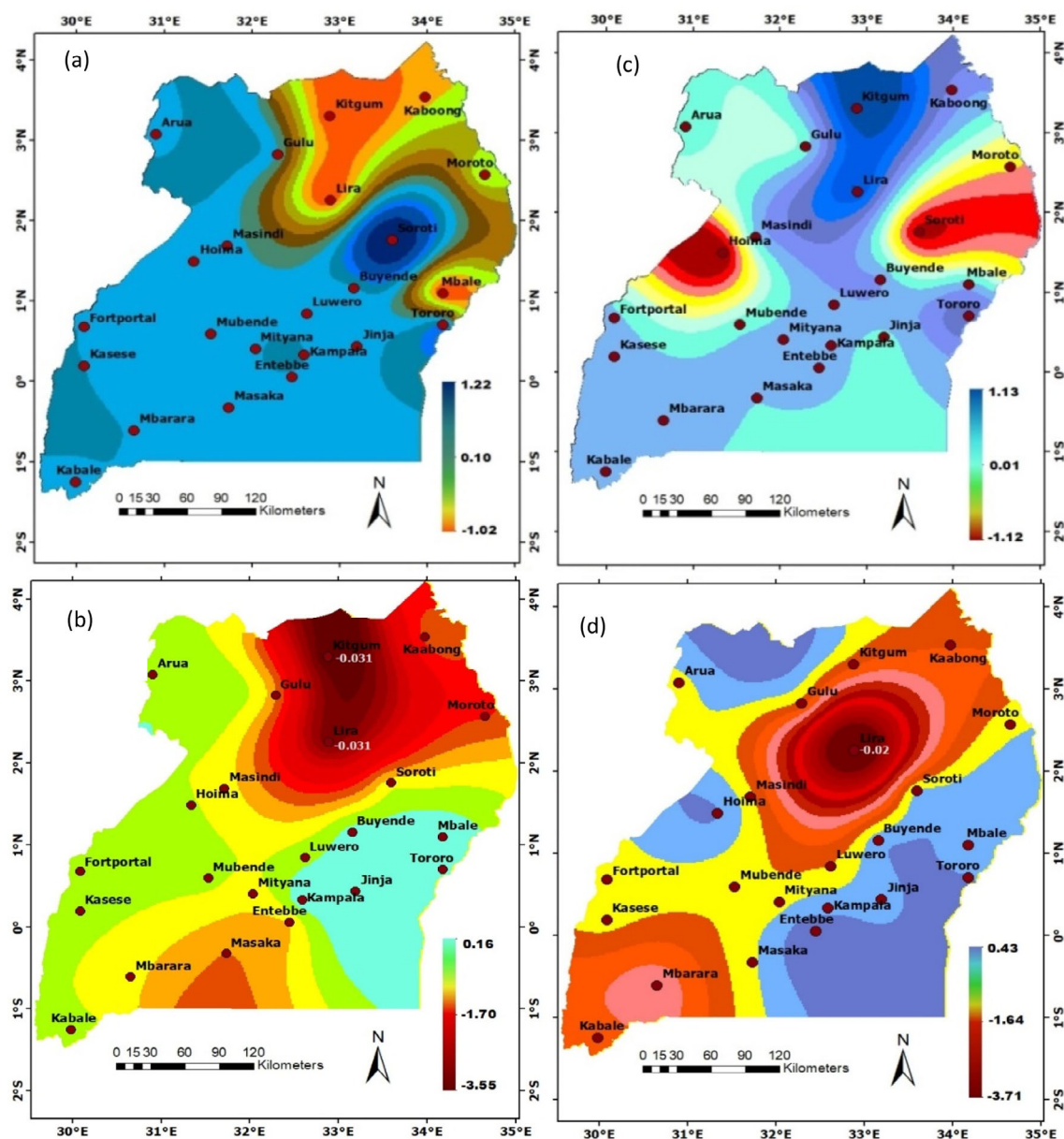


FIGURE 8 Spatial distribution of MK trends. (a) SPEI-3 (1901–1961), (b) SPEI-3 (1962–2018), (c) SPEI-6 (1901–1961) and (d) SPEI-6 (1962–2018). Values indicate significant trend magnitude in SPEI/10 years

trends, although not significant in the earlier period. During the recent period, all the drainage basins across the study area exhibited negative trends except Tororo in the east of Lake Kyoga basin. Significantly decreasing trends were recorded at Lira in the Aswa basin at a rate of  $-0.026$  SPEI units/10 years. For the 12-month timescale, the patterns are the same as those of the SPEI-3 and SPEI-6. Negatively drying trends were recorded in 30% of the sub-basins during the earlier period. These trends were only significant in the Lake Kyoga basin (in the Karamoja region) at Moroto at a rate of  $-0.008$  SPEI units/10 years. This is the only significant trend recorded in the earlier period across the study area. During the

recent period, 40% of the sub-basins recorded positive trends at SPEI-12 but none of them were significant. Negative trends were dominant at Mubende located in the cattle corridor registering significantly drying trends of  $-0.002$  SPEI units/10 years.

At SPEI-24, during the earlier period, positive trends still dominated with 74% of the sub-basins spread across the study area exhibiting wetting tendencies. None of these trends were significant though during this period (1901–1961). In the recent period, trends were mostly negative with Kaabong and Lira sub-basins registering significantly decreasing trends of  $-0.001$  and  $-0.002$  SPEI units/1 years, respectively. From the foregoing

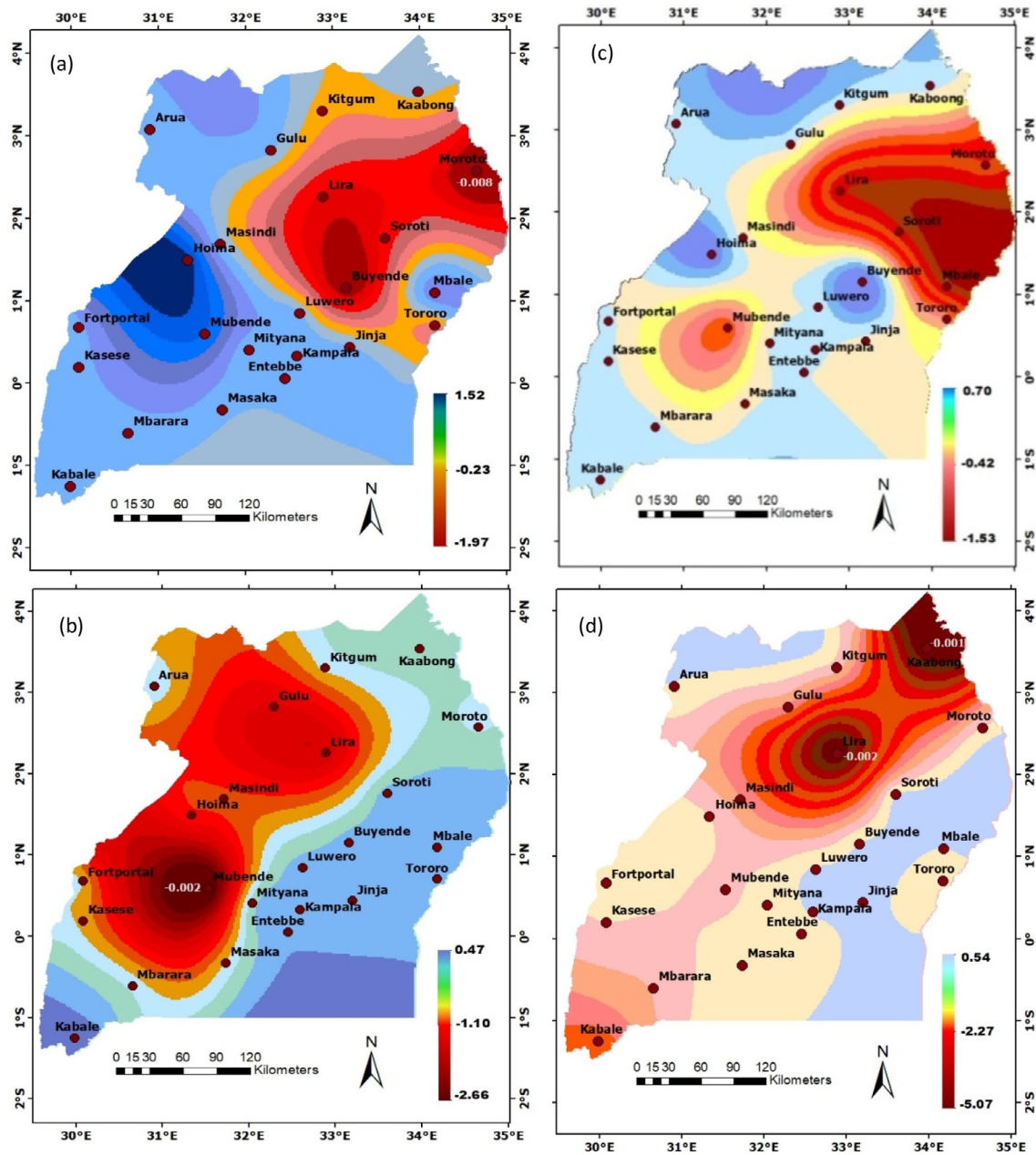


FIGURE 9 Spatial distribution of MK trends. (a) SPEI-12 (1901–1961), (b) SPEI-12 (1962–2018), (c) SPEI-24 (1901–1961) and (d) SPEI-24 (1962–2018). Values indicate significant trend magnitude in SPEI/10 years

results, it is evident that between 1901 and 1961, positive trends (tending towards wetness conditions) dominated the study area. In the subsequent period, this trend was reversed as the study area is now dominated by negative trends (tending towards dryness). The higher rate of drying in the more recent period is similar in pattern with the global warming trends. It has been reported that the warmest years on record have been in the recent past such as 2015 and 2016 with 2020 following closely (Byakatonda et al., 2020; Hansen et al., 2016). This could be a sign that probably Uganda is already experiencing

effects of climate variability and change that has disrupted a number of livelihood patterns globally (Conforti et al., 2018; Seneviratne et al., 2012).

Spatial representation of the trends at 3- and 6-month timescale is shown in Figure 8. These results reveal that at 3-month timescale during the earlier period (Figure 8a), the negative trends were concentrated in the Aswa River basin together with some locations in the Lake Kyoga basin around Mbale. The rest of the study area mainly experienced positive trends. During the recent period (Figure 8b), trends were negative with the

Aswa River basin being the most affected. In the Lake Kyoga basin, the spatial patterns show mainly positive SPEI trends at 3-month timescale. Interestingly at Mbale in the Lake Kyoga basin, the trends during the recent period remained positive even when the surrounding locations were all exhibiting drying tendencies.

The SPEI-6 trends show drying only confined in the east of Lake Kyoga basin around Soroti and in the Lake Albert basin in the earlier period (Figure 8c). Otherwise, the rest of the locations across the study area exhibited positive trends. In the recent period (Figure 8d), drying trends are seen to extend to the cattle corridor starting at Kaabong, through to Lira, then Masindi, Mubende ending at Mbarara sub-basins. The epicentre of the dryness is observed to be in the Aswa basin. In other related studies by Nakalembe (2018) and Nimusiima et al. (2013), the cattle corridor was identified to be prone to drought with incidences of livestock deaths as a result of lack of water and pasture. The east of Lake Kyoga and the Lake Victoria basins are showing wetting tendencies with positive trends in the recent period, this could also explain the landslide incidents being experienced in the Lake Kyoga basin around Mount Elgon region and the current rise in the lake levels (NBI, 2020; UNESCO, 2020).

At higher timescales of 12 and 24 months shown in Figure 9, the patterns do not significantly deviate from those at lower timescales. For SPEI-12 during the earlier period (Figure 9a), the patterns show that the Lake Kyoga and Aswa River basins are experiencing a drying trend. The same area is observed to recover during the recent period at SPEI-12 with an exception of Lira in the Aswa basin, as shown in Figure 9b. During the recent period also the Lake Albert and Lake Edward basins are observed to be experiencing drying trends reversing the wetness tendencies that had been experienced during the earlier period. For SPEI-24 shown in Figure 9c,d, the patterns depict those of the SPEI-6, with the drying of the cattle corridor in the recent period evident.

From these spatial trends, it confirms that indeed the earlier period was wetter than the recent one, which instead shows a larger area susceptible to droughts. Nevertheless, the eastern and the Lake Victoria regions have experienced fewer drying trends with more wetness events in the recent period. These events may also further confirm the influence of the inland Lakes on the microclimate. The evidence presented here may be useful in guiding mitigation strategies to shield communities from possible effects of droughts and floods. Drainage basins such as the Aswa, east of Lake Kyoga and the cattle corridor that have been found susceptible to dryness require targeted climate-smart interventions such as rainwater harvesting, irrigation and soil moisture conservation strategies, including agro-forestry.

## 4 | SUMMARY AND CONCLUSIONS

This study has conducted a compressive long-term analysis of the characteristics and behaviour of dryness and wetness events over two time periods of 1901–1961 and 1962–2018. The study applied the standardised precipitation evaporation index (SPEI) to understand the evolutions of the dryness/wetness events over the two time periods at timescales of 3, 6, 12 and 24 months. This enabled the characterization of dryness/wetness events. By investigating dryness and wetness at multiple timescales, the risk these extreme weather events pose to the agricultural and water resources across the study area was better understood. This analysis has demonstrated the applicability of SPEI in humid climates and its suitability in monitoring humid events in addition to dryness events. Through characterization of the dryness/wetness events, we have been able to identify hotspots for targeted interventions. Further still from the analysis, it is observed that 24-month timescale is not useful in monitoring wetness/dryness events across the study area due to the very low occurrence probabilities it exhibited. The study area is observed to be more prone to seasonal droughts at 6-month timescale. This could be attributed to moisture availability as a result of the bimodal seasonal rains. We can hence conclude that the study area is more prone to agricultural droughts rather than hydrological droughts. Besides, from the results and discussions presented in Section 3, the following conclusions have been deduced:

1. Homogeneity test of the rainfall time series revealed that 1961 was a change point year for most locations in Uganda. Further analysis of temperature anomalies showed that the earlier period (1901–1961) was mainly characterized with negative anomalies with a 20-year inter-annual variability. The period between 1960 and 1970 was identified as a transitional period from negative temperature anomalies to positive ones in the recent period (1962–2018). During the recent period, warming of more than 2°C above the 1961–1990 average was recorded in 2009 at most locations across the study area. The patterns closely relate to the global warming general trends.
2. Extreme droughts were rare in the study area, with occurrence probabilities of less than 1%. However, there were more than twice the number of severe droughts after 1961, with severe wetness events reducing in the period after 1961 until 2018. The SPEI performed better in identifying the historical humid events compared with droughts in the study area. The SPEI was able to identify three of the five historical

dryness events, while six of the eight severe wetness events were expressed by the evolutions.

3. The Albert Nile and Aswa River basins, including the northeast of Lake Kyoga basin, were found to be the most susceptible drainage basins towards severe droughts. Arua, Kitgum, Lira, Kaabong and Moroto sub-basins were observed to be the most susceptible locations requiring urgent mitigation measures tailor-made for these locations. The study area was found to be more prone to severe droughts at 3- and 6-month timescale tending towards agricultural droughts.
4. Trends in SPEI indicate significantly drying tendencies mainly observed in the recent period, with the Albert Nile and Aswa River basins most affected during the same period. The east of Lake Kyoga basin and the Lake Victoria basin is showing wetting tendencies in the recent period, although none of them were significant. Significantly drying trends at  $p < 0.05$  were recorded in the Aswa River basin of  $-0.031$  and  $-0.026$  SPEI units/10 years for SPEI-3 and SPEI-6, respectively. The cattle corridor is also observed to be exhibiting drying trends mainly at SPEI-6.

These results demonstrate the ability of SPEI in monitoring both dryness and wetness events in sub-humid climates. The evidence presented from this analysis provides vital information that can guide targeted mitigation measures in order to prepare communities living in the identified hotspots to be resilient to climate shocks. It is hoped that the relevant agencies can use this information in designing interventions that can reduce the impacts of weather-related disasters across the study area and within the East African region.

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## CONFLICT OF INTEREST

The authors would like to declare no conflict of interest.

## AUTHOR CONTRIBUTIONS

**Jimmy Byakatonda:** Conceptualization (equal); data curation (equal); methodology (equal); resources (equal); supervision (equal); writing – original draft (equal). **Geoffrey Openy:** Data curation (equal); software (equal). **Jotham Ivan Sempewo:** Formal analysis (equal); writing – review and editing (equal). **Dominic Banaga**

**Mucunguzi:** Project administration (equal); validation (equal); visualization (equal).

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