

# Water availability trends across water management zones in Uganda

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## Abstract

This study assessed trends in gridded ( $0.25^\circ \times 0.25^\circ$ ) Climate Forecast System Reanalysis (CFSR) precipitation, potential evapotranspiration (PET), and precipitation minus PET (PMP) across the four water management zones (WMZs) in Uganda including Kyoga, Victoria, Albert, and Upper Nile. The period considered was 1979–2013. Validation of CFSR datasets was conducted using precipitation observed at eight meteorological stations across the country. Observed precipitation trend direction was satisfactorily reproduced by CFSR data extracted at five out of eight stations. Negative (positive) values of long-term PMP mean were considered to indicate areas characterized by water scarcity (surplus). Areas with large positive PMP were confined to Lake Victoria and mountains such as Rwenzori and Elgon. The largest negative PMP values were in the arid and semi-arid areas of north and northeastern Uganda. The null hypothesis  $H_0$  (no trend) was rejected ( $p < 0.05$ ) for increasing annual precipitation trends across the various WMZs except in the extreme eastern parts of the Upper Nile, Kyoga, and Victoria WMZs (or areas along the boundary of Uganda and Kenya). The  $H_0$  (no trend) was rejected ( $p < 0.05$ ) for decreasing trends in annual PET over West Nile region of the Upper Nile, western parts of Victoria, and the Albert WMZs. For increasing trend in PMP, the  $H_0$  (no trend) was rejected ( $p < 0.05$ ) across the various WMZs except around the Mount Elgon area. The study findings are relevant for planning of water resources management across the different WMZs in the country.

## KEYWORDS

potential evapotranspiration, precipitation, trend analyses, Uganda, water availability, water management zones, water scarcity

## 1 | INTRODUCTION

Uganda is a land-locked country in East-Central Africa situated in the heart of the African Great Lakes region. To

harness the abundant opportunities across Uganda, a 30-year development master plan referred to as the Uganda's Vision 2040 was launched in 2013 (Government of Uganda, 2013). This vision was conceptualized around

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CFSR series, for instance, for hydrological prediction in a data-scarce region. Therefore, CFSR series were adopted in the present study.

To the best of our knowledge, by the time of conducting this research, there existed no studies that analysed trends in precipitation, PET, and PMP across the WMZs in Uganda and our work was aimed at addressing this research gap. This was performed while taking into account the differences in hydro-climates among the various WMZs.

## 2 | DATA AND METHODOLOGY

### 2.1 | Data

#### 2.1.1 | Precipitation

Monthly CFSR series of NCEP (Saha *et al.*, 2014) including precipitation, minimum ( $T_{\min}$ ), and maximum ( $T_{\max}$ ) temperature data over the period 1979–2013 were obtained in a gridded ( $0.25^\circ \times 0.25^\circ$ ) form (Figure 1). Being reanalyses products, CFSR series may possess some shortcomings resulting from, say, insufficient distribution of relevant instruments and uncertainties in the precipitation recovery procedures (Nair *et al.*, 2009). Therefore, the validity of CFSR dataset was evaluated using observed daily precipitation obtained from the Uganda National Meteorological Authority (UNMA) (Table 1). This requirement of validating satellite or reanalysis products prior to their application was also considered in other past studies across Uganda. Examples of such studies include Mubialiwo *et al.* (2020, 2021a, 2021b) and Onyutha *et al.* (2020). The procedure followed in validating CFSR can be found in section 2.2.2. From Figure 1, only two stations were identified and deemed representative in each WMZ. The selection of precipitation observed at only two locations was due to lack of weather stations with data over the same period as that for the CFSR series. Data quality check revealed that not greater than 10% of the total required records over the study period was missing at each selected weather station. The inversed distance weighed (IDW) interpolation approach (Shepard, 1968) was adopted to fill-in the missing precipitation records. The suitability of IDW interpolation for the precipitation over the study area was recently demonstrated by Chelangat and Abebe (2021) and Mubialiwo *et al.* (2021a).

#### 2.1.2 | Potential evapotranspiration PET

To estimate PET rates, a number of observed meteorological series (such as solar radiation, relative humidity, wind

speed, and temperature) are required. As already mentioned before, such series are lacking across the study area. Eventually, a number of methods exist for estimating PET based on the relevant datasets available. These methods fall under three categories based on whether they depend on energy mass balance, temperature, and radiation. Penman–Monteith (PM) (Allen *et al.*, 1998) is a typical approach which is based on the energy-mass balance. Methods based on temperature can be found in Linares (1977), Thornthwaite (1948), Hargreaves and Samani (1985, 1982), Blaney and Criddle (1950), and Hamon (1963). Approaches that rely on radiation can be found in Abtey (1996), Priestley and Taylor (1972), and Makkink (1957). The Penman–Monteith method (Allen *et al.*, 1998) has physical meanings, but is recommended to be applied in areas with adequate weather data. However, the Hargreaves method (Hargreaves and Samani, 1982; 1985) requires only minimum and maximum temperature and can be suitable for estimating PET over data-scarce areas. A few recent studies (Mubialiwo *et al.*, 2020; 2021b; Mukasa *et al.*, 2020; Onyutha *et al.*, 2020; Chelangat and Abebe, 2021; Onyutha *et al.*, 2021) have successfully applied the Hargreaves method in different parts of Uganda or the study area. In this line, the Hargreaves method was adopted in this study.

Daily PET ( $\text{mm}\cdot\text{day}^{-1}$ ) was estimated using the Hargreaves method (Hargreaves and Samani, 1982; 1985) which makes use of  $T_{\min}$  ( $^\circ\text{C}$ ) and  $T_{\max}$  ( $^\circ\text{C}$ ) such that

$$\text{PET} = 0.0023 \times R_a (T_{\text{mean}} + 17.8) \sqrt{(T_{\max} - T_{\min})}, \quad (1)$$

where  $R_a$  is the incoming extra-terrestrial solar radiation ( $\text{W}\cdot\text{m}^{-2}$ ) estimated using the latitude of each grid point and the calendar day of the year. Daily precipitation and estimated PET were converted into seasonal and annual time series. It is known that the East African region is characterized by largely bimodal precipitation annual cycle comprising winter dry season (January–February [JF]), the long rains season (MAM), the summer dry season (June–September [JJAS]), and the short rains season (OND) (Yang *et al.*, 2015). Eventually, JF, MAM, JJAS, and OND were considered in this study.

### 2.2 | Methodology

#### 2.2.1 | Analyses of trends

Linear trend magnitude or slope ( $m$ ) in seasonal and annual precipitation, PET, and the metric PMP was computed using (Theil (1950) and Sen (1968) such that

TABLE 1 Precipitation stations within the WMZs

S. No.	Station name	Latitude	Longitude	Record length	Long-term mean of annual data (mm·year <sup>-1</sup> )
1	Masaka Forest – Masaka	–0.33°S	31.73°E	1920–2012	448
2	Serere Agric. Station – Soroti	1.52°N	33.45°E	1920–2010	1,326
3	Masindi Met. Station	1.68°N	31.72°E	1926–2010	1,319
4	Soroti Met. Station – Soroti	1.72°N	33.62°E	1924–2012	1,322
5	Ibanda – Mbarara	0.12°N	30.50°E	1928–2010	705
6	Nkozi Experimental Farm – Mpigi	0.02°N	32.02°E	1924–2012	508
7	Wadelai WDD – Gulu	2.73°N	31.40°E	1965–2008	1,068
8	Gulu Met. Station – Gulu	2.78°N	32.28°E	1937–2010	1,446

$$m = \text{median}((x_j - x_i) \times (j - i)^{-1}), \forall i < j, \quad (2)$$

where  $x_j$  and  $x_i$  are correspondingly the  $j$ th and  $i$ th value from the sample of size  $n$  such that  $1 < i \leq (n - 1)$  and  $2 < j \leq n$ .

Trend significance was quantified using cumulative sum of the difference (CSD) between exceedance and non-exceedance counts of data points (Onyutha, 2016c; 2016d). For the adopted method, consider  $n$  as sample size. The given series is rescaled to become  $d_i$  by computing the difference between the exceedance and non-exceedance counts of data points using (Onyutha, 2016c),

$$d_i = u_i - v_i \quad \text{for } i = 1, 2, 3, \dots, n, \quad (3)$$

where  $u_i$  is the number of times each data point is exceeded and  $v_i$  denotes the number of times each data point exceeds others. The trend statistic  $T$  can be calculated using (Onyutha, 2016c),

$$T = 6 \times (n^3 - n)^{-1} \times \sum_{j=1}^{n-1} \sum_{i=1}^j d_i. \quad (4)$$

Values of  $T > 0$  and  $T < 0$  indicate increasing and decreasing trend, respectively.

$T$  is approximately normally distributed with mean of zero and the variance given by  $(n - 1)^{-1}$  (Onyutha, 2016e). The standardized trend statistic  $Z$  with a normalized distribution of mean of zero and variance equal to one can be given by

$$Z = T \times \left( \sqrt{1/(n - 1) \times \gamma} \right)^{-1}, \quad (5)$$

where the term  $\gamma$  takes care of the influence of autocorrelation on trend results (Onyutha, 2016d). Considering  $Z_{\alpha/2}$  as the standard normal variate, the null hypothesis  $H_0$  (no trend) was not rejected if  $|Z| < |Z_{\alpha/2}|$  (or  $p > 0.05$ ), otherwise, the  $H_0$  was rejected.

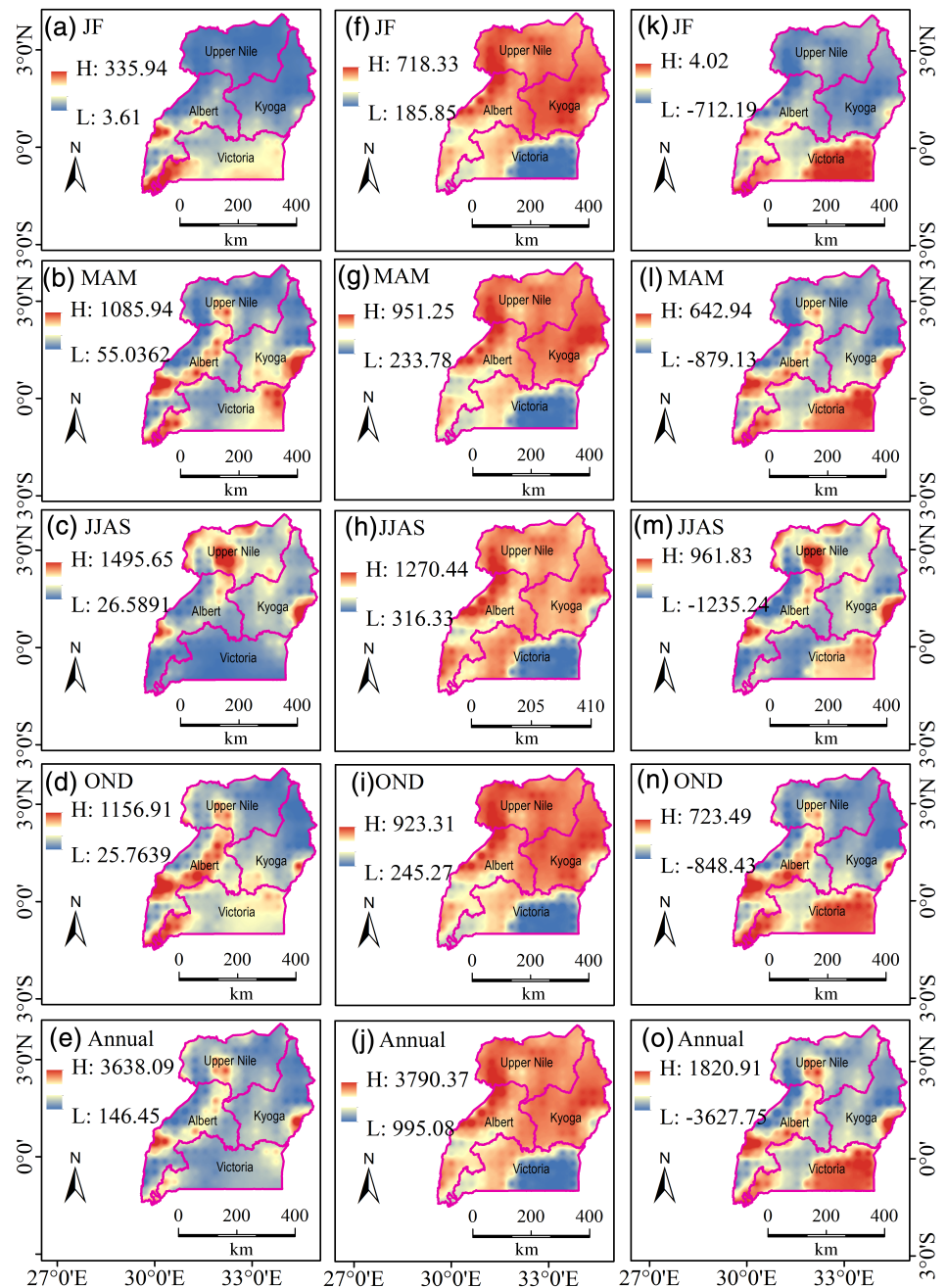
## 2.2.2 | Validation of the CFSR data

CFSR series was extracted at the location of each selected station with observed precipitation. A common period 1979–2008 (30 years) over which both observed and CFSR series had data was considered. Observed series were converted to seasonal and annual scales as done for CFSR precipitation. In the validation, the  $H_0$  (no correlation) was not rejected when the coefficient of correlation between observed and CFSR precipitation was less than the critical Pearson's correlation value at  $\alpha = 0.05$  (or 0.361 in this study). Trends from observed and CFSR-based precipitation were also compared. Validation was only conducted for precipitation because there was no observed data for evaporation or temperature. CFSR validation was conducted at annual and seasonal (JF, MAM, JJAS, and OND) time scales.

## 2.2.3 | Homogeneity of precipitation

Data which is not homogeneous requires application of a correction factor before it can be used for further analysis. Examples of studies which tested for homogeneity in climatic data include Singh *et al.* (2015), Hänsel *et al.* (2016), and Singh *et al.* (2016). In order to identify if there was a particular pattern in the deviation from long-term mean, homogeneity test was conducted using observed annual precipitation data. The applied techniques included the Pettitt's test (Pettitt, 1979), standard normal homogeneity test (SNHT) (Alexandersson, 1986), Buishand's test (Buishand, 1982), and Von Neumann's test (Von Neumann, 1941). In the four tests, the  $H_0$  (precipitation data are homogenous) was not rejected when the computed  $p$ -value was greater than the selected  $\alpha$  (0.05 in the present study). Under the alternative hypothesis  $H_1$ , the four homogeneity testing techniques assume a step-wise jump in the long-term mean at a particular point in time. Additionally, the cumulative sum (CUSUM) nonparametric

**FIGURE 2** Long-term mean (mm) of (a–e) precipitation, (f–j) PET, and (k–o) PMP at (a, f, k) JF, (b, g, l) MAM, (c, h, m) JJAS, (d, i, n) OND, and (e, j, o) annual time scales



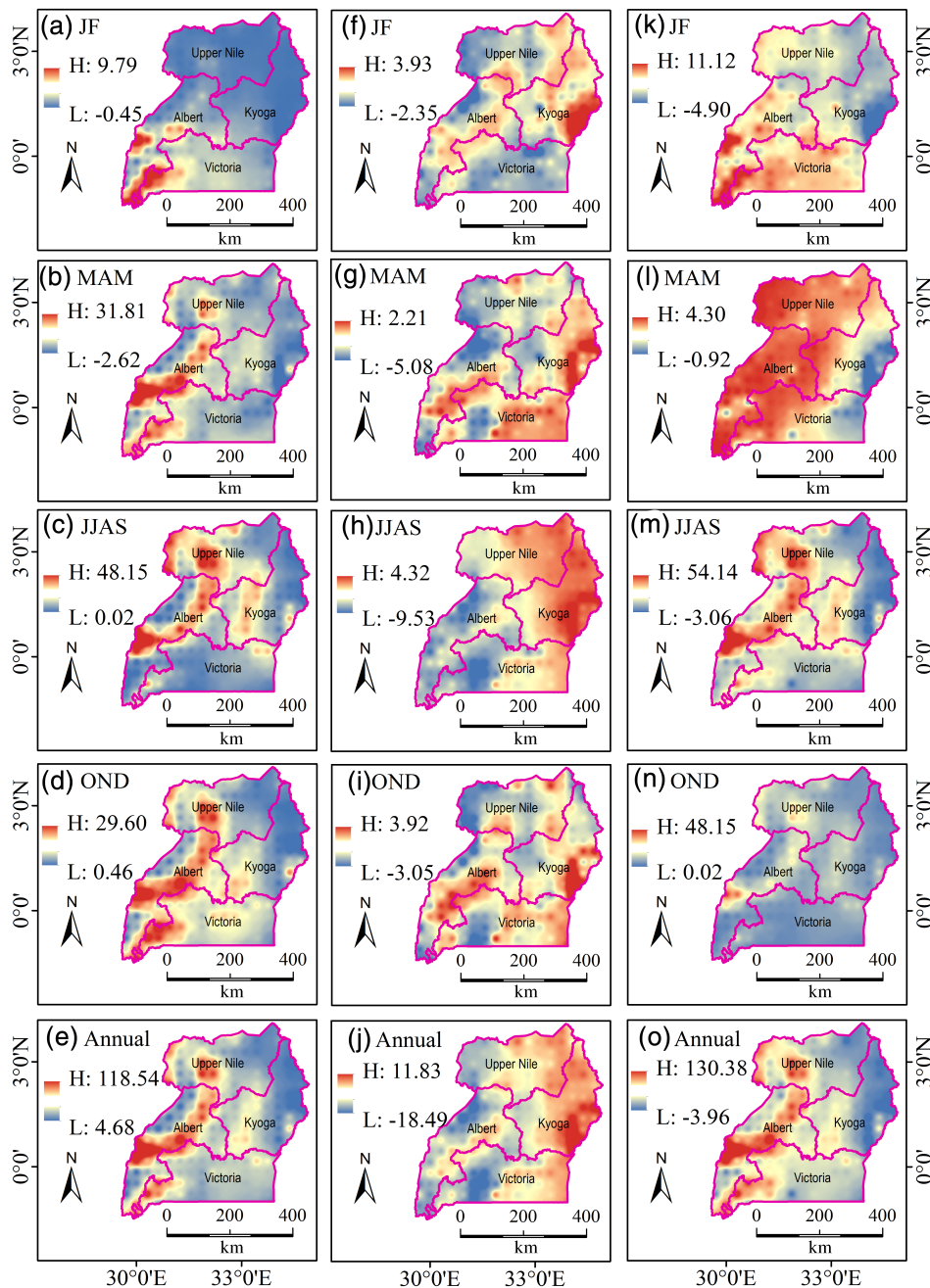
test of Page (1961) was applied. Upper and lower limits on regime shifts in the CUSUM charts were constructed based on standard deviation (SD) and in terms of the mean  $\pm 2$  SD of CUSUM data points.

### 3 | RESULTS AND DISCUSSION

#### 3.1 | Long-term mean precipitation, PET, and PMP

Figure 2 shows spatial distribution of seasonal and annual of precipitation, PET, and PMP. The Upper Nile,

Kyoga, and (a big portion of) the Albert WMZs received the least precipitation amounts during the JF season. Also, Victoria WMZ received the least (highest) JJAS (JF) precipitation (Figure 2a,c). The highest JJAS precipitation was experienced in the Upper Nile as well as some parts of the Albert and Kyoga WMZs (Figure 2c). Areas around Lake Victoria, Mount Elgon, and Rwenzori ranges and southern part of Albert WMZ received the highest precipitation amounts in MAM and OND seasons (Figure 2b,d). Spatial variation in the seasonal and annual precipitation across Uganda as shown in this study agrees to some extent with the results from Ngoma *et al.* (2021) and Cattani *et al.* (2018), especially for MAM



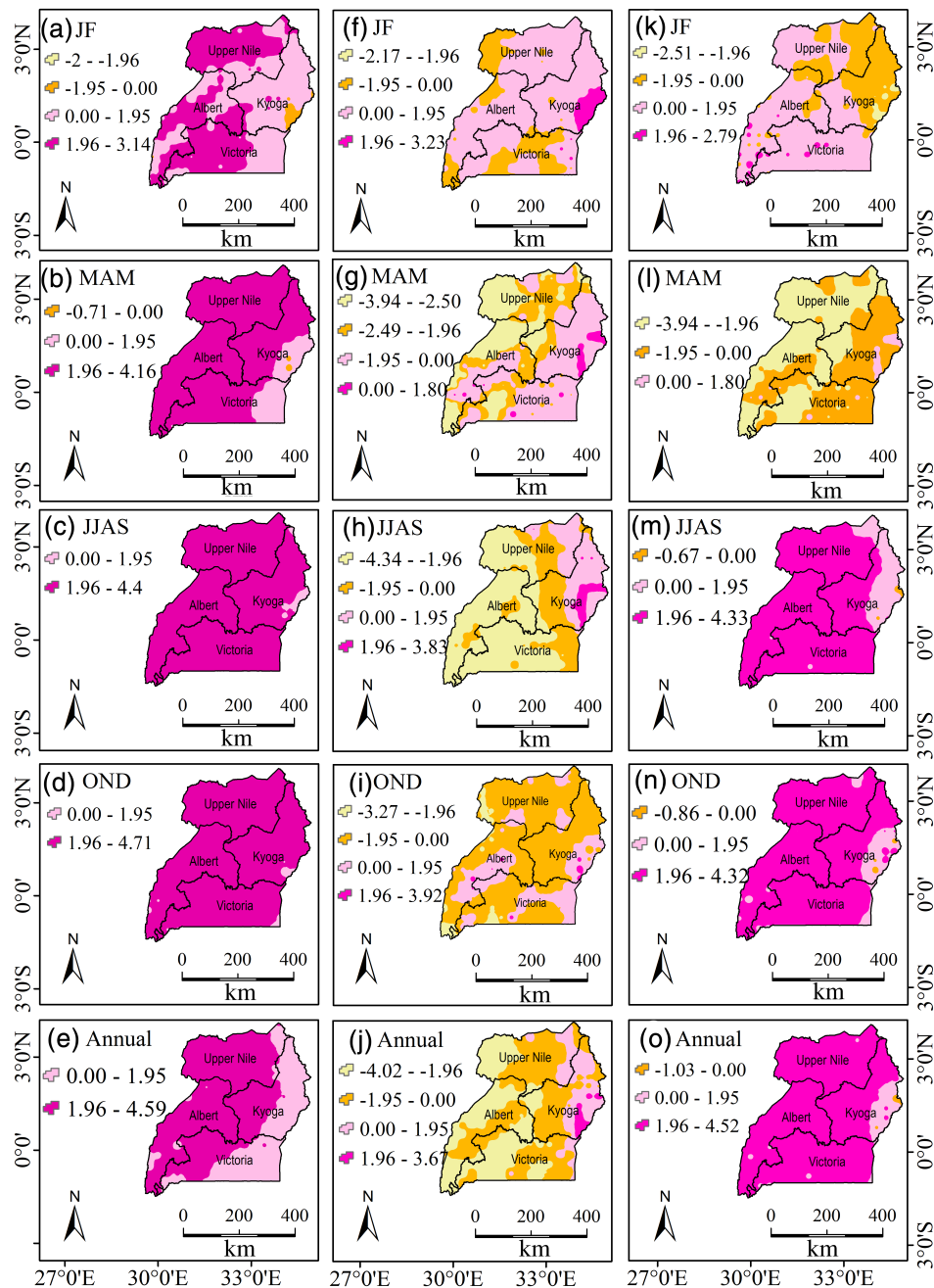
**FIGURE 3** Trend magnitude (mm-year<sup>-1</sup>) for (a–e) precipitation, (f–j) PET, and (k–o) PMP at (a, f, k) JF, (b, g, l) MAM, (c, h, m) JJAS, (d, i, n) OND, and (e, j, o) annual time scales

and annual time scales. Some mismatch between our findings and results from previous studies especially for dry seasons could be due to a few reasons. First, the CFRS series adopted in this study could be different from other reanalysis data analysed in previous studies. Second, we analysed seasonal and annual precipitation totals while others, like Cattani *et al.* (2018), considered extreme precipitation indices.

Low PET was confined to Lake Victoria (Figure 2f–j). PET represents evapotranspiration from green grass completely shading the ground with sufficient soil moisture content. Therefore, the low PET from a lake surface

could be an indication of mainly evaporation from the lake water in the absence of vegetation or green grass required for the transpiration. Generally, Kyoga and Upper Nile as well as the northern part of Albert WMZ were characterized by large PET totals (Figure 2f–j). As highlighted before, negative and positive values of PMP indicate areas characterized by water scarcity and surplus, respectively. For both seasonal and annual PMP, it is noticeable that areas where PET is less than precipitation are confined to Lake Victoria and mountains such as Rwenzori and Elgon (Figure 2k–o). This is because mountains and large water bodies tend to regulate local

**FIGURE 4** Standardized trend statistic Z (or trend direction) for (a–e) precipitation, (f–j) PET, and (k–o) PMP at (a, f, k) JF, (b, g, l) MAM, (c, h, m) JJAS, (d, i, n) OND, and (e, j, o) annual time scales



climate by attracting localized precipitation. Largest negative PMP values were in the arid and semi-arid areas of north and northeastern (or Karamoja region of) Uganda. This region grapples with prolonged dry spells and extreme hydrological and agricultural drought (Egeru *et al.*, 2014; Ministry of Water and Environment, 2017) which affect the economic activities including pastoralism. To meet water demand (especially for crop and livestock), it is necessary to practice soil and water conservation such as storage of water during the rainy seasons for use in the dry seasons.

### 3.2 | Trend analysis

#### 3.2.1 | Trends in precipitation, PET, and PMP

Figure 3 shows results of trend analysis. Corresponding significance of the trends can be seen in Figure 4. Except for the JF season, positive precipitation trends of both seasonal and annual time scales were confined to Mount Rwenzori and areas along the eastern boundary of Lake Albert (Figure 3a–e). The north and

northeastern areas of the country were characterized by decreasing precipitation trends. The entire area exhibited positive precipitation trends except JF and MAM season. Nsubuga *et al.* (2014) also reported annual precipitation increase over Uganda except in the southwestern and northwestern regions.

Increasing PET trends were exhibited around the Mount Elgon (Figure 3f–j). For the JJAS and annual PET, positive trends are noticeable over the Kyoga and Upper Nile WMZs (Figure 3h,j). Increasing trends in MAM and annual PET over Kyoga basin was also reported by Onyutha *et al.* (2020). For JJAS and annual time scales, areas with positive (negative) trends in precipitation also exhibited increasing (decreasing) trends in PMP (Figure 3c,m,e,o). Most areas except around Mount Elgon were characterized by increasing MAM PMP (Figure 3l). For JF PMP, positive trends were mainly in Kibale and around the Mount Rwenzori (Figure 3k). Generally, the OND PMP exhibited low magnitudes of increasing trend across the country except around Mount Rwenzori (Figure 3n).

The  $H_0$  (no trend) was rejected ( $p < 0.05$ ) for increasing annual precipitation trends across the various WMZs except in the extreme eastern parts of the Upper Nile, Kyoga, and Victoria WMZs (or areas along the boundary of Uganda and Kenya) (Figure 4e). The increasing trend in JJAS and OND precipitation had the  $H_0$  (no trend) rejected ( $p < 0.05$ ) over almost the entire country apart from a small region around Mount Elgon within Kyoga WMZ (Figure 4c,d).

The  $H_0$  (no trend) was also rejected ( $p < 0.05$ ) for decreasing trends in PET over West Nile region of the Upper Nile, western parts of Victoria and the Albert WMZs (Figure 4f–j). For increasing trend in PMP, the  $H_0$  (no trend) was rejected ( $p < 0.05$ ) across the various WMZs except around Mount Elgon (Figure 4k–o).

Positive (negative) trends in PMP indicates more (less) precipitation than PET totals hence available water (water scarcity). Available water, if sufficient, could be vital (a) to meet crop water requirements, (b) support ecosystem, and (c) promote water security across the various WMZs. However, excess of the available water in low-lying (mountainous) areas could imply possibilities of flooding (landslides). In arid areas (like the northern Kyoga WMZ or the Karamoja region), drought-resistant crops could be adopted for smallholder farming. In areas with significant trends in precipitation or PMP, future water resources management should consider non-stationarity of hydro-climate (Onyutha, 2017). Concepts of return period and risk for non-stationary hydrologic extreme events which should be considered, for instance, in designing hydraulic structures can be found in Salas and Obeysekera (2014).

### 3.3 | Homogeneity of precipitation

Table 2 shows results on homogeneity tests. There is close agreement among results from the four tests. All tests rejected the  $H_0$  (homogenous) ( $p < 0.05$ ) at stations 1, 3, and 5–7. The homogenous precipitation was at stations 2 and 4 (within Kyoga) as well as station 8 in the Upper Nile. Further graphical results of the Pettitt's test and CUSUM charts can be seen in Figures 5 and 6, respectively. Based on the results, the idea that inhomogeneity could be due to errors in measurement was deemed not to hold water in our study. Neither was the occurrence of the inhomogeneity of the precipitation by chance. This was because the  $H_0$  (homogenous) was rejected ( $p < 0.05$ ) in data from majority (or 62.5%) of the stations. Thus, the inhomogeneity could be due to spatial differences in the precipitation characteristics across the country over time. Strength of precipitation variability drivers can vary over time in a particular region or sub-region. Differences in precipitation characteristics across the study area may be due to the differential influences of the topographical features (Great Lakes and several mountains such as Rwenzori, Muhavura, Elgon, Moroto, Gahinga, and Sabinjo) in the various WMZs. Nevertheless, further research is required to comprehensively characterize the effects of possible interactions between regional circulation (such as localized convergence) with local geographical factors on precipitation distribution across the East African region and/or the various WMZs. The positive and negative regime shifts in the CUSUM charts depict impacts of climate variability on precipitation across the country. Thus, both trends and variability are vital for planning water resources management (Onyutha, 2021) in each WMZ.

### 3.4 | Validation of CFSR

Results on correlation between observed and CFSR-based precipitation can be seen in Table 3. At all stations, CFSR and observed precipitation were positively correlated with coefficients ranging from 0.069 (station 8) and 0.999 (station 1). At stations 1 and 5–6, the  $H_0$  (no correlation) was rejected ( $p < 0.05$ ) for both annual and seasonal time scales. For stations 2–4 and 7–8, the  $H_0$  (no correlation) was rejected ( $p < 0.05$ ) for at least one-time scale. Considering the various time scales, the  $H_0$  (no correlation) was rejected ( $p < 0.05$ ) for about 60% (or 23 out of 40) cases (Table 3). Top performance of CFSR in reproducing precipitation totals was registered in Victoria WMZ. Nevertheless, we generally deemed this performance of CFSR data satisfactory though further improvements are required in the reanalysis model to accurately reproduce the historical climatology across the various WMZs.

TABLE 2 Statistical homogeneity test results

S. No.	Station	p-value			
		Pettit's test	SNHT	Buishand's test	Von Neumann test
1	Masaka Forest – Masaka	<0.001	<0.001	<0.001	<0.001
2	Serere Agric. Station – Soroti	0.295	0.329	0.080	0.336
3	Masindi Met. Station	0.019	0.015	0.017	0.013
4	Soroti Met. Station – Soroti	0.659	0.441	0.647	0.296
5	Ibanda – Mbarara	<0.001	<0.001	<0.001	<0.001
6	Nkozi Experimental Farm – Mpigi	<0.001	<0.001	<0.001	<0.001
7	Wadelai WDD – Gulu	0.010	0.018	0.004	0.029
8	Gulu Met. Station – Gulu	0.177	0.407	0.169	0.629

Note: Values which are less than 0.05 indicate that the  $H_0$  (homogenous) was rejected.

FIGURE 5 Pettitt's test applied to annual precipitation at (a–h) stations 1–8

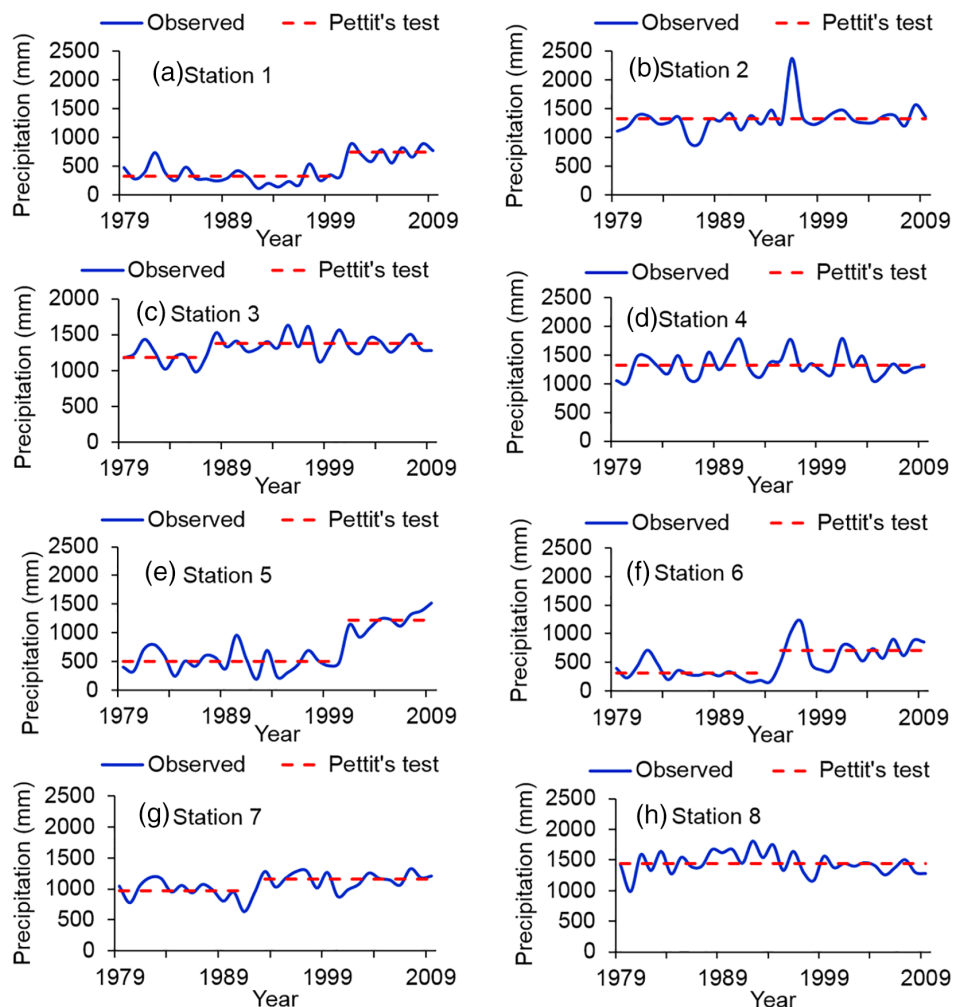


Table 4 shows comparison between the trend slopes or significance from observed and CFSR precipitation. At a given location (except at stations 3–4 and 8), both observed and CFSR data exhibited positive trends in both seasonal and annual time scales. The magnitude of

the mismatch between trend slope from observed precipitation and that of CFSR data varied from one WMZ to another. Contrasting signs of the slopes of linear trends in precipitation for the observed and precipitation data were obtained at station 8. The CFSR data

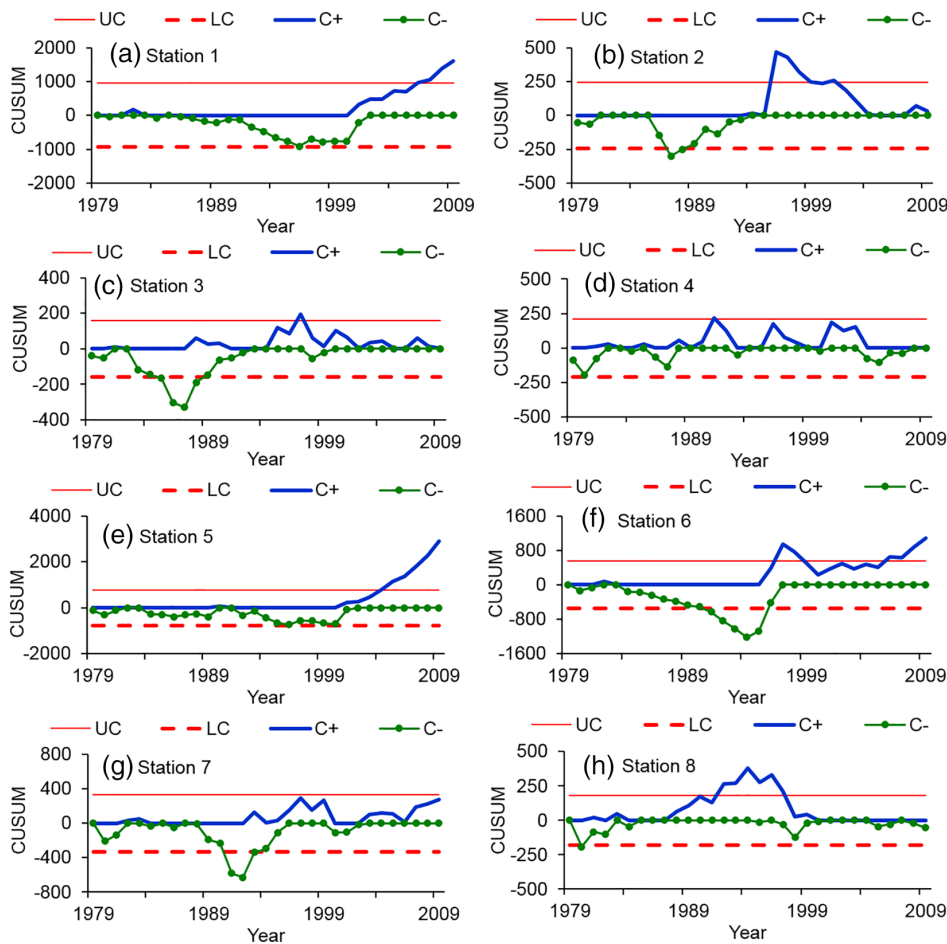


FIGURE 6 CUSUM charts for annual precipitation at (a–h) stations 1–8. UC and LC stand for upper and lower CUSUM limits, respectively. C+ and C– denote positive and negative shift, respectively

TABLE 3 Correlation of observed and CFSR precipitation

S. No.	Station (up) Grid (below)	Correlation coefficient				
		JF	MAM	JJAS	OND	Annual
1	Masaka Forest – Masaka CFSR data at station 1	0.972*	0.995*	0.980*	0.981*	0.999*
2	Serere Agric. Station – Soroti CFSR data at station 2	0.295	0.268	0.344	0.447*	0.160
3	Masindi Met. Station CFSR data at station 3	0.186	0.110	0.657*	0.259	0.168
4	Soroti Met. Station – Soroti CFSR data at station 4	0.538*	0.125	0.268	0.512*	0.115
5	Ibanda – Mbarara CFSR data at station 5	0.846*	0.911*	0.972*	0.904*	0.961*
6	Nkozi Experimental Farm – Mpigi CFSR data at station 6	0.653*	0.681*	0.900*	0.869*	0.779*
7	Wadelai WDD – Gulu CFSR data at station 7	0.106	0.127	0.509*	0.329	0.373*
8	Gulu Met. Station – Gulu CFSR data at station 8	0.256	0.366*	0.362*	0.162	0.069

Note: Asterisk indicates that  $H_0$  (no correlation) was rejected ( $p < 0.05$ ).

**TABLE 4** Trend magnitude and direction in observed and CFSR precipitation

S. No.	Station (up)	Time scale				
	CFSR grid (below)	JF	MAM	JJAS	OND	Annual
Trend magnitude, $m$ (mm-year <sup>-1</sup> )						
1	Masaka Forest – Masaka	2.46	2.76	3.29	3.83	13.90
	CFSR data at station 1	1.56	5.46	4.59	7.19	19.20
2	Serere Agric. Station – Soroti	0.09	3.72	1.36	2.25	5.46
	CFSR data at station 2	0.44	8.6	15.63	8.33	33.13
3	Masindi Met. Station	-1.02	1.00	5.98	-0.65	5.44
	CFSR data at station 3	1.69	16.93	24.9	17.86	60.97
4	Soroti Met. Station – Soroti	0.27	-3.60	1.70	2.61	1.64
	CFSR data at station 4	0.11	6.24	9.03	4.23	21.44
5	Ibanda – Mbarara	2.17	8.21	9.75	7.70	30.63
	CFSR data at station 5	0.25	5.24	6.20	6.57	22.58
6	Nkozi Experimental Farm – Mpigi	2.23	3.80	5.19	4.28	15.72
	CFSR data at station 6	1.63	6.18	5.83	8.17	23.87
7	Wadelai WDD – Gulu	0.87	1.17	2.78	3.00	6.70
	CFSR data at station 7	0.06	3.62	8.77	4.49	16.95
8	Gulu Met. Station – Gulu	-0.26	-2.24	-1.14	-0.38	-4.72
	CFSR data at station 8	0.99	11.69	26.69	20.63	62.45
Trend direction, $Z$						
1	Masaka Forest – Masaka	2.67*	1.29	3.08*	2.09*	2.55*
	CFSR data at station 1	3.14*	2.64*	4.09*	3.20*	3.51*
2	Serere Agric. Station – Soroti	0.40	1.35	0.82	1.39	1.82
	CFSR data at station 2	2.15*	2.51*	3.63*	3.95*	3.99*
3	Masindi Met. Station	-1.58	0.53	1.92	-0.05	2.02*
	CFSR data at station 3	2.10*	3.25*	3.65*	3.98*	4.11*
4	Soroti Met. Station – Soroti	0.34	-1.71	0.84	0.93	0.24
	CFSR data at station 4	1.57	2.47*	3.25*	3.72*	3.90*
5	Ibanda – Mbarara	2.11*	2.94*	3.56*	2.32*	3.30*
	CFSR data at station 5	0.41	1.88	3.96*	2.54*	2.60*
6	Nkozi Experimental Farm – Mpigi	2.40*	2.34*	3.85*	2.30*	3.21*
	CFSR data at station 6	2.35*	3.61*	4.23*	3.31*	3.90*
7	Wadelai WDD – Gulu	1.17	0.63	1.75	1.72	2.38*
	CFSR data at station 7	2.84*	3.43*	3.59*	3.64*	4.21*
8	Gulu Met. Station – Gulu	-0.63	-1.17	-0.14	-0.01	-1.18
	CFSR data at station 8	2.02*	2.69*	3.40*	4.38*	4.09*

Note: Asterisk denotes that  $H_0$  (no trend) was rejected at  $\alpha = 0.05$ .

generally over-estimated observed trends at all the selected locations except station 5. In 14 out of 40 (35%) cases, the  $H_0$  (no trend) was rejected in both CFSR and observed precipitation. Contrasting directional signs of increase or decrease were obtained in 17.5% (7 out of 40) cases of the various time scales for which CFSR and observed precipitation trends were compared. Again,

top performance of CFSR in reproducing precipitation trends was registered in Victoria WMZ (stations 1 and 6). Overall, the performance of the CFSR in reproducing trend was deemed satisfactory. Results of validation indicate that the trends in CFSR data can give insights into the actual historical precipitation trends across the various WMZs.

## 4 | CONCLUSION

This study analysed precipitation, PET, and PMP trends across the four WMZs in Uganda. The study used the gridded ( $0.25^\circ \times 0.25^\circ$ ) CFSR monthly data series over the period 1979–2013. The  $H_0$  (no correlation between CFSR and observed precipitation) was rejected ( $p < 0.05$ ) for about 60% cases of validation based on various time scales. Thus, the performance of CFSR in reproducing observed precipitation total was deemed satisfactory.

Large PET totals were over Kyoga and Upper Nile as well as the northern part of Albert WMZ. Areas with large positive PMP were confined to Lake Victoria and mountains such as Rwenzori and Elgon. Arid and semi-arid areas of north and northeastern Uganda (or the Karamoja region) exhibited the largest negative PMP values. The  $H_0$  (no trend) was rejected ( $p < 0.05$ ) for positive trends in annual precipitation across the various WMZs except in the extreme eastern parts of the Upper Nile, Kyoga, and Victoria WMZs. The  $H_0$  (no trend) was rejected ( $p < 0.05$ ) for negative trends in annual PET over West Nile region of the Upper Nile, as well as western parts of Victoria and the Albert WMZs. For positive PMP trend, the  $H_0$  (no trend) was rejected ( $p < 0.05$ ) across the various WMZs except around Mount Elgon. This study's findings are relevant for planning for water resources management over the different WMZs in the country. In other words, water cycle management system comprising planning, developing, implementing and managing the optimum use of water resources is required across the various WMZs of Uganda. This is to ensure future safety and security of the local population from impacts of water scarcity or surplus on livelihoods.

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### AUTHOR CONTRIBUTIONS

**Charles Onyutha:** Conceptualization; data curation; formal analysis; investigation; methodology; supervision; validation; writing-review & editing. **Arnold Asimwe:** Conceptualization; data curation; formal analysis; investigation; methodology; resources; validation; writing-original draft. **Lawrence Muhwezi:** Project administration; writing-review & editing. **Ambrose Mubialiwo:** Conceptualization; formal analysis; validation; writing-original draft; writing-review & editing.

### CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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