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Spatial and Temporal Analysis of Dry and Wet Spells in Upper Awash River Basin, Ethiopia

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Received: 9 October 2020; Accepted: 29 October 2020; Published: 30 October 2020

Abstract: This study aimed to analyze the probability of the occurrence of dry/wet spell rainfall using the Markov chain model in the Upper Awash River Basin, Ethiopia. The rainfall analysis was conducted in the short rainy *(Belg*) and long rainy (*Kiremt*) seasons on a dekadal (10–day) scale over a 30-year period. In the *Belg* season, continuous, three-dekad dry spells were prevalent at all stations. Persistent dry spells might result in meteorological, hydrological, and socio-economic drought (in that order) and merge with the *Kiremt* season. The consecutive wet dekads of the *Kiremt* season indicate a higher probability of wet dekads at all stations, except Metehara. This station experienced a short duration (dekads 20–23) of wet spells, in which precipitation is more than 50% likely. Nevertheless, surplus rainwater may be recorded at Debrezeit and Wonji only in the *Kiremt* season because of a higher probability of wet spells in most dekads (dekads 19–24). At these stations, rainfall can be harvested for better water management practices to supply irrigation during the dry season, to conserve moisture, and to reduce erosion. This reduces the vulnerability of the farmers around the river basin, particularly in areas where dry spell dekads are dominant.

Keywords: Markov chain model; dry/wet spell; rainfall probability; Upper Awash River Basin

1. Introduction

Precipitation modeling is essential for the planning and management of water resources and has many practical engineering and agriculture applications. The majority of hydrological methods for precipitation modeling attempt to represent the generating mechanism of the physical process and are mathematical descriptions of the nature and the structure of the sample time sequence of precipitation [1]. The analysis of the probability distribution of dry spell characteristics (occurrence and duration) provides useful information for agricultural and environmental planning and for the management of drought-prone areas, which have always been a concern for researchers [2–4].

The stochastic models used to study dry spells can be subdivided into two different categories: driven data models (e.g., the non-homogeneous Poisson model), which reproduce the primary characteristics of the available data series, and physically based models (e.g., the Markov chain model), which schematize the generating mechanisms of atmospheric precipitation [5]. The Markov chain probabilistic model is widely used to determine the relative chance of occurrence of a given rainfall to characterize a rainfall period as a dry or wet spell [5–15]. This model is also useful for agricultural water management to determine the onset and end of the rainy season, which largely determines the success of rainfed agriculture [16,17]. The Markov chain model is broadly used for the analysis of dry and wet spells in different parts of the world, such as India [6], Pakistan [18], Greece [19,20], and East Africa [21–28].

To determine the length of wet spells, decisions must often be made based on the probability of receiving a certain amount of rainfall during a given dekad—the initial probability of a dekad being wet (P_W). Then, the probability of rain during the next dekad, if rain occurs in this dekad, is the conditional probability of a wet dekad preceded by a wet dekad (P_{WW}). The probability of the next dekad being wet, if this dekad is dry, is the conditional probability of a wet dekad preceded by a dry dekad (P_{WD}). The initial and conditional probabilities for a dry dekad can be defined in a similar way [6,29–31]. These initial and conditional probabilities help determine the relative chance of the occurrence of a given amount of rainfall.

The degree of wetness is defined in terms of any amount of rainfall conventionally based on a constant (non-negative) threshold [32]. The choice of the rainfall threshold depth depends on the purpose for which different probabilities may be used [33]. Many studies using the Markov Chain Model were conducted by assuming a fixed threshold value to characterize a rainy period as being wet or dry. Reddy [34] stated that 3 mm of rainfall per day can satisfy the average crop water requirement, and a dekad (10 days) with 30 mm or more of rainfall was considered a wet dekad. Mersha [35] used the same threshold value to assess the moisture availability over the arid and semi-arid zones of Ethiopia using a Markov chain model. Similarly, Yemenu and Chemeda [36] considered a fixed threshold value of 30 mm per dekad to categorize a dekad as a wet or dry spell. Reddy et al. [34] considered a week with less than 20 mm of rainfall as a dry week and a week with 20 mm or more as wet. Admasu et al. [28] used 10 and 20 mm threshold limits for agricultural planning in the Central Rift Valley regions of Ethiopia.

Similarly, Mathugama and Peiris [37] stated that the threshold value should not be selected subjectively but should be related to the type of application. Ratan and Vanugopal [32] recommend using a varying threshold to define a rainy day to account for the spatial heterogeneity of rainfall. Therefore, in this study, a crop water requirement (ETc) of dominant crops during the initial and late-season stages in a specific area is considered to fix the threshold value and to characterize the probability of the rainy season as a dry and wet spell using Markov Chain modeling.

The Awash River Basin is the most intensively cultivated and frequently affected basin by floods and droughts in Ethiopia [38,39]. Additionally, land use in the basin is primarily dominated by agricultural land (51.39%), grassland (29.79%), and shrubland (8.11%) [40]. Water-user communities around the basin lack adequate information about the timing, variability, and quantity of seasonal and annual rainfall to relate climatic conditions and cultivation practices [41,42]. An unexpected break in rainfall early in the growing season can allow farmers to recover and resume production despite the loss of some crops. However, if such a break occurs in the middle or latter part of the growing season, all the sown crops may suffer irreparable damage, resulting in dire economic consequences for farmers [42]. Hence, spatial and temporal analyses of dry and wet spells are required to characterize the rainfall that influences agricultural production. Rainfall characterizations include identifying the date of the onset of the effective rainy season; the probability and length of wet spells are crucial elements in assessing the nature and span of the rainy season.

The Upper Awash River Basin comprises the Upland sub-basin, which is dominated by a mountainous landscape, and the Upper Valley sub-basins, which form part of the great rift valley area [43,44]. In this basin, none of the previous studies use the crop water requirements (ETc) which satisfy the water demands of a crop throughout the growing season as a threshold value. In contrast, they have been used a fixed threshold (like 30 mm/dekad or 20 mm/week) to characterize the rainy season as a wet/dry dekads. However, we analyzed the dry and wet spells using varied thresholds depending on dekadal water requirements. This assumption avoids the drawbacks of assuming fixed threshold values, which might result in over- or under-estimating dry and wet spell periods. Furthermore, the spatial and temporal analysis of dry and wet spells of rainfall in the river basin has never been done based on the crop evapotranspiration demand commonly cultivated in the basin.

Hence, such a study in the diversified topographic, climatic, and cultivation practices will give new insights to policymakers and water resource managers at a basin scale.

Thus, the objective of this study was to investigate the probabilities of dry and wet spells during the rainy season using a Markov chain model based on dekadal (10-day) meteorological variables for more than 30 years in the Upper Awash River Basin, Ethiopia. This spatial and temporal analysis of dry/wet spells indicates a potential water-scarce period, which might result in severe drought or excessively wet dekads/flooding and havoc due to flash rains from the highlands of the Upper Awash River Basin.

2. Materials and Methods

2.1. Study Area

The study area is located in the Upper Awash River Basin of Ethiopia, which includes the upland and upper valley parts of the river basin covering 10,148 km^2. The elevation in the Upper Awash basin ranges from 794–4187 meter above sea level—m.a.s.l. (Figure 1). The annual rainfall averages at the four studied stations were 889 mm (Debrezeit), 830 mm (Wonji), 872 mm (Melkassa), and 610 mm (Metehara). The monthly mean temperature varies between 18–25 °C in the study areas.

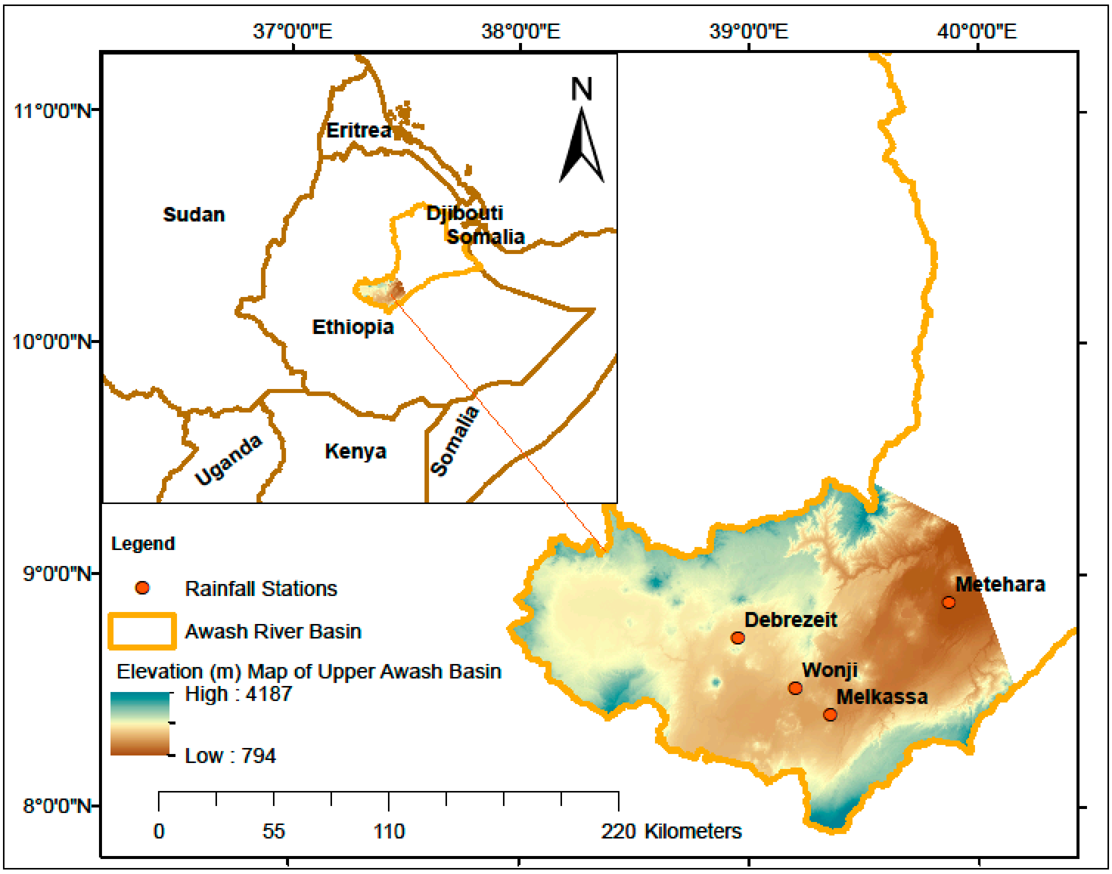

Figure 1. Location of the Upper Awash River Basin, Ethiopia.

The basin is known for its intensified agricultural activities at different scales, including small, medium, and large-scale farming practices. The 42 years historical period of land use land cover (LULC) change analysis in the Upper Awash River Basin shows continuous increment in the spatial extent of cropland and urban areas [45]. Major crops grown in the basin include *teff* (a crop native to Ethiopia cultivated around Debrezeit), maize (in Wonji and Metehara), and sorghum (in Melkassa). In addition, onions and soya beans are also cultivated in the basin [46]. This study analysis focused on those major crops in the basin stated above for setting a threshold value to characterize a dekad as a wet or dry spell.

2.2. Data Acquisition and Use

Daily meteorological data from to 1976–2009 were collected from various sources (National Meteorological Agency of Ethiopia (NMA), Wonji-Shoa Sugar Factory, Metehara Sugar Factory, and Melkassa Agricultural Research Center). To estimate the reference evapotranspiration (ETo) for a given dekad (10 days), the average maximum and minimum temperatures (°C), relative humidity (%), sunshine hours (h), wind speed at a 2-m height (km/day), and rainfall (mm) were aggregated from a daily data set.

The CROPWAT v8.0 model was developed by the Food and Agriculture Organization (FAO) to calculate the crop water requirement and irrigation requirement from existing or new climatic and crop data [47] and uses the Smith [48] Penman–Monteith method to estimate the ETo for each dekad in the study period. Table A1 shows a list of the standard meteorological dekads ([49] as cited in [50]).

The outliers and consistency of rainfall time series data were tested using the Tukey fence method [51] and double-mass curve [52], respectively. The rainfall data were consistent at all stations. Lastly, the spatial probabilities of dry and wet spells were analyzed on the dekadal time step. ArcMap 10.1 and MATLAB R2020 software were used to plot the location map and all the figures in the manuscript, respectively.

2.3. Methods

2.3.1. Reference Evapotranspiration and Crop Evapotranspiration

The evapotranspiration rate from a reference surface (not short of water) is called the reference crop evapotranspiration or reference evapotranspiration (*ETo*). The reference surface is a hypothetical grass reference crop with specific characteristics [53]. The CROPWAT model uses the FAO Penman–Monteith method to estimate the *ETo* as described below:

$$ET_o = \frac{0.408\Delta(R_n - G) + \Upsilon\frac{900}{\Upsilon+273}U_2(e_s - e_a)}{\Delta + \Upsilon(1 + 0.34U_2)}, \quad (1)$$

where *ETo* = reference evapotranspiration (mm/day); *Rn* = net radiation at the crop surface (MJ/m per day); G = soil heat flux density (MJ/m^2 per day); T = mean daily air temperature at a 2-m height (°C); u_2 = wind speed at a 2-m height (m/sec); e_s = saturation vapor pressure (kPa); e_a = actual vapor pressure (kPa); $e_s - e_a$ = saturation vapor pressure deficit (kPa), Δ the slope of the vapor pressure curve (kPa °C^{-1}) and Υ the psychrometric constant (kPa °C^{-1}).

The crop coefficient (*Kc*) value was obtained from FAO-56 documents [53]. In the *Kc* value, differences in the crop canopy and aerodynamic resistance relative to the hypothetical reference crop are considered. The *Kc* factor serves as an aggregation of the physical and physiological differences between crops and the reference definition [53]. The *Kc* value was further multiplied by the *ETo* to determine crop evapotranspiration (*ETc*) for each dominant crop (*teff*, maize and sorghum) in the study basin; this *ETc* value was used as the threshold value for computing the probability of dry/wet spells.

$$ET_c = K_c \times ET_o \quad (2)$$

2.3.2. Threshold of Onset and End of a Wet Spell

The onset or end of a wet spell marks the transition from the dry period to the wet period; the opposite is true for the end of a wet spell [54]. In this study, the *ETc* during the initial growth stages of the selected crops (*teff*, maize, sorghum) in the *Belg* season (March–May) were used as threshold values to classify the dekads into wet and dry spells. This was due to a short span of the length of the wet spell during this season. A wet dekad has cumulative rainfall equal to or exceeding the dekadal *ETc* during its initial growth stage.

In the *Kiremt* season (June–September), the dekadal *ETc* of the entire rainy season was considered a threshold value to quantify the probability of rainfall in a season. For this purpose, the *ETc* demand was analyzed using Allen et al. [53]. Therefore, the onset of a wet spell occurs when rainfall exceeds or equals the initial crop water requirements (i.e., initial crop coefficient (*Kc*, initial) multiplied by the *ETo* of the specific dekad). In contrast, the end of the wet spell is identified by rainfall less than or equal to the crop water requirements during the later stages.

2.3.3. Trend Detection Using Mann–Kendall and Sen's Slope Estimator

The non-parametric Mann–Kendall (MK) test statistics are commonly employed to detect monotonic trends in series of environmental data, climate data or hydrological data [55,56]. The number of dry spells and the maximum length of a consecutive dry spell for the time series data were evaluated using Mann–Kendall's trend test statistics and Sen's slope test (Q_2) at a 5% significance level.

Mann–Kendall Trend Test

For the time series of $x_1, x_2, \ldots, x_n$, the MK test statistics (S) [57,58] for the number of dry spells and the maximum length of a consecutive dry spell can be calculated:

$$S = \sum_{i=1}^{n-1} \sum_{j=k+1}^{n} sign(x_j - x_i)\,. \tag{3}$$

The variance of S computed as:

$$\mathrm{var}\,(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t f_t(f_t - 1)(2f_t + 5)\right], \tag{4}$$

where t varies over the set of tied ranks, and f_t is the number of times (i.e., frequency) the rank t appears, n represents the sample size.

The standard normal test statistics (Z) calculated as:

$$Z = \left\{ \begin{array}{cc} (S-1)/se, & S > 0 \\ 0, & S = 0 \\ (S+1)/se, & S < 0 \end{array} \right\}, \tag{5}$$

where se is the square root of var.

A positive (negative) value of Z indicates that the data tend to increase (decrease) with time. The null hypothesis of no trend is rejected if the absolute value of Z is higher than 1.96 at 5% significance level.

Sen's Slope Estimator

Sen [59] developed the non-parametric procedure for estimating the magnitude of a trend in the time series given by Sen's slope test (Q_2) [55,60]. The test gives a more robust estimation of the trend, especially when the trend cannot be estimated by other statistical approaches like Kendall's test statistics or regression [60]. The positive results of Q_2 in the number of dry dekads and the maximum length of consecutive dry spell dekads represent an increasing trend, while the negative values represent decreasing trends over a given time. Detailed mathematical equations for Sen's slope estimator are well presented in Gocic and Trajkovic [55] and Da silva et al. [61].

2.3.4. Probabilities of Dry/Wet Spells Based on the Markov Chain Model

For the analysis of probability of wet/dry spells using the Markov chain model method, the following parameters were estimated [6,7,29–31,36].

Initial probabilities

$$P_D = \frac{F_D}{n}, \tag{6}$$

$$P_W = \frac{F_W}{n}. \tag{7}$$

Conditional probabilities:

$$P_{WW} = \frac{F_{WW}}{F_W}, \tag{8}$$

$$P_{DD} = \frac{F_{DD}}{F_D}, \tag{9}$$

$$P_{WD} = 1 - P_{DD}, \tag{10}$$

$$P_{DW} = 1 - P_{WW}. \tag{11}$$

Probabilities of more than one dry/wet dekad occurring in successive order:

$$2D = P_{D\,d1} \times P_{DDd2}, \tag{12}$$

$$2W = P_{W\,d1} \times P_{WWd2}, \tag{13}$$

$$3D = P_{D\,d1} \times P_{DDd2} \times P_{DDd3}, \tag{14}$$

$$3W = P_{W\,d1} \times P_{WWd2} \times P_{WWd3}, \tag{15}$$

where, P_D: the probability of a dekad being dry; F_D: the number of dry dekads; P_W: the probability of a dekad being wet; F_W: the number wet dekads; n: the number of observations; P_{WW}: the probability of a wet dekad preceded by another wet dekad; F_{WW}: the number of wet dekads preceded by another wet dekad; F_{DD}: the number of dry dekads preceded by another dry dekad; P_{DD}: the probability of a dry dekad preceded by another dry dekad; P_{WD}: the probability of a wet dekad preceded by a dry dekad; P_{DW}: the probability of a dry dekad preceded by a wet dekad; $2D$: the probability of 2 consecutive dry dekads starting with any dekad; $3D$: the probability of 3 consecutive dry dekads starting with any dekad; $2W$: the probability of 2 consecutive wet dekads starting with any dekad; $3W$: the probability of 3 consecutive wet dekads starting with any dekad; P_{Dd1}: the probability of a dekad being dry (first dekad); P_{DDd2}: the probability of the second dekad being dry, given that the preceding dekad is dry; P_{DDd3}: the probability of the third dekad being dry, given that the preceding 2 dekads are dry; P_{Wd1}: the probability of a dekad being wet (first dekad); P_{WWd2}: the probability of the second dekad being wet, given that the preceding dekad is wet; P_{WWd3}: the probability of the third dekad being wet, given that the preceding 2 dekads are wet.

3. Results and Discussion

3.1. Thresholds of Wet Spells

Threshold values based on dekadal *ETc* were analyzed for the *Belg* and *Kirmet* seasons as shown in Table 1. The mean onsets of the wet spells dekads are highly stable and reliable at all stations. Based on the calculated threshold value shown, the initial and conditional probabilities of wet/dry spells in the two seasons were analyzed using the Markov chain probabilistic model for all stations.

Table 1. Threshold value based on dekadal crop water requirement in different seasons.

Stations	Threshold Value (mm/dekad)		
	'Belg' Season	*'Kiremt' Season*	
	Onset of Rainfall (MOD [1])	**Onset of Rainfall (MOD)**	**End of Rainfall (MED [2])**
Debrezeit	15.5 (dekad 9)	13.1 (dekad 17)	39.55 (dekad 27)
Wonji	13.4 (dekad 8)	13.4 (dekad 17)	35.1 (dekad 27)
Melkassa	16.2 (dekad 8)	16.9 (dekad 17)	32.8 (dekad 27)
Metehara	15.5 (dekad 9)	21 (dekad 19)	40 (dekad 24)

[1] Mean onset of rainfall dekad (MOD); [2] mean end of rainfall dekad (MED).

3.2. *Trend Detection Using Mann–Kendall and Sen's Slope Estimator*

The temporal patterns of the dry spell and consecutive dry dekads in rainy months of the *Belg* and *Kiremt* seasons are shown in Figures 2 and 3. The highest number of dry spell days in the *Belg* season were recorded in the year 1994 at Debrezeit (90 days), 1980 at Wonji (90 days), 1999 at Melkassa (90 days) and 1984 at Metehara (80 days). However, the *Kiremt* season experienced the highest dry spell period in Debrezeit (in 1997), Wonji (in 1980), Melkassa (in 1987) and Methara (in 1984, 1987, 1996 and in 2006). The longest consecutive dry dekads—the maximum length of dry spell dekad—were identified in Debrezeit (in 1992 and 1994), Wonji (in 1980), Melkassa (in 1999) and in Metehara (1984, 2002 and 2008) in the *Belg* season. In the *Kiremt* season, it was observed in 1997 and 2008 at Debrezeit, 1986 at Metehara, 1980 at Wonji and Melkassa (Figure 3).

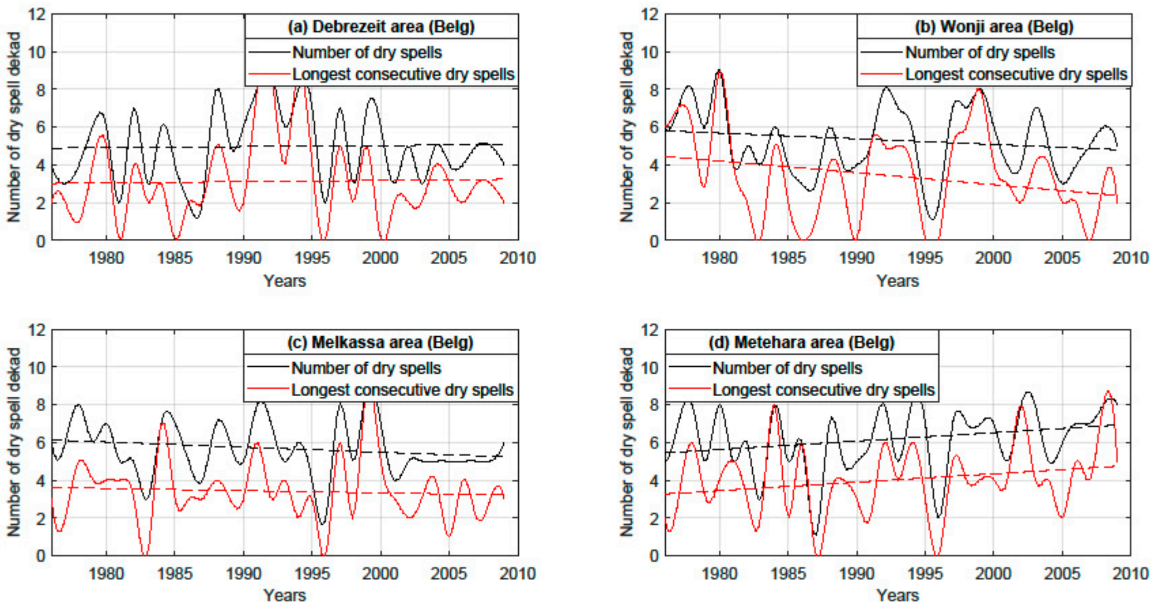

Figure 2. Temporal trends of dry spell patterns in the *Belg* season.

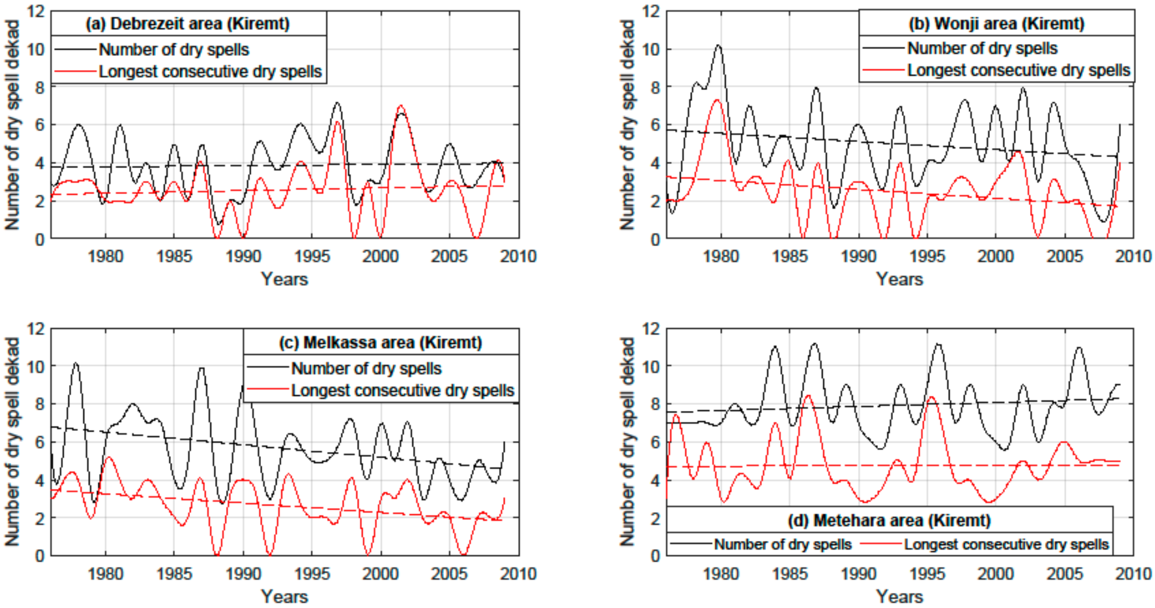

Figure 3. Temporal trends of dry spell patterns in the *Kiremt* season.

The results of Mann–Kendall's trend analysis and Sen's slope for the number of dry dekads and the longest consecutive dry dekads are presented in Table 2. At a 5% significance level, results show that an insignificant increase in the number of dry dekads and the longest consecutive dry dekads in the Debrezeit and Metehara areas in both rainy seasons, and a decreasing trend in Wonji and Melkassa were recorded. However, the decrease in the Melkassa area is statistically significant ($P = 0.04$) for the number of dry dekads with a Sen's slope of 0.08 dekad/year in the *Kiremt* season. Likewise, it is observed that only the Melkassa station had experienced a significant decreasing trend in the longest consecutive dry dekads ($P = 0.01$) with a Sen's slope of 0.05 dekad/year.

Table 2. Mann–Kendall test and Sen's slope (Q_2) results of the two rainy seasons.

Stations	Number of Dry Dekads							
	Belg Season				*Kiremt* Season			
	$S_{statistics}$	Z_{MK}	Pvalue	Q_2	$S_{statistics}$	Z_{MK}	Pvalue	Q_2
Debrezeit	16	0.25	0.81	0.00	26	0.41	0.68	0.00
Wonji	−46	−0.71	0.48	0.00	−80	−1.25	0.21	−0.04
Melkassa	−79	−1.32	0.19	0.00	−127	−2.08	0.04 *	−0.08
Metehara	107	1.62	0.11	0.00	57	0.86	0.39	0.00
	Longest Consecutive Dry Dekads							
	Belg Season				*Kiremt* Season			
Debrezeit	30	0.48	0.63	0.00	12	0.19	0.85	0.00
Wonji	−84	−1.30	0.19	0.00	−78	−1.23	0.22	0.00
Melkassa	−57	−0.94	0.35	0.00	−154	−2.59	0.01 *	−0.05
Metehara	103	1.55	0.12	0.04	59	0.90	0.37	0.00

* shows trend; Z_{MK}: standard normal test statistics; Q_2: Sen's slope test.

The linear regression results of the number of dry dekad trends showed nearly 1.2- and 5-day increments in the *Kiremt* season, and 1.3- and 2-day decrements in the *Belg* season over a 10-year period in Debrezeit and Metehara stations, respectively. In contrast, the trends in the *Kiremt* season decreased by 6 and 8 days in Wonji and Melkassa and by 3 days in the *Belg* season in the same stations. Thus, the dry spell analysis result showed no trends in the Upper Awash River Basin except in the main rainy season of the Melkassa area. However, frequent and long consecutive dry spell dekads are common phenomena in the basin, particularly in the rainy season, which affects the socioeconomic values of the farmers in the region.

3.3. Initial and Conditional Probabilities of Wet/Dry Spells

3.3.1. *Belg* Season

The initial and conditional probabilities of dry dekads (P_D and P_{DD}, respectively) are far greater than the corresponding initial and conditional probabilities of wet dekads at all stations in the *Belg* season. The maximum P_D (0.83) was recorded in dekad 14 (April 21–30) at Metehara, followed by a P_D of 0.79 in dekad 12 (May 11–20) in the same area. Overall, the probability of dry spell occurrence (P_D) in the *Belg* season was more than 50% at all the stations, and short dry spells during the critical growth stage appeared in the analysis period (Table A2).

Examining the spatial variation of dry dekads reveals that the maximum P_D was recorded in dekad 14 at Metehara (0.83), in dekad 12 at Wonji (0.70), and in dekad 7 at Melkassa (0.75) and Debrezeit (0.69). Similarly, the maxima P_{DD} in dekad 7 of 1.00, 0.96, 0.94, and 0.86 were recorded at Debrezeit, Melkassa, Metehara, and Wonji, respectively (Table A2).

These results generally show that the frequency of a dekad being dry (P_{DD} greater than 0.50) far exceeds the frequency of it being wet across the stations. The *Belg* season is depicted as less reliable for agricultural production in terms of the adequacy of available rainfall/wet spells. This finding is also consistent with Yemenu and Chemeda [62] who performed climate resource analysis in the central highlands of Ethiopia—part of the Upper Awash River Basin. In this season, consecutive dry spells persisting for more than a month might result in a mild to severe drought. Therefore, the *Belg* season requires supplemental irrigation to support plant growth and the construction of hydraulic structures to reserve water flows from the catchments.

3.3.2. *Kiremt* Season

The wet spells in the *Kirmet* season begin in dekads 17 (in Debrezeit, Wonji, and Melkassa) and 19 (in Metehara) and end in dekads 27 (in Debrezeit, Wonji, and Melkassa) and 24 (in Metehara), respectively (Table A3).

The initial and conditional probabilities of wet/dry spells in the *Kiremt* season are presented in the Table A3. Probabilistic distribution of dry and wet spells *in* the *Kiremt* season as per the threshold value indicated in Table 1.

These results generally suggest that the probabilities of wet dekads (P_W, P_{WW}) exceed the corresponding probabilities of dry dekads (P_D, P_{DD}) at all stations, except Metehara, where the probabilities of dry dekads greatly exceed the probabilities of wet dekads. The maximum initial probabilities of wet dekads (P_W) were recorded in dekads 18–20 at Debrezeit (0.94), dekads 20–21 at Wonji (0.82), dekad 20 at Melkassa (0.78), and dekad 21 at Metehara (0.75) (Figure 4). The maximum initial probabilities of wet dekads dominated in the middle of the *Kiremt* season in the basin, possibly coinciding with the peak water requirement (mid-season) of the crop during the entire growing period if the planting date is properly planned. Additionally, water storage/reservoirs may fill up if a proper water management strategy is designed. The analysis also indicated a larger number of wet dekads in Debrezeit than at any other station. Approximately 42% and 75% of the total dekads in the *Kiremt* season have initial (P_W) and conditional (P_{WW}) probabilities, respectively, equal to or greater than the upper quartile value (75%). However, the fewest number of wet dekads (in terms of both P_W and P_{WW}) were observed in Metehara (Table A3).

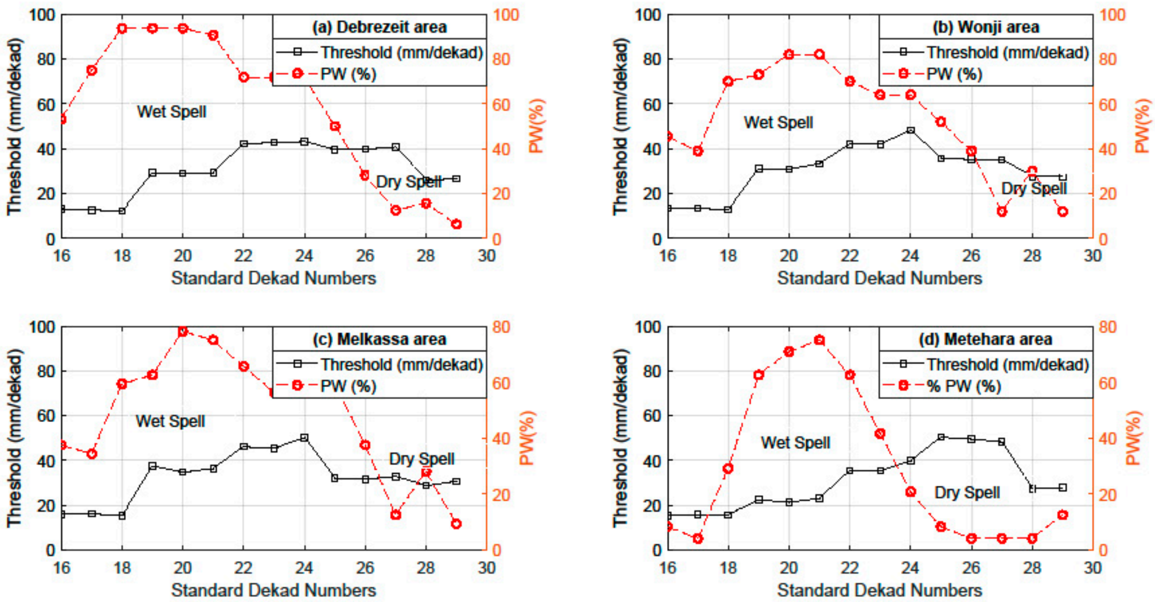

Figure 4. Initial probability of a dekad being wet (P_W) (%) value exceeding the threshold value (mm/dekad) in the *Kiremt* seasons.

The results of this analysis generally reveal that dekadal *ETc* most often exceed the dekadal rainfall only in Metehara, indicating water shortages in the *Kiremt* season without the implementation of appropriate water management options.

3.4. Probabilities of Consecutive Wet or Dry Dekads

Figure 5 showed the variations in the probabilities of two and three consecutive dry and wet dekads (2*D*, 2*W*, 3*D*, and 3*W*) starting with any dekad, in the *Belg* season. The probabilities of two consecutive dry dekads (2*D*) ranged from 0.23 to 0.79. The maximum value of 2*D* (0.79) was recorded in Metehara (in dekad 14). The minimum value of 2*D* (0.23) was recorded in the Debrezeit area in dekad 9. Similarly, the maximum (0.54) and minimum (0.14) probabilities of three consecutive dry dekads (3*D*) were recorded in Metehara (in dekad 14) and Wonji (in dekad 13), respectively.

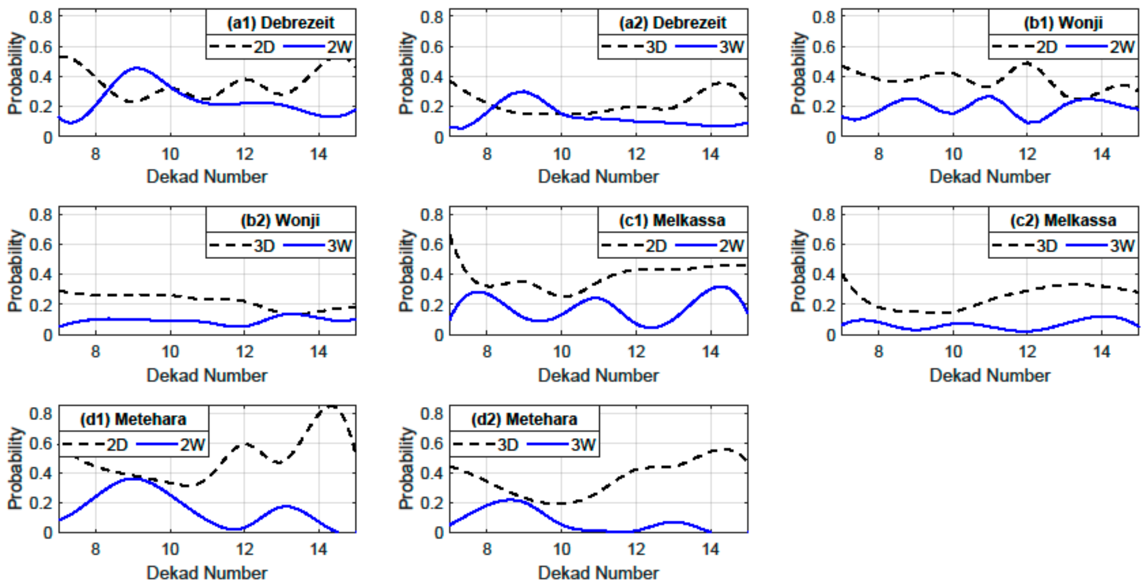

Figure 5. Probability of consecutive dry and wet dekads (2*D*, 2*W*, 3*D* and 3*W*) in the *Belg* seasons.

Overall, the probabilities of observing 2*D* and 3*D* in the *Belg* season far exceed the corresponding probabilities of 2*W* and 3*W* at all stations, except Debrezeit, where the probability of the 2*W* and 3*W* values exceeded/equaled the corresponding 2*D* and 3*D* values in dekads 9 and 10.

A continuous dry spell of three dekads (3*D*) was common between the wet dekads of the *Belg* season at all stations. Persistent dry spells might result in meteorological, hydrological, and socio-economic drought (in that order) particularly if it merges with the *Kiremt* season. Available rainfall in the *Belg* season at all stations cannot meet the water requirements of the corresponding crops unless supplemented by irrigation.

Figure 6 shows the variations of the probabilities of two and three consecutive dry and wet dekads (2*D*, 2*W*, 3*D*, and 3*W*) starting with any dekad during the *Kiremt* season. In this season, the probabilities of consecutive wet dekads (2*W* and 3*W*) far exceed the probabilities of corresponding consecutive dry dekads (2*D* and 3*D*) in Debrezeit, Wonji, and Melkassa. In Metehara, 33% of dekads had more consecutive wet spell (2*W* and 3*W*) periods than consecutive dry spells (2*D* and 3*D*). Nevertheless, a greater number of dekads (2*W* and 3*W*) exceeding the corresponding number of consecutive dry dekads were detected only at Debrezeit. The successive dry dekads (2*D* and 3*D*) indicate the need for supplemental irrigation and moisture conservation practices [6,31]. Successive wet weeks (2*W* and 3*W*) depicted the presence of excessive runoff water availability. The runoff should be conserved for recharging groundwater in the basin, and soil erosion control measures should be introduced in the area. Consequently, the *Kiremt* season showed that available rainfall amounts reliably meet the water requirements of the selected crops in all dekads, except Metehara. Thus, more surplus rainwater was recorded at Debrezeit and Wonji and must be harvested and used to supplement rainfed crops during the dry spell period. In contrast, excess rainwater might cause flooding without the use of appropriate hydraulic structures.

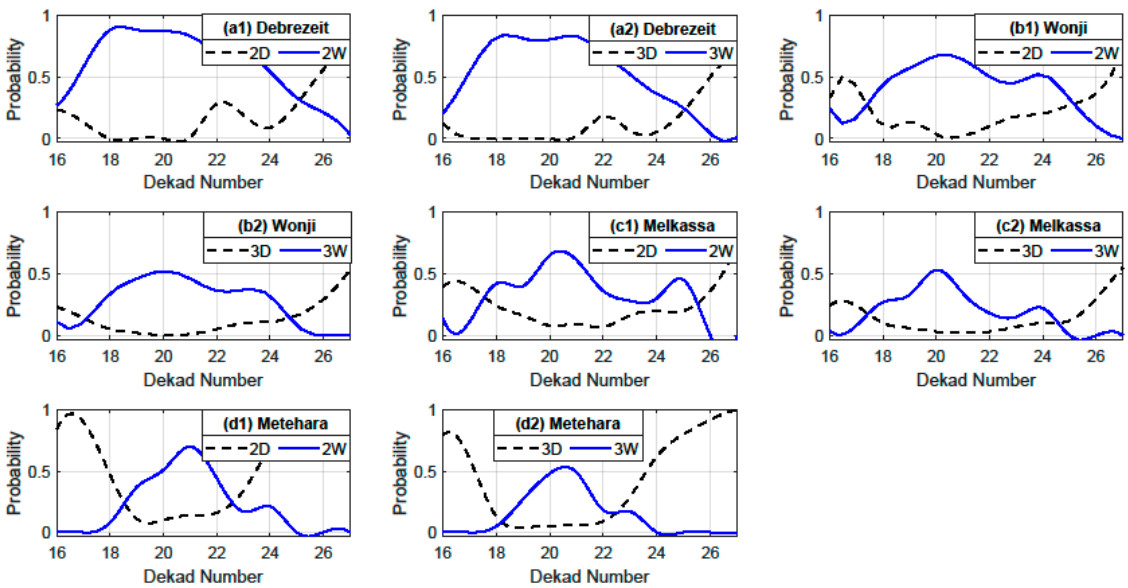

Figure 6. Probability of consecutive dry and wet dekads (2*D*, 2*W*, 3*D*, and 3*W*) in the *Kiremt* season.

Edossa et al. [39] analyzed the drought conditions in Awash River Basin using a standardized precipitation index (SPI) and also identified that the occurrence of drought ranging from mild dry to extremely dry conditions in the Awash River Basin is once in every three years. However, a short and intermittent dry spell is common on yearly basis in the rainy seasons. Similar results were reported by [63] in understanding the spatio–temporal patterns of drought affecting agriculture in Africa. This macro-level study revealed that a mixed drought pattern in eastern Africa—where the Upper Awash River Basin is located. In this region, areas with two growing seasons were affected by droughts during La Niña and zones of unimodal rainfall regimes showed droughts during the onset of

El Niño [64]. This frequent dry spell in the *Belg* season which causes the risk of drought in the Upper Awash River Basin particularly may be due to changes in the effect of La Niña and other climatological factors [64,65]. However, part of the central highland region (Debrezeit station) of Ethiopia sometimes receives above-average rainfall in the *Belg* season which resulted in high probabilities of wet dekads. In contrast, below average-rainfall during the *Kiremt* season in a basin explained by changes in the effect of El Niño [64]. Therefore, detailed understanding of probabilities of dry and wet spell occurrences of rainfall in different seasons can contribute toward efficient water management practices and early mitigating drought impacts in a basin before they create havoc.

4. Conclusions

In this study, the Markov chain model was used to evaluate the probabilities of the occurrence of dry and wet spells in the Upper Awash River Basin, Ethiopia. The key findings, conclusions, and recommendations of this study are the following:

- A high prevalence of persistent dry spells in the *Belg* season might cause meteorological, hydrological, and socio-economic drought (in that order) if it merges with the *Kiremt* seasons. Therefore, an appropriate coping mechanism must be planned to avoid weather and climate damage.
- The seasonal Mann–Kendall's trend test and Sen's slope result showed that the number of dry spell dekads and the maximum consecutive dry spell lengths are not statistically significant in the mountainous (Upland sub-basin) and valley part (Upper Valley sub-basin) of the Upper Awash River Basin, except in Melkassa station which experienced a significant decreasing trend in the longest consecutive dry dekads with a magnitude of 1 day in every 2 years.
- In the *Kiremt* season, a high probability of wet dekads was observed at all stations, except in Metehara. Nevertheless, surplus rainwater was recorded in Debrezeit and Wonji during the *Kiremt* season. In these stations, rainfall can be harvested for better water management to provide irrigation during dry seasons. In a water-scarce area (Metehara), enhancing soil moisture retention techniques is advisable.
- We hope the key findings of this study will provide insight into the development of new water management strategies by indicating potentially water-scarce dekads and/or excessively wet dekads that might cause flash flooding from rains from the highlands of the Upper Awash River Basin.
- The findings of this research can assist water resource managers, agriculturalists, climatologists, eco-hydrologists, and policymakers in the proper planning of agricultural practices and water resources in the Awash River Basin, where climatic risk is very high.

Author Contributions: Conceptualization, G.B.A. and B.A.H.; methodology, G.B.A. and B.A.H.; software, G.B.A; validation, G.B.A. and B.A.H.; formal analysis, G.B.A. and B.A.H.; investigation, G.B.A. and B.A.H.; resources, G.B.A. and W.-K.L.; data curation, G.B.A. and B.A.H.; writing—original draft preparation, G.B.A. and B.A.H.; writing—review and editing, G.B.A.; C.-H.L. and W.-K.L.; visualization, G.B.A.; B.A.H.; C.-H.L.; and W.-K.L.; supervision, G.B.A. and W.-K.L.; project administration, G.B.A.; funding acquisition, G.B.A. and W.-K.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thankfully acknowledge the support by the OJEong Resilience Institute (OJERI) at Korea University, the National Meteorological Agency (NMA) of Ethiopia, Debrezeit Agricultural Research Center, Wonji Sugar Factory, Metehara Sugar Factory, and Melkassa Agricultural Research Center for providing data for this research. In addition, we thank Fistume Yemenu and Ayalew Mamo for their constructive discussions.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Standard dekad numbers ([49] as cited in [50]).

Month	Dekad No	Date	Month	Dekad No	Date
January	1	1–10	July	19	1–10
	2	11–20		20	11–20
	3	21–31		21	21–31
February	4	1–10	August	22	1–10
	5	11–20		23	11–20
	6	21–28		24	21–31
March	7	1–10	September	25	1–10
	8	11–20		26	11–20
	9	21–31		27	21–30
April	10	1–10	October	28	1–10
	11	11–20		29	11–20
	12	21–30		30	21–31
May	13	1–10	November	31	1–10
	14	11–20		32	11–20
	15	21–31		33	21–30
June	16	1–10	December	34	1–10
	17	11–20		35	11–20
	18	21–30		36	21–31

Table A2. Probabilistic distribution of dry and wet spells in the *Belg* season.

Dekad No	P_D	P_{DD}	P_{WD}	2D	3D	P_W	P_{WW}	P_{DW}	2W	3W
Debrezeit										
7	0.69	1.00	0.00	0.53	0.37	0.31	0.00	1.00	0.13	0.06
8	0.56	0.78	0.22	0.39	0.22	0.44	0.43	0.57	0.21	0.16
9	0.41	0.69	0.31	0.23	0.15	0.59	0.47	0.53	0.45	0.30
10	0.50	0.56	0.44	0.32	0.15	0.50	0.75	0.25	0.33	0.15
11	0.53	0.65	0.35	0.25	0.16	0.47	0.67	0.33	0.22	0.12
12	0.59	0.47	0.53	0.38	0.20	0.41	0.46	0.54	0.22	0.10
13	0.53	0.65	0.35	0.28	0.19	0.47	0.53	0.47	0.21	0.09
14	0.66	0.52	0.48	0.46	0.34	0.34	0.45	0.55	0.14	0.07
15	0.63	0.70	0.30	0.46	0.23	0.38	0.42	0.58	0.18	0.09
Wonji										
7	0.67	0.86	0.14	0.47	0.29	0.33	0.36	0.64	0.13	0.05
8	0.61	0.70	0.30	0.38	0.26	0.39	0.38	0.62	0.17	0.10
9	0.58	0.63	0.37	0.38	0.26	0.42	0.43	0.57	0.25	0.10
10	0.64	0.67	0.33	0.42	0.26	0.36	0.58	0.42	0.15	0.09
11	0.55	0.67	0.33	0.33	0.23	0.45	0.40	0.60	0.27	0.08
12	0.70	0.61	0.39	0.49	0.22	0.30	0.60	0.40	0.09	0.05
13	0.61	0.70	0.30	0.27	0.14	0.39	0.31	0.69	0.21	0.13
14	0.61	0.45	0.55	0.30	0.15	0.39	0.54	0.46	0.24	0.11
15	0.61	0.50	0.50	0.30	0.18	0.39	0.62	0.38	0.18	0.10
Melkassa										
7	0.75	0.96	0.04	0.66	0.40	0.25	0.13	0.88	0.10	0.06
8	0.53	0.88	0.12	0.32	0.18	0.47	0.40	0.60	0.27	0.08
9	0.63	0.60	0.40	0.35	0.15	0.38	0.58	0.42	0.11	0.03
10	0.56	0.56	0.44	0.25	0.15	0.44	0.29	0.71	0.13	0.07
11	0.56	0.44	0.56	0.35	0.23	0.44	0.29	0.71	0.24	0.05
12	0.66	0.62	0.38	0.43	0.29	0.34	0.55	0.45	0.07	0.02
13	0.63	0.65	0.35	0.43	0.33	0.31	0.20	0.80	0.10	0.07

Table A2. *Cont.*

Dekad No	P_D	P_{DD}	P_{WD}	2D	3D	P_W	P_{WW}	P_{DW}	2W	3W
14	0.59	0.68	0.32	0.45	0.32	0.41	0.31	0.69	0.30	0.12
15	0.66	0.76	0.24	0.46	0.28	0.34	0.73	0.27	0.14	0.05
Metehara										
7	0.75	0.94	0.06	0.59	0.44	0.25	0.33	0.67	0.08	0.05
8	0.58	0.79	0.21	0.44	0.34	0.42	0.31	0.69	0.24	0.18
9	0.50	0.75	0.25	0.38	0.23	0.50	0.58	0.42	0.36	0.20
10	0.54	0.77	0.23	0.33	0.19	0.46	0.73	0.27	0.25	0.05
11	0.63	0.60	0.40	0.36	0.27	0.38	0.56	0.44	0.08	0.01
12	0.79	0.58	0.42	0.59	0.42	0.21	0.20	0.80	0.03	0.01
13	0.67	0.75	0.25	0.47	0.44	0.33	0.13	0.88	0.17	0.07
14	0.83	0.70	0.30	0.79	0.54	0.17	0.50	0.50	0.07	0.00
15	0.75	0.94	0.06	0.51	0.47	0.29	0.43	0.57	0.00	0.00

Multiply the probability (P) value by 100 to compute the percentage result (%).

Table A3. Probabilistic distribution of dry and wet spells in the *Kiremt* season.

Dekad No	P_D	P_{DD}	P_{WD}	2D	3D	P_W	P_{WW}	P_{DW}	2W	3W
Debrezeit										
16	0.47	0.73	0.27	0.23	0.12	0.53	0.47	0.53	0.27	0.20
17	0.25	0.50	0.50	0.13	0.00	0.75	0.50	0.50	0.58	0.54
18	0.06	0.50	0.50	0.00	0.00	0.94	0.77	0.23	0.88	0.82
19	0.06	0.00	1.00	0.00	0.00	0.94	0.93	0.07	0.88	0.81
20	0.06	0.00	1.00	0.00	0.00	0.94	0.93	0.07	0.87	0.80
21	0.09	0.00	1.00	0.01	0.01	0.91	0.93	0.07	0.83	0.83
22	0.28	0.11	0.89	0.28	0.19	0.72	0.91	0.09	0.72	0.69
23	0.28	1.00	0.00	0.19	0.06	0.72	1.00	0.00	0.69	0.52
24	0.28	0.67	0.33	0.09	0.05	0.72	0.96	0.04	0.54	0.36
25	0.50	0.31	0.69	0.28	0.22	0.50	0.75	0.25	0.33	0.25
26	0.72	0.57	0.43	0.56	0.50	0.28	0.67	0.33	0.21	0.04
27	0.88	0.79	0.21	0.78	0.70	0.13	0.75	0.25	0.03	0.01
Wonji										
16	0.55	0.50	0.50	0.33	0.23	0.45	0.47	0.53	0.24	0.11
17	0.61	0.60	0.40	0.42	0.14	0.39	0.54	0.46	0.17	0.11
18	0.30	0.70	0.30	0.10	0.05	0.70	0.43	0.57	0.44	0.34
19	0.27	0.33	0.67	0.14	0.02	0.73	0.63	0.38	0.57	0.46
20	0.18	0.50	0.50	0.03	0.00	0.82	0.78	0.22	0.67	0.52
21	0.18	0.17	0.83	0.02	0.01	0.82	0.81	0.19	0.64	0.46
22	0.30	0.10	0.90	0.10	0.05	0.70	0.78	0.22	0.50	0.36
23	0.36	0.33	0.67	0.18	0.10	0.64	0.71	0.29	0.45	0.37
24	0.36	0.50	0.50	0.20	0.11	0.64	0.71	0.29	0.52	0.32
25	0.48	0.56	0.44	0.27	0.16	0.52	0.82	0.18	0.32	0.08
26	0.61	0.55	0.45	0.36	0.29	0.39	0.62	0.38	0.10	0.00
27	0.88	0.59	0.41	0.73	0.53	0.12	0.25	0.75	0.00	0.00
Melkassa										
16	0.63	0.70	0.30	0.39	0.24	0.38	0.42	0.58	0.14	0.04
17	0.66	0.62	0.38	0.40	0.24	0.34	0.36	0.64	0.11	0.08
18	0.41	0.62	0.38	0.24	0.10	0.59	0.32	0.68	0.42	0.27
19	0.38	0.58	0.42	0.16	0.06	0.63	0.70	0.30	0.40	0.33
20	0.22	0.43	0.57	0.08	0.03	0.78	0.64	0.36	0.65	0.53
21	0.25	0.38	0.63	0.09	0.02	0.75	0.83	0.17	0.61	0.34
22	0.34	0.36	0.64	0.07	0.03	0.66	0.81	0.19	0.36	0.18

Table A3. *Cont.*

Dekad No	P_D	P_{DD}	P_{WD}	2D	3D	P_W	P_{WW}	P_{DW}	2W	3W
23	0.44	0.21	0.79	0.16	0.07	0.56	0.56	0.44	0.28	0.15
24	0.44	0.36	0.64	0.20	0.10	0.56	0.50	0.50	0.30	0.22
25	0.41	0.46	0.54	0.20	0.12	0.59	0.53	0.47	0.45	0.00
26	0.63	0.50	0.50	0.36	0.30	0.38	0.75	0.25	0.00	0.00
27	0.88	0.57	0.43	0.72	0.55	0.13	0.00	1.00	0.00	0.00
Metehara										
16	0.92	0.68	0.32	0.84	0.79	0.08	0.00	1.00	0.00	0.00
17	0.96	0.91	0.09	0.90	0.60	0.04	0.00	1.00	0.00	0.00
18	0.71	0.94	0.06	0.47	0.13	0.29	0.00	1.00	0.08	0.05
19	0.38	0.67	0.33	0.11	0.04	0.63	0.27	0.73	0.37	0.27
20	0.29	0.29	0.71	0.10	0.05	0.71	0.59	0.41	0.51	0.48
21	0.25	0.33	0.67	0.14	0.06	0.75	0.72	0.28	0.70	0.49
22	0.38	0.56	0.44	0.16	0.09	0.63	0.93	0.07	0.44	0.18
23	0.58	0.43	0.57	0.34	0.29	0.42	0.70	0.30	0.17	0.17
24	0.79	0.58	0.42	0.68	0.62	0.21	0.40	0.60	0.21	0.00
25	0.92	0.86	0.14	0.84	0.80	0.08	1.00	0.00	0.00	0.00
26	0.96	0.91	0.09	0.92	0.92	0.04	0.00	1.00	0.00	0.00
27	1.00	0.96	0.04	1.00	1.00	0.04	0.00	1.00	0.00	0.00

Multiply the probability (P) value by 100 to compute the percent result (%).

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