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Characteristics of Hydrological and Meteorological Drought Based on Intensity-Duration-Frequency (IDF) Curves

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Abstract: As a catastrophic phenomenon, drought has destructive impacts on water resources, the environment, and the ecosystem. Consequently, drought plays a vital role in risk assessment, water resources management, and drought mitigation plans. The main aim of this research is to obtain critical intensity-duration-frequency (IDF) drought curves and to provide a comprehensive understanding of the drought characteristics by considering the meteorological Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), and hydrological Standardized Streamflow Index (SSI). Critical IDF curves for the drought index and return period selection are identified. Also, new terms are defined as the specific drought duration, the maximum drought duration, and the critical intensity based on drought IDF curves. The results show that the SPI3 based on run theory for 500 years return period has higher drought intensity compared with other drought indices. In some IDF curves, the 2-year return period of a 12-month duration timescale is not provided. Regarding the maximum drought duration, the SPEI12 gave a longer duration. With the new concepts in this research, the presented IDF drought methodology has a novel additional practice to identify the critical intensity and maximum drought duration. Using this methodology for any drought index will contribute to converting data with mathematical calculations into IDF curves for design and risk assessment purposes.

Keywords: drought intensity; intensity-duration-frequency (IDF) curve; standardized precipitation index (SPI); standardized precipitation evapotranspiration index (SPEI); standardized streamflow index (SSI)

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1. Introduction

Drought is a creeping natural phenomenon related to a significant decrease in rainfall water balance and runoff lower than a standard value. Droughts affect water supply and demand as a result of precipitation lack and also affect the economy, industry, and agriculture [1–4]. According to a recent United Nations World Water Development Report [5], four billion people worldwide face water shortages at least one month a year. Global economic losses are more than six billion USD due to the negative impacts of drought [6]. Moreover, according to research on droughts by scientists, environmentalists, and hydrologists, the impact of droughts is increasing, coupled with climate change, rapid population growth, and water scarcity [7–10]. Precise and comprehensive drought risk assessment and monitoring are vital to protect ecosystems and mitigate drought disasters [7,11,12].

Wilhite [13] classified drought into four different types as meteorological drought, which relates to decreasing rainfall compared with standard rainfall, temperature, and evapotranspiration; agricultural drought, which occurs when there is a decrease in precipitation, driving soil moisture reduction and especially affecting plants and trees with relation to evapotranspiration, crop production and type, soil moisture storage, etc.; hydrological drought which is related to shortages in water storage causing problems in water supply with low levels of water resources and demand [14]; and finally, socioeconomic drought as the combined effects of the three abovementioned drought types on the economic and social parts [15].

Several standardized drought indices have been used to assess and monitor droughts. Each type depends on single or multiple hydro-meteorological variables representing a specific type of drought. For example, the Standardized Precipitation Index (SPI) [16] depends on precipitation and is used for meteorological drought. On the other hand, the Standardized Streamflow Index (SSI) [17] depends on streamflow and is applied to hydrological drought. Additionally, the standardization concept has the advantage of converting the drought index into a non-dimensional index for comparison objectives among different precipitation time series records. The standardization concept is also utilized here for the same purpose.

Common drought indices are based on statistical and probability theories. The differences between the indices and the definitions of drought can significantly change the conception and the drought characteristics. For example, Mckee et al. [16] developed the SPI, and they proposed that the drought event starts when the drought index (DI) is under a negative threshold value (-1, according to Mckee et al. [16] and ends when the DI returns to a positive value. On the other hand, Yevjevich [18] suggested a different method for drought analysis and its characteristics by applying the statistical run theory. Regarding this theory, a certain threshold (zero) is accepted for identifying drought events and characteristics. Both SPI and run theories have been frequently used worldwide [19,20]. The selected threshold has a vital role regarding drought characteristics; therefore, changing the threshold will seriously affect the drought events and characteristics. The drought frequency analysis was explained under one parameter framework in the literature by individually calculating the probability distribution function (PDF) of drought severity and duration [21,22]. In this research, (SPI), Standardized Precipitation Evapotranspiration Index (SPEI) [23], and Standardized Streamflow Index (SSI) are used to describe the drought events and the drought characteristics based on SPI and run theories.

Traditional approaches and definitions [24] describe the hydrological drought based only on the water deficit, without a comprehensive understanding of drought characteristics and the water deficit within a specific period and the relation between these characteristics, which may not be the actual reflection of the drought characteristics complexity [21]. A single or even a few indices cannot describe the complexity of the drought phenomenon. In conventional methods and existing drought assessments, drought events are treated as a package without understanding the formulation of each drought event. Drought duration and intensity are the main variables in drought events [19,21]. Subsequently, more explanation and knowledge related to the maximum intensity within drought duration, the maximum severe months, and the relationship between duration and intensity for each event should be carried out. Intensity/severity-duration-frequency (IDF/SDF) curves are an established method in meteorological and hydrological research and have been applied to rainfall studies. Here, we propose to use this approach to analyze the drought characteristics comprehensively. These curves are helpful in evaluating the relation between intensity/severity and frequency at several drought durations, providing valuable and useful information and analysis about drought events using a single graph. Consequently, the IDF curves will be used to design the capacity of water supply systems such as dams and manage water resources. The concept of IDF/SDF in drought analysis is similar to rainfall IDF curve utilization in risk assessment and hydraulic structures such as culverts, dams, and stormwater drains, which presents the probability of a specific rainfall intensity and duration potential to happen at a specific location. We apply the same concept to calculate and quantify the occurrence of droughts based on intensity and duration.

IDF drought curves are rarely used in drought risk assessment. Also, studies related to the drought IDF/SDF curves are generally limited and insufficient in terms of drought characteristics. Drought SDF curves based on Palmer Drought Severity Index (PDSI) were calculated by the use of tables [25]. Shiau and Modarres [26] developed drought SDF by combining the drought severity and duration of the basis of probabilistic methods and copulas on SPI. In addition, Halwatura et al. [27] developed SDF curves at several timescales based on bivariate functions to calculate drought duration and severity. Heidari et al. [28] developed IDF curves for socioeconomic drought. Ma et al. [29] investigated the SDF curves for the streamflow drought analysis in the source area of the Yellow River. Regarding drought risk assessment, Jafari et al. [30] determined the spatiotemporal characteristics of droughts using SDF contour maps. Also, detailed procedures and approaches are suggested to identify the relation between Severity/Intensity-Duration-Frequency curves and drought analysis and risk assessment [25,31–33].

In order to comprehensively analyze and understand a drought, its events, and its characteristics, multiple hydrological SSI and meteorological SPI and SPEI indices according to basic definitions of SPI and run theories are analyzed and evaluated. This research presents the methodology using a new framework and concepts, which includes specific drought duration (SD), maximum consecutive severity (MCS), and critical intensity (CI). The new framework divides the drought event into smaller pre-defined durations based on SD, which improves our understanding of drought characteristics and fills the gaps in the conventional method which treats the drought event as one package. The main aim is to obtain the drought IDF curves of the drought indices based on SPI and run theories. These will be helpful tools in water management, risk assessment, design purposes, and drought mitigation plans.

2. Materials and Methods

2.1. Study Area and Data Collection

The application of the determined drought methodologies is presented for two areas. The first one is Durham City, located in the northeast of the UK. Durham City has a hybrid temperate maritime climate with normal summers and cool winters from a global perspective. On average, July is the hottest month in summer, and January is the coldest month in winter. The average temperature ranges between 5.2 °C (in winter) and 12.5 °C (in summer), and the average annual precipitation is 643 mm. The monthly precipitation (P) and monthly average temperature (T) records are between 1868 and 2021 (154 years) as provided from the Durham University meteorological station. The Durham Observatory weather record is the third-longest continuous climate series in the United Kingdom. Records from sites such as Durham Observatory provide us with a long period of data (about 150 years), which is better for SPI and SPEI calculation because of using fitted probability distribution functions. The SPI and SPEI meteorological drought indices are carried out for Durham City. Both precipitation and temperature are employed to calculate the SPI and SPEI, respectively.

Second, monthly streamflow records are considered from Lüleburgaz, Turkey, covering about 59 years from 1957 to 2015. The hydrological drought index is carried out for Lüleburgaz, which is the largest city of Kırklareli Province in the Marmara region of Turkey. The average temperature ranges between 12.2 °C and 26.7 °C, with average annual precipitation of 430 mm. Table 1 summarizes the longitude, latitude, monthly average precipitation and temperature, and monthly average streamflow from the Ergene River, with standard deviation for all obtained data. All obtained data (precipitation, temperature, and stream flow) are prepared and checked for consistency and continuity. The preferred areas are examples of applying the new concepts and framework proposed in this research.

Table 1. Climatic information of the observed data.

Station's Name	Lat (N)	Long (W)	Monthly Precipitation (P)—mm	Standard Deviation (mm)	Monthly Temperature (T)—°C	Standard Deviation °C
Durham University Station	54.77	1.59	54.37	31.74	8.6	4.46
Station's Name	Lat (N)	Long (E)	Monthly Stream flow (Q)—m^3/s	Standard Deviation (m^3/s)	-	-
Lüleburgaz station	41.35	27.35	9.57	13.2	-	-

2.2. Standardized Drought Indices

In general, the drought indices are the major variables for monitoring, assessing, and evaluating the effect of drought with its characteristics such as duration, severity, and intensity. A standardized concept is used to convert the meteorological or hydrological record time series into an internationally recognized drought index for comparison. In this paper, three standardized drought indices are considered, namely, SPI, SPEI, and SSI.

2.2.1. Standard Precipitation Index (SPI)

The SPI evaluates the meteorological drought at different timescales, such as 3-month, 6-month, and 12-month durations, based only on the monthly precipitation records. The original monthly precipitation records are first fitted to a proper probability density function (PDF). Wang et al. [34] stated that the Gamma PDF is the best PDF for SPI evaluation in most studies. Selecting a proper PDF is performed by checking the goodness-of-fit tests for the original records (precipitation for SPI) by Chi-Square and Kolmogorov-Simirnov [35]. The probabilities are calculated based on monthly precipitation records, and the resulting probabilities are probabilistically standardized into standard normal PDF with zero mean and unit standard deviation. An important issue that needs more attention is that there is a difference between statistical standardization and probabilistic standardization procedure, which converts any PDF into a normal PDF using cumulative probabilities instead of subtracting the mean from the original data set [36].

2.2.2. Standard Precipitation Evapotranspiration Index (SPEI)

Vicente-Serrano et al. [23] developed the SPEI, which is similar to the SPI method. The main difference between them is in the use of precipitation and potential evapotranspiration. Potential evapotranspiration can be calculated using many methods like the Thornthwaite method [37] and the Penman-Monteith method [38]. The Thornthwaite method calculates the potential evapotranspiration through the average monthly temperature records. The prime variable in the SPEI method is the difference between precipitation and potential evapotranspiration records, which are fitted to suitable PDFs. In most research, the Logarithmetic-Logistic was the best PDF for calculating SPEI [34]. By considering the Chi-Square and Kolmogorov-Simirnov tests [35], the probabilities resulting from a proper PDF are calculated for water balance records. Finally, the probabilities are transformed into standard normal PDF utilizing a classical approximation method [39]. More details and information about the SPEI method can be found in [23].

2.2.3. Standardized Streamflow Index (SSI)

This drought index developed by Shukla and Wood [17] is like the SPI and SPEI indices. One main difference is that the monthly streamflow data is considered in calculating the drought index and characteristics.

3. Methodology and Basic Concepts

3.1. Basic Concepts

The first step in drought analysis and assessment is the calculation of the drought index, and based on this index, four characteristics are calculated, including duration (D), severity (S), intensity (I), and frequency (T). Two of the most common definitions of drought characteristics are based on the run theory developed by Yavjevich [17] and the SPI theory developed by Mckee et al. [16]. According to Yavjevich [17], a drought event starts when the drought index (any drought index) is under zero and ends when it returns to above zero. In contrast, Mckee et al. [16] identified drought events based on -1 thresholds. There is a significant difference between the run approach and SPI theory in calculating drought characteristics. Run theory gave more extreme duration values, and SPI theory gave more extreme intensity values [40]. In this research, both run and SPI theories are used to calculate drought characteristics. The main concepts used in this research have been defined below:

Drought Duration (D): Based on run theory, drought duration (D) is defined as the length of time of the consecutive negative values based on the drought index (DI). Figure 1 shows the drought duration based on the run and SPI theories.

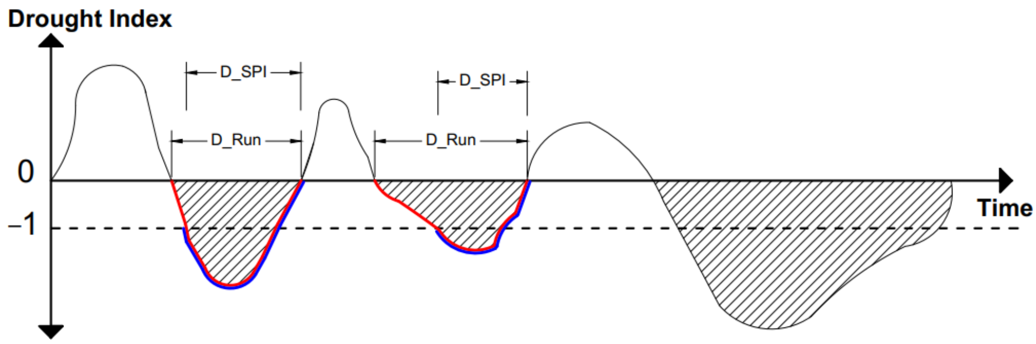

Figure 1. Drought duration based on run theory (red line) and SPI theory (blue line). D is the drought duration [40].

On the other hand, according to Abu Arra and Şişman [40], drought duration (D) based on SPI theory is less than the run theory. Based on SPI theory, drought duration is defined as the number of months when the DI at the first month is less than −1 and continues until the DI returns to a positive value. Drought duration (D) based on the SPI theory is shown by Mckee et al. [16]:

$$D_{\text{SPI theory}} = \left\{ \text{Number of months} \middle| DI_{\text{1st month}} < -1 \text{ and } DI_{\text{until any month return to a positive}} \right\} \quad (1)$$

Specific duration (SD): Any drought duration shorter or equal to the drought duration (D). For example, in 4 months drought duration, the SD can be 1, 2, 3, or 4 months.

Maximum Consecutive Severity (MCS): Maximum consecutive summation of the DI with a specific drought duration called maximum consecutive severity (MCS). For example, for 3 months of specific drought duration, the first step is a calculation of the summation of each of three consecutive DI. The summation is attributed to the last month of the specific drought duration. The maximum absolute summation is considered as the MCS value. In other words, the MCS is the maximum cumulative and consecutive DI value for each specific drought duration.

$$\text{MCS} = \text{Max.} \sum_{i=n}^{SD} |DI| \quad (2)$$

where n is any month, and D is the drought duration. For example, when SD is 3, and n is May, the three consecutive months are May, June, and July; for drought analysis, all of them can be dry, and according to the run and SPI theories, the threshold of 0 or −1 is considered, respectively. If none is dry, another three consecutive months should be selected.

Critical Intensity (CI): It is calculated by dividing MCS by the specific drought duration as in Equation (3).

$$CI_D = \frac{\text{MCS}}{\text{SD}} \quad (3)$$

Year without any drought: It is calculated for each drought duration. It is any year without any critical intensity (CI). A zero value is assigned for the year without any drought.

Each year, a drought value should be defined to find and calculate IDFcritical, which is assumed as critical intensity for each specific drought duration as CI_{SD}, where SD is the specific drought duration. In a year without any CI, a zero value is assigned. The drought event for each duration is assigned to the month it ends with its year. This assumption applies regardless of the drought event's starting and ending months. For example, a drought event with 9 months specific drought duration can start in a year and ends in another year. CI_9 starts from June 2022 to February 2023. IDF calculations should assign the CI value to the second year (2023).

On the other hand, the maximum duration of a drought event contains many drought durations. For example, 12 months drought duration contains 1-2-3-....-11-12 months duration, etc. A year without any drought event can be noticed in some years based on DI. The CI value is also zero for these years. These years are considered in IDF calculations. They affect the probability of each drought event but do not involve the selection of an appropriate PDF.

3.2. Methodology

After DI calculation, IDF resulting from the proposed methodology is calculated for each meteorological station. The following points explain the main steps for IDF drought curve calculations.

* The proposed methodology calculates the DI with any drought index. In this research, there are three ways, two of which are meteorological drought indices SPI and SPEI, and the other is the hydrological drought index SSI.
* Determination of whether the month is dry or wet based on the drought definition using DI according to run and SPI theories. This point provides added value to this research because it is based on a comprehensive definition of drought characteristics.
* Determination of the specific drought duration (SD).
* Calculation of the maximum consecutive severity (MCS) and critical intensity (CI) for each specific duration (SD). CI_{SD} is assigned to the last month and year of the drought duration. (See Figure 2).

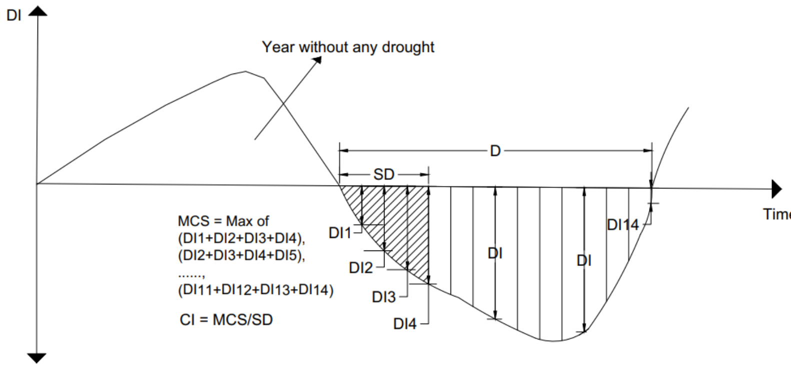

Figure 2. The main concepts used in this research (DI: drought index, D: drought duration, SD: specific drought duration, MCS: maximum consecutive severity, CI: critical intensity).

* Finding the years with CI value and those without drought events.
* Frequency analysis includes the return period (T) determination, which can be 2-year, 10-year, or 500-year. The probability for each return period P(T) is calculated using Equation (4); the probability of years without any critical intensity P(0) by Equation (5); the probability of drought years P(d) or non-zero years by Equation (6).

$$P(\mathrm{T}) = \frac{1}{\mathrm{T}} \tag{4}$$

where P(T) is the probability of the return period, and T is the return period.

$$\mathrm{P}(0) = \frac{\text{Number of years without any drought } (\mathrm{N_0})}{\text{Total number of years } (\mathrm{N})} \tag{5}$$

$$\mathrm{P}(\mathrm{d}) = \frac{\text{Number of years with drought events } (\mathrm{N_D})}{\text{Total number of years } (\mathrm{N})} = 1 - \mathrm{P}(0) \tag{6}$$

The probability that CI_D will not be equaled or exceeded in any year of the return period:

$$P(I < CI_{SD}) = 1 - \frac{1}{T} \tag{7}$$

* The probability cumulative distribution function (CDF) of the drought years (non-zero values) at zero level is calculable in Equation (8). This probability will predict the critical intensity (CI) for each drought duration and return period.

Table 2 summarizes the main concepts in frequency analysis (5th step).

$$P^*(d) = \frac{1 - \frac{1}{T} - P(0)}{1 - P(0)} \tag{8}$$

Table 2. Explanation of frequency analysis used in the calculation of IDF.

Specific drought duration	SD
Total number of years	N
Number of drought years	N_D
Number of years without any drought	$N_0 = N - N_D$
The probability of years without any drought event	$P(0) = \frac{N_0}{N}$
The probability of drought years	$P(d) = \frac{N_D}{N}$
Return period	T
The probability of each return period	$P(T) = \frac{1}{T}$
The cumulative probability distribution function of the drought years	$P^*(d) = \frac{1-\frac{1}{T}-P(0)}{1-P(0)}$

The selection of an appropriate PDF through the goodness-of-fit tests is checked by Chi-Square and Kolmogorov-Simirnov tests [35]. PDF can be any function, such as normal PDF, Log-normal PDF, Gamma PDF, etc. It depends on the data used.

Prediction of CI for each specific drought duration and return period using an appropriate PDF from step six according to PDF from step five. The resulting CI is CI_{SD_T}, where SD is the specific drought duration, and T is the return period. For each specific drought duration and return period, there is a critical intensity. Table 3 below summarizes how the CI values will be:

Table 3. Critical Intensity (CI) for any specific drought duration and each return period.

		SD (Month)			
T (Year)	$\frac{1}{T}$	**1**	**2**	**3**	**4**
2	0.5	CI_{1_2}	CI_{2_2}	CI_{3_2}	CI_{4_2}
5	0.2	CI_{1_5}	CI_{2_5}	CI_{3_5}	CI_{4_5}
10	0.1	CI_{1_10}	CI_{2_10}	CI_{3_10}	CI_{4_10}
25	0.04	CI_{1_25}	CI_{2_25}	CI_{3_25}	CI_{4_25}
50	0.02	CI_{1_50}	CI_{2_50}	CI_{3_50}	CI_{4_50}
100	0.01	CI_{1_100}	CI_{2_100}	CI_{3_100}	CI_{4_100}
200	0.005	CI_{1_200}	CI_{2_200}	CI_{3_200}	CI_{4_200}
500	0.002	CI_{1_500}	CI_{2_500}	CI_{3_500}	CI_{4_500}

Note: CI_{SD_T}: SD is the specific drought duration and T is the return period.

The last step is IDF identification, which is the main aim of this research. The IDF curves are calculated to fill the gap between the theoretical model and the actual condition. These curves can be used in the risk assessment and design of meteorological, hydrological, and agricultural drought applications. The IDF curves use standardized values. Figure 3 shows the methodological approach used in this research.

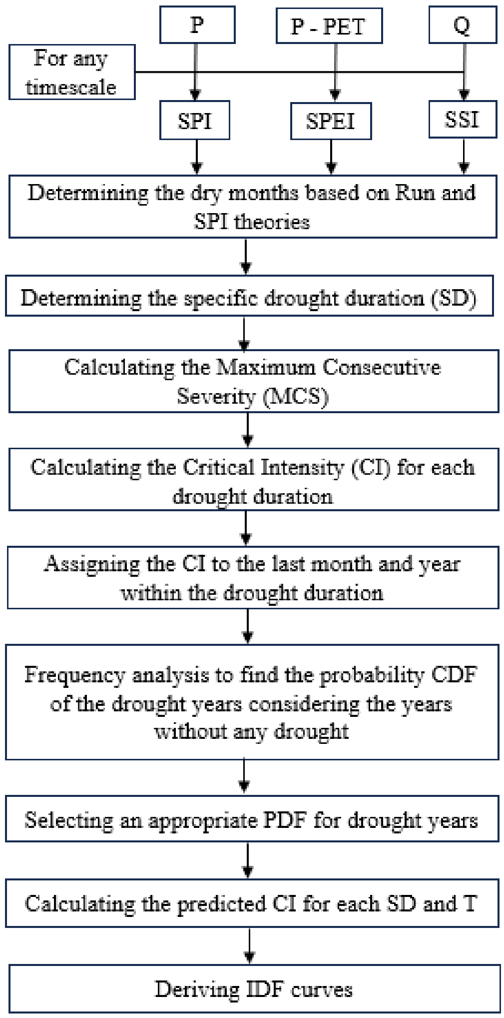

Figure 3. Methodological approach.

4. Results and Discussion

The selected timescales are 3 months and 12 months, corresponding to short-period and long-period timescales, respectively. Each DI is calculated based on run and SPI approaches. For example, SPEI3 is calculated based on the run and SPI methods. The period in the SPI and SPEI calculation is from 1868 to 2021 (154 years) using Durham University meteorological station, and the period in the SSI calculation is from 1957 to 2015 (59 years) using the Lüleburgaz station.

Dry months are identified using run and SPI theories. The first result is that the months and the drought duration from the run theory are longer than those from the SPI theory, which is as expected and investigated by Abu Arra and Şişman [40]. In other words, the run theory gave longer and more extreme drought duration. The other result is a specific number of data that should exist to derive an appropriate PDF. As can be noticed in this study, increasing the drought duration to more than 10, 12, or 14 months decreases the number of drought events. For example, in some cases, the number of drought events with 15 months of drought duration is eight. A suitable PDF cannot be derived using eight samples of data. Subsequently, the drought duration IDF identification in this research is between 9 and 14 months based on drought timescales and the available drought events. The CDF of drought years from Equation (8) can be negative for low return periods (T) such as 2 years and with a high probability of zero values P(0).

Table 4 shows the main variables in the IDF calculation. For each specific drought duration (SD), the total years, drought years, years without any drought, P(0), P(D), PDF with its parameters, and the critical intensity (CI) for each return period (T) and each specific drought duration are summarized in the table. It has been noticed that the normal PDF is dominant in the IDF calculation with arithmetic mean (μ) and standard deviation (σ) parameters. Increasing SD led to a decrease in the years with drought and CI because of the new intensity definition. At 12 months specific drought duration, the number of years with drought was 34 events. Increasing the SD for more than 12 months decreased the drought events, making producing CDF complicated and inaccurate. To produce and calculate any probability distribution function, there is a limit to the sample size; using a small sample size decreases the confidence between the data and the results. In general, longer duration gave lower intensity. The CI value at 100 years return period for SPI12 based on SPI theory for a 1-month SD duration is −2.68; for a 12-month SD duration, it is −1.75 (Table 4). With high critical intensity, such as −2.68, drought impacts are higher and more destructive. Increasing the SD up to 12 months makes the drought impacts lower but longer. The negative value of CI is because of using DI, which is negative. But the absolute value has been used for comparison reasons and for deriving IDF curves.

Table 4. The main variables including total years, P(0), P(d), PDF with its parameters, and T with CI for IDF calculation using SPI12 based on SPI theory at Durham meteorological station.

D (month)	1	2	3	4	5	6	7	8	9	10	11	12
Total Years	154	154	154	154	154	154	154	154	154	154	154	154
Years with drought	81	79	75	65	63	61	55	51	47	43	37	34
Years without drought	73	75	79	89	91	93	99	103	107	111	117	120
P(0)	0.47	0.49	0.51	0.58	0.59	0.60	0.64	0.67	0.69	0.72	0.76	0.78
P(d)	0.53	0.51	0.49	0.42	0.41	0.40	0.36	0.33	0.31	0.28	0.24	0.22
PDF	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.	Nor.
μ *	−1.5	−1.39	−1.34	−1.35	−1.35	−1.33	−1.35	−1.34	−1.28	−1.29	−1.14	−1
σ *	0.57	0.59	0.58	0.59	0.59	0.59	0.58	0.57	0.55	0.54	0.49	0.44
T (Year)	Critical Intensity (CI) for 12 months											
5	−1.67	−1.55	−1.47	−1.39	−1.36	−1.32	−1.26	−1.15	−1.06	−0.98	−0.67	−0.42
10	−2.00	−1.90	−1.82	−1.77	−1.76	−1.72	−1.69	−1.60	−1.52	−1.49	−1.24	−1.05
25	−2.31	−2.23	−2.15	−2.12	−2.11	−2.08	−2.06	−1.96	−1.90	−1.87	−1.62	−1.40
50	−2.51	−2.43	−2.35	−2.33	−2.32	−2.30	−2.27	−2.19	−2.11	−2.08	−1.82	−1.59
100	−2.68	−2.61	−2.52	−2.51	−2.51	−2.48	−2.46	−2.37	−2.29	−2.26	−2.00	−1.75
200	−2.83	−2.76	−2.69	−2.68	−2.68	−2.64	−2.62	−2.54	−2.46	−2.42	−2.14	−1.88
500	−3.02	−2.95	−2.88	−2.87	−2.87	−2.85	−2.81	−2.73	−2.63	−2.61	−2.32	−2.04

Note: *: μ is the mean and σ is the standard deviation of the normal distribution function.

Furthermore, frequency analysis and return periods are used for risk assessment, water management, and drought mitigation plans. The CI values increased with increasing the return period. For example, for SPI12 based on SPI theory, the CI at 5 years return period is −1.67, but it was −3.02 at 500 years return period (Table 4). Selecting the return period depends on the design purpose and can be determined by engineers and decision-makers. Table 4 is made for SPI12 based on SPI theory. For each DI, the same table is made.

The IDF curves for SPI12 based on SPI theory are calculated as in Table 4. For each DI, the same procedure as mentioned above is applied. Figure 4 shows the SPI3 and SPI12 IDF curves based on run and SPI theories. Figure 5 shows the SPEI3 and SPEI12 IDF curves based on run and SPI theories. Figure 6 shows the SSI3 and SSI12 IDF curves based on run and SPI approaches. For all DI and timescales, the rate change in CI with drought duration based on SPI is more than that based on run theory.

(a)
SPI3 _run theory

(b)
SPI12 _Run theory

(c)
SPI3 _SPI theory

(d)
SPI12 _SPI theory

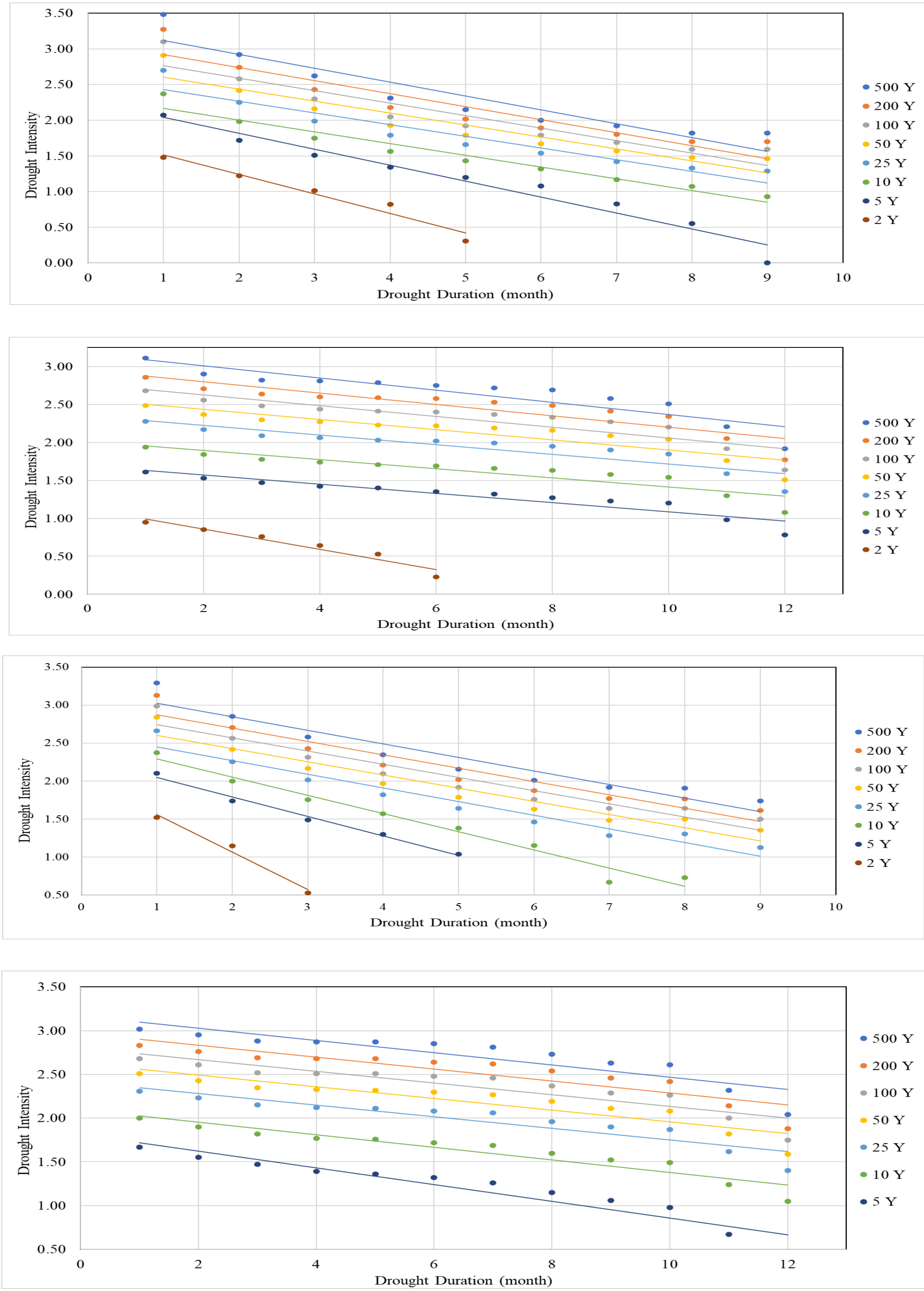

Figure 4. Resulting IDF curves using SPI for both run and SPI theories for 3- and 12-month timescales: (**a**) IDF using SPI3 based on run theory. (**b**) IDF using SPI12 based on run theory. (**c**) IDF using SPI3 based on SPI theory. (**d**) IDF using SPI12 based on SPI theory.

(**a**)
SPEI3 _run
theory

(**b**)
SPEI12
_Run theory

(**c**)
SPEI3 _SPI
theory

(**d**)
SPEI12 _SPI
theory

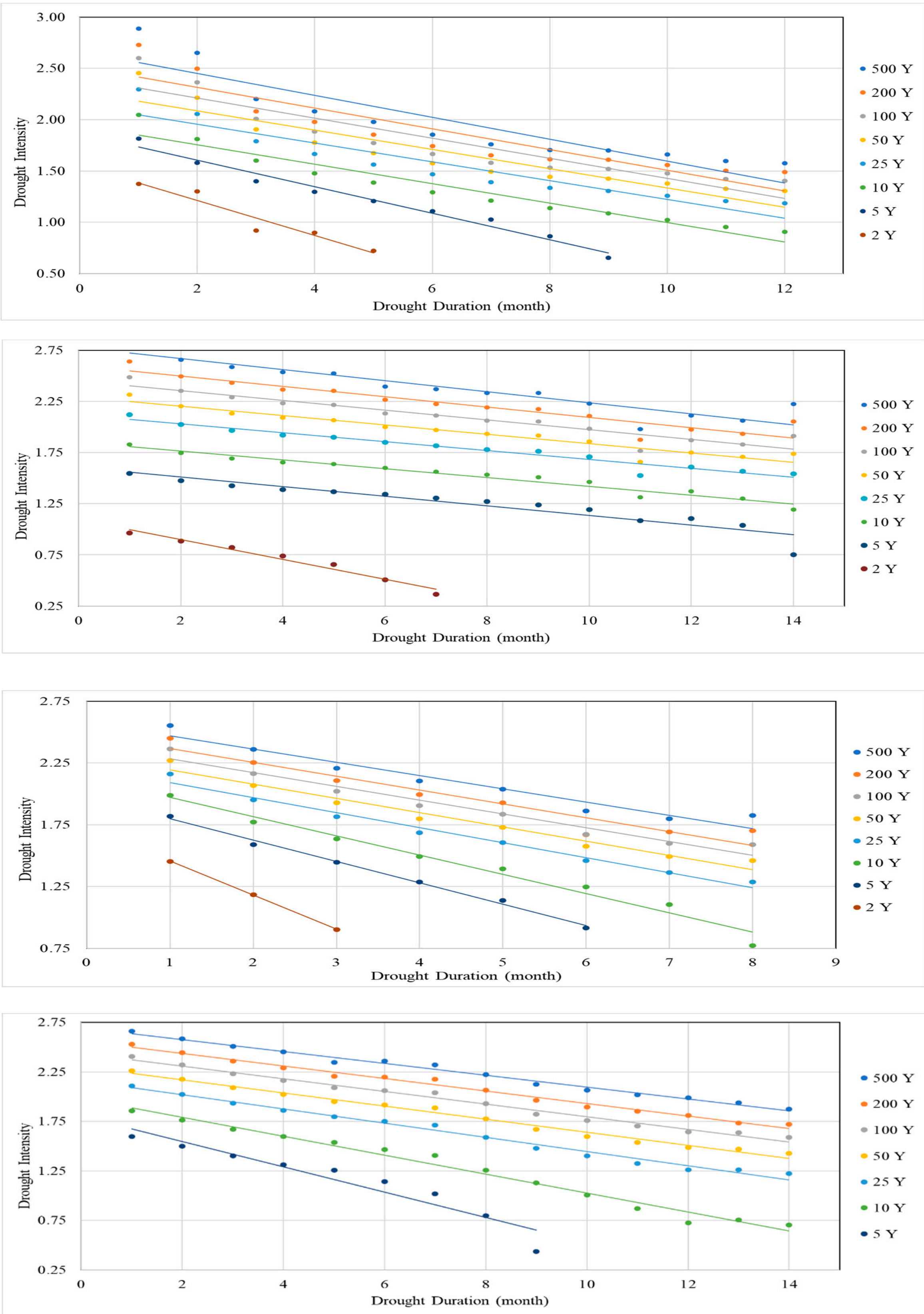

Figure 5. Resulting IDF curves using SPEI for both run and SPI theories for 3- and 12-month timescales: (**a**) IDF using SPEI3 based on run theory. (**b**) IDF using SPEI12 based on run theory. (**c**) IDF using SPEI3 based on SPI theory. (**d**) IDF using SPEI12 based on SPI theory.

(**a**) SSI3 _run theory

(**b**) SSI12 _Run theory

(**c**) SSI3 _SPI theory

(**d**) SSI12 _SPI theory

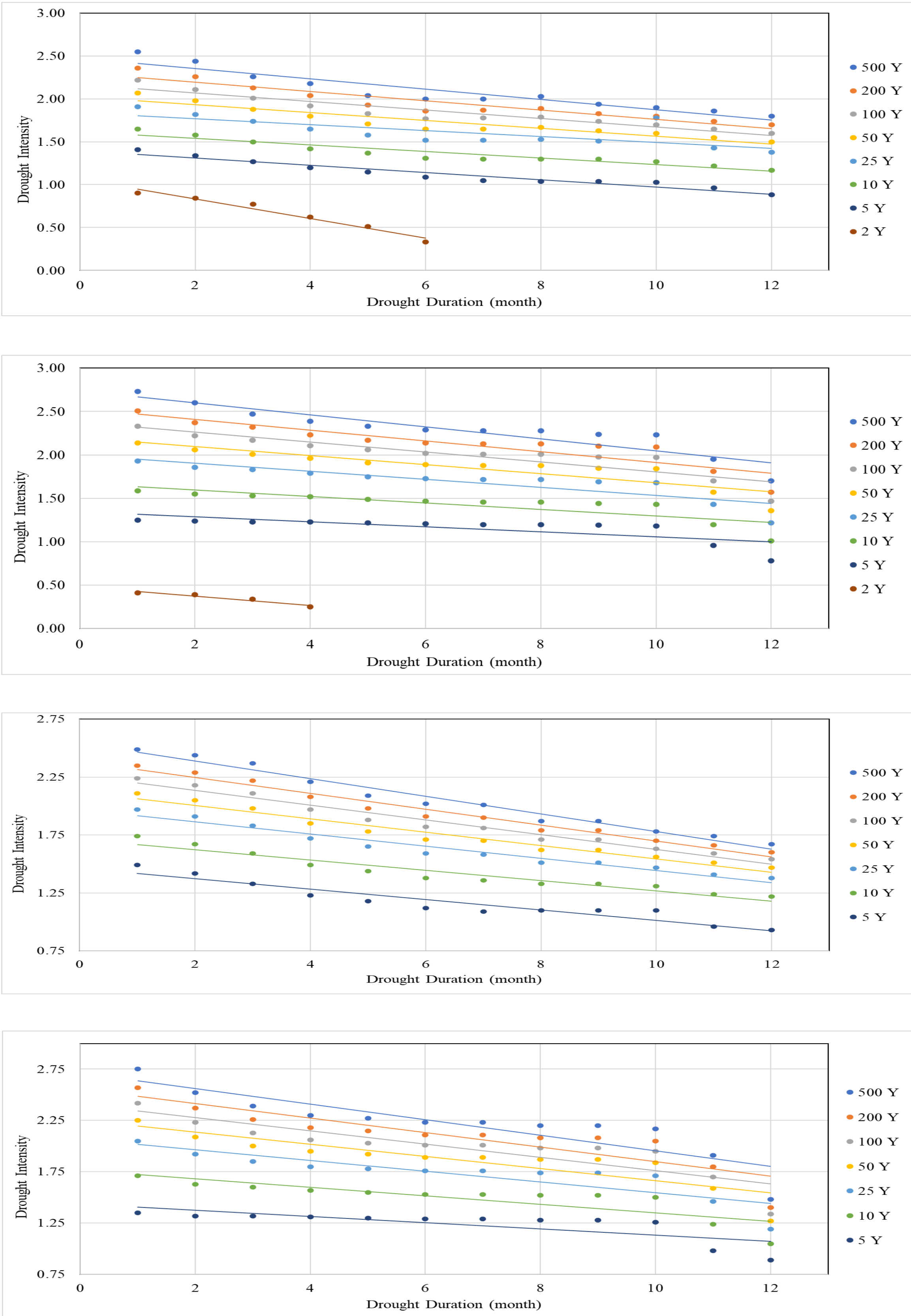

Figure 6. Resulting IDF curves using SSI for both run and SPI theories for 3- and 12-month timescales: (**a**) IDF using SSI3 based on run theory. (**b**) IDF using SSI12 based on run theory. (**c**) IDF using SSI3 based on SPI theory. (**d**) IDF using SSI12 based on SPI theory.

The maximum predicted specific drought duration, the maximum predicted intensity, and the rate of change in intensity (slope) are calculated for each return period using each DI (Table 5). The maximum predicted drought duration is the intersection point of the X-axis, and the maximum predicted intensity is the intersection point of the Y-axis. The rate of change is a significant variable in understanding the formulation of a drought event; a high slope indicates more change in DI with a small specific duration with more destructive impacts. No consistent relation can be found between the change rate and the return period. In addition, this table can be used to compare SPI and SPEI methods between run and SPI theories. Figure 4a and Table 5 show that the maximum D for 2 years return period using SPI3 based on run theory was 6.5 months. A drought event with D between 1 and 6.5 months is predicted every two years. However, it is not expected to have any drought event with 6.5 months duration or more for 2 years return period. For 2 years return period, the results differed between the used DI, timescale, and drought definition. For SPI12, based on SPI theory, no drought event with any D is expected for 2 years return period. This result is rational because SPI12 means that 12 consecutive months have existed, and the occurrence of this situation every 2 years can be impossible (See Figure 4d).

Table 5. Maximum drought duration, maximum intensity, and slope of IDF curves for each return period using SPI and SPEI.

Timescale = 3 Months												
	SPI_Run Theory			**SPI_SPI Theory**			**SPEI_Run Theory**			**SPEI_SPI Theory**		
T (Year)	**Max. D**	**Max. I**	**Slope**	**Max. D**	**Max. I**	**Slope**	**Max. D**	**Max. I**	**Slope**	**Max. D**	**Max. I**	**Slope**
2	6.5	1.79	0.274	4.4	2.06	0.495	9.1	1.55	0.171	6.3	1.73	0.276
5	11.0	2.17	0.197	9.0	2.31	0.257	14.4	1.86	0.129	11.4	1.97	0.173
10	14.1	2.33	0.165	10.5	2.53	0.24	20.4	1.94	0.095	13.3	2.13	0.16
25	15.9	2.59	0.163	14.6	2.63	0.18	23.5	2.14	0.091	18.1	2.21	0.122
50	16.5	2.77	0.168	16.3	2.77	0.17	24.1	2.27	0.094	20.1	2.31	0.115
100	16.8	2.94	0.175	16.8	2.92	0.174	24.6	2.41	0.098	21.6	2.4	0.111
200	16.9	3.1	0.183	17.3	3.05	0.176	25.0	2.52	0.101	22.1	2.48	0.112
500	17.1	3.31	0.1942	17.9	3.2	0.179	25.0	2.67	0.107	24.1	2.58	0.107
Timescale = 12 Months												
	SPI_Run Theory			**SPI_SPI Theory**			**SPEI_Run Theory**			**SPEI_SPI Theory**		
T (Year)	**Max. D**	**Max. I**	**Slope**	**Max. D**	**Max. I**	**Slope**	**Max. D**	**Max. I**	**Slope**	**Max. D**	**Max. I**	**Slope**
2	9.6	1.28	0.134	-	-	-	11.2	1.1	0.098	-	-	-
5	27.9	1.7	0.061	19.0	1.82	0.096	34.3	1.61	0.047	13.8	1.8	0.13
10	33.5	2.01	0.06	29.2	2.1	0.072	43.0	1.85	0.043	20.6	1.98	0.096
25	36.7	2.35	0.064	36.1	2.42	0.067	48.2	2.12	0.044	30.0	2.16	0.072
50	38.4	2.57	0.067	39.1	2.62	0.067	50.0	2.3	0.046	34.8	2.3	0.066
100	39.0	2.77	0.071	41.8	2.8	0.067	51.0	2.45	0.048	38.1	2.44	0.064
200	39.3	2.95	0.075	43.7	2.97	0.068	52.0	2.6	0.05	40.6	2.56	0.063
500	39.6	3.17	0.08	45.3	3.17	0.07	51.5	2.78	0.054	45.0	2.7	0.06

Generally, the maximum drought duration based on run theory for SPI, SPEI, and SSI is longer and more conservative. This result is attributed to the definition and start date of the run theory (Figure 1). Moreover, regardless of the used theory, the maximum drought duration based on SPEI gave longer durations (Table 5). For SPI and SPEI and return periods between 2 and 50 years, the maximum intensity based on the SPI theory had higher values than the run theory. Nevertheless, the maximum intensity based on the run theory for more than 50 years of return periods had higher intensities. For SSI, the maximum intensity based on SPI theory for all return periods had higher intensities (Table 6). Related to the maximum duration for SSI, no specific relation is found. In some cases, low return periods have longer maximum drought duration.

Table 6. Maximum drought duration, maximum intensity, and slope of IDF curves for each return period using SSI.

	Timescale = 3 Months						Timescale = 12 Months					
	SSI_Run Theory			SSI_SPI Theory			SSI_Run Theory			SSI_SPI Theory		
T (Year)	Max. D	Max. I	Slope	Max. D	Max. I	Slope	Max. D	Max. I	Slope	Max. D	Max. I	Slope
2	9.30	1.06	0.114	-	-	-	9.1	0.48	0.053	-	-	-
5	35.00	1.4	0.04	32.4	1.46	0.045	46.2	1.34	0.029	46.5	1.44	0.031
10	42.37	1.61	0.038	38.9	1.71	0.044	43.9	1.67	0.038	42.9	1.76	0.041
25	52.57	1.84	0.035	37.9	1.97	0.052	42.9	2	0.0466	39.8	2.07	0.052
50	43.91	2.02	0.046	36.6	2.12	0.058	42.3	2.2	0.052	37.5	2.25	0.06
100	43.20	2.16	0.05	35.3	2.26	0.064	41.8	2.38	0.057	37.1	2.41	0.065
200	42.59	2.3	0.054	34.5	2.38	0.069	41.0	2.54	0.062	36.1	2.56	0.071
500	41.17	2.47	0.06	33.4	2.54	0.076	39.7	2.74	0.069	35.7	2.71	0.076

Table 7 summarizes the main difference between the conventional method in assessing drought events and the newly proposed method using IDF drought curves based on SPI12. There was no drought event for a specific drought duration, such as 3 or 4 months. Drought intensity is calculated as each drought duration's average and maximum value. Some drought events occurred once, and some of them many times, such as the 6-month drought event. For a 6-month drought duration, the maximum intensity based on the conventional method is −1.11, but using IDF drought curves, it ranges between −1.32 to −2.85. This is attributed to the importance of the frequency of each drought duration and dividing each drought event into pre-defined intervals based on SD. Using IDF drought curves gives comprehensive results for each drought duration and return period and gives more conservative results (Table 7), which is a significant point for design purposes.

Table 7. Comparison between conventional and IDF drought curves methods regarding drought intensity using SPI12 for Durham station.

	SPI12 Using Conventional Method		SPI12 Using IDF Drought Curves						
			T (Years)						
Duration (m)	Average	Maximum	5	10	25	50	100	200	500
2	−0.82	−1.28	−1.55	−1.9	−2.23	−2.43	−2.61	−2.76	−2.95
3	−1.36	−0.94	−1.47	−1.82	−2.15	−2.35	−2.52	−2.69	−2.88
4	- (*)	-	−1.39	−1.77	−2.12	−2.33	−2.51	−2.68	−2.87
5	-	-	−1.36	−1.76	−2.11	−2.32	−2.51	−2.68	−2.87
6	−0.87	−1.11	−1.32	−1.72	−2.08	−2.3	−2.48	−2.64	−2.85
7	−0.75	−1.25	−1.26	−1.69	−2.06	−2.27	−2.46	−2.62	−2.81
8	−1.19	−2.02	−1.15	−1.6	−1.96	−2.19	−2.37	−2.54	−2.73
9	−0.65	−1.01	−1.06	−1.52	−1.9	−2.11	−2.29	−2.46	−2.63
10	−1.1	−1.6	−0.98	−1.49	−1.87	−2.08	−2.26	−2.42	−2.61
11	−0.53	−1.22	−0.67	−1.24	−1.62	−1.82	−2	−2.14	−2.32
12	-	-	−0.42	−1.05	−1.4	−1.59	−1.75	−1.88	−2.04

Note: *: (-) indicates no drought event with this drought duration.

The IDF drought curves method offers distinct advantages in understanding and capturing the relationship between intensity, duration, and frequency. It provides simplicity and ease of interpretation. IDF curves provide a straightforward graphical representation that stakeholders, decision-makers, and water resources managers easily understand. Also, IDF curves allow for accurate quantification of the relationship between drought characteristics. Finally, it has many applications worldwide, including engineering design and emergency response.

Risk assessment depends on the IDF rainfall concept and is commonly used as a standard approach by engineers to design hydraulic structures such as dams [41,42]. This research aims to explain how these concepts can be used for drought analysis, drought risk assessment, and design purposes, providing a comprehensive understanding of drought characteristics and ecosystem rehabilitation failure due to drought. For example, a drought event with an SD of 30 months, CI of −2.5, and 100 years return period can be used for dam design and water supply calculation. The results related to critical intensity and return periods are generally as investigated by Elsebaie et al. [43]. Halwatura et al. [27], Hailegeorgis et al. [42], and Elsebaie et al. [43] mentioned the importance of using IDF drought curves for the planning and design of hydraulic structures and risk assessment, which our research is trying to answer.

5. Conclusions

This research presented the methodology for developing IDF drought curves using new concepts and framework to comprehensively understand the drought characteristics in terms of drought duration and intensity based on the run and SPI theories. This tool will be helpful in drought risk assessment, water resources management, and the design of hydraulic structures. Both hydrological and meteorological drought indices have been calculated at two different timescales: 3 and 12 months. The key findings of our research can be summarized as follows:

1. To comprehensively understand and analyze drought characteristics, there is a need to divide a drought event into many specific drought duration intervals. Consequently, the severity and intensity of each specific drought duration should be evaluated.
2. Drought characteristics are different based on drought definition. Both SPI and run theory must then be carried out to obtain the extreme drought characteristics.
3. The normal probability distribution function was the dominant and suitable PDF for critical intensity values.
4. Developed IDF drought curves should be used directly by designers and decision-makers for design and risk assessment purposes because of their simplicity and ease of interpretation, precise quantification, and practical application.
5. Based on the dry years for both the run and SPI theories, the specific drought duration remained between 9 and 14 months. Data were insufficient for a specific drought duration longer than 14 months for deriving a suitable PDF.
6. For 2 years return period, the IDF drought curve was calculated up to 4 months of specific drought duration. The CI for a longer specific drought duration cannot be calculated.
7. Compared to the conventional risk analysis methods which depend on the drought events, the new concepts and framework provide us with a comprehensive understanding and range of choices regarding drought duration and return period.
8. One of the major outcomes of our research is to provide water managers and suppliers with a new tool and approach to making decisions on appropriate management actions regarding drought frequency.

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