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Comparison of the Calculated Drought Return Periods Using Tri-variate and Bivariate Copula Functions under Climate Change Condition

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Abstract

Concerning the various effects of climate change on intensifying extreme weather phenomena all around the world, studying its possible consequences in the following years has attracted the attention of researchers. As the drought characteristics identified by drought indices are highly significant in investigating the possible future drought, the Copula function is employed in many studies. In this study, the two- and three-variable Copula functions were employed for calculating the return period of drought events for the historical, the near future, and the far future periods. The results of considering the two- and three-variable Copula functions were separately compared with the results of the calculated Due to the high correlation between drought characteristics, bivariate and trivariate of Copula functions were applied to evaluate the return periods of the drought.

The most severe historical drought was selected as the benchmark, and the drought zoning map for the GCM models was drawn. The results showed that severe droughts can be experienced, especially in the upper area of the basin where the primary water resource is located. Also, the nature of the drought duration plays a decisive role in the results of calculating the return periods of drought events.

Keywords: Drought Return Period, Climate Change, Copula Function, Drought Map

1. Introduction

Drought occurs for long periods of unusual hydrological conditions resulting in a sharp decline in rainfall. Fundamentally, drought is an aridity type caused by the decrease in rainfall. Meteorological measurements are the first sign of a drought (Bazarafshan 2017; Abdulkadir 2017; Khan et al. 2018). All climate conditions may experience this phenomenon (Chen et al. 2013). Moreover, extreme weather events, such as drought, are the main causes of risk to agricultural systems (Ben-Ari et al. 2016; Hernandez-Barrera et al. 2017; Pascoa et al. 2017; Zampieri et al. 2017; Ribeiro et al. 2018). Drought analysis is mostly done by calculating its characteristics, such as drought duration and severity, via drought indices (Yang 2010; Liu et al. 2016). Analyzing drought indices are important for assessing the drought conditions because the incident provides various methods to determine drought severity, arrival (Cahng et al. 2016; Hao et al. 2016; Tian et al. 2018; Mukherjee et al. 2018). Some indices are the Standardized Precipitation Index (SPI), the Reconnaissance Drought Index (RDI), the modified SPI index, and the Joint Deficit Index (JDI). The values of modified SPIs are integrated with different time scales through multiple Copula distribution functions and create the JDI to determine the overall drought situation in the JDI (Kao and Govindarajo 2010; Ma et al. 2016). The SPI is proper for measuring meteorological drought

since it is based on precipitation data. As climate change could cause extreme hydrological phenomena, investigating its effects is one of the necessities of water resources management (Ahmadalipour et al. 2017; Oguntunde et al. 2017). In the northern hemisphere, areas between latitudes 15 and 45 degrees are susceptible to more severe droughts (Mousavi 2005; Barlow et al. 2016; Gazol et al. 2016).

Research has been done for investigating the effects of climate change on the drought via several drought indices (Mathbout et al. 2018; Thomas and Prasannakumar 2016; Lee2017 et al. 2017; Bazrafshan et al. 2017). Examples include the SPI and the RDI, the Percent of Normal Precipitation Index (PNPI), the Agricultural Rainfall Index (ARI), the Multivariate Standardized Drought Index (MSDI), and JDI Index, having utilized for drought analysis in different parts of the world including Iran (Bazrafshan et al. 2017; Hoffman et al. 2009, Kirono et al. 2011, Selvaraju and. Baas 2007, Lee et al. 2013, Serinaldi et al. 2009; Mirabbasi et al. 2013; MirAbbasi et al. 2013; Madadgar and Moradkhani 2011; Lee et al. 2013; Kirono et al. 2011; Srinaldi et al. 2009; Hoffman et al. 2009; Selavarajo and Bass 2007).

There is a significant correlation between duration and severity of droughts (Ayantobo et al. 2019; Santos et al. 2019; Wu et al. 2017; Ayantobo et al. 2017; Madadgar and Moradkhani 2011). Drought analysis based on just one characteristic can only cause a misunderstanding of droughts. By calculating the return period only based on one drought characteristic ignores all other drought characteristics and their relevant characteristics (Ge et al. 2016; Thilakarathne and Sridhar 2017). Besides, the return period of a drought can be measured as a sample for the severity larger than a certain value. Nevertheless, the return period cannot provide information on other drought characteristics, such as drought duration (Taskirirs et al. 2016; Kwon and Lall 2016). Planning for a longer period needs more reflection. Also, it is crucial to plan for the happening years in advance occasionally. Therefore, knowing about the

return period of drought along with paying attention to the drought characteristics for managing water resources is vital (Zhang et al. 2017). Several trivariate copula functions were conducted for multivariate frequency analysis of extreme hydrological events such as droughts (Maddadgar and Moradkhani 2011; Chen et al. 2011; Hao et al. 2017; Hangshing and Dabral 2018; Zhu et al. 2019). Contrary to conventional methods such as normal multivariate distribution, the Copula function is independent of marginal distribution functions, so that any type of marginal distribution function can be considered for each of the variables (Da Rocha Júnior et al. 2020; Zhang and Singh 2007; Favre et al. 2004). Also, the current drought index and the copula-based analysis of drought properties present a new concept for appropriate management practices in the changing environment (Das et al. 2019). Investigating the use of Copula functions, such as Gumbel, Frank, Clayton, and Gaussian, in analyzing drought characteristics, Lee et al. (2013) calculated the SPI in four stations of Canada and Iran and utilized Copula functions for analyzing the drought. Wang et al. (2010) employed a trivariate Copula to analyze the drought characteristics in the New South Wales area of Australia. They calculated the SPI to assess the characteristics of the drought. Dashe et al. (2019) coupled the hydrological Soil Water Assessment Tool (SWAT) with the multivariate copulas for prediction of the drought years. The results showed that the developed SWAT-Copula-based method has can be employed in data-scarce regions for effective drought monitoring with the minimum observed inputs. Daneshkhah et al. (2016) and Luo et al. (2019) constructed a different flood risk management model via the Copula-based Bayesian network to analyze the flood risk. Ribeiro et al. (2019) employed the copula theory for estimating joint probability distributions describing the dependence degree between drought conditions and crop yield anomalies of two major rainfed portions of cereal. The Standardized Precipitation Evapotranspiration Index (SPEI), the satellite-derived indices

Vegetation Condition Index (VCI), and Temperature Condition Index (TCI) are employed. The results showed that while TCI is commonly employed in copula models indicating better probabilities of joint extreme high values of wheat and drought indicators, the VCI and SPEI are related to copula models illustrating higher probabilities of joint extreme low values. Balistrocchi and Grossi (2020) predicted the effect of climate change on urban drainage systems in northwestern Italy via a copula-based approach, finding the seasonal distribution of storms critical for urban drainage systems. Chatrabgoun et al. (2020) used the copula functions in a new mathematical framework with nonlinear analysis, investigated the effects and dangers of frost on the vine. The study revealed that the developed Caspian model is a proper instrument for predicting the return period of glacial events. Kiafar et al. (2020) used the copula-based genetic algorithm method to monitor meteorological droughts of Qazvin station in Iran. The drought characteristics are measured via the monthly SPI. The study shows that drought probabilistic characteristics could be used for water resources management and planning.

The return periods of drought events has been largely ignored in previous drainage basin studies and also some basins face some complications, and providing drought zoning maps will lead to a better understanding of the situation of basins, which has not been sufficiently discussed in previous studies, especially the Zayandeh Rud basin in Iran. Hence the purpose of this study was to employ, the Standardized Precipitation Index (SPI) to calculate the duration, severity, and peak intensity of a drought in the basin throughout history, in the near future, and far future using data from 15 GCM models obtained from the fifth IPCC report (AR5).

2. Materials and Methods

2.1 The SPI

The SPI was developed by McKee et al. (1993). The SPI value can be positive or negative, with positive values indicating periods when precipitation is above the average and negative values indicating periods when precipitation is below the average (Shiau 2006). The SPI also can be calculated for different time scales (1, 3, 6, 12, 24, and 48 months). While the SPI of 1-3 months is utilized for meteorological drought study, SPI of 1-6 months is applied for agricultural drought study, and the SPI of 6-24 months is employed for hydrological drought determination (World Meteorological Organization 2012). In calculating this index, initially, the gamma distribution function is adjusted to the precipitation data, then the cumulative probability obtained from the gamma distribution is transferred to the normal standard cumulative distribution with an average of zero and a mean deviation of one. Equation (1) is illustrated as the SPI calculation method.

$$F(X) = \int_0^X f(X)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^X X^{\hat{\alpha}-1} e^{\frac{-X}{\beta}} dx \qquad (1)$$

The severity, duration, and peak intensity of drought are calculated based on the RUN theory proposed by Yevjevich (1967). According to this method, the threshold level for determining drought was considered as (-1) to examine more severe drought conditions (Table 1). Since the precipitation data were only available for 30 years, the 3-month SPI calculation was considered to better comprehend seasonal meteorological drought. According to the definition, drought duration means consecutive months in which the SPI value is less than (-1). The drought severity is the absolute value of SPI cumulative values in periods when SPI values are consistently less than (-1), and the drought peak intensity is the minimum SPI-value for every drought event.

Distribution functions are utilized to fit drought characteristics including log-normal distribution function, exponential distribution function, gamma distribution function, and

Weibull distribution function. The most suitable distribution functions for drought severity and duration have been determined using the Bayesian information criterion (BIC) method. The relation of BIC calculation is used as BIC = -2loglikelihood + d.log (N) in which N is the sample size and d is the number of parameters; lower the value, better the fitness (Li et al. 2013).

Table 1- SPI classification

SPI Value	Drought Condition
	Extremely Wet
2.0 and more	Very Wet
1.5 to 1.99	Moderately
1.0 to 1.49	Wet
-0.99 to 0.99	Near Normal
-1.0 to -1.49	Moderately
-1.5 to -1.99	Dry
-2 and less	Severely Dry
	Extremely Dry

2.2 The Multivariate Probabilistic Distribution of a Copula Function

The Copula function is a multivariate joint function applied to connect various probabilistic distribution functions. Furthermore, a random vector (x_1, x_2, ..., X_n) with continuous marginal distribution functions of $F_i(x) = P\ [X_i \leq x]$ has been considered. For each member of this random vector, uniform margins (U_1, U_2, …, U_d) are available as follows (Nelson 2007):

$$(U_1, U_2, \ldots, U_d) = \left(F_1(X_1), F_2(X_2), \ldots, F_d(X_d)\right) \quad (2)$$

Therefore, the C Copula function can be defined as a joint distribution function of (U_1, U_2, …, U_d) for the vector (x_1, x_2, …, x_n):

$$C(U_1, U_2, \ldots, U_d) = P[U_1 \leq u_1, U_2 \leq u_2, \ldots, U_d \leq u_d] \quad (3)$$

The relation is described as follows:

$$C(U_1, U_2, \ldots, U_d) = P \quad (4)$$

Scalar theory (1959) showed that C Copula function for each n-dimensional cumulative distribution function of H with different margins F_1, ..., F_n is defined as follows: (Nelson 2007)

$$H(X_1, X_2, \ldots, X_n) = C[F_1(X_1), F_2(X_2), \ldots, F_n(X_n)] = C(U_1, U_2, \ldots, U_n) \quad (5)$$

In which u_1, …, u_n is the distribution functions of X_1, …, X_n (Madadgar and. Moradkhani, 2011).

Marginal functions should be uniform in the 0 and 1 range. Copula functions have different families, and some of them are increasingly used in hydrological studies (Yan 2007). According to the literature review, normal Copula and t Copula were considered to be in the family of elliptical Copulas and Gumble, Frank, and Clayton Copulas were considered in the family of Archimedes Copulas of the Copula functions that had been used in this study (Chen et al. 2013; Yang 2010; Lee et al. 2013; Serinaldi et al. 2009; Mirabbasi et al. ; 2013, Madadgar and Moradkhani, 2011 ; Chen et al. 2011; Chen et al. 2011; Chen et al. 2012; Chen et al. 2011; Madadgar and Moradkhani 2011; Sarinaldi et al. 2009).

2.3 Return period based on Copula function

It is important to know the frequency of extreme phenomena in hydrological studies. To assess the drought, the time between the arrival of a drought phenomenon and the arrival of

the next drought is called the inter-arrival time, and the mean inter-arrival time of two drought phenomena occurrences is defined as the return period (Srinaldi et al. 2009).

In the single variable mode, the return period is calculated as (6) and (7):

$$T_d = \frac{E(L)}{P_D(D \geq d)} \tag{6}$$

$$T_d = \frac{E(L)}{P_S(S \geq s)} \tag{7}$$

Where T_d is the return period of the drought, $E(L)$ is the expected value of the drought`s inter-arrival time, D indicates the duration of the drought, and S is the severity of the drought. The formula for calculating the return period for a multivariate return period can also be developed based on the method of calculating the return period of a single variable. According to Xia's (2006) method, the calculation of the return period in multivariate mode is done with via two logical operators "and" and "or". The operator "and" indicates the return periods in which all variables are greater than or equal to the specified values, and the operator "or" indicates a state in which at least one of the variables is greater than or equal to the specified values.

The return period is calculated for the case of $D \geq d$ and $S \geq s$, as well as for $D \geq d$ or $S \geq s$ mode with the help of relations (8) and (9):

$$T_{and} = \frac{E(L)}{P(D \geq d, S \geq s)} = \frac{E(L)}{1 - F_D(d) - F_S(s) + C[F_D(d), F_S(s)]} \tag{8}$$

$$T_{or} = \frac{E(L)}{P(D \geq d \text{ or } S \geq s)} = \frac{E(L)}{1 - C[F_D(d), F_S(s)]} \tag{9}$$

The calculation relations of the return period with the help of trivariate Copula functions for I≥i, $S \geq s$ and $D \geq d$modes, as well as I ≥i or $S \geq s$or $D \geq d$ modes, are as described in (10) and (11):

$$T_{and} = \frac{E(L)}{1-P(D\geq d, S\geq s, I\geq i)} = \frac{E(L)}{1-F_D(d)-F_S(s)-F_I(i)+C[F_D(d),F_S(s)]+C[F_D(d),F_I(i)]+C[F_S(s),F_I(i)]-C[F_D(d),F_S(s),F_I(i)]}$$

(10)

$$T_{or} = \frac{E(L)}{1-P(D\geq d \text{ or } S\geq s \text{ or } I\geq i)} = \frac{E(L)}{1-C[F_D(d),F_S(s),F_I(i)]} \quad (11)$$

In the above equations, D indicates the duration of drought, S indicates the severity of drought, I indicates the peak intensity of drought in each period, d indicates the duration of the determined drought, s indicates the severity of the specified drought and i indicates the peak intensity of drought in a period whose value is predetermined.

The return period for drought phenomena, where the duration, severity, and peak intensity of drought are greater than a certain amount, signals a more severe drought phenomenon. Therefore, the T_{and} calculation was considered in this study.

2.4 Climate Change Scenarios

Investigating climate change in the future includes several factors, such as greenhouse gas emissions, technology development, changes in energy production methods, land use, regional economy, population growth, and more. Various groups are examining these issues under the supervision of the Intergovernmental Panel on Climate Change (IPCC). The Fifth Assessment Report (AR5) was published based on the scenarios of Representative Concentration Pathways (RCP), which represent the pathways for emission and concentration of gases and the obtained results until 2100 (Wayne, 2013). Since AR5 is the latest report released by IPCC, this study employed the data from AR5. The report has defined four RCP scenarios: RCP2.6, RCP4.5, RCP6, and RCP8.5. Two RCP4.5 and RCP8.5 scenarios were selected for this study. The RCP8.5 scenario includes procedures that along with increasing land-use change in agricultural lands and lawns, will also concern the increase in the world's

population. Therefore, this scenario indicates an increase in greenhouse gas emissions over time, resulting in a high level of greenhouse gas concentrations (Riahi et al. 2007; Riahi et al. 2011). This scenario is similar to the SRES A1F1 scenario compared to the fourth IPCC report scenarios. The RCP4.5 scenario is a scenario in which greenhouse gas emissions are stabilized until 2100 in order not to exceed the desired emission level (Thomson et al. 2011; Wise et al. 2009; Clark et al. 2007; Smith and Wigley 2006). This scenario is similar to the SRES B1 scenario compared to climatic scenarios and emission scenarios in the fourth report (Wayne 2013). NASA has provided researchers with an accuracy of 0.25 degrees and the predicted data of Earth's global daily exchange on the NASA website named NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP). The data does not require to be downscaled since it is downscaled for each network on the site (Thrasher et al. 2013). In this study, daily precipitation data for the 30-year historical period from 1979 to 2008 as well as daily precipitation data from 15 GCM models under the RCP4.5 and RCP8.5 scenarios for the next 84-year period of 2016 to 2099 were downloaded from the NASA site.

2.5 Study Area

Zayandeh Rud drainage basin is located in Isfahan Province in Iran. The geographical location of this basin has been shown in Figure 1. The basin is a completely closed basin that has no access to the sea. The Zayandeh Rud drainage basin covers an area of 26,917 square kilometers and is located between the latitudes 31°-34° north and longitudes 49°-53° east. Zayandeh Rud River originates from the Zagros Mountain chain in Western Iran and flows into the basin, ending up in Gavkhuni Wetland in the southeast of Isfahan Province (Figure1). The water level of different parts of the basin varies from 1446 meters to 3925 meters, which leads to different climatic conditions in the basin. In general, the mean annual precipitation in the basin is 211 mm, widely varying in annual precipitation in various parts of the basin.

Also, the mean annual potential evapotranspiration in the basin is 1500 mm. The basin's mean annual temperature is (14.5) degrees Celsius with the lowest temperature of (-12.5) degrees Celsius recorded in January and the highest temperature of 42 degrees Celsius recorded in July. Safavi et al. (2014), in a study on the Zayandeh Rud Basin, reported eleven dry years, four normal years, and six wet years between 1991-2011. In a study by Gohari et al. (2013), the effects of climate change on agricultural products and water consumption efficiency in the Zayandeh Rud drainage basin were investigated from 2015-2044. The results showed an annual decrease in the precipitation of 11-31 percent, taking into account changes in precipitation in different months of the year. Furthermore, a study conducted by Sabzevari (2013) showed that recent droughts in the basin have been very devastating in reducing surface water and groundwater resources, especially in the western parts.

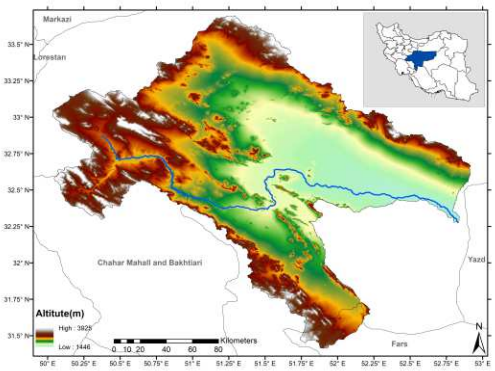

Figure 1: Geographic location of the Zayandeh Rud basin

2.6 Data and Information

2.6.1 Observational Data

To better understand the pattern of precipitation in the basin, two specific stations were selected at two different points in the basin. One of the stations was upstream and the other was located downstream of the basin. Figure (2) shows the monthly changes in precipitation at the two selected stations. As can be seen in the figure, the amount of precipitation at the upstream station was higher than the amount of precipitation at the downstream station.

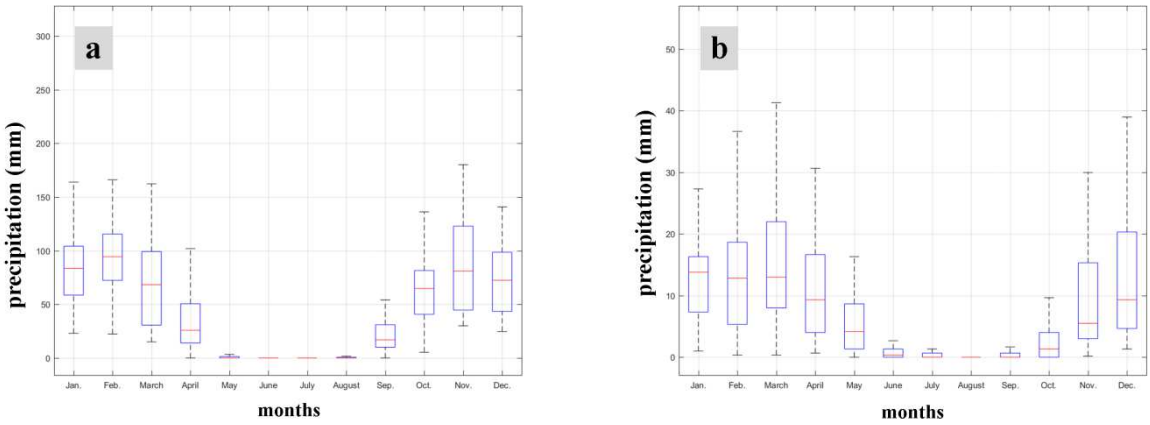

Figure 2: Changes in monthly precipitation in the past (1979-2008): a) station located upstream b) station located downstream

2.6.2 Data Analysis

Zoning of the results on a map is an optimal method to better comprehend the status of the basin. Using such maps, it is easier to study the general condition of the basin and identify the more critical parts of the basin. It was decided to use the existing historical data of NEX-GDDP, which was available for 57 networks within the basin.

2.6.3 Analysis of Historical Drought

The linear correlation between duration parameters, severity, and peak intensity of drought has been calculated and almost all obtained values were above 0.5 (Figure 3). The correlation range of drought severity and duration was between 0.5 and 0.7. Also, the correlation between the severity and peak intensity of drought was between 0.8 and 1, and the correlation between the duration and peak intensity of drought was between 0.4 and 0.7.

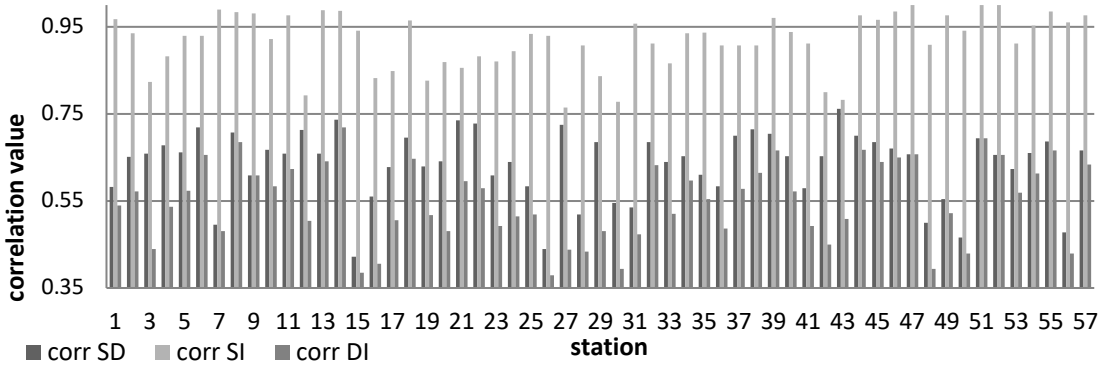

Figure 3: Linear correlation between drought characteristics (S indicates severity, D indicates duration, and I indicates the peak intensity of drought in each period.)

According to recent studies, to determine the distribution functions appropriate for each drought characteristic (Xu et al. 2015; Shiau 2006), the Exponential, Gamma, Log-normal, Weibull distribution functions are appropriate for the duration, severity, and peak intensity of the drought. These distribution functions are fitted to calculate drought characteristics in the historical period. The most appropriate function is determined for each station in the basin. For each marginal distribution function, Table (1) has identified the number of stations, in which, the specified distribution function was the best fit for each drought characteristic. Table (2) illustrates the selected distribution functions for each drought characteristic. The maximum likelihood estimation (MLE) method was utilized to estimate function parameters. The BIC method was employed to determine the best function suitable for drought severity, duration, and peak intensity. The assigned functions were also used to extract the severity

distribution functions, drought duration, and peak intensity of drought in the historical and future periods.

Table 1: Number of stations with the most appropriate function specified for each drought characteristic

Drought characteristics	**Exponential function**	**Gamma function**	**Log-normal distribution**	**Weibull distribution**
Severity	**6**	**1**	**41**	**9**
Duration	**0**	**0**	**57**	**0**
The Peak Intensity of drought	**52**	**0**	**3**	**2**

Table 2: Distribution functions selected for each drought characteristics

Drought characteristics	**Selected distribution function**
Severity	Log-normal
Duration	Log-normal
The Peak Intensity of drought	Exponential

The most appropriate Copula function for each station in the basin was selected using the BIC method. Table 3 shows the number of stations, where the specified Copula function was the best-calculated function. Table 4 shows the selected Copula functions for severity-duration, the severity-peak intensity of drought, duration-peak intensity of drought, and duration-severity-peak intensity of drought.

Table 3: The number of stations with the best-specified Copula functions

Copula	t	Normal	Gumbel	Frank	Clayton
severity-duration Copula	**0**	**6**	**48**	**3**	**0**
severity-maximum amount of drought	**0**	**25**	**8**	**13**	**11**
duration-maximum amount of drought	**0**	**21**	**29**	**6**	**1**
duration-severity-maximum amount of drought	**21**	**32**	**4**	**0**	**0**

Table 4. Selected Copula functions

Copula marginal function	**Selected Copula function**
Severity-Duration	**Gumbel**
Severity-Peak Intensity	**Normal**
Duration-Peak Intensity	**Gumbel**
Duration-Severity-Peak Intensity	**Normal**

3. Results and Discussion

3.1 Effects of Climate Change on the Drought under RCP4.5 S

In this study, 90% of the highest values of severity, duration, and peak intensity of drought in each period of the historical era were considered as the benchmark severe drought in the basin. Accordingly, the characteristics of the most severe historical drought, which was considered as a criterion for measuring droughts, included the severity of drought with an SPI value of (-4.39), the duration of drought equal to 6 months, and the peak intensity in each period with an SPI value of (-1.36). Considering these characteristics, the drought`s return period was calculated for all points of the network within the basin for the historical period (1979-2008), the near future (2016-2057), and the distant future (2058-2099). The results were displayed in spatial maps in the GIS software using the inverse distance weighting (IDW) method. Low values indicated more drought occurrence. According to the results of frequency analysis with the help of the bivariate and trivariate Copula function, the return period of the most severe drought in different parts of the basin is based on all three types of bivariate and trivariate Copula varied between 2 to 500 years. Due to the varied topography in different parts of the basin, this range was logical for the return period. According to Figure (4) which shows the results for the historical period (1979-2008), it is clear that most parts of the basin suffered from severe drought in this historical period (drought severity less than (-4.39) and drought duration more than six months and peak intensity less than (-1.36) with a return period of fewer than 10 years.

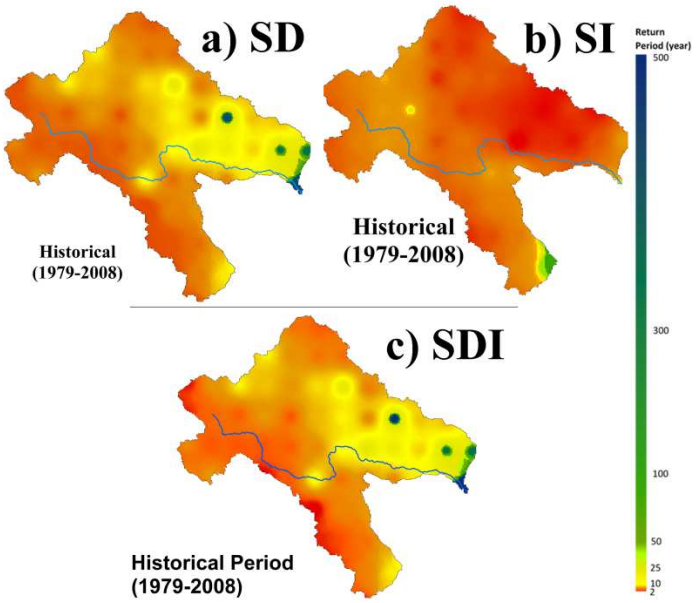

Figure 4: Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the historical period (1979-2008) a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

3.2 scenarios

According to the Fifth Evaluation Report published by IPCC, the RCP4.5 scenario indicated a stabilized emission of greenhouse gases. Using the output data of GCM models under the RCP4.5 scenarios, the amount of SPI, as well as the severity and duration and peak intensity of drought for all network points within the basin were calculated based on the obtained SPIs. Then the Log-normal distribution function was adjusted to the values of severity and duration and the Exponential distribution function was adjusted to the values of the peak intensity of the drought. Finally, using the bivariate Gumbel Copula function for the severity-duration Copula, the bivariate normal Copula function for the severity-peak intensity of the drought

and the tri-variate normal Copula function for the severity-duration-peak intensity of the drought, the return period of the most severe drought in the network points within the basin was obtained and the zoning map was drawn for each model.

The spatial map of the drought return period for GCM models under the RCP4.5 scenario had been drawn based on the return period calculated with the three mentioned Copulas for the near future (2016-2057) as shown in Figure (5). In the bivariate severity-duration Copula during this period, the GFDL-ESM2M model showed almost similar to or a little worse conditions as the drought conditions during the historical period. Other models showed better conditions; regarding the intended severe drought, they showed less occurrence frequency than the historical period. Most of the used GCM models predicted the occurrence frequency of the intended severe drought to be about 25 years. In some models. the return period of severe drought in the major part of the basin was about 50 years. In the bivariate Copula of severity- peak intensity of the drought, the period of intended severe drought was less than 5 years in all models. This means that up to once every 5 years, a severe drought with an SPI value of less than (-4.39) and a peak intensity of drought with an SPI value of less than (-1.36) was likely in the basin. During this period, the CNRM-CM5 model showed drought conditions almost similar to the drought conditions during the historical period. In the tri-variate Copula of the severity-duration-peak intensity of the drought, the GFDL-ESM2M model in this period showed the drought conditions almost similar to or a little worse than the historical period in the basin. Most models predicted the severe drought return period in the basin to be less than 25 years. In other words, the occurrence frequency of severe droughts varied from less than 10 years in the past to less than 25 years in the future.

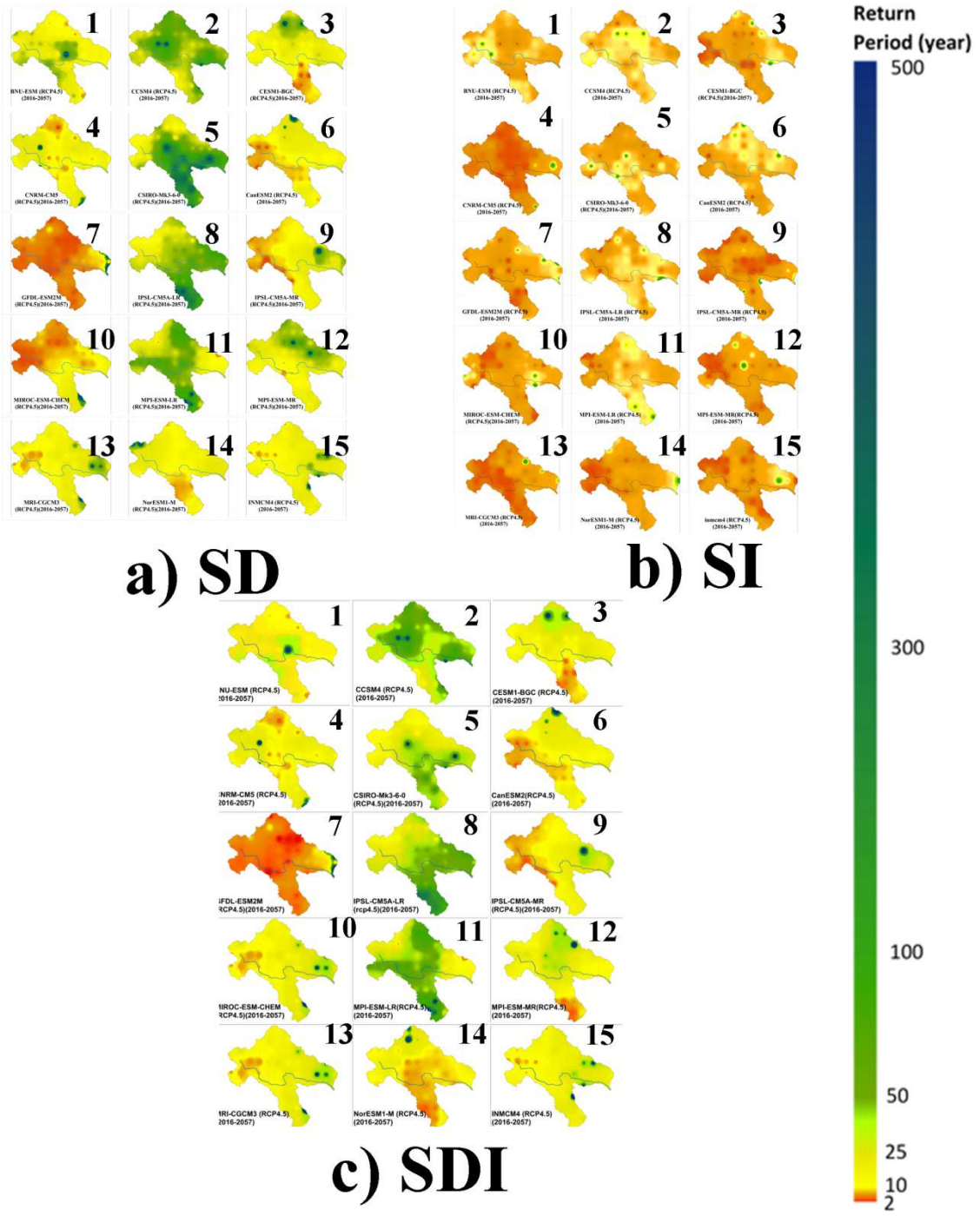

Figure5: Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the near future (2016-2057) using 15 GCMs with RCP4.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

The spatial analysis of the drought return period for GCM models under the RCP4.5 scenario calculated with the three mentioned Copula for the distant future (2058-2099) is shown in Figure (6). In the bivariate severity-duration Copula, in the GFDL-ESM2M model, the entire basin was exposed to severe drought and the frequency of severe drought was less than 5 years. Other GCM models predicted a lower occurrence frequency of the severe drought, and in some cases, the return period was calculated to be more than 50 years for the severe drought. In the bivariate Copula of the severity-peak intensity of drought, the results of the GFDL-ESM2M model indicated similar or a little better conditions to historical conditions. In this model, the whole basin was exposed to severe drought and the occurrence frequency of severe drought was less than 3 years. Other GCM models predicted a lower occurrence frequency of the severe drought, and the probability of intended severe drought has increased to less than 5 years. As shown in this figure, in the tri-variate Copula of the severity-duration-peak intensity of the drought, the range of changes in the severe drought frequency from the 15 GCM models under the RCP4.5 scenario in the distant future (2058-2099) was much greater. The results of the GFDL-ESM2M model showed that the entire basin will be prone to severe drought with a frequency of fewer than 2 years. Other GCM models predicted a lower frequency for severe droughts and in some cases, the return period of severe droughts was extended to more than 50 years.

3.3 Effects of Climate Change on the Drought under RCP8.5 Scenario

According to the previous section, zoning maps from the above calculations were also prepared based on the RCP8.5 scenario. The effects of climate change on the drought based on the data from GCM models under the RCP8.5 scenario for the near future (2016-2057) are shown in Figure (7). In the bivariate Copula of the severity-duration, most GCM models predicted a longer return period than in the past for possible severe droughts in the near

future, which meant less occurrence of the frequency of this drought. In general, according to the results of the GCM models used under the RCP8.5 scenario in the near future, a return period of about 25 years is expected for the severe drought in the basin. In the bivariate Copula of the severity-peak intensity of drought, most GCM models predicted a higher return period than the past for possible severe droughts in the near future, which meant less occurrence of the frequency of this drought. In general, according to the results of the GCM models used under the RCP8.5 scenario in the near future, a return period of about less than 10 years is expected for severe drought in the basin. In the tri-variate Copula of the severity-duration-peak intensity of the drought, while in the central part of the basin, the severe drought return period was less than the historical period in this area. Most GCM models predicted a more severe drought return period for the near future than the historical period, indicating a lower occurrence frequency of severe drought than the historical period, with some models even reaching a 50-year return period.

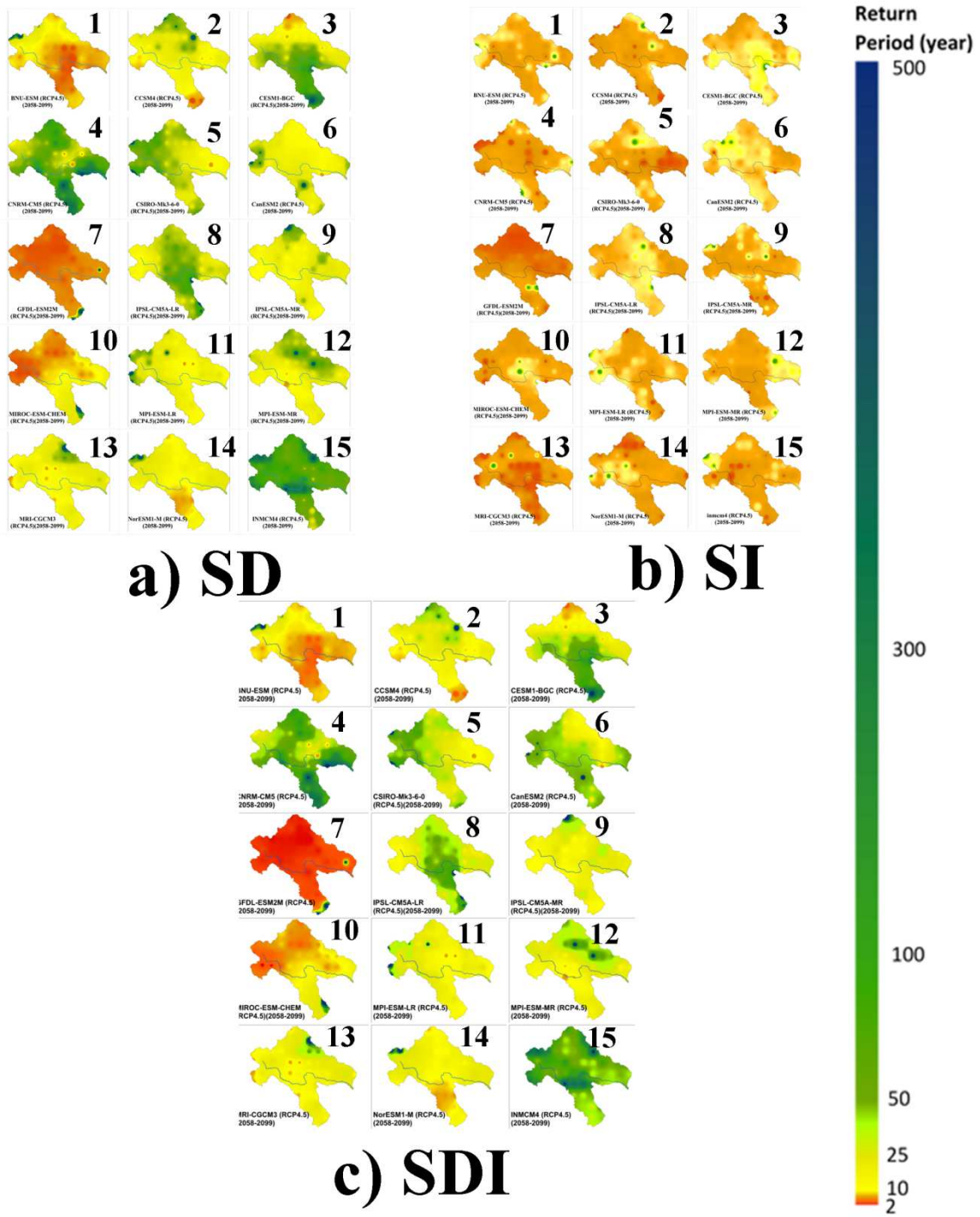

Figure 6: Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the distant future (2058-2099) using 15 GCMs with RCP4.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

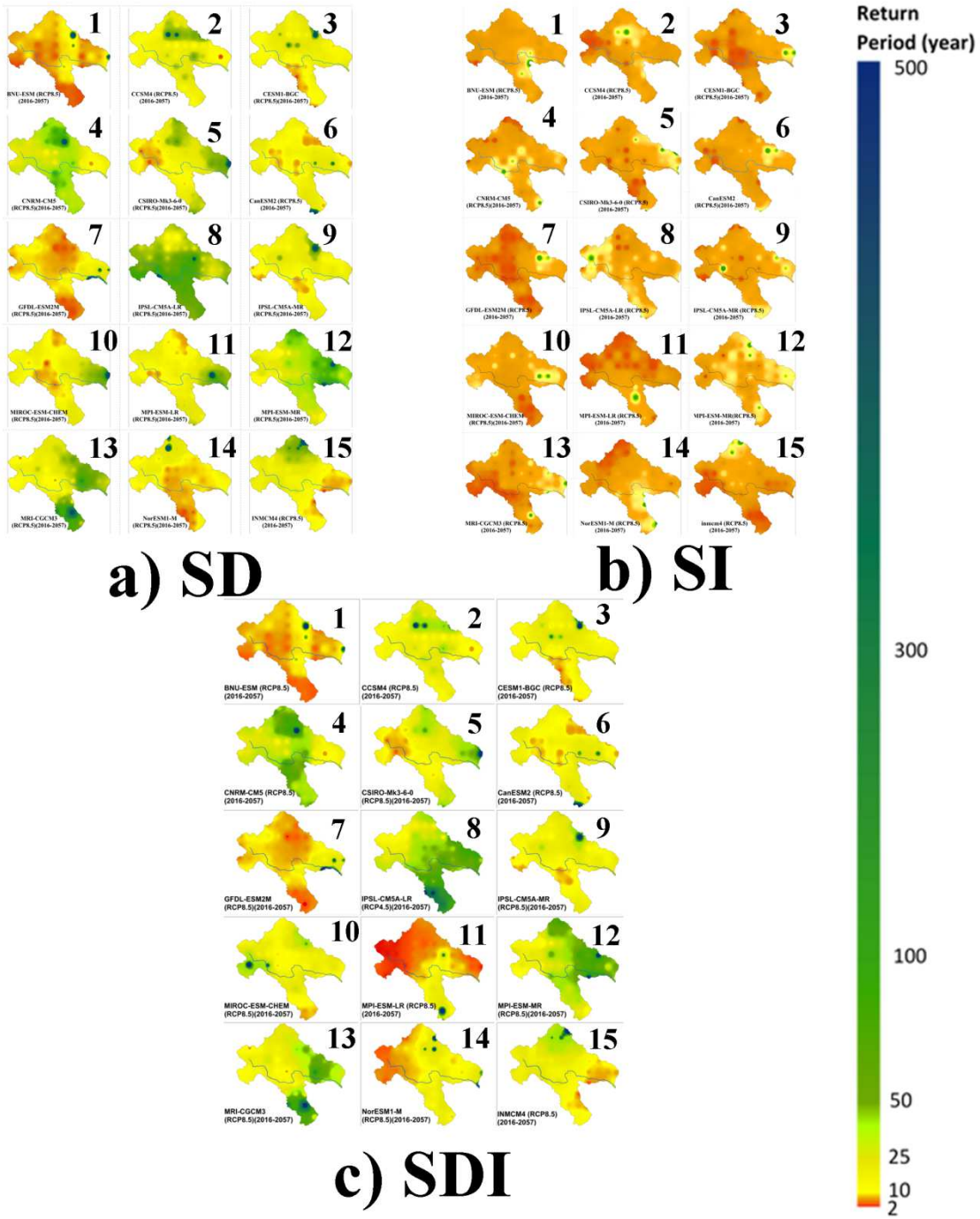

Figure 7: Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the near future (2016-2057) using 15 GCMs with RCP8.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

The effects of climate change on the drought based on the data from GCM models under the RCP8.5 scenario for the distant future (2058-2099) are shown in Figure (8). In the bivariate Copula of severity-duration, the range of variations in the return period of the calculation varied from about less than 10 years to about 400 years. Some models predicted a return period of more than 100 years. Other models predicted a return period of about 25 years for the severe drought intended for the basin. In the bivariate Copula of severity - peak intensity of the drought, the CanESM2 model predicted conditions similar to those of the historical period. Other models predicted a return period of about 10 years for the intended severe drought. Depending on the tri-variate Copula of the severity-duration-peak intensity of drought, the range of return period values in the distant future for the intended basin varies between 10 years to 400 years. In the CESM1-BGC and the IPSL-CM5A-MR models, the return period of severe drought has been more than 100 years for almost all parts of the basin, and the decrease in the occurrence frequency of severe drought in the basin is predicted. Other GCM models predicted a return period of about 25 years for the severe drought in the basin.

Based on the results of the calculations performed with the help of bivariate Copula of severity-duration, the drought return period in the near and distant future for the basin increases from less than 10 years to about 25 years compared to the historical period. According to the bivariate Copula of the severity-peak intensity of drought, the return period of the drought in the near and distant future for the basin increases from less than 5 years to more than 10 years compared to the historical period. The results did not provide information on the duration and durability of the severe drought. Without the knowledge of the duration of each drought, planning for water resources is difficult and inaccurate. According to the tri-

variate Copula of the severity-duration-peak intensity of the drought in each period, the return period of the drought in the distant future for the basin increases from less than 10 years to more than 25 years compared to the historical period. Based on GCM models, despite the slight increase in precipitation in the future, due to the uncertainty of climate change forecasts, it is recommended to have a comprehensive water resources management plan in the basin to deal with long-term severe droughts.

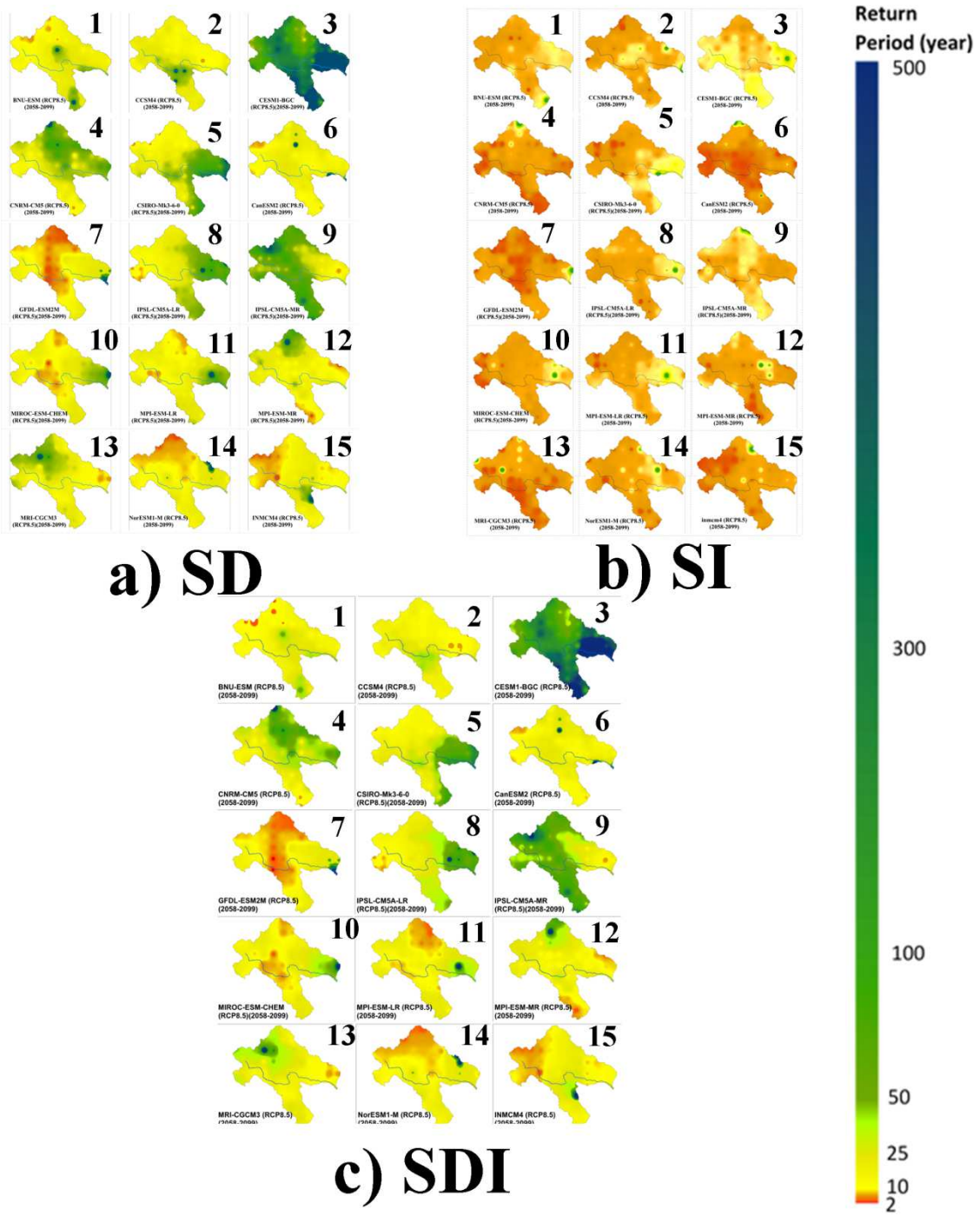

Figure 8: Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the distant future (2058-2099) using 15 GCMs with RCP8.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

3.4 Frequency Analysis of the Most Severe Drought using Bivariate and Tri-variate Copula Functions

According to the results of the drought frequency analysis with the help of bivariate Copula functions of severity-duration, severity-peak intensity, and the tri-variate Copula of the severity-duration-peak intensity of the drought, it is quite clear that the results of bivariate Copula function of severity-duration and tri-variate Copula of the severity-duration-peak intensity were very close to each other, with similar results for the analysis of historical drought as well as the drought in the near and distant future. However, the results of drought analysis with the help of bivariate Copula of severity- peak intensity, was very different from the results of the previous two Copulas and predicted severe droughts occurring with more frequency.

Figure (9) shows the return period of the severe drought based on different drought parameters in the historical period (1979-2008). As shown in the figure, the calculated return period based on the tri-variate Copula was larger. This means that the occurrence frequency of severe drought with higher values than the specified values of severity, duration, and peak intensity, was less. After that, the highest value of the return period results was obtained based on the drought analysis using the bivariate Copula of the duration-peak intensity. Then, the results of the bivariate Copula of the severity-duration were most similar to the tri-variate Copula, and three modes obtained the return period of severe drought for the basin more than other models. The bivariate Copula of severity- peak intensity, showed a lower return period for the relevant drought, and as shown in the figure, the results were more consistent with the results of the calculation of the drought return period based on only one of the variables of

the severity of peak intensity. The implications of this figure and the results suggest that the duration of the drought plays a large role in the drought level return period in the basin, and the higher the intended continuity and duration of drought, the higher the return period for that drought. While the basin has been exposed to a high frequency of drought occurrences, these droughts have not lasted long and have been short-lived.

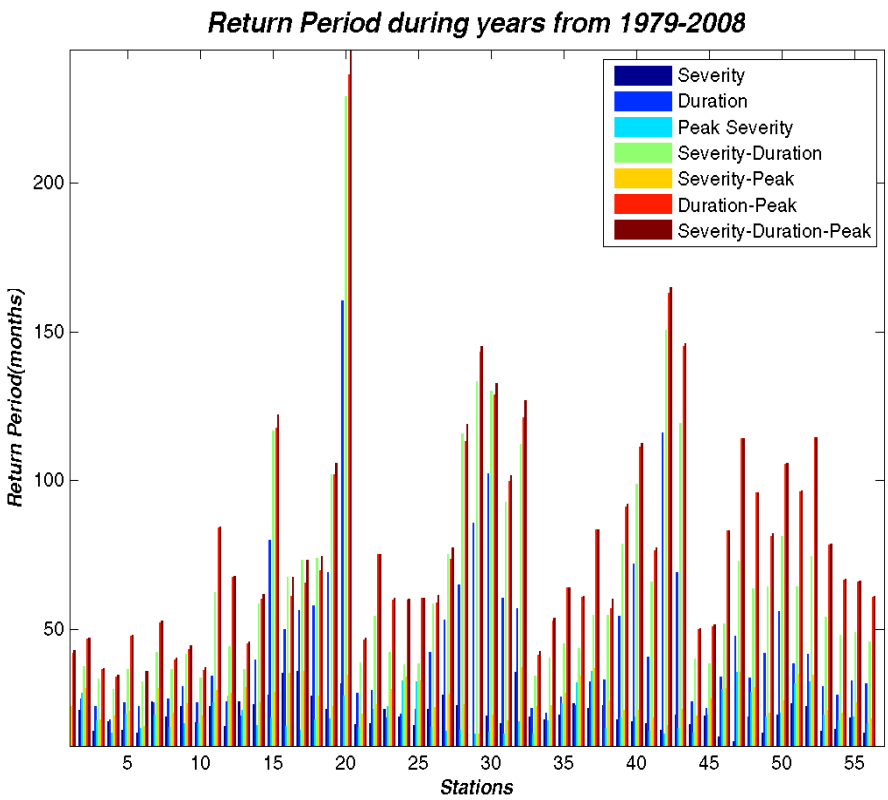

Figure 9: Return period of severe drought based on various drought parameters in the Historical Period (1979-2008)

4 Conclusion

As mentioned, drought is an extreme phenomenon that has far-reaching effects on agriculture and water resources. Considering simultaneously the phenomenon of climate change and drought, different effects are expected depending on the location and environmental

conditions of the region. Therefore, assessing the effects of climate change on the drought is of particular importance to water resource planners. In this study, three main steps have been considered, which are: 1) Calculating the duration, severity, and peak intensity of the drought based on SPI, fitting different distribution functions to them and determining the best distribution function for each characteristic, determining one of the most severe historical drought events with the highest value of duration, severity, and peak intensity, and finally using the appropriate Copula functions to estimate the frequency of drought occurrences with the predefined highest values, 2) Investigating the effects of climate change using general circulation models (GCM) for future periods, 3) Assessing the return period of the future drought using Copula functions and calculating the characteristics of drought events in the future and drawing spatial maps of the return period of future drought.

The SPI was used to calculate the duration, severity, and peak intensity of drought in the basin in the historical period (1979-2008). Among the phenomena that occurred during this period, 90% of the highest severity, duration, and peak intensity of drought were selected as the benchmark severe drought in the basin. The values included a drought severity with an SPI value of less than (-4.39); drought duration more than 6 months, and peak intensity with an SPI value of less than (-1.36).

Due to the high correlation between drought characteristics, bivariate and tri-variate Cupula joint functions were used to analyze the return period of future droughts in the basin. For this purpose, three types of widely used Cupula functions in the Archimedes family (Frank, Clayton, Gumbel-Hoggard) and two types of the most widely used Cupula functions of the elliptical family (t and normal) were utilized in this study. Then the best Cupula function was selected based on the BIC method. The effects of climate change on the drought were also investigated using 15 GCM models under RCP4.5 and RCP8.5 scenarios. The future period

was divided into two near future (2016-2057) and the distant future (2058-2099) periods to assess the drought situation.

The results of the GCM models under both scenarios for the near and distant future were almost the same and predicted a longer return period for severe drought than in the past. Contrary to this prediction for the basin based on GCM models, due to the uncertainties in climate change forecasting methods, planning for long-term droughts in the basin seems necessary to manage existing water resources.

Also, by examining the calculated return period based on different drought parameters in the historical period (1979-2008), the results of the bivariate Copula of the severity- peak intensity can be more compatible with the results of the drought return period based only on one of the variables of severity or the peak intensity of droughts. It appears that the drought duration variable plays an important role in the drought return level in the basin; having increased the continuity of drought duration, the return period of that drought is increased, or in other words, the occurrence frequency is reduced.

It is recommended to compare the results of research using AR4 with the current study to find the preference of AR5 in comparison with AR4 in the case of a copula. Also, it is worthwhile to analyze the uncertainty of the prediction by the GCMs and to estimate the probability levels for each model. Besides, it will be advantageous in future studies to analyze the uncertainty of calculated past return periods.

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Declarations

Ethics approval and consent to participate (Approval was obtained from the ethics committee of Shahid Chamran University. The procedures used in this study adhere to the tenets of the Declaration of Helsinki

Consent for publication (Not applicable)

Availability of data and material (All data generated or analysed during this study are available from the corresponding author)

Competing interests (The authors declare that they have no competing interests)

Funding (Not applicable)

Authors' contributions: Material preparation, data collection, study conception, design and analysis were performed by Dr. Elaheh Motevali Bashi Naeini and then it was involved in planning and supervised by Dr. Ali Mohammad Akhoond-Ali and Dr. Fereydoun Radmanesh. The first draft of the manuscript was written by Elahe Javadi and then Dr. Jahangir Abedi Koupai commented on previous versions of the manuscript. Dr. Shahrokh Soltaninia verified the analytical methods and performed some calculations. All authors discussed the results and contributed to the final manuscript and approved the final manuscript.

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Figures

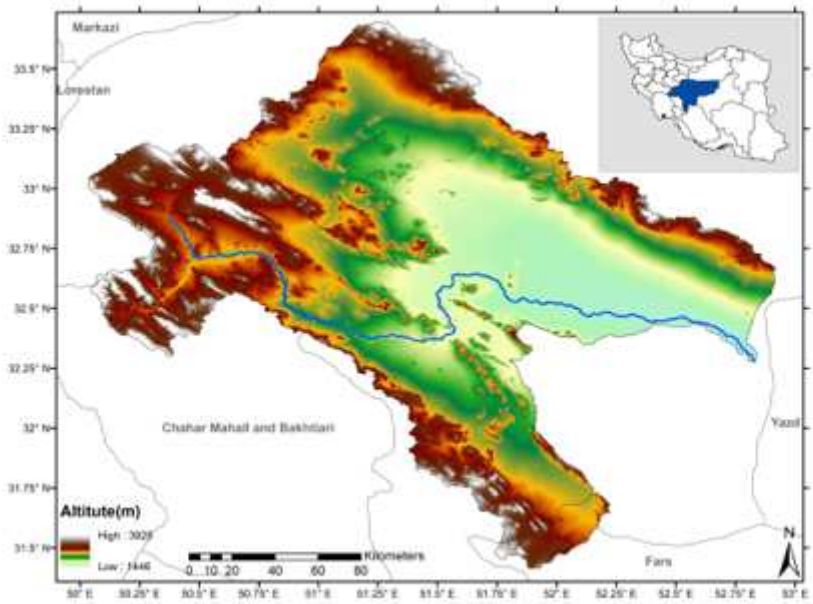

Figure 1

Geographic location of the Zayandeh Rud basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

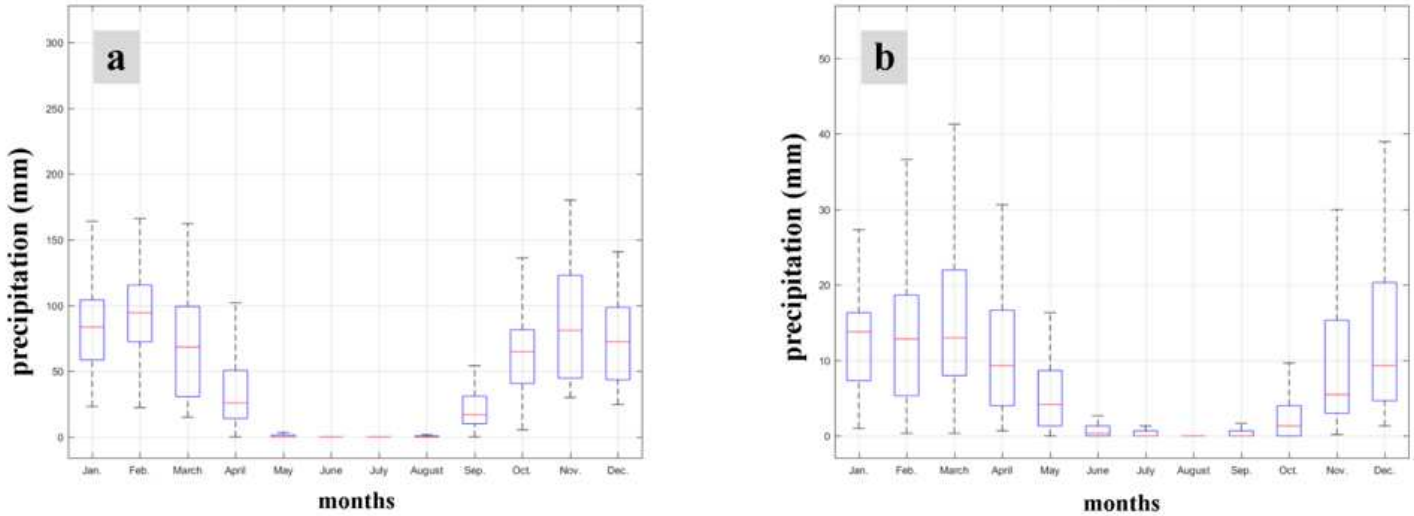

Figure 2

Changes in monthly precipitation in the past (1979-2008): a) station located upstream b) station located downstream

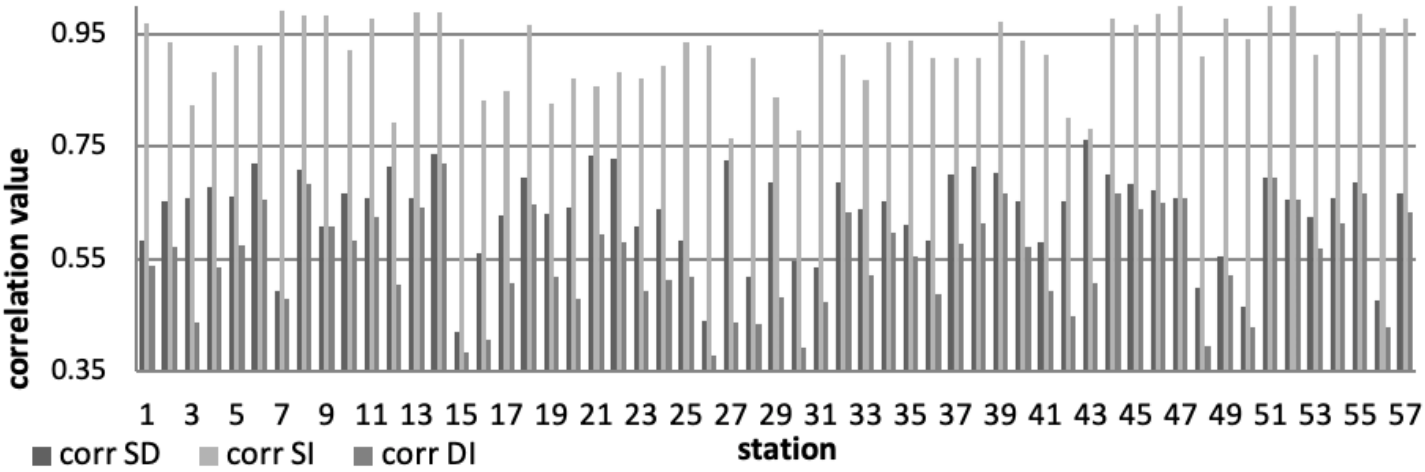

Figure 3

Linear correlation between drought characteristics (S indicates severity, D indicates duration, and I indicates the peak intensity of drought in each period.)

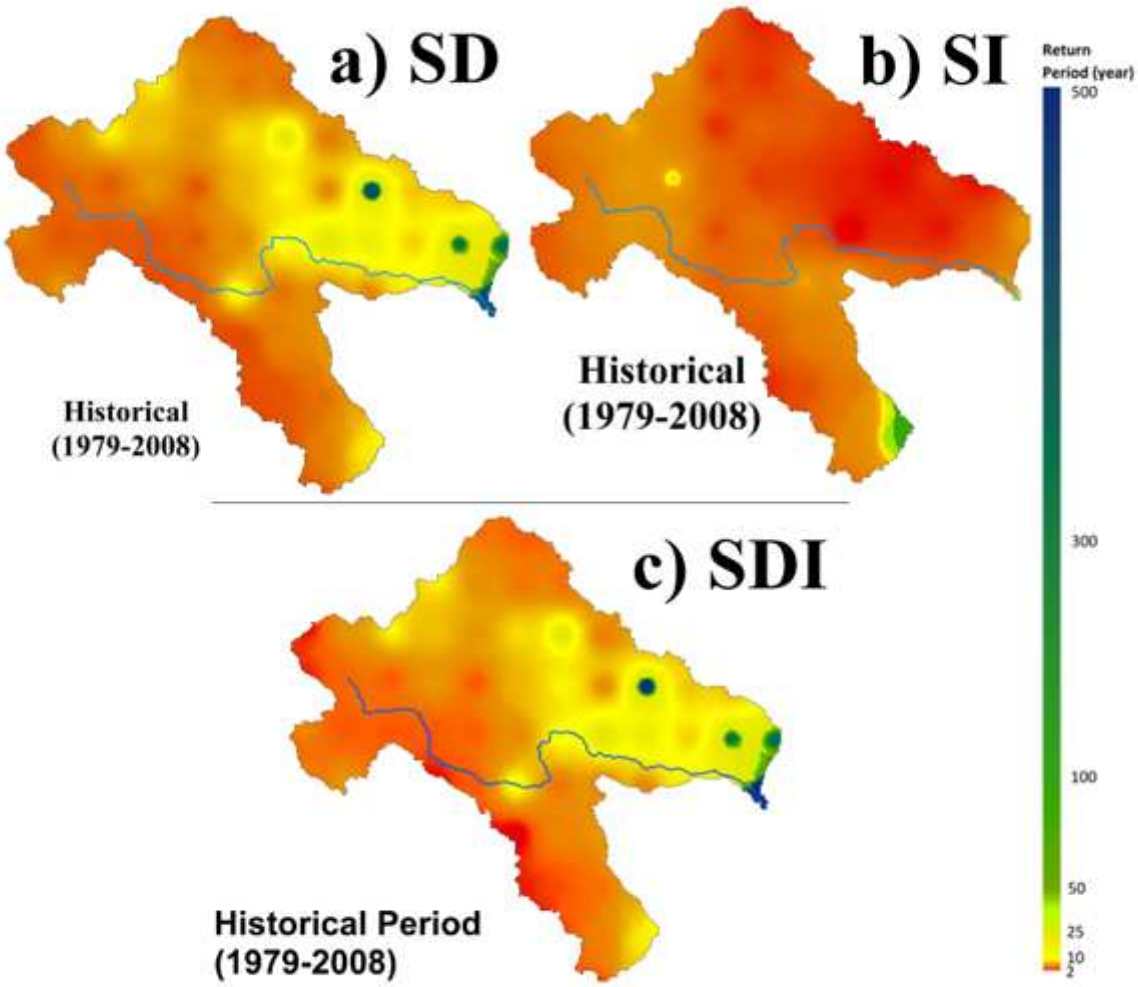

Figure 4

Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the historical period (1979-2008) a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

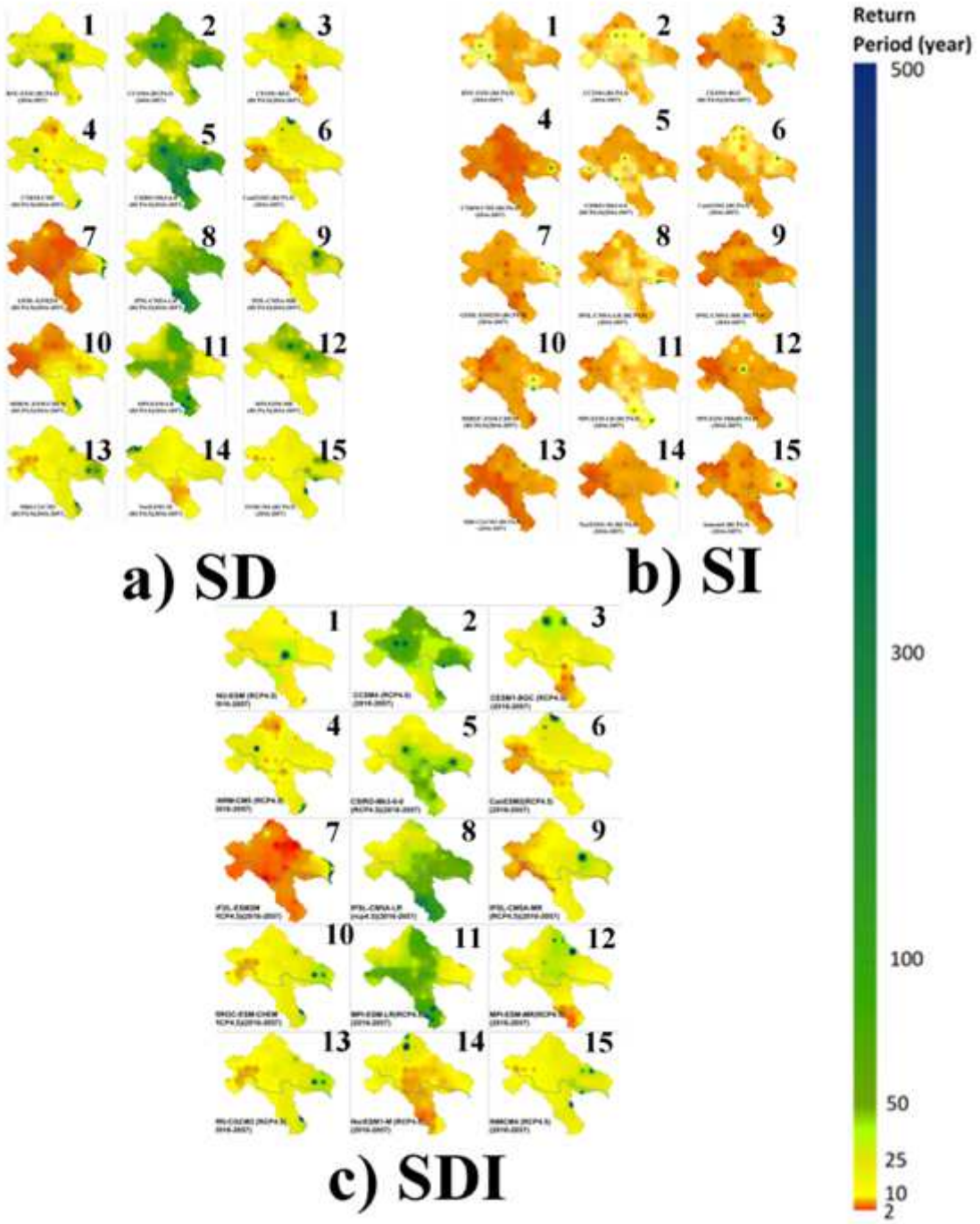

Figure 5

Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the near future (2016-2057) using 15 GCMs with RCP4.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

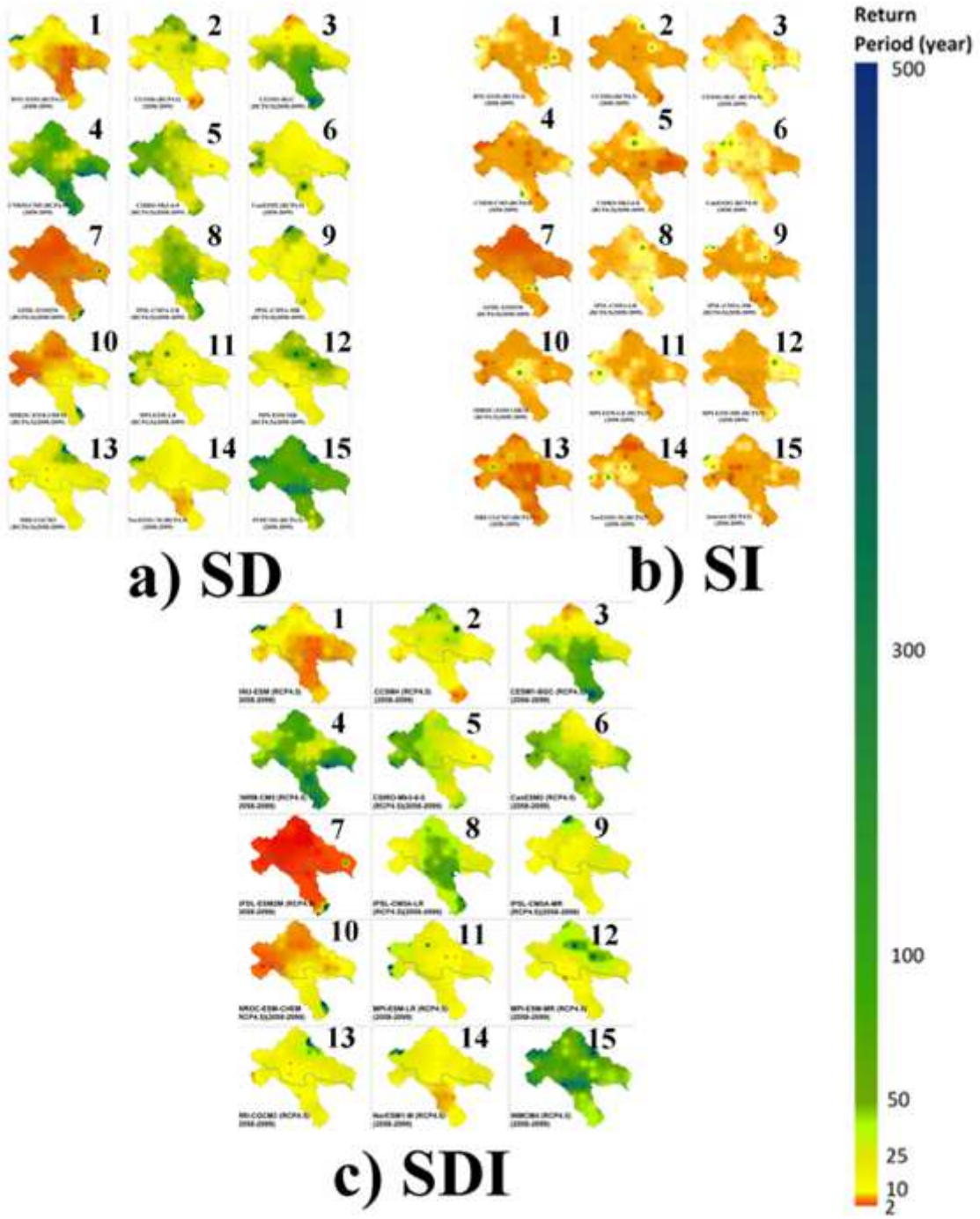

Figure 6

Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the distant future (2058-2099) using 15 GCMs with RCP4.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

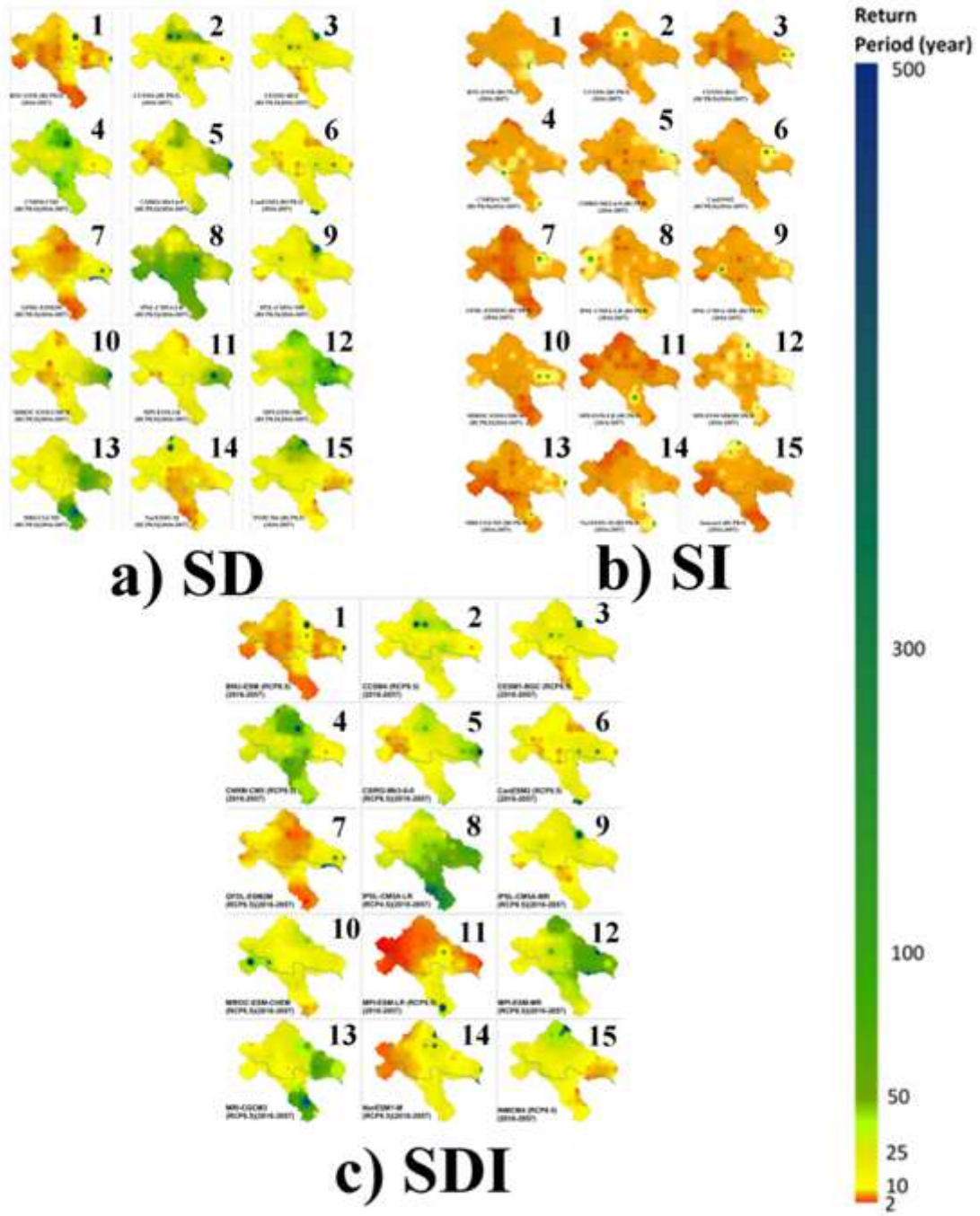

Figure 7

Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the near future (2016-2057) using 15 GCMs with RCP8.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

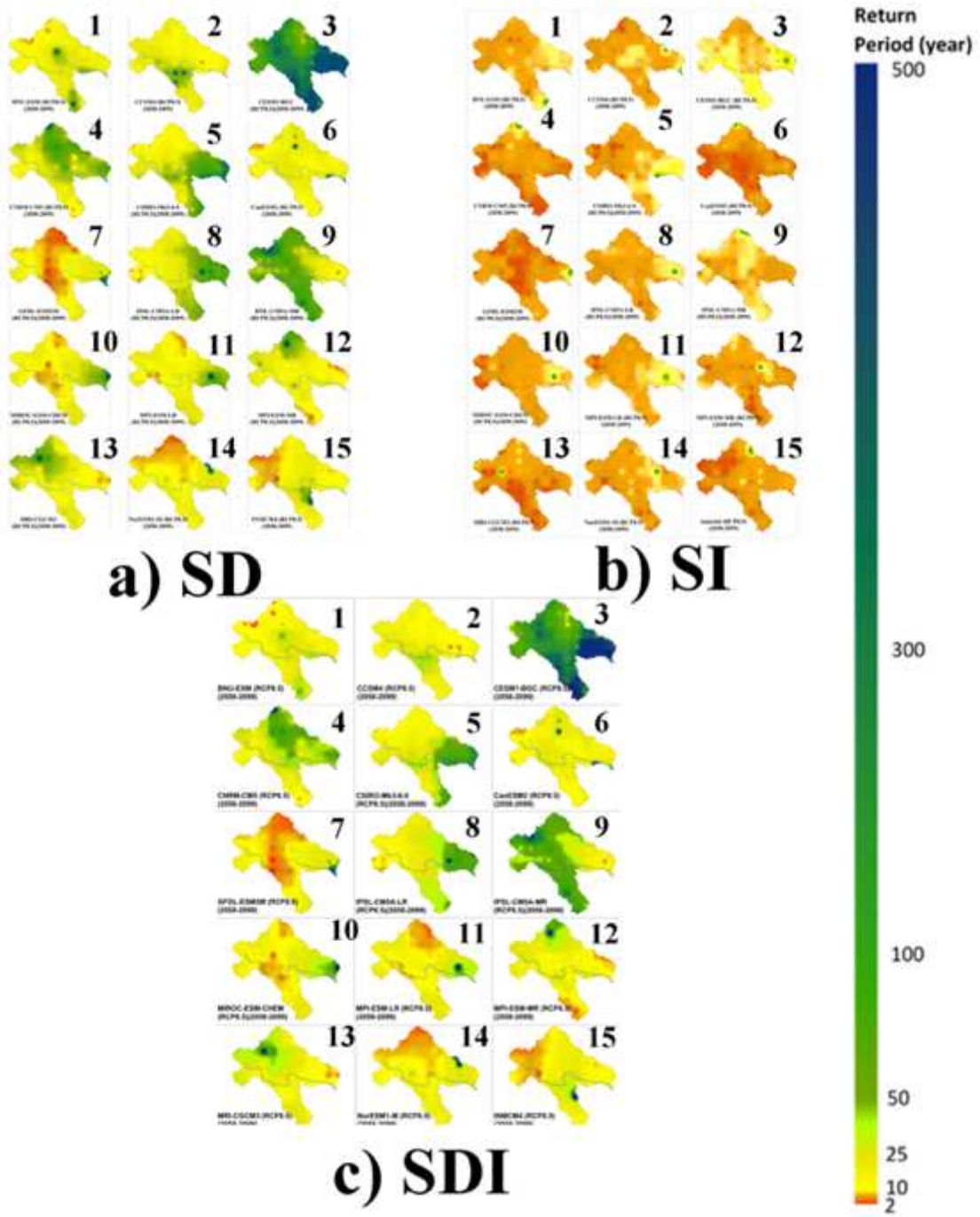

Figure 8

Comparison of the calculated return period of the severe drought using tri-variate and bivariate copula functions in the distant future (2058-2099) using 15 GCMs with RCP8.5 a) SD: bivariate copula of Severity-Duration b) SI: bivariate copula of Severity-Peak intensity and c) SDI: tri-variate copula of Severity-Duration-Peak intensity.

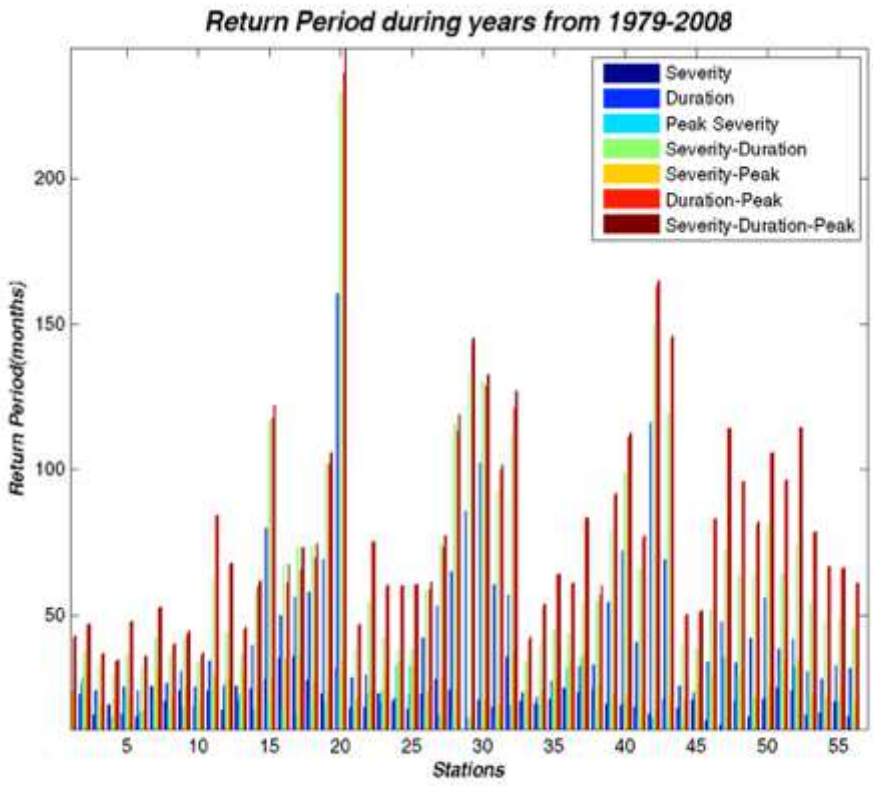

Figure 9

Return period of severe drought based on various drought parameters in the Historical Period (1979-2008)