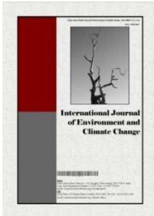

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Comprehensive Drought Analysis Using Statistical and Meteorological Indices Approach: A Case Study of Badin, Sindh

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Authors' contributions

All authors contributed equally in the analysis and writing of this manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Drought is a global phenomenon that can occur in any ecological zone and render significant damages to both the natural environment and human lives. However, hydro-climatic stresses are growing distinctly in the arid zones across the globe. Literature suggests that the analysis of a long-term data-set could help in strengthening of mitigation planes and rationalization of disaster management policies. Thus, the present study is aimed to analyze the evidence-based historical drought events happened in arid-zone Badin, Pakistan and predict its occurrence and severity for the next 82 years (2018-2099). Drought indices *viz* standardized precipitation index and reconnaissance drought index have been used to detect the severity of the drought events. Thirty years (1988 to 2017) past data of precipitation and temperature were used to categorize the drought severity and validated against the local data. Climate projections based on RCP 4.5 and 8.5 made at 25x25 km resolution used for future drought analysis. The results demonstrate that the region faced severe to extreme drought in 1990-91 and 2001-04. While, in future 2020-21, 2036-37,

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2038-39 would be the extreme driest years under RCP 4.5 and 2029-30, 2089-90 under RCP 8.5. Further insight revealed that the average annual temperature has increased and precipitation has decreased w.r.t the base year 1988. It is concluded that drought detection with SPI and RDI is suitable and drought prediction with the RCP 4.5 and 8.5 could be a better option.

Keywords: Drought; standard precipitation index; reconnaissance drought index; climate projections.

1. INTRODUCTION

Climate change is now a globally recognized phenomenon. Extreme variabilities in temperature and precipitation make any region more vulnerable, and it can lead to climate hazards like floods, droughts, heat waves and cyclones [1]. In addition to other natural disasters, droughts are becoming more common and turn out a threat at global, regional, and local levels. Globally droughts occur almost in all landscapes and damage the vegetation, human lives, and animals [2]. Droughts generally occur in those regions, which experience less precipitation than normal over a longer period of time. Mainly droughts are of four kinds: meteorological, agricultural, hydrological, and socio-economic [3]. Meteorological droughts occur due to a deficiency in precipitation and an increase in temperature (heat wave) [4]. Agricultural droughts occur due to soil water deficiency [5]. However, hydrological droughts occur due to a shortage of surface water in streams, lakes, and reservoirs [6] and socioeconomic droughts occur when any weather-related fluctuations in water supply result in an increase in demand of goods with respect to supply [7]. Though, it is slow occurring, it regularly affects all parts of the world [8]. In India, a larger proportion of the country is perennially reeling under the repeated drought impacts [9]. Droughts are responsible for millions of death and billions of dollars of economic losses. Most recently the emergency response database reported that between 1990 and 2011, 11 million people were killed in the drought.

Pakistan is one of the most marginalized countries confronting with the serious hazards of climate change [10] and continuously facing significant water scarcity. Population growth, urbanization, industrialization and agricultural development are rapidly increasing the demand for water resources. Pakistan experiences droughts frequently in southern parts of the country. According to National drought monitoring center (NDMC), Sindh and Baluchistan provinces are more vulnerable to droughts, as shown in Fig. 1.

The Badin district is one of the major regions of Pakistan that contributes to the national economy in the form of oil, gas, rice, and seafood. Despite these valuable deposits, the region is marginalized and vulnerable to natural disasters. It is prone to disasters like flash floods, droughts, earthquakes, and desert storms. Drought conditions have emerged due to lack of monsoon rains because water demands in this region are generally met by monsoon rains. The weakening of monsoon was observed in all the talukas of Badin including Badin city, Golarchi (S.F.Rahu), Matli, Talhar, and Tando Bago. Monsoon rains play a substantial role in the irrigation of the land, however, the absence of irrigation system worsens the situation and region becomes infertile. In that situation, agricultural production and livestock suffer badly. The existence of drought for a longer period is seriously harmful to agriculture, the health of humans, water management, forestry, ecosystem, and several other factors.

Therefore, drought mitigation planning is essential; it involves different tools. These tools include policies, programs, activities, and planning. But, before mitigation, it is important to identify the historical and future drought events in the region. For assessing and characterizing drought, several indices are proposed by different researchers [12]. Globally, the SPI is used, because of its capability to analyze the different aspects of drought [13] and it only depends on precipitation. However, in arid regions, the temperature is also a key factor in increasing drought severity. In this regard, RDI has been used in various driest areas around the world [14]. It depends on potential evapotranspiration along with precipitation. So, this is a more suitable index that computes the severity of the drought.

The objectives of this study are to identify historical and future drought events occurred in

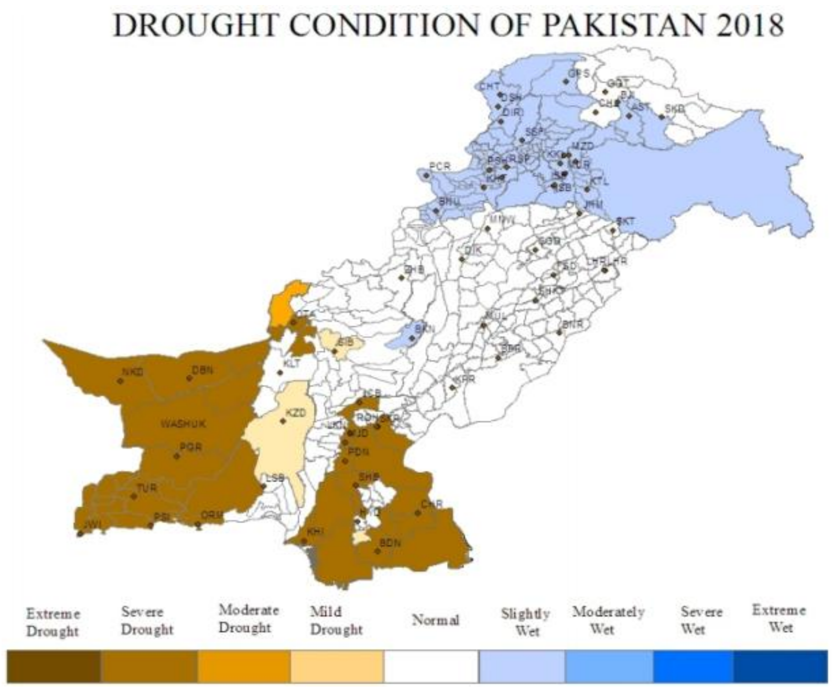

Fig. 1. Pakistan map showing drought condition in 2018 [11]

Badin district, using SPI and RDI. It is expected that the results of this research provide useful evidence to decision makers and stakeholders to trigger drought preparedness plans, and findings of this study will be helpful to serve as a scientific reference for drought assessment.

2. MATERIALS AND METHODS

2.1 Study Area

Badin is located in the southern Sindh, Pakistan, extending over 24°38’45.09 N and 68°50’47.96 E. It comprises of five talukas, i.e. Badin, Golarchi (S.F.Rahu), Matli, Talhar, and Tando Bago. The district covers an area of 6,726 km^2. It lies between the coastal stretches of the Arabian Sea and the Thar Desert [15]. The location of the Badin district is shown in Fig. 2.

The average annual precipitation of Badin is 235 mm. The annual temperature and precipitation variation for Badin district is presented in Fig. 3.

2.2 Data Description

Historical data of temperature and precipitation, covering the period of 1988–2017 for Badin weather station were obtained from Pakistan meteorological department (PMD). The future projections of temperature and precipitation under RCP 4.5 and 8.5 were downscaled for Badin at 25×25 km resolution under the guideline of the intergovernmental panel on climate change IPCC [16] from 2018 to 2099.

2.3 Drought Indices

The drought severity (i.e. extreme, severe and moderate) was computed by using drought indices SPI and RDI. We have described these indices below.

2.3.1 Standardized precipitation index (SPI)

The SPI was designed by researchers at Colorado State University [17,18] to compute the drought severity at multiple time scales. According to McKee et al. [18], drought event starts when the value of SPI becomes -1.0 or less. The drought will not end until the SPI returns to positive. This index is being used worldwide [19]. SPI is computed according to the following formula:

$$\mathrm{SPI} = \frac{X_i - \overline{X}}{\sigma} \qquad (1)$$

where X_i is precipitation, $\overline{X}$ is average precipitation, and σ is the standard deviation.

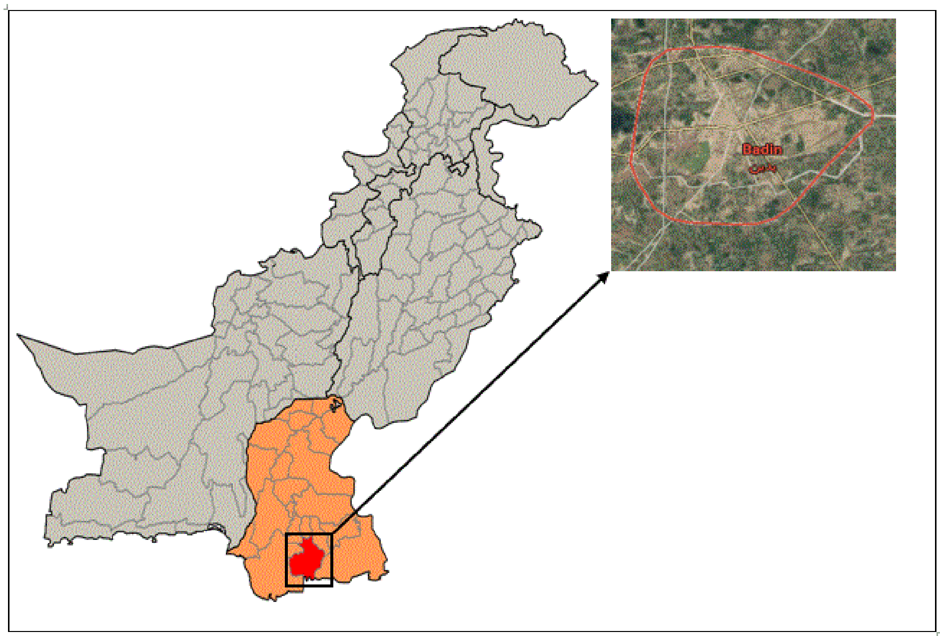

Fig. 2. Location map of Badin district, Sindh, Pakistan

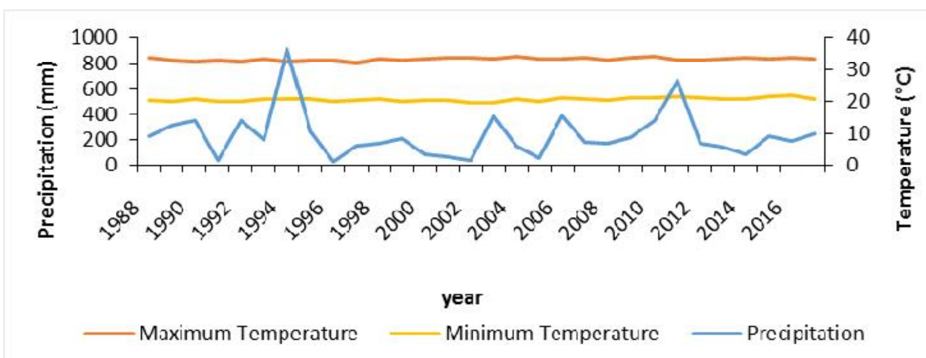

Fig. 3. Annual temperature and precipitation data of Badin for last 30 years (1988-2017)

2.3.2 Reconnaissance drought index (RDI)

The RDI was designed by researchers [20,21]. It is mostly used in arid regions [22,23]. It is used to calculate the severity of the drought more precisely because it incorporates potential evapotranspiration (PET) along with the precipitation (P), which provides a more realistic insight of the drought situations. It is expressed as the initial value (α_k), normal value (RDI_n) and standard value (RDI_{st}).

The initial value is given as

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^{k} P_{ij}}{\sum_{j=1}^{k} PET_{ij}} \qquad (2)$$

Where P_{ij} is precipitation, and PET_{ij} is potential evapotranspiration, i is the no of years, j is no of months and n is total no of years.

The normal value (RDI_n) is given as:

$$RDI_n^{(i)} = \frac{\alpha_k}{\overline{\alpha}_k} - 1 \qquad (3)$$

where $\overline{\alpha_k}$ = mean of α_k

The standard value (RDI_{st}) is calculated as:

$$RDI_{st(k)}^{i} = \frac{y_k^i - \overline{y_k}}{\sigma_{y_k}} \qquad (4)$$

where y_k =ln (α_k), $\bar{y}$ is average and σ_{yk} is the standard deviation.

Table 1. Classification of drought based on SPI and RDI

Classification	SPI / RDI
Extreme wet	≥2.0
Very wet	1.5 to 1.99
Moderate wet	1.0 to 1.49
Near normal	-0.99 to 0.99
Moderate drought	-1.0 to -1.49
Severe drought	-1.5 to -1.99
Extreme drought	≤ -2

2.4 Representative Concentration Pathway (RCP)

The RCPs are the greenhouse gas concentration trajectories used by the IPCC in its Fifth Report (AR5) 2014. For climate research and modeling, four paths describing different climate scenarios were chosen. The RCPs cover the time period up to 21st century. RCPs are consistent with various possible changes in future greenhouse gas (GHG) emissions [24]. There are four RCPs, RCP 2.6, 4.5, 6, and 8.5 [25]. RCP 2.6 assumes that greenhouse gas emissions peaked between 2010 and 2020, after which emissions were significantly reduced. Emissions in RCP 4.5 peaked around 2040 and then declined. Emissions in RCP 6, peaked around 2080 and then fell, whereas emissions in RCP 8.5 continue to rise throughout the 21st century [26].

2.5 Significance Test

2.5.1 Mann–Kendall test

The linear trend of annual rainfall and temperature were computed by using the Mann Kendall test [27], which is generally used to analyze the time series trend [28]. To compute the variance, the following procedure was used:

$$\mathrm{Var(S)} = \frac{1}{18}\left[\mathrm{n(n-1)(2n+5)} - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \quad (5)$$

where q has the same value of sample data and $t_p$is the data values of the p_{th} group.

The statistic S is calculated by using the following formula

$$\mathrm{S} = \sum_{j=1}^{n-1}\sum_{k=j+1}^{n} \mathrm{sgn}(x_k - x_j) \quad (6)$$

where sgn (θ) is a significant function, j and k are the data values and n denotes the length of the data.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}} & if\ S < 0 \end{cases} \quad (7)$$

The Z value is distributed normally, and Z value greater than 1.96 represents an upward trend, while Z value less than −1.96 represents a downward trend.

2.5.2 Sen's slope method

The Sen's method was used to compute the slope of the linear trend [29].

$$\mathrm{G\ (t) = Xt + Y} \quad (8)$$

where G(t) is the function of a linear trend, X represents the slope and Y represents the constant. The magnitude of the trend is computed by the following formula:

$$\mathrm{Q} = \mathrm{median}\ \frac{x_i - x_j}{t_i - t_j} \quad (9)$$

where x_i and x_j are the values of data at times t_i and t_j (i > j), respectively.

3. RESULTS AND DISCUSSION

In this study, drought analysis was presented at annual timescale. We used 30 years observed data, 82 years of future projected data and drought indices SPI and RDI to analyze the droughts events in Badin during 1988–2017 and 2018-2099.

3.1 Historical Drought Events over the Past 30 Years (1988-2017)

The drought events computed by SPI and RDI at annual timescale is depicted for Badin regions of Sindh during 1988–2017 as shown in Fig. 4. The horizontal axis represents a yearly series, while the vertical axis represents the value of indices. The moderate drought appeared in 1995-96, 1997-1998, 1999-2001, and 2013-14 However, the severe drought occurred in 1990-91, 2001-02. Furthermore, an extreme drought occurred in 2003-2004 as shown in Fig. 4.

3.2 Drought Prediction for 2018–2099 under RCP 4.5 Scenario

The results of future drought assessment under RCP 4.5 using SPI and RDI are presented in Fig. 5. In this study, the driest years were located; the severe dry events were found between 2040 and 2050, however, in 2035-40 and 2070 extreme drought events are predicted to occur.

3.3 Drought Prediction for 2018–2099 under RCP 8.5 Scenario

The results of future drought assessment under RCP 8.5 using SPI and RDI are shown in Fig. 6, the average value of SPI is above -2 in 2029-30, 2089-90.So, the drought in these years is classified as extreme drought. RDI shows similar results with SPI. The average value of RDI is above -2 in 2029-30, 2089-90. So, the drought in these years is classified as extreme drought.

3.4 Meteorological Drought: Intensified Warming and Diminished Precipitation

The mean temperature and precipitation in Badin showed significant changes during (1988-2017).

Precipitation has displayed a slightly decreasing trend while temperature has shown an increasing trend. Precipitation is decreased by 0.395 mm yr^{-1} and temperature is increased by 0.029°C yr^{-1}, as shown in Fig. 7.

Model projections for the same region indicate an increasing trend of temperature for the region in the future.

Fig. 4. Time series of SPI and RDI for the Badin during the period (1988–2017)

Table 2. Annual temperature and precipitation trends in Badin district during 1988-2017

Parameter	Man-Kendall test Z	Result	Sen slop test Q
Rainfall (mm)	-0.14	Not significant	-0.395
Temperature (°C)	3.27	Significantly increasing	**0.029**

Bold values represent significance at a 99% confidence level

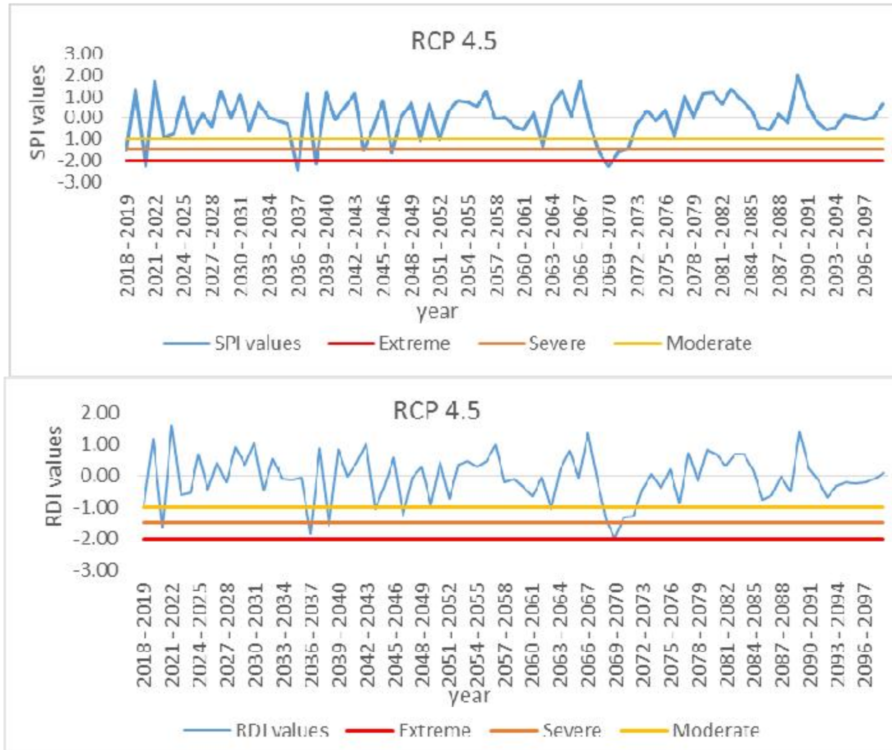

Fig. 5. Time series of SPI and RDI for Badin during (2018-2099) under RCP 4.5

Fig. 6. Time series of SPI and RDI for Badin during (2018-2099) under RCP 8.5

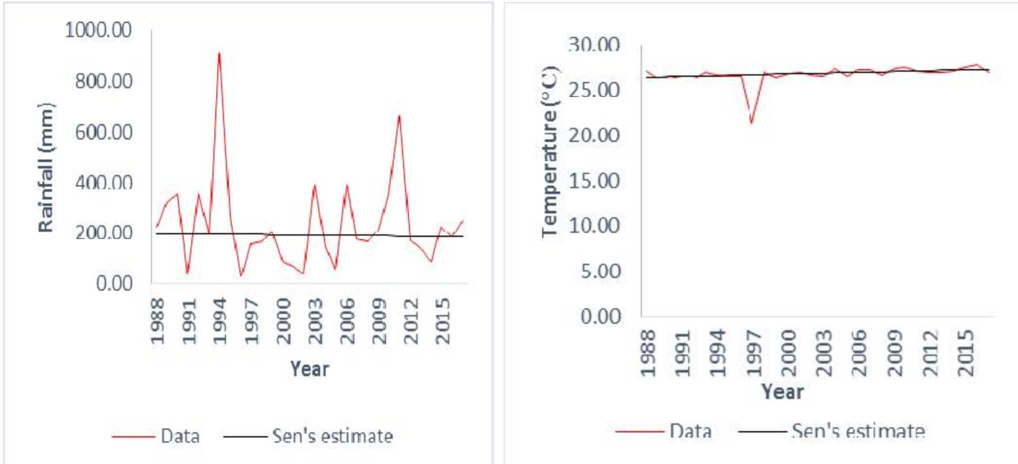

Fig. 7. Temporal changes in annual precipitation and mean annual temperature during (1988–2017)

Table 3. Annual temperature and precipitation trends in Badin district during 2018-2099

Parameters	Mann-Kendall trend test Z	Result	Sen slop test Q
Rainfall (RCP 4.5)	0.55	Not significant	0.019
Rainfall (RCP 8.5)	-0.70	Not significant	-0.023
Temperature (RCP 4.5)	6.84	Significantly increasing	**0.028**
Temperature (RCP 8.5)	10.64	Significantly increasing	**0.076**

Bold values represent significance at a 99 % confidence level

The temperature will increase at the rate of 0.028°C yr^{-1} under RCP 4.5 and 0.076°C yr^{-1} under RCP 8.5, respectively. A slightly increasing trend was observed in the annual precipitation under RCP 4.5. The precipitation will increase at the rate of 0.019 mm yr^{-1} under RCP 4.5. But, the slightly decreasing trend was observed in precipitation under RCP 8.5. The precipitation will decrease at the rate of 0.023 mm yr^{-1} under RCP 8.5, as shown in Fig. 8.

In recent years, numerous studies on drought have been carried out in Pakistan. Many researchers have identified drought-affected areas in Pakistan. Anjum, Saleem, Cheema, Bilal, and Khaliq analyzed precipitation maps in Pakistan to find drought-prone areas and concluded that the drought frequency in Sindh and Baluchistan is much higher than in other provinces of Pakistan [30]. Mazhar & Nawaz used annual precipitation data of 36 weather stations in Pakistan to map the intensity of meteorological drought [31]. It is found that Sindh is one of the driest regions in the country and has more chances of intense drought in the future. The districts Sukkur, Khairpur, Umerkot, Sanghar, Badin, Tharparkar, Thatta, Jamshoro and Dadu are frequently hit by drought [32]. Khan & Gadiwala assessed drought over Sindh and concluded that almost all stations of Sindh, including Badin, had an extreme drought in 2001-02 [33]. Similarly Adnan, Ullah, & Gao have carried out regional drought analysis over Sindh and concluded that most severe historical drought occurred in 2002 [34]. However, the drought in 2004 being the worst that affected Sindh province the most [35]. All these findings are consistent with the drought assessments made with the indices approach as exhibited in Table 2. Statistical analysis of annual rainfall and temperature trend using the Mann-Kendall test and the Sen's Slope estimates have been carried out for temporal scale for 1988-2017 and 2018-2099. Z and Q values have been computed for temperature and precipitation as shown in Tables 2 and 3, respectively. The severity of droughts is directly related to variation in rainfall and temperature. Therefore, trend analysis of temperature and precipitation is significant for management and planning of water resources.

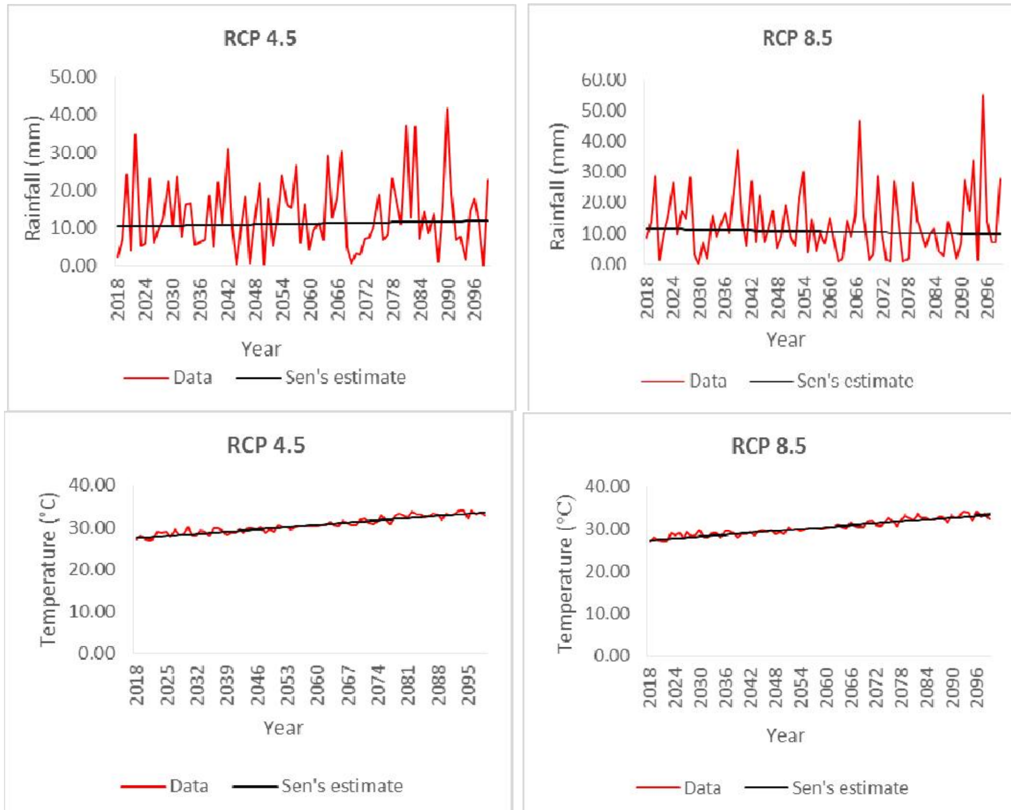

Fig. 8. Annual temperature and precipitation trends in Badin by Man-Kendall test along with Sen-slope estimate during 2018-2099

4. CONCLUSION

In this study, we used long-term historical and future meteorological data and drought indices (SPI and RDI) to quantify meteorological drought in Badin during 1988-2017 and 2018-2099. The study provided drought assessment and discussed characteristics of meteorological drought. Drought analysis using indices SPI and RDI indicated that the region, during the past 30 years, has experienced frequent and irregular drought events. The 30 years historical analysis indicates that in 2001-02 and 2003-04, the region faced extreme drought events. The forecasted SPI and RDI for the next 82 years showed the presence of more vulnerable droughts in the future under the RCP 4.5 and 8.5 scenarios. The SPI and RDI show good results to analyze the drought in the arid and semi-arid region. Temperature and precipitation showed significant changes during 1988-2017 and 2018-2099. The intensified warming and reduced rainfall in recent decades have intensified the drought severity in the region. It is suggested that all the stakeholders, water resource managers, and planners are to come up with a better policy to tackle the drought and make the condition less severe in a region. It is also suggested that the governments of all the countries that are tended to suffer from the problem must be prepared in advance to cope with the issue.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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