

Meteorological Drought Assessment in Sharjah, UAE Using Drought Indices

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Abstract—Drought is a natural disaster that significantly affects environmental and socio-economic conditions. It occurs when there is a period of below average precipitation in a region, and it results in water supply shortages affecting various sectors and life adversely. Droughts impact the ecosystems, crop production, and erode livelihoods. Monitoring drought is essential especially in the United Arab Emirates (UAE) due to the scarcity of rainfall for an extended period of time. In this study, drought is assessed in Sharjah UAE using monthly precipitation and average temperature data recorded for 35 years (1981-2015) at the Sharjah International Airport. The standardized precipitation Index (SPI), and the Reconnaissance Drought Index (RDI) are selected to predict future droughts in the region. SPI and RDI are fitted to the statistical distribution functions (gamma and lognormal) in an annual time scale and then, a trend analysis of index values is carried out using Mann-Kendal test. The correlation between SPI and RDI indices was found to be high where both showed high drought frequencies and a tendency to get drier over time, thus indicating the need of appropriate drought management and monitoring.

Index Terms—Drought, climate change, precipitation, SPI, RDI.

I. INTRODUCTION

Drought is a complex natural phenomenon that results in serious economic, environmental, and social impacts. The effects of drought accumulate slowly, and its impacts spread over a larger geographical area than other natural hazards [1]. Droughts results in prolonged water supply shortages adversely impacting ecosystems, agriculture, and residents in a region. Annual global economic loss caused by drought is around 6-8 billion US dollars [2].

Droughts occur when there are prolonged periods of rainfall deficiency for a season or more causing decreases in stream flows and water levels in lakes and reservoirs. In addition to climatic factors, human activities such as deforestation, construction, and agriculture negatively impact the water cycle and cause droughts. Other causes such as soil moisture depletion and increases in surface temperatures are likely to result in more severe droughts [3]. Over the last century, global warming has emerged as another major driver

of severe droughts. Global warming causes change in several climate variables, namely precipitation, humidity, and wind speed, which lead to more frequent flood and drought events.

The Middle East and North Africa (MENA) region is one of the most climate change sensitive regions in the World. Barlow [4] reported significant temperature increase with a rise in the number of warm days and heat-wave events. Climate change has significant effects on water resources availability and management in MENA region. Even though climate change and drought studies are very important from many points of views, there are very limited studies for the same in the MENA region. Kelley [5] studied drought in Syria and reported that the drought conditions have been aggravated due to human-induced climate change. Hameed [6] investigated meteorological drought over Iraq during the period of 1948–2009 and showed that a drying trend over Iraq with severe to extreme drought conditions was governing the first decade of the 21st century. Prudhomme [7] also reported an increase of drought days by more than 50% around the Mediterranean by the end of the 21st century for representative concentration pathways (RCP)8.5. AIEbri [8] showed the effects of El Niño and La Niña on weather patterns and specifically on rainfall. They have discovered that the United Arab Emirates (UAE) continues to face challenges that are related to adaptation to weather and climate change, where they linked the fluctuations of weather in the UAE to El Niño and La Niña. Sherif [9] conducted an analysis of rainfall and drought in the UAE and found that the average drought duration is about 2.8 years in the UAE, which classifies the country as an arid region.

Evidently, limited studies considered climate change in drought analysis using future climate projections. Forecasting climate change is important, specifically drought, how it is changing over time, and impacts on sustainability and society functioning. In this study, climate change effects on droughts are investigated. The emirate of Sharjah located in the UAE is the selected study area due to availability of long-term relevant climate data and tremendous need of water to meet the growing demand over the past few decades. Climate change effects on droughts in Sharjah are investigated by calculating the Standardized Precipitation Index (SPI), Reconnaissance Drought Index (RDI), as well as trend analysis. The outcome of this study will make a significant contribution to climate change and drought studies. It will also aid in providing successful drought management in the study area.

II. STUDY AREA AND DATA

The Emirate of Sharjah is located in UAE covering an area of approximately 2,600 km² with a total population of 1.4

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million. The Sharjah Emirate falls on coordinates of 25.3 °N 55.5 °E along the southern coast of the Arabian Gulf on the Arabian Peninsula as shown in Fig. 1. Sharjah is classified as a dessert with hot climate and characterized with its great arid land. Sharjah has mean annual temperature of 18-34 °C. Rain in Sharjah occurs lightly and infrequently with an average of 100 mm/year. The rainfall season occurs from November to March, and about two-thirds of the year's rainfalls concentrate between February and March.

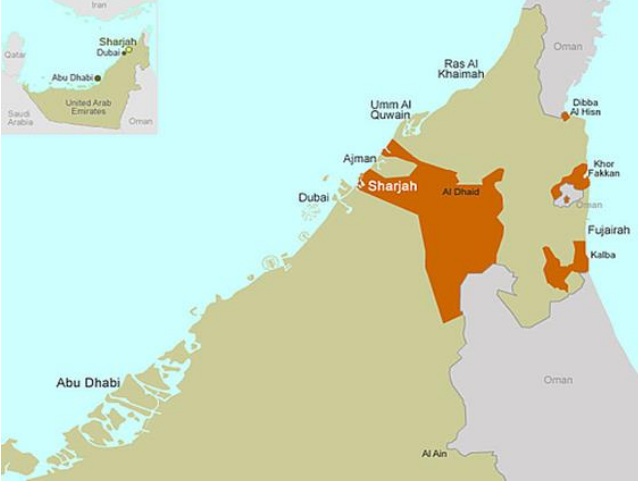


Fig. 1. Location of Sharjah, UAE (Source: Universes in Universe, 1997).

Two types of monthly precipitation data sets were used in this study: (1) Observed monthly rainfall data over the period of 1981 to 2015, (2) Future (projected) data from Global Climate Models (GCMs) for two different periods: near future for the period of 2030 to 2064, and far future for the period of 2065 to 2099. Observed data were received from weather observation station at the Sharjah International Airport. Future data projections were obtained from four GCMs NASA Goddard Institute for Space Sciences E2 meteorological Research Institute model (MRI_CGCM3) as recommended by Yilmaz [10].

III. METHODOLOGY

This study consists of five main steps including (1) Calculation of SPI, Aridity Index (AI), and RDI. (2) Drought occurrence evaluation. (3) Trend analysis of drought indices (5) Goodness of fit analysis.

A. Calculation of Drought Indices

Drought indices are essential elements for an efficient drought monitoring system. SPI, AI, and RDI are the commonly adopted indices in the literature [11], [12] due to the advantages offered by those indices for analyzing drought.

1) Standardize precipitation index (SPI)

SPI is a widely adopted index in various drought-related applications worldwide because of its flexibility and the dependency on only precipitation [13], [14]. SPI's main strength is that it can be computed for different timescales (e.g., 1, 3, 6, 12, 24 months). The impact of drought on the availability of the water resources is casted in those timescales. Relatively short scale can monitor soil moisture conditions, where the longer-term precipitation anomalies are

reflected by groundwater, streamflow, and reservoir storage. Long-term (30 year or more monthly data) precipitation record is required to calculate SPI for any location. The precipitation time series is then fit to a probability distribution, which is transformed into normal distribution with an average SPI value equal to zero. This makes positive values wet and negative values dry [15]. The classification scale used to define drought events resulting from the SPI is shown in Table I.

TABLE I: SPI CLASSIFICATION

SPI Values	Class
+2.0 and more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
-2.0 and less	Extremely dry

For precipitation time series, gamma distribution is originally used for SPI calculation [16]. In addition to gamma distribution, many researchers have used the log-normal distribution, which also provided reliable results. The term “magnitude” refers to the positive sum of the SPI for all the months within a drought event. Table II presents the classification of drought magnitude depending on the probability of occurrence of drought events [17], as well as the probability of the precipitation necessary to end it [13].

TABLE II: THE CLASSIFICATION OF DROUGHT MAGNITUDE DEPENDING ON THE PROBABILITY OF OCCURRENCE OF DROUGHT EVENTS

SPI	Category	Number of times in 100 years	Severity of event
0 to -0.99	Mild dryness	33	1 in 3 yrs.
-1.00 to -1.49	Moderate dryness	10	1 in 10 yrs.
-1.5 to -1.99	Severe dryness	5	1 in 20 yrs.
< -2.0	Extreme dryness	2.5	1 in 50 yrs.

The probability density function of the gamma distribution is defined as:

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \text{ for } x > 0 \quad (1)$$

where α is a shape parameter ($\alpha > 0$), β is a scale parameter ($\beta > 0$), ($x > 0$) is the amount of effective precipitation, and $\Gamma(\alpha)$ is the gamma function, expressed as $\int_0^\infty y^{\alpha-1} e^{-y} dy$.

The parameters α and β are estimated through the following formulation:

$$\hat{\alpha} = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right), \quad \hat{\beta} = \bar{x} / \hat{\alpha} \quad (2)$$

where \bar{x} is mean precipitation and A is given by $A = \ln(\bar{x}) - n^{-1} \sum \ln(x)$ and n is the number of observations.

The cumulative probability, G(x), of a precipitation event is

$$G(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^\alpha e^{-x/\beta} dx \quad (3)$$

Letting $x = x/\hat{\beta}$, the expression is reduced to incomplete gamma function:

$$G(x) = \frac{1}{\Gamma(\hat{\alpha})} \int_0^x t^{\hat{\alpha}-1} e^{-t} dt \quad (4)$$

Given that gamma distribution is not defined for $x = 0$, and the probability of zero precipitation (q), the cumulative probability becomes

$$H(x) = q + (1 - q)G(x) \quad (5)$$

For SPI calculation, the cumulative probability distribution is transformed into normal distribution using the following approximation [18]:

$$\alpha\text{SPI} = -(t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}), \quad 0 < H(x) \leq 0.5 \quad (6)$$

in which $t = \sqrt{\ln(1/H(x)^2)}$

$$\alpha\text{SPI} = t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}, \quad 0.5 < H(x) \leq 1.0 \quad (7)$$

in which $t = \sqrt{\ln(1/(1 - H(x)^2))}$

In approximation, following constants are used: $c_0 = 2.515517$, $c_1 = 0.802853$, $c_2 = 0.010328$, $d_1 = 1.43278$, $d_2 = 0.189269$, $d_3 = 0.001308$. The probability density function of a lognormal distribution is defined as [19], [20]:

$$f(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right), \quad x > 0 \quad (8)$$

where μ is the scale parameter and σ is the shape parameter calculated as:

$$\hat{\mu} = n^{-1} \sum_k \ln x_k \quad (9)$$

$$\hat{\sigma}^2 = n^{-1} \sum_k (\ln x_k - \hat{\mu})^2 \quad (10)$$

2) Reconnaissance drought index (RDI)

RDI is characterized as a general meteorological index for the drought assessment of severity and duration, and to approach the water deficit in a more accurate way, as a sort of balance between input and output in a water system [21], [22]. The RDI is based both on precipitation (P) and potential evapotranspiration (PET). The α_k is usually calculated for the i^{th} year and a time basis k (months) using the following equation:

$$\alpha_k^{(i)} = \frac{\sum_{j=1}^k P_{ij}}{\sum_{j=1}^k PET_{ij}} \quad (11)$$

where P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration of month j of hydrological year i . In this study, Thornthwaite method was used to calculate the PET as similar to [23]-[25].

B. Trend Analysis

After calculation of indices, Mann-Kendal (MK) was applied to detect trends. MK is a rank based nonparametric

test that was developed by Mann and Kendall for detecting linear or non-linear trends [26] and it is commonly used in hydro-meteorological trend analysis [27], [28].

IV. RESULTS AND DISCUSSION

A. Drought Evaluation

The calculated RDI and SPI values did not show a consistent pattern over the observed data period, 1981 and 2015 as shown in Figure II. The wetter years with highest positive index value (very to extremely wet years) were 1982, 1995 and 1997. On the other hand, the lowest index value representing the drier years were 1985 and 2001. In near future period (2030 to 2064), the highest index value was observed in year 2046 (RDI is 2.18, whereas SPI is 2.11), and the lowest index value was detected in 2034 (RDI is -1.59 and SPI is -1.74). Similarly, the drought values of the future years from 2065 to 2099 raised significantly in some years such as 2079 and 2081 with drought values of 1.83 and 1.94 based on SPI, respectively. Further, a steep drop was observed in RDI in 2069 (-1.66) and 2085 (-1.65). This drop caused a severely dry period in these two years. The decreasing trend line shown in Figure II demonstrates a drier future. Based on comparison between the two indices, RDI values had stronger decreasing trends relative to the SPI values.

Table III gives occurrence of drought events by percentage, and it can be observed that more than 60% of the years were classified as near normal condition in observed, near future, and far future periods. While the percentages ranged from 5.7 to 14.3 for moderately and severely drought conditions respectively, it is important to note that extremely dry conditions were detected in lognormal distribution-based SPI (ranging from 2.9 to 5.7%).

When looking into the two indices, SPI (gamma) had relatively lower drought occurrences in comparison to the other index and distribution. But overall, the two indices and distributions had similar behavior in classifying the drought events in the different years.

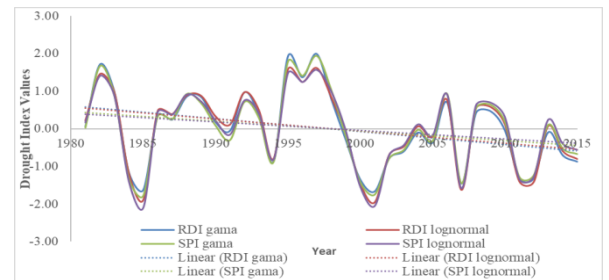


Fig. 2. Results of SPI and RDI graph for both gamma and lognormal observations.

As discussed above, the gamma and lognormal distributions were used in calculation of SPI and RDI values. The performance of these two distributions based on goodness of fit analysis is checked using Anderson-Darling, Kolmogorov-Smirnov, and Chi-squared tests. Based on analysis given in Table IV, these three tests agreed that both distributions fitted the data well in both indices.

According to the Chi-squared test, the Gamma function showed better results in comparison of the lognormal distribution with few exceptions including observed and far future for RCP6 and RCP8.5.

TABLE III: OCCURRENCE OF DROUGHT EVENTS PERCENTAGES

Occurrence of drought events (%)												
Drought classification	Observed				Near Future				Far Future			
	SPI		RDI		SPI		RDI		SPI		RDI	
	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log
Near normal	65.7	68.6	68.6	68.6	65.7	65.7	68.6	68.6	68.6	68.6	65.7	65.7
Moderately dry	14.3	8.6	14.3	11.4	8.6	5.7	11.4	8.6	8.6	5.7	11.4	8.6
Severely dry	5.7	5.7	5.7	8.6	8.6	8.6	11.4	8.6	8.6	5.7	8.6	11.4
Extremely dry	0.0	5.7	0.0	0.0	0.0	2.9	0.0	0.0	0.0	5.7	0.0	0.0

TABLE IV: GOODNESS OF FIT RESULTS

Anderson–Darling													Kolmogorov–Smirnov				Chi-squared			
		SPI		RDI				SPI		RDI				SPI		RDI				
Time period		Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log	Gamma	Log			
Observed		0.30	0.57	0.27	0.52	0.10	0.12	0.07	0.13	1.62	2.08	0.89	1.33							
Near Future	RCP2.6	0.27	0.47	0.27	0.52	0.08	0.10	0.08	0.10	0.40	2.04	0.36	2.11							
	RCP4.5	0.27	0.52	0.31	0.55	0.08	0.10	0.11	0.10	0.36	2.11	0.19	1.99							
	RCP6	0.27	0.54	0.34	0.64	0.08	0.11	0.11	0.12	0.88	1.51	1.29	3.30							
	RCP8.5	0.30	0.55	0.33	0.57	0.08	0.11	0.12	0.11	1.09	2.09	0.80	0.93							
Far Future	RCP2.6	0.30	0.52	0.29	0.52	0.09	0.13	0.11	0.13	4.92	2.21	2.60	0.88							
	RCP4.5	0.24	0.42	0.25	0.49	0.09	0.09	0.11	0.11	1.08	1.56	0.11	2.08							
	RCP6	0.30	0.50	0.32	0.55	0.10	0.13	0.12	0.12	2.26	2.04	5.12	2.81							
	RCP8.5	0.33	0.55	0.38	0.62	0.09	0.12	0.13	0.12	2.29	2.28	5.85	1.40							

B. Trend Analysis

As mentioned earlier, MK test was used to examine the trends in drought indices. Table V shows the z statistics values of each index for three periods (observed, near and far future) and four RCPs. It should be noted that the bold numbers in Table V represent the statistically significant trends with 90% significance level. Further, as can be seen in Table V, all z-statistics were negative indicating a decreasing trend (drier trend). Although decreasing trends were calculated for SPI values, none of those values are statistically significant. On the other hand, majority of (decreasing) trends in RDI are statistically significant.

TABLE V: TREND ANALYSIS RESULTS

Time period	SPI		RDI	
	Gamma	Lognormal	Gamma	Lognormal
Observed	-1.449	-1.449	-2.045	-2.031
Near Future	RCP2.6	-1.051	-1.037	-1.619
	RCP4.5	-1.079	-1.079	-1.576
	RCP6.0	-1.122	-1.108	-1.733
	RCP8.5	-1.108	-1.108	-1.676
Far Future	RCP2.6	-1.207	-1.207	-1.69
	RCP4.5	-1.051	-1.065	-1.747
	RCP6	-1.065	-1.065	-1.647
	RCP8.5	-1.094	-1.079	-1.775

V. CONCLUSION

In this study, droughts in Emirates of Sharjah, UAE was assessed by quantifying droughts using RDI and SPI indices. For analysis, observed monthly rainfall data of the period of 1981-2015 and future (projected) data including near future for the period of 2030-2064 and far future for the period of 2065-2099 under four different RCPs are used. The SPI and RDI indices were generated through fit of the data to gamma and lognormal distributions, and the goodness of fits were evaluated using Anderson–Darling, Kolmogorov–Smirnov, and Chi-squared tests. Temporal trends in index values were also investigated using MK test to identify changes in index values (level of drought) over years. To sum up the major

points of this study, it significant to mention the trend and correlation status. The decreasing trends in index values were detected indicating a drier future, RDI gave stronger decreasing trends in comparison to SPI, the correlation between the SPI and RDI was very high for all data periods (observed, near and far future) and all RCPs. More than 60% of the years were classified as near normal drought condition, while the 5.7 to 14.3% of years showed of moderately and severely drought status. The Gamma distribution function outperformed lognormal distribution in goodness of fit. Finally, to comprehensively investigate drought levels and trends over the entire UAE, based on the present study, it is recommended to extend the methodology presented herein to include observed data from several stations and the future projection of global climate models suitable for study area.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Abdullah Yilmaz conducted the research; Mhamd Oyounalsoud & Arwa Najah analyzed the data and wrote the paper; Abdullah Yilmaz, Mohamad Abdallah & Mohsin Siddique reviewed and edited the paper.

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Dr. Abdallah has published his research work in many international refereed journals and conference proceedings. In his current position at the University of Sharjah, he was awarded internal and external research grants at around \$300 thousand and has published over twenty research papers mostly in high-ranked Q1 journals.



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