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ESTIMATION OF REGIONAL DROUGHT FREQUENCY AND SPATIAL EXTENT IN PAKISTAN USING STANDARDIZED PRECIPITATION INDEX

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ABSTRACT

Drought is a persistent, natural, local or regional phenomena. It provides an impression of water scarcity owing to inadequate precipitation over an extended period. Drought is different from other natural hazards because of the slow onset process with an unpredictable ending. It develops gradually and impacts may endure for years after termination of the event. Pakistan has wide latitudinal extent and rainfall variability. The northern part of Pakistan receives more rains as compared to the southern and south west region of the country that has the lowest precipitation, where frequent meteorological drought occurs. According to the Pakistan Meteorological Department drought frequency and severity is increasing in the country due to an oscillated pattern of rains caused by climate change. This study focuses on the estimation of regional drought frequency and the spatial extent in Pakistan. In current research a drought index named as the Standardized Precipitation Index (SPI) is used for drought analysis and assessment. The SPI permits to analyze the drought frequency, severity and duration in a region at different time scales. In the current research it is used to explain a spatial extent of droughts in Pakistan from 1970. The analysis is made using long term homogenous monthly rainfall data of 50 years to compute SPI values. The negative and positive SPI values show the probability occurrence of dry or wet events in the study area. Parallel to this, drought prone areas were also identified by using Kriging spatial interpolation technique in GIS environment. The results divulge that drought exists in all the four climatic zones of Pakistan with different duration, severity and frequency. Humid Zone faces mild to moderate seasonal drought with a downward trend line that adversely impacts on the hydrological network of the country in the later stages. Severe drought exists in Semi-Arid and Arid Zones has a negative impact on soil moisture. Long dry episodes persist in the Extremely-Arid Zone of Pakistan. These episodes lead to create water stress in the country. This study reveals that both in actual time series data and SPI values, a temporal variation found in drought occurrences. These variations have significant economic, social, and environmental impacts on the studied area. This paper properly concluded the results and suggested a strategic plan to minimize the impacts of drought in Pakistan.

KEY WORDS: Drought, Rainfall variability, Standardized Precipitation Index, Pakistan.

1. INTRODUCTION

Drought is a natural hazard correlated with insufficiency of water sources in a large geographical region (Zarch, 2011). Droughts are extensive phases deprived of precipitation (Heim, 2002). The other perception of drought is the lacking of water scarcity and decline of economic goods by less rainfall

(Daraei, 2010). Every definition of drought defines a relation between the water scarcity and reduced rainfall with its impact on aridity and soil moisture. On the basis of frequency, intensity and duration drought is categorized into different types. American Meteorological Society, (2004) has been formulated four different types of drought, i.e. Hydrological, Meteorological, Agricultural and Scio-economic drought. Drought, has a slow onset nature. It is a hazardous and illusive climatic activity because it develops progressively (Mukherjee, 2018). Globally, harmful drought impacts are recognized on agriculture yield, irrigation system and socio-economic conditions (Mohammed, 2018).

Pakistan is experiencing an increase in the frequency and severity of drought due to the oscillated pattern of rain. During the past three decades, hydro-meteorological hazards have increased in Pakistan (Rahman, 2018). It is defined by the Pakistan Meteorological department that many areas of Pakistan are receiving less or below averages seasonal rainfall. The areas of Sindh and Baluchistan provinces are receiving 69.5 and 45 percent below average rainfall respectively. This condition leads to severe drought in 8 districts of Sindh and 18 districts of Baluchistan. Whereas, the South-eastern region of Pakistan passes through a severe dry spell in summers with high temperature range (Kahlown, 2007). A survey conducted by Natural Disaster Management Authority (NDMA) briefs that in all over the country except northern highlands, the average annual rainfall is less than 250mm. Whereas, few mountain slopes receive more than 500mm rainfall that covers 7 percent area of the country. Even the Hindu Kush Himalayan region is highly vulnerable to numerous threats (Rahman, 2016). The rest of the 20 percent area receives less than 125mm rainfall. However, in areas with low rainfall, Provincial Government works for improvement and upgradation with the cooperation of private authorities. Such as Cholistan Development Authority (CDA), Baluchistan Development Authority, Thal development authority, Sindh Arid Zone Development Authority, and KP Development Authority (Ahmed, 2018).

Pakistan is an agro-economic country. All the water sources and gross domestic products are severely affected by the below average rainfall. Water scarcity leads to severe environmental hazards i.e. desertification and soil degradation. In this situation, the evaluation of the spatio-temporal rainfall variability, fresh water planning and management is the essential requisite of the time. It is compulsory to predict and prevent the region from extreme hydro-meteorological episodes i.e. drought. The understanding, occurrences and monitoring of drought is required to make new policies and strategies to cope with the current water-scarce situation.

2. MATERIAL AND METHODS

To estimate the regional drought frequency and the spatial extent in Pakistan 77 meteorological stations have been selected in all over the country, including both plain and hilly areas. The total monthly observed rainfall data from 1970-2019 were used to calculate a well-known drought evaluation index named as SPI. This index evaluates the drought severity, frequency and duration at various timescales. The index is helpful for assessing the short-term and long-term drought impacts on soil moisture and ground water, streamflow and reservoir storage within the region respectively. All the data is of good quality and according to the desired time period. Unfortunately, few areas have not complete rainfall data, for the required study period that is filled with long-term average values. To examine the spatial extent of drought in the country IDW interpolation has been done under GIS environment.

Various, simple and complex drought indices were presented by the meteorologists and climatologists. The Standardized Precipitation Index (SPI) is a simple flexible tool. All the statistical analysis depends on a single parameter that is Rainfall. Through this Index dry and wet periods are calculated at the same time. The minimum and maximum consecutive rainfall datasets of 20-30 and 50-60 years respectively are accounted to analyze drought conditions (Hayes et al., 1999). The SPI was formulated in 1993 by McKee to quantify the rainfall values at different timescales for different regions. This Index measures the availability of the amount of water under different timescales such as the short-timescales presents seasonal rainfall anomaly and its impact on the soil moisture. Whereas, long-timescale presents, water shortages in reservoirs and stream flows. The SPI is calculated under different timescales i.e. 3-month, 6-month, 12-month, 24-month, 48-month return period. The first step of the index is calculated by the fitting a long-term rainfall record in a probability distribution and then transformed into a normal distribution. A zero value means the occurrence of normal conditions in an area (Edwards and McKee, 1997). The SPI calculates positive and negative values for wet and dry episodes respectively occur in a region.

Mathematically expressed as:

$$\mathrm{g(x)} = \frac{1}{\beta^{\alpha}\,\Gamma(a)} x^{a-1} e \frac{-x}{\beta} \;, for\; x > 0 \qquad \text{..... (1)}$$

As equation (1) shows, α is a form parameter; β is a scale parameter, while x is the amount of precipitation. $\Gamma(a)$ is expressed as Gamma function:

$$\Gamma(a) = \int_0^\infty x^{a-1}\, e^{-x} dx \qquad \text{…… (2)}$$

The SPI involves the calculation of gamma and frequency distribution of total rainfall for one meteorological station. The parameters α and β of a gamma PDF are calculated for each met-station, at different time scales such as 1, 3, 6, 9, 12, 24 and 48 months. A cumulative probability $G(x)$ equation defines observed rainfall in a month and for a specific period of time.

$$\mathrm{G(x)} = \int_0^x g(x)dx = \frac{1}{\beta^\alpha\, \Gamma(a)} \int_0^x x^{a-1}\, e \frac{-x}{\beta} dx \qquad \text{…….. (3)}$$

For $x = 0$ means no gamma function.

$$H(x) = q + (1 - q)G(x) \qquad \text{…….. (4)}$$

Whereas *q* is the possibility of zero precipitation (Khadr, 2017a).

McKee in 1993 has drawn a drought intensity table (Table 1). This table presents positive and negative values for defining extremely dry to extremely wet conditions in an area. These values also show the drought intensity and severity occurred in a region.

Table 1 SPI Values by McKee et al., 1993

2.0 +	Extremely Wet
1.5 - 1.99	Very Wet
1.0 - 1.49	Moderately Wet
- .99 - .99	Near Normal
-1.0 - -1.49	Moderately Dry
-1.5 - -1.99	Severely Dry
-2 and less	Extremely Dry

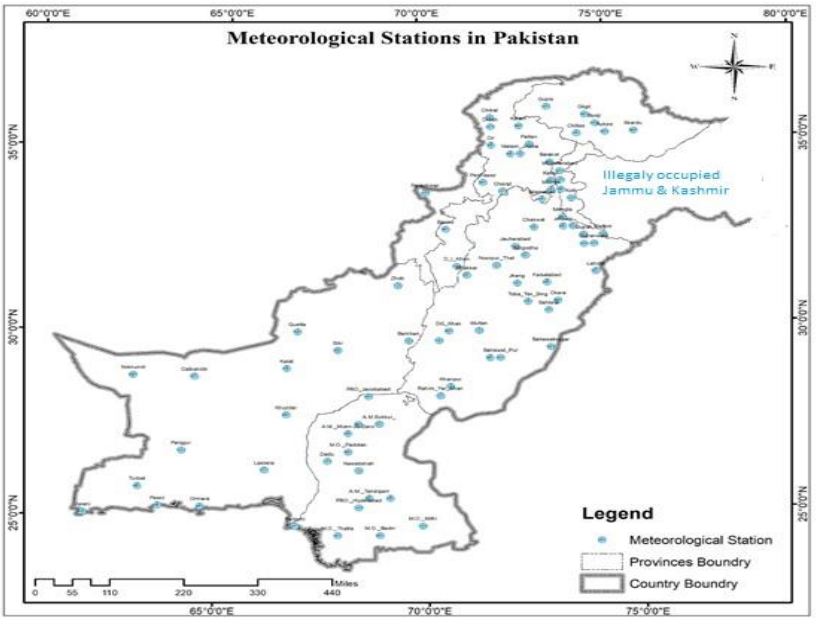

Figure 1, Pakistan Meteorological Stations

3. RESULTS AND DISCUSSIONS

To evaluate the drought frequency and the spatial extent in Pakistan, 77 heterogeneous meteorological stations are kept under consideration. The total monthly rainfall (mm) for fifty years (1970-2019) is analyzed. All the meteorological stations were well distributed with the altitudinal and latitudinal extent, completeness and reliability of data. However, long-term averages have been taken to filled-up the missing data values. Further microclimatic zones were developed on the basis of Koppen-Geiger's climate classification.

3.1. Drought Frequency, Duration and Intensity in Humid Zone

The geographical location of the humid zone is between 32.56N° to 35.12N° and 71.51E° to 73.43E° (Sajjad, 2014). The region is consisted on the Northern Highlands, Northern Punjab, few areas of KP and Azad & Jammu Kashmir. Most of the area of the humid zone located on the southern slopes of great Himalayan Mountains with 251-2,169m, altitude range (Adnan, 2017). Long cold snowy winters and short mild summers exist in this zone. In summer the highest temperature reaches till 32C° whereas, in winter temperature goes down till 0-15C°. It is a monsoon dominated area receiving more than 750mm mean annual rainfall. This regional is vulnerable to flash floods and seasonal drought (Shahazada, 2017). This zone receives maximum amount of water with the summer monsoon rainfall and winter

western disturbances rainfall system (Adnan, 2009). 18 meteorological stations have been selected for the humid region according to Koppen climate classification.

As the (Table 2) describes the meteorological stations with geographical locations and mean annual rainfall values. The results have shown the highest mean annual rainfall existed in Murree 1732mm. The second and third highest mean annual rainfall occurred in the Malam Jabba 1714mm and Rawalakot 1606mm. Humid zone is a significant region of Pakistan. A downfall in the seasonal rain spells may result water scarcity in all over the country. All the country's water requirements fulfill by the seasonal rainfall in this zone.

Table 2 Pakistan: Meteorological Stations of the Humid Region and Rainfall

Met Stations	Latitude (dd)	Longitude (dd)	Mean (mm)
Garhi Dupatta	34.1	73.6	1437
Kotli	33.6	73.8	1221
Muzaffarabad	34.3	73.6	1496
Rawalakot	33.8	73.6	1606
Saidu Sharif	34.8	72.3	994
Balakot	34.6	73.3	1559
Gujranwala	32.3	74.3	816
Islamabad	33.6	73.1	1195
Mangla	33.1	73.6	982
Murree	33.8	73.3	1732
Sialkot	32.6	74.6	1039
Dir	35.1	71.8	1392
Parachinar	33.8	70.1	997
Pattan	35.1	72.8	1127
Kalam	35.6	72.6	1038
Malam Jabba	34.8	72.6	1714
Jhelum	32.8	73.6	889
Kakul	34.1	73.3	1329

Source: Pakistan Meteorological Department

To analyze the drought occurrence, severity and frequency in the humid zone a drought index (SPI) has been applied for mean annual rainfall values. To calculate the seasonal and long-term drought conditions in the zone, SPI has been calculated at different timescales such as 3-month, 12-month and

24-month (Figure 2). According to SPI analysis the humid zone has faced 17 mild droughts in different years, i.e., 1970-1972, 1982-1987,1993, 1999, 2000, 2005, 2008, 2016 and 2017. While, moderate drought has occurred only in four years i.e., 2001, 2002, 2012 and 2016. In past fifty years zero severe and extreme droughts are calculated in the humid zone. However, rainfall trend line is going down because of less rainfall. It means frequency and intensity of rainfall is decreasing day by day in the humid zone of Pakistan that is alarming for agriculture and energy sectors as well as the economy of the country. A mild seasonal drought exists according to 3-month return period values due to the unavailability of seasonal rainfall (Figure 2). Whereas, 12-month return period is presented the long-term hydrological drought in the humid region (Figure 3). While, 24-month return period analysis described a sequence of drought occurrence after every eight to nine years (Figure 4).

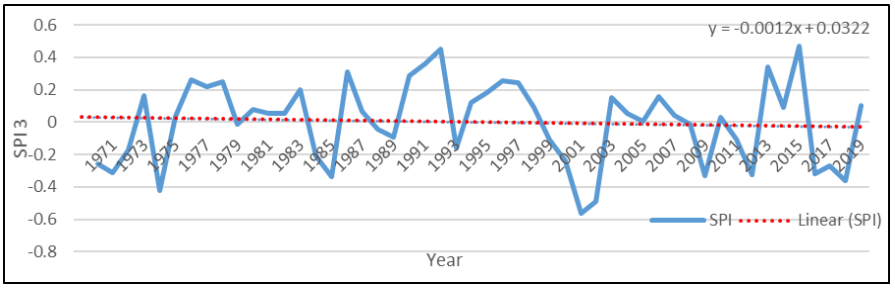

Figure 2, 3MRP-SPI Calculations for Humid Zone

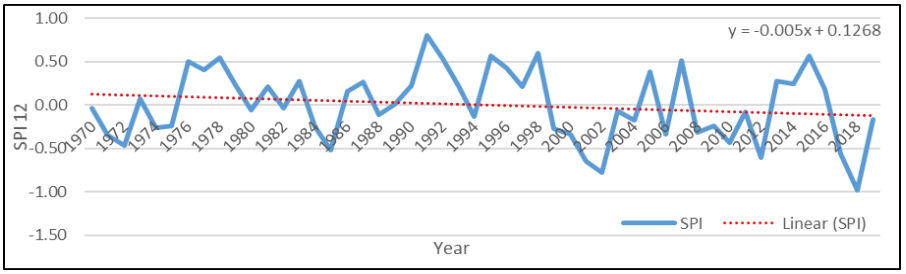

Figure 3, 12MRP-SPI Calculations for Humid Zone

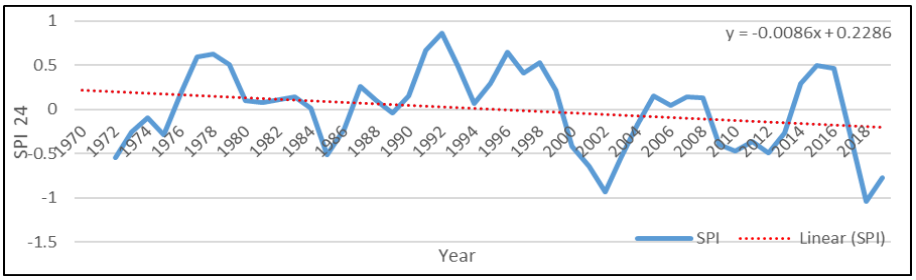

Figure 4, 24MRP-SPI Calculations for Humid Zone

3.2. Drought Frequency, Duration and Intensity in Semi-Arid Zone

Semi-arid zone has a dry to mild climate with less rainfall than the potential evapotranspiration. The mean annual rainfall is 500-750mm. Most of the rainfall occurs in summer because of the monsoon episodes. Eight meteorological stations have been selected for semi-arid zone according to koppen climate classification. The geographical locations and mean annual rainfall values of every met station in a semi-arid region have shown in the (Table 3). The results have shown that the areas with the highest mean annual rainfall are Mandi Bahauddin 734mm, Gujrat 728mm and Lahore 671mm. The semi-arid zone is a well-known agriculture area of Pakistan. It is best in the production of a rice crop.

Table 3 Pakistan: Meteorological Stations of Semiarid Zone and Rainfall

Met Stations	Latitude (dd)	Longitude (dd)	Mean (mm)
Chakwal	32.8	72.8	645
Gujrat	32.6	74.1	728
Jauharabad	32.3	72.3	521
Drosh	35.6	71.8	555
Cherat	33.8	72.1	617
Mandi Bahauddin	32.8	73.8	734
Noorpur Thal	31.8	71.8	565
Lahore	31.6	74.3	671

Source: Pakistan Meteorological Department

Drought index has been calculated for the selected areas of semi-arid zone. According to the results of a 3-month return period 16 mild and 2 moderate drought occurred in the region (Figure 5). While, 8 moderate type of drought persisted in the region according to the 12-month return period (Figure 6). Whereas, 3 severe type of drought has revealed within the 24-month return period calculations (Figure 6).

The 3-month return period has shown a seasonal rainfall fluctuation. While, 12-month return period and 24-month return period analysis has presented long term hydrological and agriculture drought impacts. These droughts have adverse impact on the soil moisture and irrigation system. The most dangerous impact is the crop failure and loss of the economic goods that leads to scio-economic drought conditions in the region.

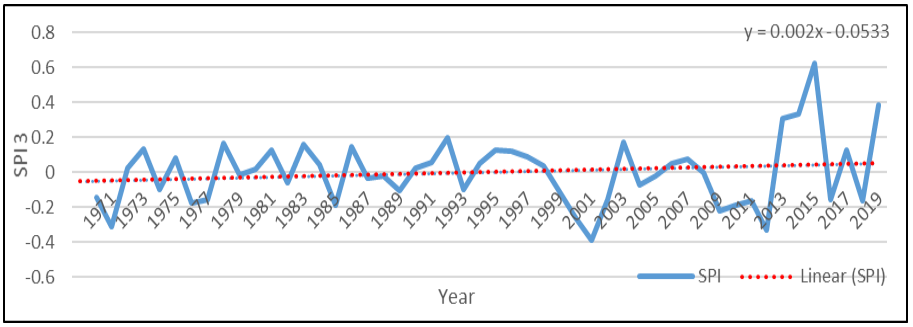

Figure 5, 3MRP-SPI Calculations for Semi-Arid Zone

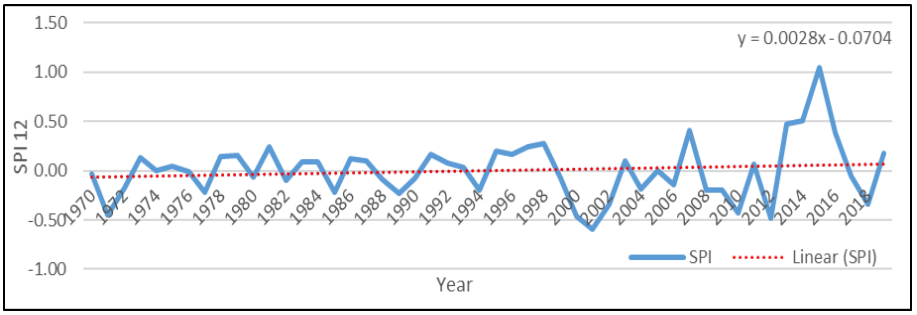

Figure 6, 12MRP-SPI Calculations for Semi-Arid Zone

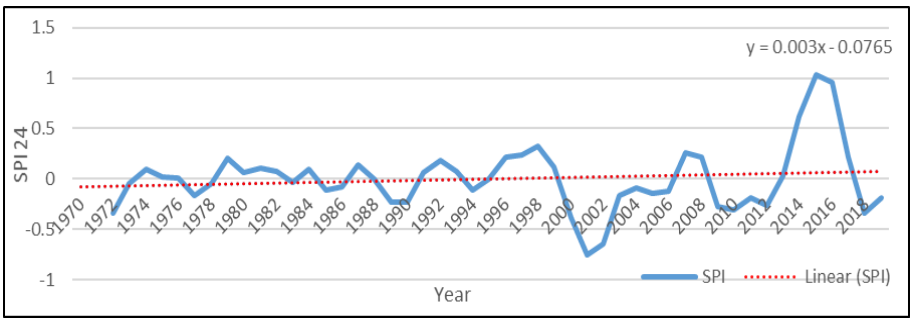

Figure 7, 24MRP-SPI Calculations for Semi-Arid Zone

3.3. Drought Frequency, Duration and Intensity in Arid Zone

Arid zone is a dry zone with high temperatures ranges and very less rainfall. It receives 250-500mm mean annual rainfall. Most of the areas from southern side of the country are included in this zone, i.e. Southern Punjab, Southern Sindh and Central Southern Baluchistan. These areas are highly vulnerable to drought because of high temperature ranges and below average summer and winter rain. A well-developed risk assessment and regular monitoring is very important to prevent worsening of conditions in

the area. The geographical locations and mean annual rainfall of 17 selected meteorological stations have been shown in Table 4. According to the results in the Arid zone Astore receives highest mean annual rainfall 474mm. The second and third highest mean annual rainfall receives by the Sargodha 455mm and Peshawar 449mm respectively.

Table 4 Pakistan: Meteorological Stations of Arid Zone and Rainfall

Met Stations	Latitude (dd)	Longitude (dd)	Mean (mm)
Astore	35.3	74.8	474
Quetta	30.1	66.8	255
D.I.Khan	31.8	70.8	300
Barkhan	29.8	69.6	422
Khuzdar	27.8	66.6	257
Mithi	24.8	69.8	358
Zhob	31.3	69.3	281
Chitral	35.8	71.8	436
Sargodha	32.1	72.6	455
Peshawar	34.1	71.6	449
Bannu	32.8	70.6	365
Bhakkar	31.6	71.1	334
Faisalabad	31.3	73.1	388
Jhang	31.3	72.3	391
Toba Tek Singh	30.8	72.6	411
Okara	30.8	73.3	427
Sahiwal	30.6	73.1	356

Source: Pakistan Meteorological Department

The historical analysis represents that Arid zone has faced 68 mild droughts and 7 moderate droughts. According to 3-month return period analysis, seasonal rainfall fluctuations can be seen since past few decades (Figure 8). Whereas, a 12-month return period has shown hydrological drought in 1970-1972 and 1998-2001 (Figure 9). While, 24-month return period analysis of the Arid zone has presented long dry episodes with near 0 rainfall (Figure 10). Those episodes had adverse impact on agriculture production and caused scio-economic drought. The study reveals that severe drought conditions occurred in the country in the years of 1971-1972 and 2000-2002.It was the time when GDP of the country has declined by 2.6 percent. In the near time seasonal drought persisted in the 2018. These regular

periodic drought spells make the region drier and creates an alarming situation in the country.

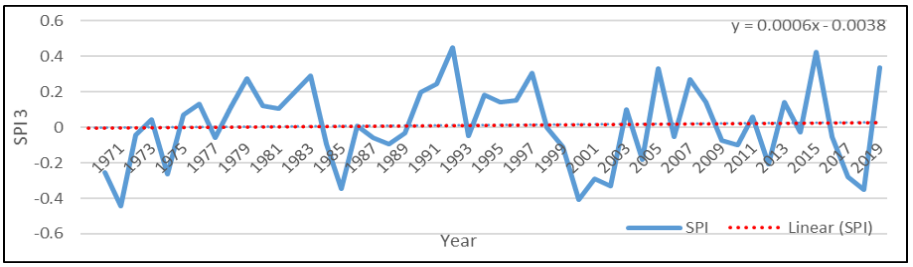

Figure 8, 3MRP-SPI Calculations for Arid Zone

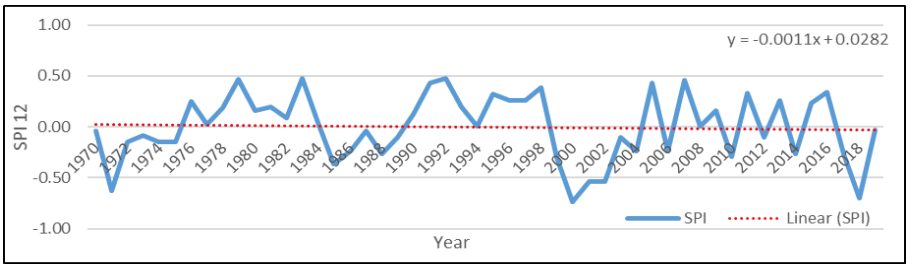

Figure 9, 12MRP-SPI Calculations for Arid Zone

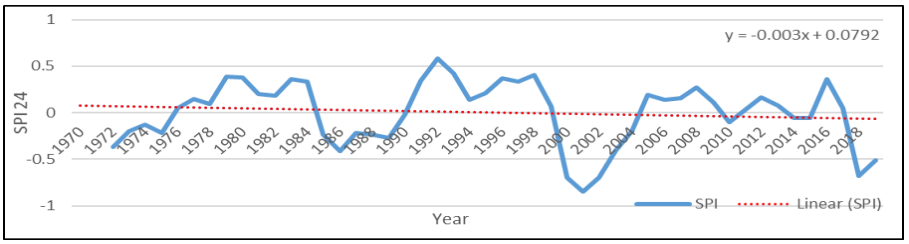

Figure 10, 24MRP-SPI Calculations for Arid Zone

3.4. Drought Frequency, Duration and Intensity in Extremely Arid Zone

This is an extremely dry zone of the country with the highest maximum temperature range and below average rainfall. The 50C° temperature has been recorded in many areas of this zone and rainfall is always less than 250mm. Southeastern desert and the extreme northern area of Pakistan is included in this zone because of below normal rainfall.

To analyze the extremely Arid zone 34 selected meteorological stations with their geographical location and mean annual rainfall have been shown in (Table 5). According to the results, Bahawalnagar and Skardu with a value of 245mm have shown the highest mean annual rainfall in the zone. The

second highest mean annual rainfall areas are D. G. Khan 239mm and Badin 226mm. Whereas, many areas of the extremely arid zone have 0 annual mean minimum rainfall, i.e., Dadu, Nawabshah, Badin, Kalat, Turbat, Nokkhundi, Karachi, Ormara, Pasni, Jiwani and Sibbi. As results have shown that it is the driest zone of the country and receives mild to extreme drought conditions every year. This type of harsh climate situation needs to be monitor and assess regularly. More drought researches are necessary for evaluating the applicability, new drought monitoring information and tools to support decision-making at relevant scales. Furthermore, a well-developed water saving and distribution system enables the country in resolving the water shortage issues in extremely arid areas.

Table 5 Pakistan: Meteorological Stations of Extremely Arid Zone and Rainfall

Met Stations	Latitude (dd)	Longitude (dd)	Mean (mm)
Bahawalpur	29.3	71.8	187
Bahawalnagar	29.6	73.1	245
D. G. Khan	30.1	70.6	239
Multan	30.1	71.3	213
Bunji	35.6	74.6	163
Chillas	35.3	74.1	189
Rahim Yar khan	28.3	70.3	124
Karachi (AP)	24.8	66.8	190
Dadu	26.6	67.6	155
Gilgit	35.8	74.3	140
Gupis	36.1	73.3	192
Skardu	35.3	75.6	245
Nawabshah	26.3	68.3	148
Hyderabad	25.3	68.3	153
Mirpurkhas	25.6	69.1	203
Baddin	24.6	68.8	226
Thatta	24.6	67.8	209
Kalat	29.1	66.6	189
Panjgur	26.8	64.1	98
Turbat	25.8	63.1	102
Mohenjo-Daro	27.3	68.1	118
Dalbandin	28.8	64.3	82
Nokkhundi	28.8	62.8	36
Jacobabad	28.3	68.6	134
Lasbela	26.3	66.1	181

Sibbi	29.6	67.8	173
Khanpur	28.6	70.6	127
Paididan	26.8	68.1	122
Larkana	27.6	68.3	121
Sukkur	27.6	68.8	103
Ormara	25.3	64.6	78
Pasni	25.3	63.6	103
Jiwani	25.1	61.8	103
Tando Jam	25.6	68.6	178

Source: Pakistan Meteorological Department

The results for a 3-month return period have shown, 13 mild and 2 moderate intensity droughts in the extremely arid zone since 1970-2019 (Figure 11). Whereas, 12-month return period analysis has presented 21 mild and 5 moderate intensity droughts (Figure 12). While, 24-month return period calculations have depicted 9 mild and 7 moderate droughts in the zone (Figure 13). These long dry spells have made the region highly vulnerable to extreme drought. As study has shown, many areas in the extreme north of Pakistan are facing same arid situations because of the absence of a good quantity of seasonal rainfall. A little decline in the seasonal rainfall may not have impact locally, but can be worst for agriculture sector in the long run.

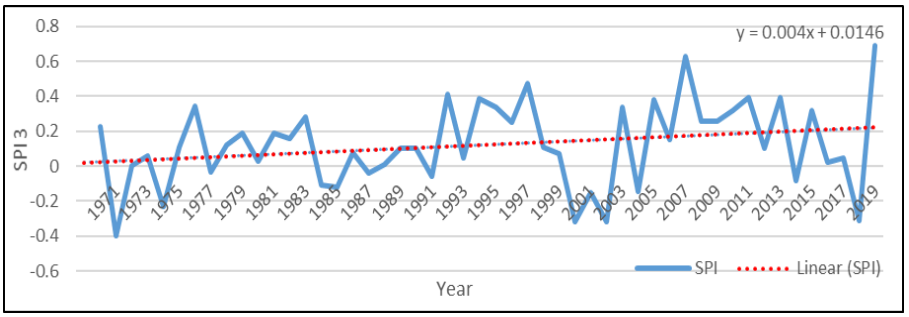

Figure 11, 3MRP-SPI Calculations for Extremely-Arid Zone

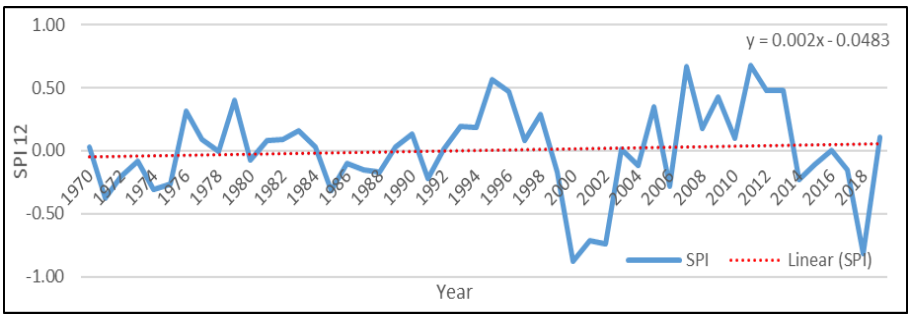

Figure 12, 12MRP-SPI Calculations for Extremely-Arid Zone

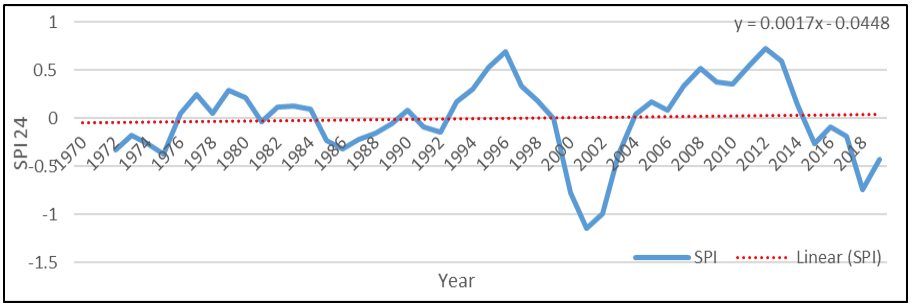

Figure 13, 24MRP-SPI Calculations for Extremely-Arid Zone

3.5. Spatial Drought Extension in Pakistan

Overall, Pakistan has been facing drought in the past fifty years. The drought intensity can vary with place and time. Seasonal drought has been recorded in almost entire Pakistan because of the occurrence of relatively low seasonal rainfall (Figure 14). As the rainfall pattern is changing from the Northeast to the Southwest in Pakistan, the drought with 3MRP may not occur in the South-eastern and Western part of Pakistan.

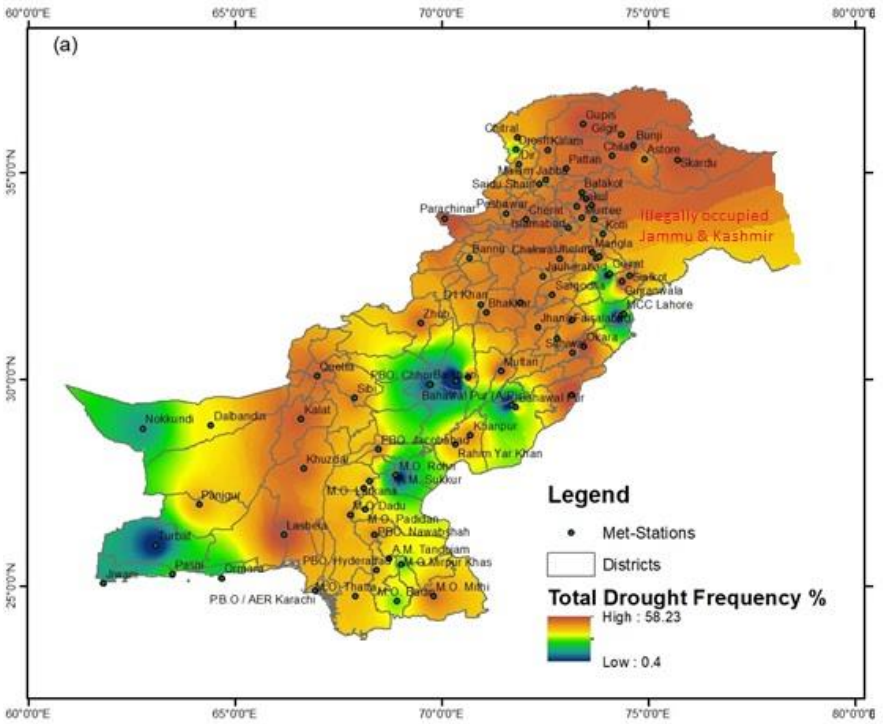

Figure 14, Pakistan: Spatial Distribution of Drought-3MRP

The results of the total drought conditions with 12MRP, have been shown in (Figure 15). Only severity may have increased in Balochistan, Central Punjab and the Sindh region. High water demand, relatively low rainfall, high evaporation, and high dependence on groundwater resources makes these areas more vulnerable to long duration of droughts.

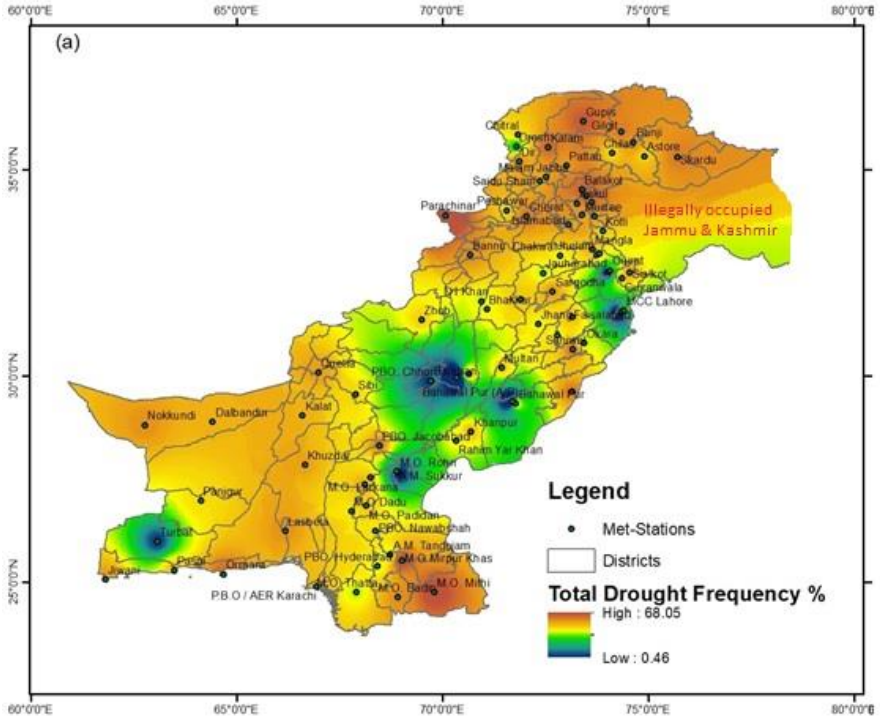

Figure 15, Pakistan: Spatial Distribution of Drought-12MRP

Multi-season droughts are a recurrent feature in Pakistan. Spatial distribution has been showing drought occurrence in almost all over the country because of the timing and strength of the monsoon rainfall (Figure 16). Such episodes place water supplies under immense stress as the competing needs of the society, agriculture, commerce and the environment must be reconciled.

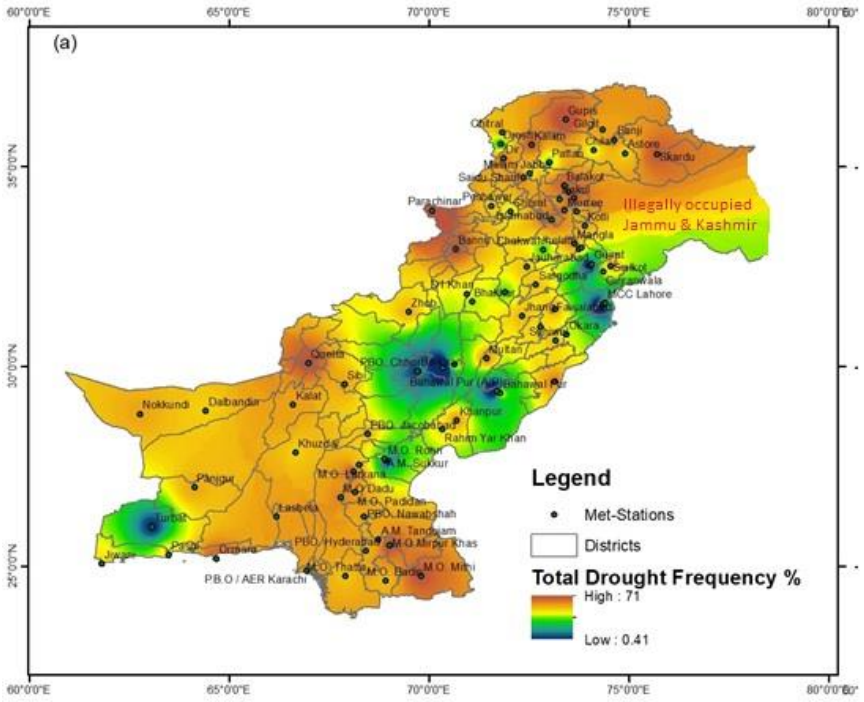

Figure 16, Pakistan: Spatial Distribution of Drought-24MRP

4. CONCLUSION

Pakistan is facing a severe water scarcity threat since last few years due to unpredicted rainfall patterns. These astonishing conditions generate different natural hazards in a region. Drought is the most dangerous hazard that exacerbates by the water-scarce conditions and brings negative impacts on scio-economic conditions of the country. The current study evaluates the regional drought intensity and a spatial extent since 1970-2019 in different zones of Pakistan. The analysis was based on the calculation of the drought frequency, severity and duration using the Standardized Precipitation Index (SPI). According to the results in the past fifty years' humid zone has faced 17 mild droughts, 4 moderate droughts and zero severe and extreme drought. Whereas, the semi-arid zone determines the existence of 16 mild droughts and two moderate droughts. Results have shown, 68 mild droughts and 7 moderate droughts in the arid zone. In the extremely-arid zone, according to 3-month SPI, 13 mild and 2 moderate intensity droughts are identified. According to 12-month SPI results, 21 mild and 5 moderate intensity droughts are observed while 9 mild and 7 moderate droughts are identified by 24-month SPI calculations. In the extremely-arid zone, periodically droughts occurred. The 1971-72 and 2000-2002 are declared the worst drought years in Pakistan's history.

During these years, GDP of Pakistan has dropped down with 2.6 percentage. Recently, 2018 is considered the driest year due to the below average rainfall. These periodic incidence of drought episodes needs attention of planners and stakeholders. Well coordinating water resource planning, preparedness and management is required.

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