https://dx.doi.org/10.22161/ijaers.4.6.12 ISSN: 2349-6495(P) | 2456-1908(O)

Proposing a Popular Method for Meteorological Drought Monitoring in the Kabul River Basin, Afghanistan

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***Abstract*—*This paper investigates meteorological drought in one of Afghanistan's most important socio-economic river basins called Kabul River Basin (KRB) using a 38 years monthly precipitation data. Several drought indices such as Standardized Precipitation Index (SPI), Percent of Normal Precipitation Index (PNPI), Deciles Index (DI), and China-Z Index (CZI) were applied for the first time on the basin in order to observe the correlation among the indices in the basin for drought, and to see which method is suitable for drought monitoring in KRB. Due to the concerns that climate is changing and especially the rapid snowmelt that accounts for 80% of the precipitation in Afghanistan, it was essential to carry such a study in order to warn the responsible bodies in the country for a better drought management. Moreover, the rapid population increase and usage of more water for both drinking and agricultural purposes in the basin with a possible decrease in the annual precipitation make it necessary to undertake such a study. The results of the investigation show that KRB area experienced drought conditions continuously from 2000 to 2004 with a peak extreme drought in 2001 which confirm to the reported worst drought in the region. It is noted that log-SPI, gamma-SPI, and Deciles captured the historical extreme and severe drought periods successfully, therefore, these methods are recommended to be applied to this region as drought assessment tools.*
Keywords*— *Afghanistan, Kabul River Basin, Drought Analysis, SPI, PNPI, DI, CZI.

I. INTRODUCTION

The term drought is defined as ''a long period with no rain, especially during a planting season.'' [1] Moreover, [2] define drought as a period of abnormally dry weather sufficiently prolonged for the lack of precipitation to trigger a serious hydrologic imbalance, carrying connotations of a moisture deficiency with respect to man's usage of water. Thus, the effects of drought on the environment and ecosystem may cause disasters and result in socio-economic problems. Numerous drought indices have been developed for monitoring meteorological droughts such as the Palmer Drought Severity Index (PDSI) [3; 4; and 5] developed by [6], Standardized Precipitation Index (SPI) [7; 3; 4; 8; 9; 10; 11; 12; and 13] developed by [14], the Drought Severity Index (DSIe) [15], China-Z index (CZ) [16, and 17], Reconnaissance Drought Index (RDI) [18; 17; and 19], Percent of Normal Precipitation Index (PNPI) [20], and Deciles Index (DI) proposed by [21]. Among all the indices, the most popular ones are the SPI [5; 22; 23; 24; and 17] and PDSI [17; and 25]. These indices have different methods of application with different variables. Different drought indices are used in different areas of the world and even several indices are applied for drought analysis on the same area to see the differences among the indices and chose the suitable one for a specific area. For Afghanistan, there is yet no information about any drought index that might be useful to apply. However, some drought studies have been undertaken in the Indus River Basin, of where the Kabul River Basin (KRB) is part. KRB has significant socio-economic importance for Afghanistan since the basin has an annual water discharge of about 18.2 – 20.9 billion m3 [26; and 27] and accounts for a population of 35% in the country [28; and 29] Majority of the population is relied on agriculture [28], that is why the economic growth of the area mostly depends on the precipitation and availability of water resources. It is also important to mention that Kabul River is flowing into Indus River system in Pakistan, hence Indus River in Pakistan is also receiving some of its waters for Kabul River. To the best knowledge of the authors, the meteorological drought in the basin is analyzed for the first time by applying well known methods in this study.

II. STUDY AREA AND DATA COLLECTION

Kabul River Basin (KRB) is located in the eastern part of Afghanistan (shown in Figure 1) with a total area of 108,392.00 km^2 and an annual total precipitation of 32,301.00 million m^3 that makes about 20% of the country's total annual precipitation. The longest river of KRB is Kabul River which is 560 km long within

https://dx.doi.org/10.22161/ijaers.4.6.12 ISSN: 2349-6495(P) | 2456-1908(O)

Afghanistan [30; and 31] It is a transboundary river flowing into Pakistan. According to [32], Afghanistan makes 72,500.00 km^2 or 6.68% of Indus River Basin (IRB) that is 1,086,000.00 km^2 in total comprising Pakistan, India, and China with areas of 609,100.00, 283,800.00, and 120,600.00 km^2, respectively. Therefore, a major area of KRB is also a part of the famous IRB. The cause of selecting this area for our study is due to its importance of socio-economic factor for the country and where the capital and metropolitan city of Kabul with a population of about 4 million is located in.

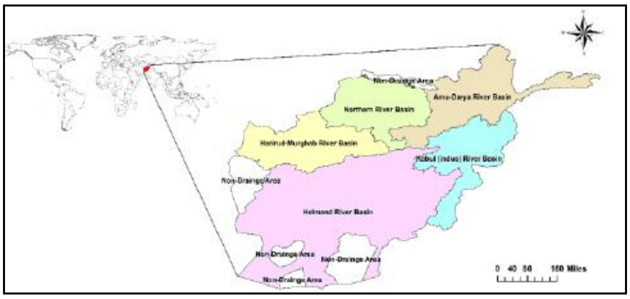

Fig.1: Five major river basins of Afghanistan

Meteorological data from four stations, named Asmar (34.915° N-71.202° E), Gulbahar (35.149° N-69.289° E), Pul-i-Surkh (34.367° N-68.770° E), and Pul-i-Kama (34.469° N-70.557° E), are shown in Figure 2. The data for a period of 38 years is obtained from the Ministry of Energy and Water (MEW) of Afghanistan, which is the responsible body for meteorological data recording in the country. The precipitation data for longer period than 38 years does not exist due to lack of meteorological stations in the area. Thus, the data could be obtained just for the mentioned period of time. Also, the reason for selecting the mentioned fours stations is that these stations almost cover the entire KRB basin. Thirty-eight years (1979-2016) monthly recorded precipitation data used for the stations in this study is shown in Figure 3, where the annual mean precipitation in Asmar, Gulbahar, Pul-i-Surkh, and Pul-i-Kama is 525.92, 381.26, 321.28, and 212.83 mm, respectively.

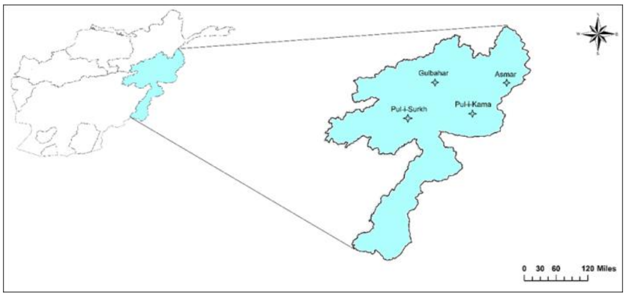

Fig.2: Kabul River Basin and four precipitation stations

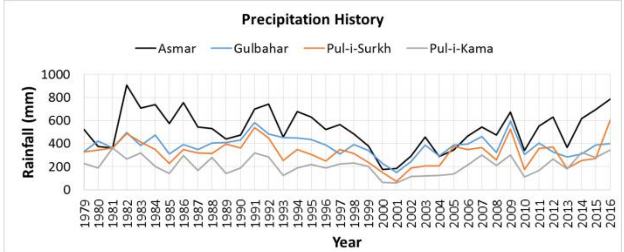

Fig.3: Monthly recorded precipitation data for the stations

III. METHODOLOGY

In this study, the Standardized Precipitation Index (log-SPI, normal-SPI, and gamma-SPI), Deciles Index (DI), China-Z index (CZ), and Percent of Normal Precipitation Index (PNPI) are used for the meteorological drought detection in KRB by using a 38 years of monthly precipitation data from four stations in the basin. Each method is explained below in brief to show the capabilities and characteristics of each one.

3.1 STANDARDIZED PRECIPITATION INDEX (SPI)

This method is one of the easiest and widely used index estimating the meteorological drought severity. The index was developed by [14] where the SPI calculation is based on the long-term precipitation series for a specific duration such as 1, 3, 6, and 12 months [33]. The long-term record is fitted to a gamma probability distribution that is then transformed into a normal distribution, with zero mean and unit variance [34]. The drought classification for z-score (SPI) index is shown in Table 1. The negative SPI values indicate dry periods, whereas positive SPI values indicate wet periods. Three types of widely used SPI distribution are used in this study such as Gamma Distribution SPI, Log-normal SPI, and Normal SPI [35].

Table.1: Drought classification for SPI values [Barua et al. 2010]

SPI value(z-score)	Drought Classification
2.00 or more	Extremely wet
1.50 to 1.99	Very wet
1.00 to1.49	Moderately wet
0.99 to -0.99	Near normal
-1.00 to -1.49	Moderate drought
-1.50 to -1.99	Severe drought
-2.00 or less	Extreme drought

3.1.1 Log-SPI

Log–SPI is non-negative and positively skewed distribution with a simple logarithmic transformation of the data. By applying the log-normal distribution with the sample mean of logarithmic transformed data, the SPI becomes:

$$SPI = z = \frac{\ln(x) - \mu}{\sigma} \quad (1)$$

https://dx.doi.org/10.22161/ijaers.4.6.12 **ISSN: 2349-6495(P) | 2456-1908(O)**

3.1.2 Normal-SPI

The normal-SPI uses the normal probability distribution instead of the gamma distribution [36]. In terms of mathematics, it is easy to calculate, while in this case, the SPI index simply becomes:

$$SPI = z = \frac{x-\mu}{\sigma} \quad (2)$$

where z = SPI value, μ = population mean, and σ = standard deviation.

3.1.3 Gamma-SPI

Gamma-SPI is the most widely applied observational model for precipitation data. It involves fitting a gamma probability density function to a given time series of precipitation [36]. It is defined by its probability density function as:

$$g(x)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}e^{\frac{-x}{\beta}} \quad \text{for } x > 0 \quad (3)$$

where α>0 is a shape parameter, β>0 is a scale parameter, and x>0 is the amount of precipitation. Γ(α) is the gamma function, which is defined as:

$$\Gamma(\alpha)= \int_0^{\infty} y^{\alpha-1}e^{-y}dy \quad (4)$$

α and β parameters can be estimated as follows [42]:

$$\alpha = \frac{1}{4A}\left(1 + \sqrt{1+\frac{4A}{3}}\right), \beta = \frac{\bar{x}}{\alpha}, \text{with} \quad A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n}$$

(5)

In Eq. (5), n is the number of observations. After estimating α and β coefficients, the probability density function is integrated with respect to x, which yields the following expression G(x) for the cumulative probability:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\int_0^x x^{\alpha-1}e^{-x/\beta}dx \quad (6)$$

Substituting t for x/β in Eq. (6):

$$G(x) = \frac{1}{\Gamma(\alpha)}\int_0^x t^{\alpha-1}e^{-t}dt \quad (7)$$

As the gamma function is not defined for x=0, for possibility of zero values, the cumulative probability function becomes:

$$H(x) = q + (1-q)G(x) \quad (8)$$

where q is the probability of zero precipitation, then the cumulative probability distribution is transformed into the standard normal distribution to yield the SPI. The approximate conversion provided by [37] is given as:

$$for\ 0 < H(x) < 0.5 \quad (9)$$

$$z = SPI = -\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right), t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)}$$

$$for\ 0.5 < H(x) < 1.0 \quad (10)$$

$$z = SPI = +\left(t - \frac{c_0+c_1t+c_2t^2}{1+d_1t+d_2t^2+d_3t^3}\right), t = \sqrt{\ln\left(\frac{1}{(1.0-H(x))^2}\right)}$$

where c_0 = 2.515517, c_1 = 0.802853, c_2 = 0.010328, d_1 = 1.432788, d_2 = 0.189269, and d_3 = 0.001308.

3.2 PERCENT OF NORMAL PRECIPITATION INDEX (PNPI)

The (PNPI) is a drought index for evaluation of meteorological data as the percent of the actual precipitation to the normal precipitation. It is generally applied to long-term mean precipitation where at least a 30-year mean is considered [38; and 39]. Generally monthly, seasonally, and yearly PNPI values are calculated for drought index to be 100%, where, less than 100% of PNPI values indicate dry periods. However, the same PNPI may show different results in the different locations. Therefore, it is not a useful method to apply it alone [40]. Drought index classification for the PNPI values is shown in Table 2.

Table.2: Drought index classification for PNPI [41]

NP values	Drought Classification
180% or more	Extremely wet
161% to 180%	Very wet
121% to 160%	Moderately wet
81% to 120%	Near normal
41% to 80%	Moderate drought
21% to 40%	Severe drought
20% or less	Extreme drought

3.3 DECILES INDEX (DI)

The Deciles approach is developed by [21]. In this method, the long-term monthly precipitation is ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is divided in ten parts or deciles on the basis of equal probabilities [41]. The deciles values and drought ranking classifications are given in Table 3.

Table.3: Deciles drought ranking classification

Deciles values	Drought Classification
Deciles 1-2 (lowest 20%)	Much below normal
Deciles 3-4 (next lowest 20%)	Below normal
Deciles 5-6 (middle 20%)	Near normal
Deciles 7-8 (next highest 20%)	Above normal
Deciles 9-10 (highest 20%)	Much above normal

IV. RESULTS

SPI (Normal-SPI, Log-SPI, and Gamma-SPI), Percent of Normal (PNPI), Deciles Index (DI), and China-Z Index

https://dx.doi.org/10.22161/ijaers.4.6.12 ISSN: 2349-6495(P) | 2456-1908(O)

(CZI) annual values were computed for the four stations of KRB of Afghanistan as explained below.

4.1 ASMAR STATION

The results of Normal-SPI, Log-SPI, Gamma-SPI, and CZI are shown in Figure 4. The results of DI are shown in Table 4, and Figure 5. The results of PNPI are presented in Figure 6. As seen; Normal-SPI, Log-SPI, Gamma-SPI, and CZI indicate that the extreme drought occurred in 2000 and 2001. The Normal-SPI and CZI show same moderate droughts but could not capture the severe droughts. The Log-SPI and Gamma-SPI captured severe drought in years 2002 and 2004. The Log-SPI and CZI indicated that years 1981, 2004, 2005, and 2010 have moderated droughts. The Log-SPI and Gamma-SPI have shown the years 2005 and 2010 as moderate drought.

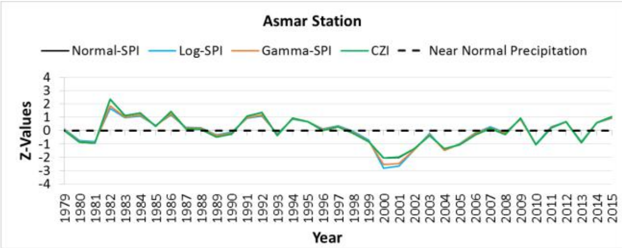

Fig.4: SPI and CZI results for Asmar station

The Deciles results and threshold ranges for Asmar Station are given in Table 4. According the results, the drought condition occurred when precipitation was less than 527.5 mm/year. When precipitation is less than 474.9 mm/year and 370 mm/year severe and extreme drought occur, respectively. Comparing the deciles results with SPI and CZI results as show in Figure 5, Deciles index indicates longer extreme and severe drought conditions than SPI and CZI. Extreme drought years have happened in 1981, 2000, 2001, 2002, 2004, 2005, 2010, and 2013. The severe drought years happened in 1980, 1993, 1999, 2003, 2006, and 2008.

Table.4: Deciles result for all four stations

Annual Precipitation Values				Classification
Asmar	Gulbahar	Pul-i-Surkh	Pul-i-Kama	
326.2 - 370	291.2 - 309.9	187.5-230.3	118.4-137.7	Much below normal
455.2 - 474.9	331.4 - 378.5	256 - 311	169.7-188.6	Below normal
527.5 - 554.8	388.4 - 397.7	336.3-348.3	206.8-224.8	Near normal
627.7 - 688.4	407.1 - 443.4	362.9-372.4	265.4-290.9	Above normal
739.7 - 908.1	476.5 - 595.4	459.2-603.1	319.2-363.7	Much above normal

The PNPI could not capture any extreme drought (Figure 6). It indicated severe drought in years 2000 and 2001, but these two years are classified as extreme drought by the other five methods. This result indicates that PNPI differs from the others. Compared with the other indexes, PNPI shows a longer moderate drought period for years 1980, 1981, 1999, 2004, 2005, 2010, and 2013.

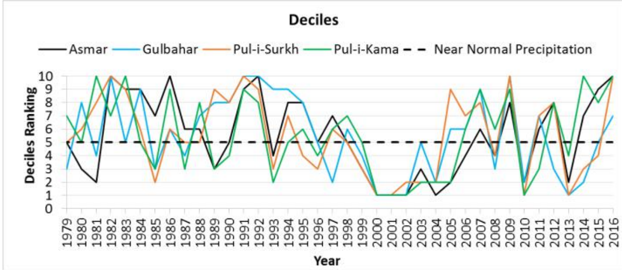

Fig. 1: Deciles ranking for all four stations

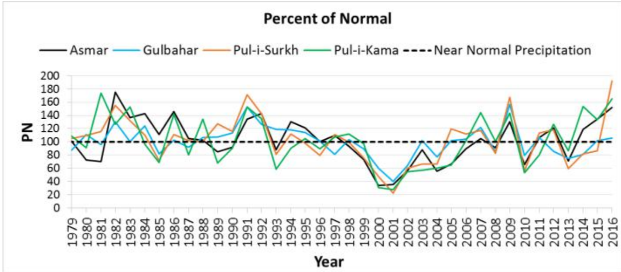

Fig. 2: PNPI results for all four stations

4.2 GULBAHAR STATION

In this station, the Normal-SPI, Log-SPI, Gamma-SPI, and CZI show the same results for extreme, severe, and moderate drought intensities. Based on the results from the mentioned four methods, the extreme drought occurred 2001, severe in 2000 and 2002, and moderate drought in 2004 and 2013, as shown in Figure 7.

Based on the Deciles method, the drought condition happened when precipitation was less than 388.4 mm/year. Also, precipitation less than 378.5 mm/year and 309.9 mm/year are indicators of severe and extreme drought conditions, respectively, as summarized in Table 4. Additionally, Figure 5 shows the Deciles ranking for this station that are from 0 to 10 along the whole period of 38 years. As in Asmar station, the Deciles ranking shows longer periods of extreme and severe drought conditions, as opposed to the SPI and CZI. The extreme drought years are 1997, 2000, 2001, 2002, 2004, 2010, and 2013, while the severed drought years are 1979, 1981, 1985, 1987, 1999, and 2008.

Figure 6 represents the results for the PNPI that has not indicated the extreme drought condition for this station, but the severe drought is captured in 2001. Besides, the moderate drought based on this method are happened in 1985, 1997, 2000, 2002, 2004, 2010, and 2014 summarized in Table 5.

https://dx.doi.org/10.22161/ijaers.4.6.12 **ISSN: 2349-6495(P) | 2456-1908(O)**

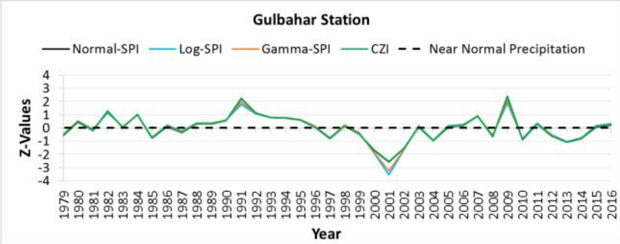

Fig. 3: SPI and CZI results for Gulbahar station

4.3 PUL-I-SURKH STATION

In this station, we can summarize that all four indices such as Normal-SPI, Log-SPI, Gamma-SPI, and CZI show the same results for the three kind of drought intensities with just a minor difference in moderate drought condition for Log-SPI where it does not detected it for years 2003 and 2004. All results are the same while the extreme drought occurred in 2001, severe in 2000, and moderate in 2002, 2003, 2004, 2010, and 2013, respectively. The graphs for SPI and CZI drought results are shown in Figure 8.

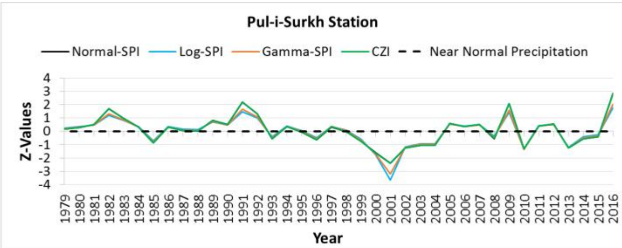

Fig. 4: SPI and CZI results for Pul-i-Surkh station

The classification of deciles method indicates that drought happened when the precipitation was less than 336.3 mm/year in the station (Figure 5). Moreover, the precipitation less than 311 mm/year and 230.3 mm/year show a severe and extreme drought conditions, respectively as described in Table 4. The periods of extreme droughts according to the results shown in Table 5 are 1985, 2000, 2001, 2002, 2003, 2004, 2010, and 2013, while the severe drought periods are 1993, 1995, 1996, 1999, 2008, 2014, and 2015.

Similar to the results of PNPI for Asmar and Gulbahar stations, Pul-i-Surkh station does not detected the extreme drought condition (Figure 6). The PNPI results again show longer periods of moderate drought in years 1985, 1996, 1999, 2000, 2002, 2003, 2004, 2010, and 2013. The severe drought condition is captured in 2001, while the severe drought is detected by SPI and CZI methods in year 2000.

4.4 PUL-I-KAMA STATION

The results of Normal-SPI, Log-SPI, Gamma-SPI, and CZI are the same for moderate drought conditions in years 1993, 2002, 2003, 2004, and 2010 (see Figure 9). Extreme and severe drought conditions are similar for Normal-SPI and CZI for years 2001 and 2000 respectively, but in Log-SPI and Gamma-SPI, the severe drought condition is not detected. However, the extreme drought period is specified to be 2000 and 2001 for both mentioned indexes.

The Deciles method classification shows a state of drought when the precipitation was less than 206.8 mm/year in the station (Figure 5). Furthermore, the precipitation less than 188.6 mm/year and 137.7 mm/year show severe and extreme drought situations in Table 4 respectively. The severe and extreme drought durations are longer and different in the deciles results than the SPI and CZI methods. Severe drought condition occurred in 1985, 1987, 1989, 1990, 1996, 2011, and 2013. The extreme drought state happened in 1993, 2000, 2001, 2002, 2003, 2004, 2005, and 2010.

Considering the PNPI results, the extreme drought condition is not detected in Pul-i-Kama station the same as in other three stations (Figure 6). The severe drought state is shown in 2000 and 2001, and the moderate drought situation happened to be in 1985, 1997, 1989, 1993, 2002, 2003, 2004, 2005, and 2010 as shown in Table 5.

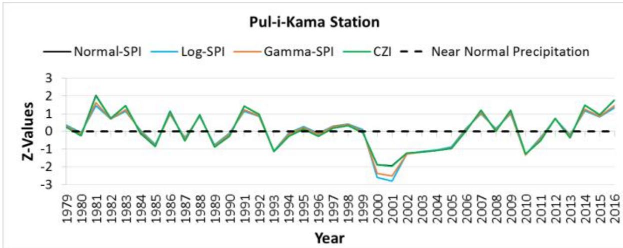

Fig. 5: SPI and CZI results for Pul-i-Kama station

V. CORRELATION ON THE RESULTS

Table 5 summarizes the drought intensities for both stations. The extreme, severe, and moderate drought intensities are listed for normal-SPI, log-SPI, gamma-SPI, CZI, and PNPI methods. The moderate drought intensity is not listed for deciles method because this method just indicates extreme and severe droughts.

The normal-SPI, log-SPI, gamma-SPI, and CZI method are almost same for each station and gamma-SPI captured the drought successfully, thus, the gamma- SPI is selected to compare the Z-values for all station as given in Figure 10. Figure 5 and Figure 6 illustrate the results and comparison of deciles and PNPI methods, respectively. Based on these results from all methods, the common extreme drought year is 2001 in all stations and the year 2000 was also predicted as extreme drought only for Asmar station. The common severe drought were almost predicted in 2000 and 2002 years. The Asmar station also faced severe drought in 2004. The common moderate drought conditions occurred in 2004 and 2010. The extreme wet conditions are also generally common for both stations as in 1982, 1991, and 2009. Therefore, both stations experienced almost the same occurrences of drought and wet conditions in the same period.

https://dx.doi.org/10.22161/ijaers.4.6.12 ISSN: 2349-6495(P) | 2456-1908(O)

Table. 5: Summary of indicated historical drought by six DI methods

Stations	Methods																
	Normal-SPI			Log-SPI			Gamma-SPI			CZI			PN			Deciles	
	Drought Intensity																
	Extreme	Severe	Moderate	Extreme	Severe	Moderate	Extreme	Severe	Moderate	Extreme	Severe	Moderate	Extreme	Severe	Moderate	Extreme	Severe
Asmar	2000 2001	—	1981 2004 2005 2010	2000 2001	2002 2004	2005 2010	2000 2001	2002 2004	2005 2010	2000 2001	—	1981 2004 2005 2010	—	2000 2001	1980 1981 1999 2002 2004 2005 2010 2013	1981 2000 2001 2002 2004 2005 2010 2013	1980 1993 1999 2003 2006 2008
Gulbahar	2001	2000 2002	2004 2013	2001	2000 2002	2004 2013	2001	2000 2002	2004 2013	2001	2000 2002	2004 2013	—	2001	1985 1997 2000 2002 2004 2010 2013	1997 2000 2001 2002 2004 2010 2013	1979 1981 1985 1987 1999 2008
Pul-i-Surkh	2001	2000	2002 2003 2004 2010 2013	2001	2000	2002 2010 2013	2001	2000	2002 2003 2004 2010 2013	2001	2000	2002 2003 2004 2010 2013	—	2001	1985 1996 1999 2000 2002 2003 2004 2010 2013	1985 2000 2001 2002 2003 2004 2010 2013	1993 1995 1996 1999 2008 2014 2015
Pul-i-Kama	2001	2000	1993 2002 2003 2004 2010	2000 2001	—	1993 2002 2003 2004 2010	2000 2001	—	1993 2002 2003 2004 2010	2001	2000	1993 2002 2003 2004 2010	—	2000 2001	1985 1997 1989 1993 2002 2003 2004 2005 2010	1993 2000 2001 2002 2003 2004 2005 2010	1985 1987 1989 1990 1996 2011 2013

The results point out that the PNPI method could not predict the extreme drought. PNPI tends to over predict the number of moderate drought years as opposed to the SPI and CZI methods. The deciles ranking indicates two drought intensities as below normal (severe drought) and much below normal (extreme drought) as given in Table 5. Therefore, deciles method shows more years of extreme and severe drought than other methods. The results also show that the normal-SPI and CZI methods indicated the drought and wet behaviors similar. The normal-SPI and gamma-SPI methods almost predicted the same and extreme drought conditions.

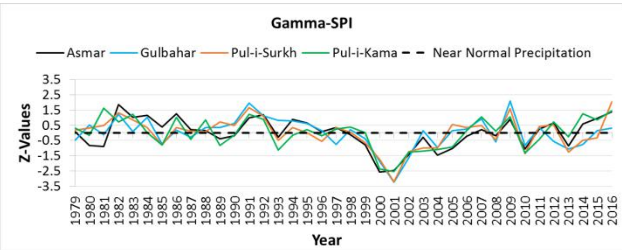

Fig.10: Gamma-SPI Z-Values comparison for all stations

In summary, Asmar station area experienced the drought conditions frequently from 1999 to 2005 with a peak extreme drought in 2001, also, in 1980, 1981, 2010, and 2013. The Gulbahar, Pul-i-Surkh, and Pul-i-Kama stations area experienced the drought conditions continuously from 2000 to 2004 with a peak extreme drought in 2001, same as Asmar station. These results confirm the reports about Afghanistan's droughts during the last three decades. As discussed earlier the central and south-west parts of Afghanistan and neighboring regions of the study area in Iran and Pakistan experienced the extreme drought mostly between 1998 and 2002 years with peak in 2001.

VI. CONCLUSION

This study investigated the performances of six popular drought indexes (log-SPI, normal-SPI, and gamma-SPI, Deciles Index (DI), China-Z index (CZ), and Percent of Normal Precipitation Index (PNPI)) in Kabul River Basin in Afghanistan. The six DI methods provide almost same results for all stations in the basin. Kabul River Basin experienced more droughts from the end of 1990s to the beginning of 2000s with the extreme drought conditions in 2001 which confirm to the reported worst drought in the region. When precipitation is less than 370 mm/year, 309.9 mm/year, 230.3 mm/year, 137.7 mm/year extreme drought occurs in Asmar, Gulbahar, Pul-i-Surkh, and Pul-i-Kama stations, respectively. It is noted that normal-SPI, CZI, and PNPI indicated less and moderate drought condition while log-SPI, gamma-SPI, and deciles captured the historical extreme and severe drought periods successfully, therefore, these methods are recommended to be applied to this region as drought assessment tools.

ACKNOWLEDGEMENTS

The authors acknowledge and thank the Ministry of Energy and Water of Afghanistan for providing meteorological data for this research.

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