Research Article

Investigation of Characteristics of Hydrological Droughts in Indus Basin

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Abstract | Drought is a natural event that can have significant impact on the economy. Pakistan is a semi-arid country where hydrological drought generally causes adverse impacts on agricultural production and hydropower generation. In this research, the characteristics of hydrological droughts in Indus River basin using stream flow data of major rivers of Pakistan were investigated. Stream flow drought indices (SDI) were used to determine the severity of droughts for the Indus, Jhelum, Chenab and Kabul River at Tarbela, Mangla, Marala and Warsak hydrological stations for the period 1962-2011. A drought spell starting from 1999 and ending in 2002 was observed for all stations and is considered to be the worst drought in the history of Pakistan. Analysis of historical streamflow data indicated an increased occurrence of droughts in the last 12 years, which may be attributed to climate change. Extreme drought events were observed at Tarbela during October-September and at Mangla during October-June with SDI value of -2.36 and -2.74, respectively. Moderate to severe wet conditions were also detected in the analysis period. Several strategies for the mitigation of adverse impacts of droughts in the study region are recommended.

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Introduction

Droughts and floods are the two extreme natural events that can have considerable economic, societal and environmental impacts (Pasha et al., 2015). Conventionally, drought is a prolonged period of receiving less precipitation than normal over a large area. The occurrence of drought is very complicated to define, quantify, and monitor, mainly due to the large number of variables involved in the phenomenon. Based on the choice of interest, drought can be defined in a number of ways, such as meteorological, hydrological, agricultural and socioeconomic drought (Shiau et al., 2012). Meteorological drought is associated with deficient precipitation for an extended period of time over an area. Hydrological drought occurs as a result of significant decrease in the water availability in the land phase of the hydrological cycle (Sardou et al., 2014). Agricultural drought refers to the reduction in final crop yield due to low soil moisture content for reasonable time period. Socioeconomic drought refers to socio-economic problems caused by insufficient water supplies in the water resource system due to natural or human factors (Mishra and Singh, 2010).

Drought is an interconnected phenomenon which rises from less precipitation limiting the surface and ground water availability which leads to agricultural drought affecting socioeconomic status of the people and the country. Wong et al. (2013) applied statistical tools and models to investigate the connection between meteorological and hydrological drought characteristics. He concluded that both meteorological (precipitation) drought and hydrological (ground water and stream flow) drought were correlated in terms of their duration and severities. The importance of drought management cannot be ignored as it impacts our economic sectors and daily activities to a great extent (Santos et al., 2011). Drought conditions also impact energy production, both in terms of water availability for hydropower and cooling water in electricity generation, river navigation, agricultural and public water supply (Feyen et al., 2009). Obtaining detailed information on past drought variations may allow water managers and planners to properly manage water resources for future risk of drought (Xu et al., 2015). Each drought event is characterized through four parameters, namely, drought index (its severity), time of onset and its duration, areal extent, and its frequency of occurrence (Sardou and Bahremand, 2014). The prediction of these parameters is generally conducted through various drought indices used in the literature (e.g. Shafer and Dezman, 1982; Weghorst, 1996; Palfai, 2002; Nalbantis, 2008; Vicente-Serrano et al., 2012). These indices either use stream flow as an individual input variable or in combination with other variables in the hydrological cycle. For instance, the surface water supply index (SWSI) takes reservoir storage, streamflow, snowpack and precipitation as an input parameter (Shafer and Dezman, 1982). Standardized precipitation index (SPI) uses only precipitation as input variable and used to monitor meteorological drought. Similarly, the reclamation drought index (RDI) uses temperature as an additional input parameter with the above parameters (Weghorst, 1996). Nalbantis (2008) introduced stream flow drought index (SDI) that requires only stream flow data as an input parameter and thus reduces calculation difficulties and the data requirements from other sources.

A number of studies (Tigkas et al., 2012; Tabari et al., 2012; Gumus and Algin, 2017) have been conducted around the world to assess hydrological drought using SDI method. Pathak et al. (2016) used SDI and standardized runoff index (SRI) to assess hydrological drought in the Ghataprabha river basin. The authors concluded that moderate drought appear between 1986-1988 and 2001-2005 continuously. According to the study by Sardou and Bahremand (2014), hydrological drought varied from mild to severe across Halilrud basin from upstream to downstream. Pandey et al. (2008) reported that the upper reaches of Betwa river course were more susceptible to sever droughts than were the lower reaches. Over the past 50 years, Pakistan faced a number of major drought events. Most remarkable drought-intensive periods are late 1960-1970, the middle 1980's and the late 1990s to early 2000s. The drought that started in 1998 is considered to be the worst which affected agricultural growth by 2.6% during 2000-2001 (Ahmad et al., 2004). The drought spell 2001-2002 resulted in water shortage of up to 51% of normal supplies as against 40% of the previous year (Ahmad et al., 2004). In Sindh and Baluchistan provinces 30,000 livestock perished in the drought year of 2000 (Pasha et al., 2015). Sheikh (2001) investigated meteorological drought conditions using the data from 1961-1990, and concluded that whole of Pakistan is vulnerable to drought. Baluchistan and Sindh provinces are the most arid parts of the country and have high probability of extreme droughts (Mazhar et al., 2015). According to World Disasters Report (2003), 6,037 people were killed and 8,989,631 were directly or indirectly affected by the drought spell that lasted from 1993-2002.

The previous studies (Ahmad et al., 2004; Mazhar et al., 2015; Pasha et al., 2015; Sheikh, 2001) analyzed meteorological and agricultural drought only, while this study focused on hydrological drought using long-term streamflow data. As the stream flow is the most crucial part of hydrological cycle which can be stored and used for irrigated agricultural, industrial and domestic purposes. Hence, its seasonal quantification in terms of high and low river flow is critically important for water managers. Therefore, the aim of this research is to analyze characteristics of hydrological droughts in Indus River basin using the streamflow data of four major rivers in Pakistan namely; Indus, Jhelum, Chenab and Kabul.

Study area

Surface water resources of Pakistan mostly depend upon Indus river basin system. The main rivers in this system are Indus, Jhelum, Chenab, Kabul, Ravi and Sutlej (Figure1). The total area of the Indus river

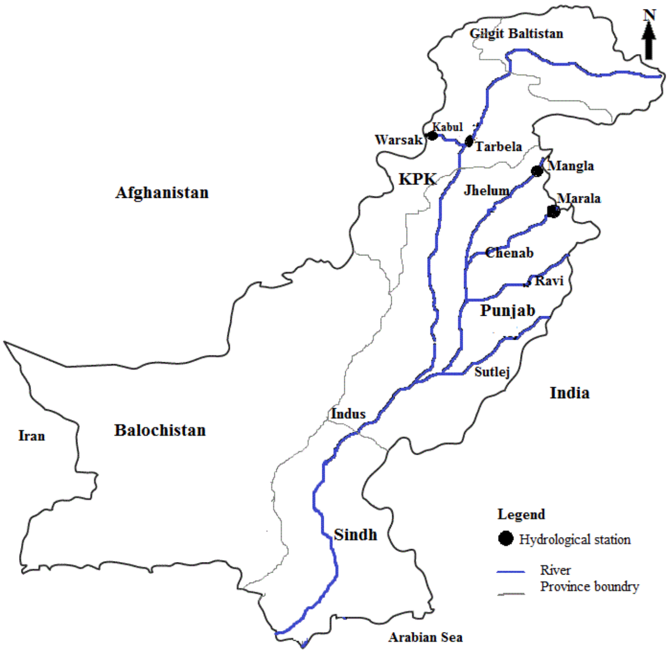

Figure 1: *Indus River basin system in Pakistan.*

basin is 1.12 million km^2 shared between Pakistan (47%), India (39%), China (8%) and Afghanistan (6%) (Wolf et al., 1999). The basin stretches from the Himalayan Mountains in the north to the dry alluvial plains of Sindh province in Pakistan in the south and finally flows into the Arabian Sea (Negi, 2004). About 50% of the inflow to this basin is generated from snow and glacier-melt in the northern mountains (Winger et al., 2005). Agriculture is the largest economic sector of Pakistan accounting for about a quarter of the country's gross domestic product (Qureshi, 2011; Khalil et al., 2014). But at the same time, the country has an arid climate with mean annual rainfall of 250 mm and agriculture mostly depends on irrigation water. According to Agricultural statistics of Pakistan (2008), irrigation is used on 80% of all the arable land. The main supply source for irrigation is the Indus basin irrigation system (IBIS) which comprises of five major rivers as already mentioned. These rivers provide total runoff volume of 173 billion cubic meter (BCM) out of which 130 BCM is drawn for irrigation purposes to irrigate 18 Mha of land through a network of barrages, headworks and canals (Khattak et al., 2011). The remaining 43 BCM of water goes to Arabian Sea. For this study, the hydrological stations selected on Indus, Jhelum, Chenab and Kabul rivers are Tarbela, Mangla, Marala and Warsak, respectively. The selected stations have high significance due to their critical locations in the IBIS. Deficiency in water availability at these stations will ultimately affect irrigated agriculture and economy of the country. Knowing the past behavior of the past hydrological drought will help the water managers to properly plan and manage the water resources and early mitigation strategies in response to future drought.

Materials and Methods

The 10-daily streamflow data of the Indus, Jhelum, Chenab and Kabul at Tarbela, Mangla, Marala and Warsak hydrological stations, respectively were obtained from the Provincial Irrigation Department, Lahore for the period of 1962-2011. This data is converted to monthly values. These monthly values set are then used to evaluate hydrological drought in the study period at selected stations. To analyze the hydrological drought, we used SDI method developed by Nalbantis and Tsakiris (2009) because of its simplicity and high effectiveness.

The streamflow drought index (SDI)

According to this method, if monthly stream flow volumes are available within the hydrological year, then the streamflow volumes can be calculated as:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \qquad \text{..... (1)}$$

i=1,2,3,….;N (hydrological year); j=1,2,3,……,12 (j = 1 for October and j =12 for September); k=1,2,3,4 (k = 1 for October-December; k = 2 for October-March; k = 3 for October-June and k = 4 for October-September period).

Where; $V_{i,k}$ is the cumulative stream flow volumes within the ith hydrological year and the kth reference period and $Q_{i,j}$ is the stream flow for the jth month within the ith hydrological year.

The mean $\bar{V}_k$ and standard deviation S_k of the cummulative stream flow volume is calculted from which one can find the SDI for kth reference period within ith hydrological year via the following equation:

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{S_k} \qquad \text{...... (2)}$$

k=1,2,3,4 i=1,2,3,……..N

In this definition, the truncation level is set to $\bar{V}_k$ although other values could be used. Based on the calculated SDI, states of hydrological droughts are defined. The SDI values have been classified by Al-Faraj et al. (2014) from extreme drought to extreme wet conditions and are given in Table 1.

Table 1: *Hydrological drought with the aid of SDI state.*

State	Description	Criterion
3	Extreme Wet	SDI ≥ 2.0
2	Severe Wet	1.5 ≤ SDI < 2.0
1	Moderate Wet	1.0 ≤ SDI < 1.5
0	Near normal	-1.0 < SDI < 1.0
-1	Moderate drought	-1.5 < SDI ≤ -1.0
-2	Severe drought	-2.0 < SDI ≤ -1.5
-3	Extreme drought	SDI ≤ -2.0

Estimation of frequency of drought states

The process of estimating the frequency of drought states is assumed to be a non-stationary Markov Chain (Isaacson and Madsen, 1976). Markov Chains are widely used in the water resources to predict drought events and its occurrence probabilities (Lohani and Loganathan, 1997, Ochola and Kerkides, 2003, Paulo and Pereira, 2007 and Sardou and Bahremand, 2014). This study also employed the non-stationary Markov Chain process to predict the occurrence frequency of each degree of drought and wet severity.

We used monthly stream flow data to calculate cumulative stream flow volumes using Equation (1). Then SDI values are calculated for each reference period within the hydrological year using Equation (2). Based on the SDI values drought states of each severity ranging from -3 to 3 are defined according to the criteria of Table1. Finally, the frequency of each state is estimated using the following equation:

$$F_{m,k} = \frac{n_{m,k}}{N} \quad .....(3)$$

Where; $F_{m,k}$ is the frequency of each state m (-3, -2, -1, 0, 1, 2, 3) in reference period k (k=1 for Oct-Dec, k=2 for Oct-Mar, k=3 for Oct-Jun and k=4 for Oct-Sep). And N is total available sample years and $n_{m,k}$ is the number of drought occurrences of each state *m* within the k reference period. Further detail can be seen in Yeh et al. (2015) and Sardou and Bahremand (2014). SDI values are calculated at 3-month overlapping time step (October-December, October-March, October-June and October-September) for the period of 1962-2011.

Results and Discussions

SDI analysis result

To evaluate hydrological drought the results are compared with the standard drought criterion given by Al-Faraj et al. (2014). The maximum and minimum SDI values at different stations during different seasons are given in Table 2. The positive values show wet condition while negative values show drought condition. It indicates that for a reference period Oct-Sep extreme drought was experienced at Tarbela and Mangla stations of magnitude -2.36 and -2.14, respectively. A severe drought at Mangla and Warsak of magnitude -2.74 and -2.44 at Marala and Warsak station can be seen during Oct-Jun. It also reveals that Tarbela station exhibit an extreme wet conditions of magnitude of 3.05 during the reference period October-March.

Table 2: *Maximum and minimum SDI values observed at different stations during the analysis period.*

Station	Oct-Dec		Oct-Mar		Oct-Jun		Oct-Sep	
	Max	Min	Max	Min	Max	Min	Max	Min
Tarbela	2.05	-2.19	3.05	-2.05	3.01	-2.02	2.02	-2.36
Mangla	2.32	-1.99	2.07	-2.44	2.18	-2.74	2.06	-2.14
Marala	2.51	-2.06	2.13	-2.09	2.00	-2.25	1.97	-1.89
Warsak	2.18	-2.11	2.34	-2.00	2.53	-2.44	1.87	-1.80

The number of drought events is presented in Table 3. Almost all the stations exhibit a good number of drought events. It has also been observed that every station experience more number of drought events in the first two reference periods Oct-Dec and Oct-Mar. The results also show that equal number of drought events occur at all the stations with no marginal difference. Almost all stations exhibit the same number of drought pattern. It may be due to the fact that as 50% of the inflow to these stations is generated from snow and glacier melt (Winger et al., 2005).

Table 3: *Number of drought events at 3-month time step during 1962-2011.*

Station	Oct-Dec	Oct-Mar	Oct-Jun	Oct-Sep
Tarbela	26	28	23	24
Mangla	25	24	23	23
Marala	26	25	22	25
Warsak	26	23	26	24

Table 4: *Hydrological drought characteristics for reference period October-September at different stations during the analysis period 1962-2011.*

S. No	Station	Event	Onset of drought event (year)	Termination of drought event (Year)	Duration* (Years)	Average SDI value	Drought Description
1	Tarbela	1	1974	1977	3	-1.16	Moderate
		2	1978	1983	5	-0.67	Near normal
		3	1984	1987	3	-0.65	Near normal
		4	1999	2002	3	-1.14	Moderate
		5	2006	2009	3	-0.53	Near normal
2	Mangla	1	1969	1972	3	-1.14	Moderate
		2	1998	2002	4	-1.93	Severe
		3	2005	2008	3	-0.43	Near normal
3	Marala	1	1968	1972	4	-1.28	Moderate
		2	1998	2002	4	-1.03	Moderate
		3	2006	2011	5	-0.94	Near normal
4	Warsak	1	1984	1990	6	-0.96	Near normal
		2	1998	2004	6	-1.07	Moderate

** Droughts that lasted for more than two years have been selected.*

The hydrological drought characteristics, including the onset and termination of a drought event, its severity and duration has been evaluated for the reference period (Oct-Sep) and is given in Table 4. The severe drought with an average magnitude of -1.93 occurred during the period 1998-2002 at Mangla station which lasted for four years. The longest mild to moderate drought was experienced at Warsak. A mild to severe drought occurred at all stations during 1998-2002. Three drought spells, namely 1969-1972, 1999-2002 and 2006-2008 are common for Mangla and Marala stations.

The SDI series for six months reference period (October-March) are shown in Figure 2. The period from October – March is the non-monsoon rainfall period. Results indicate that the reference period encompasses the classes of normal to severe drought events. As shown in Figure 2, the drought at Mangla and Marala commences from the year 1969 and shows an oscillatory behavior during different years till 2011. This shows that Mangla and Marala have similar drought characteristics. The maximum drought event was observed at Tarbela during this reference period. Also, the longest drought spell at Tarbela was observed in 1973, which continued for 13 years up to 1986 in this reference period. Extreme drought with an SDI value of -2.44 occur at Mangla during 2000-01, while extreme wet condition with an SDI value of 3.05 occur at Tarbela during 1990-91. Tarbela and Warsak station experienced a number of successive drought events during 1968-1986, while wet conditions prevailed during 1989-1996 and 2003-2011. The hydrological year 1988-89 is the turning point for Tarbela and Warsak after which the number of drought events tends to decrease and wet conditions tend to increase. The drought spell that began in 1999 and terminated in 2002 was found to be common for all the stations. The results also reveal

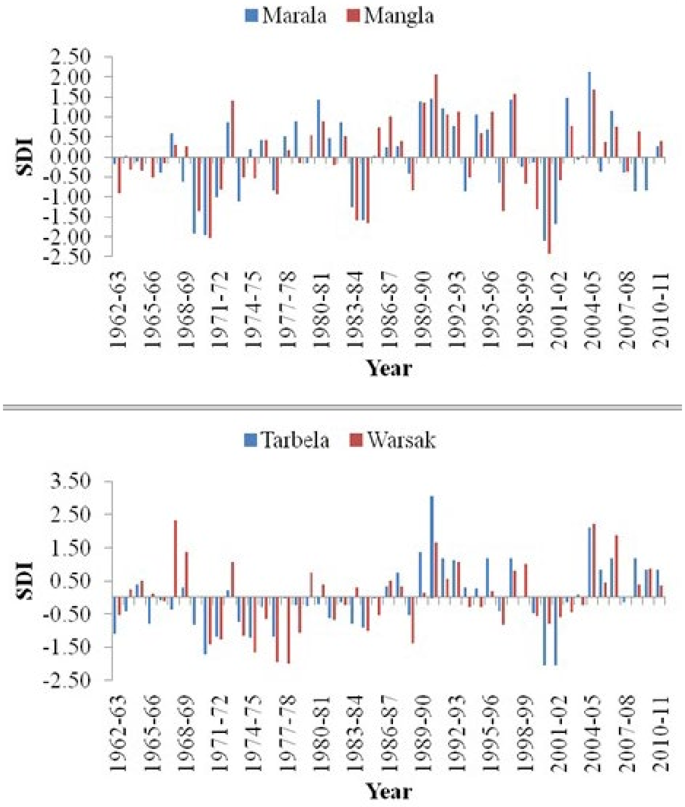

Figure 2: *SDI series for the reference period October-March.*

that drought severity decreases after 2002 and wet condition arises and continues up to 2011.

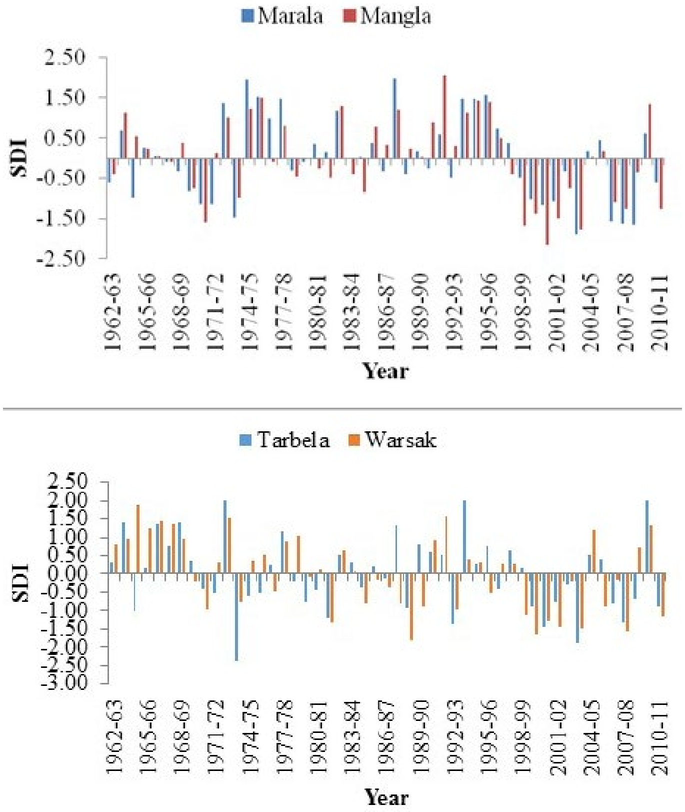

Figure 3: *SDI series for the reference period of October-September.*

In addition to the analysis of drought severities in dry periods (October-March), the SDI analysis for wet and dry season (October-September) was addressed in this study. Figure 3 presents the analysis of SDI results for the reference period Oct-Sep. As shown in Figure 3, Tarbela and Warsak have the similar drought characteristics. In the beginning of the period between 1962-1969 there are moderate to wet conditions which change to normal to extreme drought conditions between 1999-2011. During this reference period the number of drought events is less than the first three reference periods at all stations except Warsak. At Tarbela and Mangla extreme drought was observed while at Marala and Warsak severe drought was detected. An analysis of the results of the past 12 years shows that a number of successive drought events occur at all the stations. The analysis result revealed two longest drought spells at Warsak. Tarbela exhibited a number of drought spells that lasted for more than two years. During the mid period of 1974-1997, a successive number of moderate to extreme droughts occurred at Mangla and Marala while Tarbela and Warsak exhibited both drought and wet conditions. Normal to extreme wet conditions were observed at all stations during the hydrological years 1963-64, 1972-73, 1977-78, 1982-83, 1991-92, 1993-94, 1995-96 and 2009-10.

Estimation of frequency values of drought occurrences using markov chains

In this study the method of Markov Chains was used to analyze frequencies of drought conditions ranging from drought to lack of drought. Tables 5 and 6 shows the frequency of drought to wet conditions at each station. In other words, the very extreme drought events have less frequency than near normal. The results show that with an increase in the duration of frequency, the state of drought decreases. The results also indicate that about 90% of frequencies lie within the range of moderate drought to moderate wet states. As the analysis reference time period increases, the severity of drought events decreases while that of wet events increases.

Table 5: *Frequency of each state at Mangla and Tarbela during study period.*

State	Mangla				Tarbela			
	Oct-Dec	Oct-Mar	Oct-Jun	Oct-Sep	Oct-Dec	Oct-Mar	Oct-Jun	Oct-Sep
3	0.04	0.02	0.02	0.02	0.02	0.04	0.02	0.04
2	0.04	0.04	0.04	0.00	0.06	0.00	0.04	0.02
1	0.06	0.12	0.08	0.20	0.08	0.14	0.10	0.10
0	0.67	0.67	0.69	0.59	0.69	0.67	0.67	0.71
-1	0.10	0.06	0.06	0.10	0.08	0.08	0.10	0.08
-2	0.08	0.04	0.06	0.06	0.04	0.02	0.04	0.02
-3	0.00	0.04	0.04	0.02	0.02	0.04	0.02	0.02

Table 6: *Frequency of each state at Marala and Warsak during study period.*

State	Marala				Warsak			
	Oct-Dec	Oct-Mar	Oct-Jun	Oct-Sep	Oct-Dec	Oct-Mar	Oct-Jun	Oct-Sep
3	0.04	0.02	0.02	0.00	0.02	0.04	0.02	0.00
2	0.06	0.00	0.02	0.08	0.06	0.04	0.02	0.06
1	0.06	0.16	0.14	0.10	0.12	0.08	0.12	0.12
0	0.69	0.65	0.63	0.61	0.65	0.65	0.67	0.63
-1	0.10	0.06	0.10	0.12	0.04	0.12	0.12	0.10
-2	0.02	0.08	0.06	0.08	0.04	0.06	0.00	0.08
-3	0.02	0.02	0.02	0.00	0.02	0.00	0.04	0.00

Conclusions and Recommendations

The present study investigated the hydrological drought characteristics at Tarbela, Mangla, Marala and Warsak for the period of 1962-2011 using SDI. The results of the analysis conducted herein clearly indicates that there were a large number of hydrological droughts in the period of analysis considered. The severity of the droughts at different stations as determined on the basis of SDI ranged from mild to extreme. The results of the present study can be potentially utilized by the water resource managers to formulate strategies for future drought risk in their respective basins. The following specific conclusions were drawn from this study:

1. All hydrological stations experienced several hydrological droughts as well as wet events of normal to extreme severities. The largest number of drought events occurred at Tarbela followed by Marala and Warsak.
2. All the stations experienced a common drought of moderate to severe appearing in 1998 and terminating in 2002. This is also considered the worst drought spell in the history of Pakistan. The analysis of results showed that several drought events occurred in the last 12 years. The two longest drought events occurred at Warsak in the period 1984-1990 and 1998-2004 with SDI values of -0.96 and -1.07, respectively. Extreme drought events were observed at Tarbela during October-September and at Mangla during October-June with SDI value of -2.36 and -2.74, respectively.
3. Several drought measures like construction of water storage reservoirs, adoption of deficit and high efficient irrigation systems are recommended.

Author's Contribution

Muhammad Shahzad Khattak: Developed the research idea and write up of the paper.
Amjad Khan: Data analysis and development of tables and figures.
Mahmood Alam Khan: Assisted in compilation and presentation of results.
Waqas Ahmad: Improved the manuscript.
Shafiq ur Rehman: Contributed in literature review.
Mohammad Sharif: Reviewed the manuscript and improving its readability
Sajjad Ahmad: Reviewed the manuscript and provided useful inputs

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