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Analysis of streamflow data for trend detection on major rivers of the Indus Basin

Muhammad Shahzad Khattak[1], Naseem Ur Reman[1], Mohammad Sharif [2] and Mahmood Alam Khan[1]

[1]Department of Agricultural Engineering, University of Engineering and Technology, Peshawar
[2]Department of Civil Engineering, Jazan University, Saudi Arabia

Abstract

The main objective of this study is to evaluate discernible long term trends in streamflows of four major rivers of Pakistan, namely Kabul, Indus, Jhelum, and Chenab. For each river, the first hydrological station where flow rate is measured after its entry to Pakistan, has been selected. The stations, thus selected on Kabul, Indus, Jhelum and Chenab are Warsak, Tarbela, Mangla and Marala, respectively. The average monthly streamflow data for each of the four stations was collected from Irrigation department, Lahore for the period 1962-2011. The annual as well as seasonal analysis of average monthly streamflows was conducted using the Mann Kendall non-parametric test. For each case, the trend slopes were estimated using the Sen's slope method. A trend free pre-whitening (TFPW) approach was used to account for the auto correlation in the time series. Results indicate increasing trends for winter streamflows and decreasing trends for summer streamflows. For the spring season, Warsak exhibited decreasing trend, whereas the other stations showed increasing trends. Annual flow had a decreasing trend at all stations. The trends identified in this study may be partially attributed to the effects of climate change in Pakistan.

Keywords: Climate change; Trends;Stream flow; Mann Kendall test; Sen's slope.

1. Introduction

The atmospheric concentration of carbon dioxide has shown a dramatic rise from about 280 ppm in pre-industrial era to 379 ppm in 2005 (IPCC, 2007a). The years 1998 and 2005 were the hottest years in the available air temperature record since 1850. Temperature trend for the last 100-years is shown in Figure 1. The updated 100-year trend (1906–2005) of 0.74°C is larger than the 100-year warming trend of 0.6°C projected in the third assessment report of the Intergovernmental Panel on Climate Change (IPCC), possibly due to occurrence of relatively warmer years in the last decade or so. The global mean temperature is likely to experience a rise of about 4°C by the year 2100 if urgent steps are not taken (IPCC 2007a). Even a single degree rise in temperature could lead to a rise of around 6-8% in the atmospheric water vapor (Buchdahl et al., 2002). Consequently, some parts of the globe may experience prolonged and intense periods of precipitation leading to increase in flood frequencies. The other parts of the world may experience decreased precipitation thus resulting in increase of drought frequency. According to the IPCC (2001, 2007a) reports some larger changes have been observed in the high latitude Northern Hemisphere places like North America, Europe and Asia since 1976 where winter temperature has increased substantially. A pattern of constant rise in air temperatures over the South Asian region has been observed during the past 100-years or so (IPCC, 2007a).

A significant consequence of enhanced warming in the Asia region is the melting of Himalayan glaciers. Major Asian rivers originating from the Himalayas, namely the Indus, Ganges, Brahmaputra, Salween, Mekong, Yangtze and Huang are the main source of water for 2 billion people in the region (IPCC 2007b). Many great regions of the world have experienced long term trends in precipitation from 1900 to 2005. Results indicate that the wet areas are becoming wetter and drier, whereas dry areas are becoming drier. Annual land precipitation has continued to increase in the

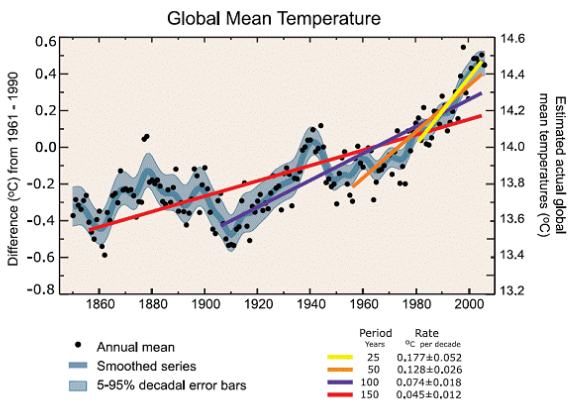

Fig.1. Global temperature trend for the last century (Source: IPCC 2007a)

middle and high latitudes of the Northern Hemisphere except over Eastern Asia. Rainfall exhibits both positive and negative trends over the South Asian region; however, the trend direction varies with the location (IPCC 2007b). An excellent review of changing precipitation patterns using observed records from stations around the world has been presented by Dore (2005).

Scientific studies reveal that stream flow is affected by both climatic variability and anthropogenic activities. (Ye et al., 2013). Water utilization for agricultural and industrial development also causes significant changes in the water cycle and affects the variation of surface and sub-surface runoff (Du et al., 2012). Due to ever increasing importance of water management, investigation of changes in stream flow and water resources due to climatic variations and human activities has received considerable attention in recent years (Scanlon et al., 2007). Shanshan et al. (2012) concluded that the annual stream flow decreased significantly ($p > 0.05$) by 1.7 mm/annum in Baiyangdian Lake the largest wetland in North China. In a study conducted by Peng et al. (2013) in the Hutuo River Basin in China, it was concluded that climatic variability is primarily responsible for reduction in river flow by 70% and 62% estimated by the two-parameter and linear regression model, respectively. They further reported that the respective percent attributions due to human activities were found as 30% and 38% as estimated by two different techniques. In another study, Liang et al. (2013) concluded that reduction of streamflow due to climatic variability and human activities were 30% and 70%, respectively.

Studies in Pakistan have primarily focused on trends in temperature and precipitation. Streamflow related studies are currently in their infancy stage in developing countries like Pakistan. The overarching aim of this research is to analyze trends in average monthly inflows at one station on each of four major rivers in Pakistan, namely Kabul, Indus, Jhelum, and Chenab. The stations selected on Kabul, Indus, Jhelum, and Chenab is Warsak, Tarbela, Mangla and Marala, respectively. Each of these stations is the first hydrological station on the river after its entry into Pakistan. Analysis of trends in streamflows has been carried on annual as well as seasonal scale.

2. Study area

The trans-boundary Indus River basin has a total area of 1.12 million km^2 distributed between Pakistan (47%), India (39%), China (8%) and Afghanistan (6%) as given in Table 1 (Wolf et al., 1999). The Indus River 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). The Kabul, Indus, Jhelum, Chenab, Ravi and Sutlej are the major rivers of the basin (Fig 2). About 50% of water is generated from snow and glaciers-melt in this basin (Winger et al., 2005). Several storage reservoirs have been constructed in the Indian and the Pakistani part of the Indus basin. The salient features of such reservoirs are presented in Table 2.

The Kabul River originates from Sanglakh Range of Afghanistan. It passes through the cities of Kabul, Chaharbagh, Jalalabad, and Nowshera and meets River Indus near Attock. It flows about 700 km before joining the River Indus near Attock. The average annual precipitation in the basin is of the order of 600 mm, and temperature ranges between 9 and 36^{o}C. The major soil types in the basin are sandy, silty, and silty clay. Major tributaries of Kabul River are Logar, Panjsher, Kunar, Alingar, Bara and Swat rivers. Dams in the basin have been constructed both in Pakistan and Afghanistan. The salient features of various dams are presented in Table 3. In Pakistan, Warsak dam has been constructed on Kabul River about 30 km west of Peshawar to meet the requirement of irrigation and hydro power generation.

Indus River arises from the north side of the Himalayas at Kaillas Parbat in Tibet. The river travels about 800 km in the northwesterly direction, and is joined by the Shyok River near Skardu. Before it reaches Nanga Parbat and joined by Gilgit River, Indus River flows for 160 km in the same direction. The Indus then flows for another 320 km in the south-western direction pouring into the plains at Kalabagh. Indus River is joined by Kabul River near Attock. One of the important features of this study area is the existence of Tarbela Reservoir on the Indus River in Pakistan which became fully operational in 1976. Currently its gross storage capacity is 10.3 billion m3 which has been reduced by 28% (Haq and Abbas, 2006). The reservoir serves two major purposes; irrigation and hydropower generation besides controlling floods during the summer season.

Jhelum River begins from a deep spring of Vernag in the Jammu and Kashmir state. Then it flows towards north-west from the northern slope of Pir Panjal and flows parallel to Indus River. The important feature of Jhelum River is the existence of Mangla Reservoir, which was brought into operation in 1968. Presently its gross storage capacity stands at 5.7 billion m^3, a loss of 20% to its original capacity (Haq and Abbas, 2006). To recover this loss, raising of the dam was revised by a height of 9 m. This height provides an additional storage capacity, which is more than enough for recovering the 20% loss (Kayani, 2013). At the dam site, the river continues through the foothills of Siwalik range and finally enters the plains of Punjab.

Chenab River originates from Kulu and Kangra districts of Himachal Pardesh, a province in India. The river enters in Pakistan near village of Diawara in Sialkot district. It passes through alluvial plains of the Punjab province and finally joins Jhelum River at Trimmu. Jhelum and Chenab meet Ravi and Sutlej rivers and finally flows into Indus at Mithankot located 60 km below Punjnad. Due to topographic condition, no dam is constructed on the Chenab in Pakistan territory; however, in Pakistan five barrages are constructed on Chenab River to provide water for agricultural land in Punjab. India has constructed a dam at Salal for hydroelectric generation in the Jammu territory about 65 km in upstream of Marala barrage.

3. Data and methodology

The monthly streamflow data for four stations, namely Warsak, Tarbela, Mangla and Marala on Kabul, Indus, Jhelum, and Chenab, respectively was obtained from Irrigation department, Lahore for the period 1962-2011. Details of different hydrological stations considered in this study are shown in Table 4. The flow data was arranged on

Fig.2. Map showing Indus River Basin System (Source: Shah, 2008)

monthly basis after averaging the long term (50 year) flow records during different months of the year. The flow of Indus River ranged between 460.9 m^3/s and 7282.4 m^3/s. Seasonally, flows in Kabul and Indus Rivers are the lowest in February whereas maximum flow for Kabul River is noted in June and for Indus River it is in the month of July. However, minimum streamflows occur in December and maximum in June and July to August for Jhelum and Chenab Rivers, respectively. It has been reported that July-September peaks are the result of the rainfall combined with the snowmelt while higher itself over successive time intervals before testing for trends. There are two types of correlations:

Table 2. Large dams in the Indus River Basin.

Country	Name of Dam	Nearest city	River	Year	Height (m)	Capacity (M m^3)	Main use *
India	Bhakra	Nangal	Sutlej	1963	226	9620	I,H
	Nangal	Nangal	Sutlej	1954	29	20	I,H
	Pandoh	Mandi	Beas	1977	76	41	I,H
	Pong	Mukenan	Beas	1974	133	8570	I,H
	Salal	Reasi	Chenab	1986	113	285	H
	Baglihar	---	Chenab	2008	---	33	H
					Total	**18 589**	
Pakistan	Mangla	Mangla	Jhelum	1968	116	10150**	I,H
	Tarbela	Ghazi	Indus	1976	137	11960	I,H
	Chashma	Mianwali	Indus	1971	---	870	I
					Total	**22 980**	

Source: FAO, 2011, * I = irrigation; H = Hydropower; ** Includes recent raising of 3.58 km3. Total storage capacity in these large reservoirs are 41569 million cubic meter (M m^3) out of which 55% storage capacity is in Pakistan.

Table 3. Storage reservoirs on the Kabul River System in Pakistan

Dam	Purpose	Installed Capacity (MW)	River
Warsak	Electricity + Irrigation	343	Kabul River
Golen Gol	-do-	106	Chitral Tributary
Matiltan	Electricity	84	Swat River
Dargai	Electricity + Irrigation	Jaban=20 Dargai=20 Malakand III=81	Swat River
Amandara	Irrigation	NA	Swat River
Munda	Irrigation	740 (planned)	Khyalay (Swat+Panjkora)
Bara Dam (diversion)	Irrigation+Drinking+Electricity	NA	Bara River
Jinday	Diversion	NA	Jinday River

Source: FAO, 2011, NA stands for not available, MW= Mega Watt

Positive serial correlation: A serial correlation in which positive error for one observation increases the probability of a positive error for another observation and vice versa.

Negative serial correlation: A serial correlation in which positive error for one observation increase the probability of negative error for another observation and vice versa.

Specifically, if time series has positive serial correlation, then non-parametric test will suggest a significant trend in time series that is in fact, random more often than specified by the significant level as given in KulKarni and Van Storch (1995). Even a moderate serial correlation makes the test impartial, and leads to p-values lower than the actual p-values. Von Storch and Navarra (1999) suggested that the influence of serial correlation should be removed prior to applying the Mann-Kendall test. Yue and Wang (2002) applied only pre-whitening technique to remove the influence of serial correlation on the Mann Whitney test. Yue et al. (2002) proposed pre-whitening technique to remove the effect of serial correlation in the data. This method has been applied to detect trends in hydrological and meteorological parameters (Aziz and Burn, 2006; Oguntude et al., 2011). This study examines the possible statistically significant trends in a stream flow observation (X1, X2……… Xn) using the techniques suggested by Yue et al. (2002).

3.1.2. Mann-Kendall nonparametric test

The Mann-Kendall test was originally proposed by Mann (Mann, 1945) and later Kendall obtained its statistical distribution (Kendall, 1975). It is one of the most widely applied tests for the evaluation of trends in climatology and in hydrologic time series (e.g. Yue and Wang, 2004; Tabari et al., 2012; Yaseen et al., 2014). There are two advantages of using this test. First, it is a non-parametric test and does not require the data to be normally distributed. Second, the test has low sensitivity to sudden breaks (changes) due to non-homogeneous time series (Tabari et al., 2011). The Mann-Kendall is applicable when the data elements Xi of a time series can be assumed to obey the following equation:

$$\mathbf{X}_i = f(t_i) + €i \quad (1)$$

where f (t) is a continuous increasing or decreasing function of time and residuals €i can be assumed from the same distribution with zero mean. It is therefore assumed that the variance of the distribution is constant in time. For time series withless than 10 data points the S test is used, and for time series with 10 or more data points the normal approximation is used. The number of annual values in the studied data series is denoted by n. The differences of annual values x were determined to compute the Mann-Kendall statistics. The Mann-Kendall statistic, S was computed using the following equation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{Sgn}(x_j - x_k) \quad (2)$$

Table 4. Mean monthly flow data (m^3/s) of the major rivers at various gauging stations.

Station	River Name	Latitude (dd)	Longitude (dd)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Warsak	Kabul	34.16	71.35	173.5	166.7	238.3	627.7	1049.2	1458.5	1408.4	1015.5	471.5	238.0	196.0	180.4	602.0
Tarbela	Indus	34.09	72.69	461.5	460.9	551.2	890.3	2134.4	5037.5	7282.4	6569.1	3015.2	1116.3	700.8	541.0	2396.7
Mangla	Jhelum	33.14	74.31	244.8	411.8	807.9	1289.8	1663.7	1675.8	1549.2	1217.1	697.9	364.8	259.3	238.8	868.4
Marala	Chenab	33.67	74.46	261.9	361.4	568.4	707.7	1056.4	1692.5	2483.7	2528.9	1311.2	438.9	251.7	227.0	990.8

where sgn (xj - xk) is an indicator function that takes on the values 1, 0 or -1 according to sign of difference (xj - xk), where j >k and

$$\mathrm{Sgn}(x_j - x_k) = \begin{bmatrix} 1 & \text{if} & (x_j - x_k) > 0 \\ 0 & \text{if} & (x_j - x_k) = 0 \\ -1 & \text{if} & (x_j - x_k) < 0 \end{bmatrix} \quad (3)$$

The values X_j and X_k are the annual values in the year j and k respectively. A positive and negative of S represents an upward and downward trend, respectively. However, the assumption regarding the normality of the data does not hold if there are several tied values in the time series. The variance S was computed by the following equation which takes into account that tied values.

$$\mathrm{Var}(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5) \right] \quad (4)$$

where q is the number of tied groups and T_p is the number of data in the pth group.

Test Z_{mk} statistic was calculated from S and VAR values as follow:

$$Z_{mk} = \begin{bmatrix} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \\ 0 & \text{if } S = 0 \end{bmatrix} \quad (5)$$

The presence of a statistically significant trend was evaluated using the Z_{mk} value. A positive (negative) value of Z_{mk} indicates an upward (downward) trend. The statistic Z_{mk} has a normal distribution. The null hypothesis, Ho is true if there is no trend and thus uses the standard normal table to decide whether to reject Ho .To test for either an upward or downward monotonic trend (a two-tailed test) at α level of significance, H0 is rejected if the absolute value of Z_{mk} is greater than Z1- α /2, where Z1- α /2 is obtained from the standard normal cumulative distribution tables. In this study the existence and significance of trend were evaluated with α value of 10%. The non-parametric robust estimate of the magnitude of the slope,β, is given by Sen (1968):

$$\beta = \mathrm{Median}\left(\frac{x_j - x_k}{j - k}\right) \quad \forall k < j \quad (6)$$

4. Results and discussions

4.1. Serial correlation

The values of lag-1 serial correlation coefficients obtained using the TFPW technique are shown in Table 5. The bold values indicate serial correlation coefficients that are significant at 10% significance level. A result presented in Table 5 indicates that significant correlation was observed in the study period from 1962-2011. The winter flow was found to be serially correlated significantly at Warsak on Kabul River and Tarbela on Indus River. At Mangla on Jhelum River spring, summer and annual flow were serially correlated, whereas serial correlation was present in spring and annual flows at Marala on Chenab River. The highest serial correlation was present at the Warsak station (0.519). Overall, about 40% of the data was serially correlated.

4.2. Variation of seasonal and annual stream flows

Table 6 presents the result of trend analysis at Warsak, Tarbela, Mangla and Marala stations using non-parametric statistical test (MK test) and Sen's slope method for seasonal and annual flow for the study period 1962-2011. On a seasonal basis, an increasing trend of stream flow was detected only in winter flow at Warsak at the rate of 0.0003x109 m^3 /year with a p-value of 0.861.

In the spring flows, a decreasing trend with a slope of -0.025 x109 m3/year and p-value of 0.122 was found. In the summer flows, a statistically significant decreasing trend (p-value = 0.001) with a slope of -0.075 x109 m^3/year was found. At Tarbela, increasing trends were observed in the winter and spring flows with slopes of 0.016x109 m^3/year and 0.055x109 m^3/year, respectively. Both the trends were significant with p-values of 0.00001 and 0.001, respectively. For the summer flows, a decreasing trend having a slope of -0.067x109 m^3/year was observed, but it was statistically insignificant (p-value = 0.398). At Mangla, anincreasing trend of flow at the rate of 0.011x109 m3/year and 0.009x109 m^3/year were detected for winter and spring seasons, respectively. Both the trends were insignificant with p-values of 0.14 and 0.553, respectively. For the summer season, a significant decreasing trend at Mangla was observed at the rate of -0.071x109m^3/year with p-value of 0.04. The winter and spring flows at Marala exhibited increasing trends with slopes of 0.008x109 m^3/year and 0.055x109 m^3/year, and p-values of 0.184 and 0.808, respectively. A statistically insignificant decreasing trend was found in the summer flows at Marala.

Results of trend analysis indicate that for several of the variables, many more trends were identified than can be expected to occur by chance. The seasonal linear trends with time series plot at Warsak, Tarbela, Mangla and Marala are shown in Figures 3, 4, 5, and 6, respectively. It is evident from these figures that all the stations exhibited a long term decreasing trend in summer flows. While winter and spring flow had long term increasing trend at all stations except Warsak. Our finding are consistent with the report of Stewart, (2009), who found that snowmelt dominated basins would show reductions in winter snowpack, reduced summer streamflows, and increased winter streamflow. This reduction in flow during summer will have a negative effect on irrigation and hydroelectric power generation, and eventually on the economy of the country. Streamflow trends are associated with climatic factors (temperature, precipitation) and watershed characteristics including human factors such as urbanization, stream regulation, and water diversions. All such data in the study basin have not been mutually shared among the contributing countries to investigate the causes of flow trends. Therefore, the increasing or decreasing trends in streamflow in this study can not be fully attributed only to climate change. However, winter and spring warming and summer cooling reported by Khattak et al. (2011) and Fowler and Archer (2006), with no increasing or decreasing trends in the precipitation in the upper Indus River basin may be considered as one of the cause of increasing trend of streamflow during winter and spring seasons and decreasing trends of flow during summer season.

5. Conclusions

The present study investigated the seasonal and annual stream flow at Warsak, Tarbela, Mangla and Marala for the period 1962-2011 using Mann-Kendall non-parametric test. Although statistically trends in seasonal flows at some stations were found, but they can only partially be attributed to climate change. The results of the present study could potentially be utilized by the basin managers to formulate climate change mitigation and adaptation strategies in their respective basins. The following specific conclusions from this study are drawn:

1. For summer flow only a statistically significant decreasing trend was detected at Warsak at the rate of -0.075 x109 m^3/year with a p- value of 0.001.
2. For winter and spring flow, strong increasing trends were detected at Tarbela

Table 5. Results of lag-1 Serial Correlation Coefficient using TFPW technique.

Station	Season				
	Winter	Spring	Summer	Autumn	Annual
Warsak	**0.519**	0.121	0.114	0.200	0.163
Tarbela	**0.301**	0.004	**-0.274**	-0.041	-0.247
Mangla	0.065	**0.413**	**0.339**	-0.026	**0.434**
Marala	0.038	**0.412**	0.180	-0.057	**0.270**

Bold values indicate significant serial correlation at 10% significant level

Table 6. Result of Mann Kendall (MK) Test of stream flow on seasonal and annual basis.

Station	**River Name**	**Season**	**Trend Slope (10^9 m^3/year)**	**MK Trend T est**	
				Z_{mk}	p-value
Warsak	Kabul	Winter	0.0003	0.17	0.861
		Spring	-0.025	-1.55	0.122
		Summer	-0.075	-3.25	**0.001**
		Autumn	-0.003	-0.74	0.457
		Annual	-0.110	-2.47	**0.014**
Tarbela	Indus	Winter	0.016	4.42	**0.00001**
		Spring	0.055	3.35	**0.001**
		Summer	-0.067	-0.84	0.398
		Autumn	0.021	1.26	0.207
		Annual	-0.009	-0.04	0.967
Mangla	Jhelum	Winter	0.011	1.48	0.139
		Spring	0.009	0.60	0.553
		Summer	-0.071	-2.06	**0.039**
		Autumn	-0.004	-0.41	0.682
		Annual	-0.051	-1.07	0.281
Marala	Chenab	Winter	0.008	1.33	0.184
		Spring	0.055	0.24	0.808
		Summer	-0.044	-1.41	0.157
		Autumn	-0.001	-0.13	0.900
		Annual	-0.050	-1.12	0.266

Bold p-values indicate significant at 10 % level. Positive sign of trend slope or Z_{mk} shows increasing trend and the negative sign shows a decreasing trend.

at the rate of 0.016 m^3/year and 0.055x109 m^3/year, and p-values of 0.00001 and 0.001, respectively.

3. For winter and spring flows, increasing trend was observed at Mangla with slopes of 0.011x109 m^3/year and 0.009x109 m^3/year, respectively. None of these trends were statistically significant; however a significant decreasing trend in flow was detected during summer with p-value of 0.04.

4. For winter and spring flows, an increasing trend was detected at Marala at the rate of 0.008 x109 m3/year and 0.055x109 m^3/year, respectively. However, both the trends were statistically insignificant.

5. In autumn flow both increasing and decreasing trends were observed, but were statistically insignificant at 10 % level.

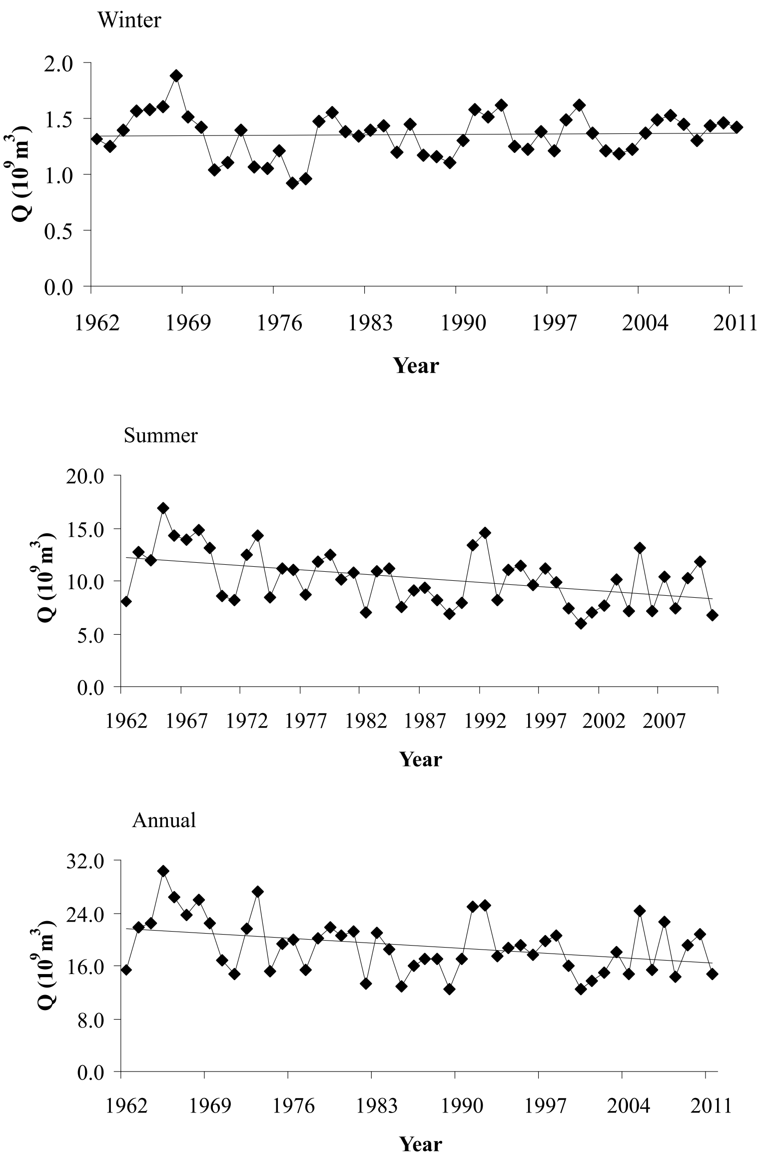

Fig. 3. Time series plot with trend line at Warsak during winter, summer and on annual basis.

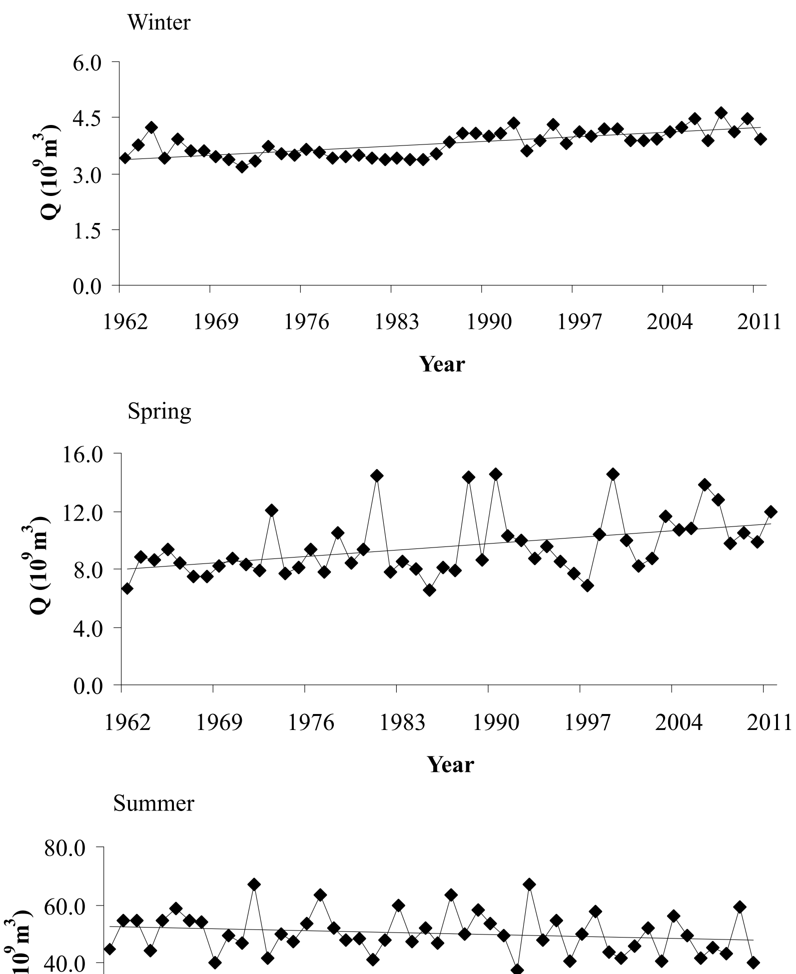

Fig. 4. Time series plot with trend line at Tarbela during winter, spring and summer seasons.

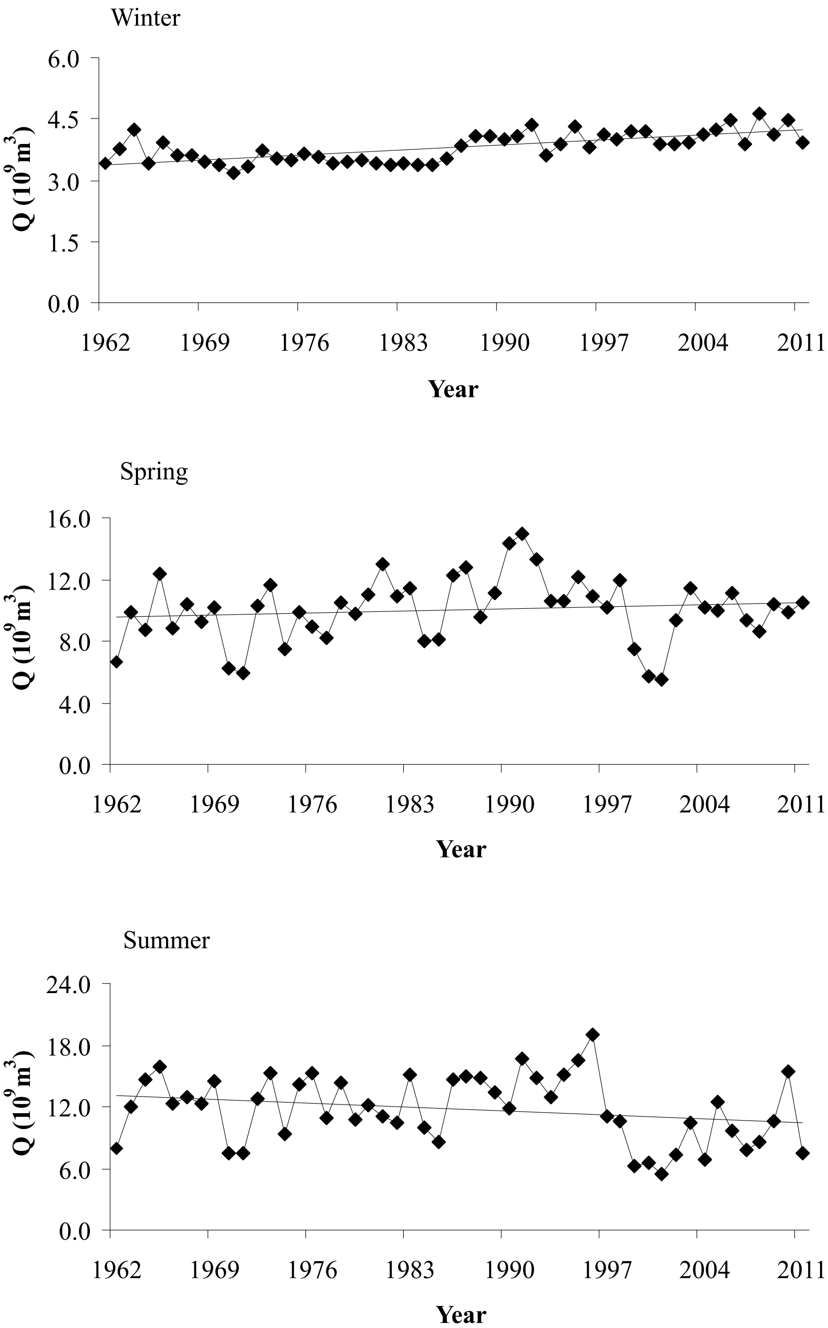

Fig. 5. Time series plot with trend line at Mangla during winter, spring and summer seasons.

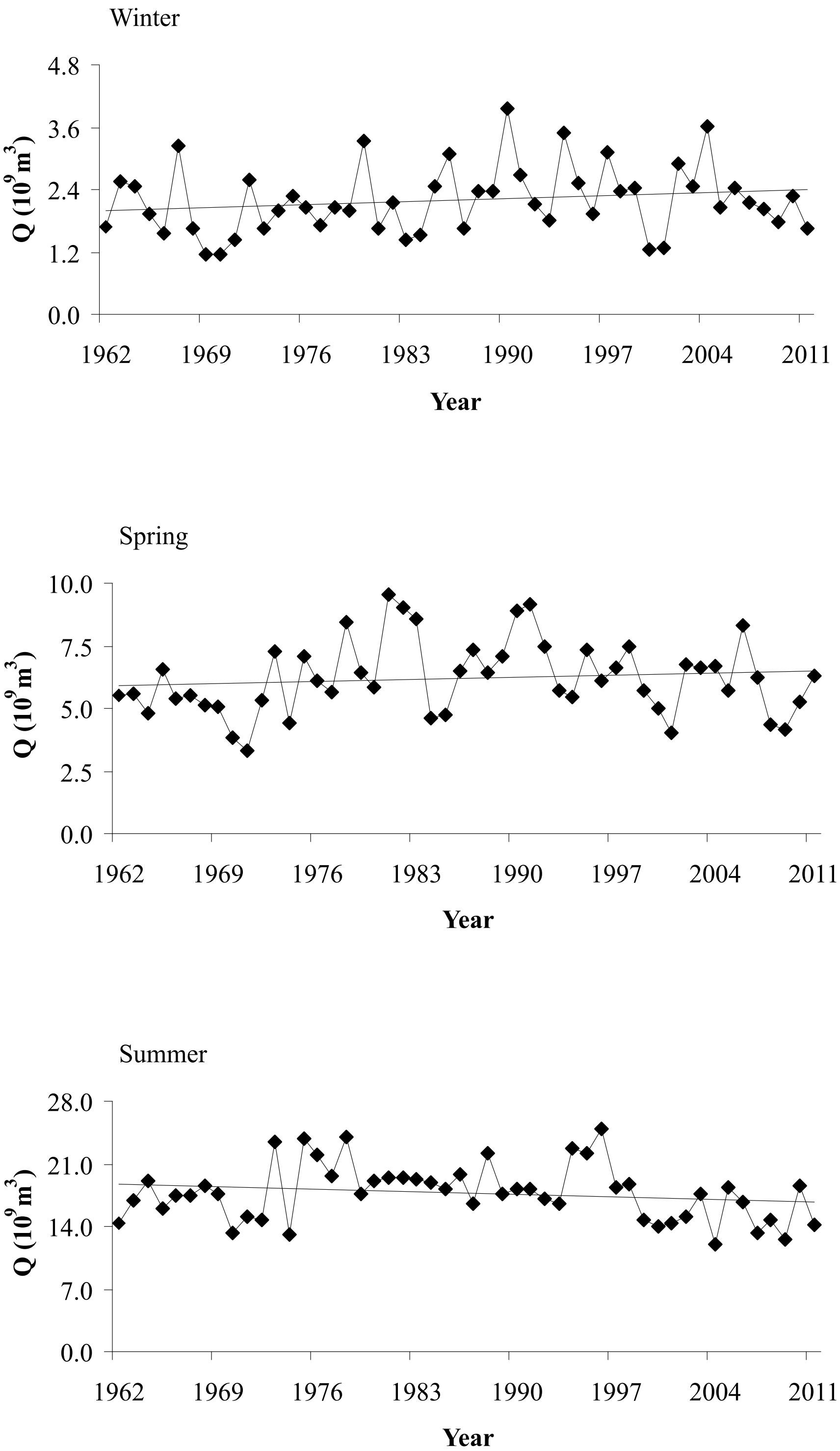

Fig. 6. Time series plot withtrend line at Marala during winter, spring and summer seasons.

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