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STUDY OF LONG-TERM TREND IN RIVER DISCHARGE OF SUTLEJ RIVER (N-W HIMALAYAN REGION)

ABSTRACT. Sutlej basin, a mountainous river basin is located in N-W Himalayan region. This basin has highest potential for hydropower generation as compared to other basins of Indus River system. Recent studies have revealed rise in mean annual surface temperature which will modify pattern of Sutlej River flow in this basin. The present paper has aimed for studying annual and seasonal patterns of river discharge at different gauging sites of Sutlej River basin (middle catchment), India. The study has been performed over three gauging sites, namely, Kasol, Sunni and Rampur located under different physiographic and climatic conditions. The daily historical records (1970–2010) of 41 years river discharge data have been employed for statistical analysis. The annual and seasonal Standardized Discharge Indices (SDI) has been derived in order to preserve uniformity and facilitate comparison between flows of Sutlej River at different sites. Mann-Kendall (MK) test, a non-parametric test method, has been applied to detect trend in annual and seasonal SDI for periods 1970–2010. Decadal (annual and seasonal) patterns in SDI have also been discussed. The results of annual and seasonal trend analysis have revealed decreasing trends in SDI at all the gauging sites. The trend in annual SDI is statistically significant (95% confidence level) at Rampur (0,04 cumec/year) and insignificant at Kasol (0,02 cumec/year) and Sunni (0,01 cumec/year) respectively. The study of annual decadal change in SDI at all the sites shows that reduction in river discharge has occurred in the decade of 2001–2010. Before this, continuous rise in annual discharge has been reported at all the sites from decades 1970–1980 to the last decade of 20th century (1991–2000). The decline in river flow may affect agriculture and electricity production as well as there may be problems related with drinking water. The present study is expected to be useful for planning water resources related projects that can be undertaken in the Sutlej basin.

KEY WORDS: Standardized Discharge Indices (SDI), Mann-Kendall test, discharge, trend analysis, N-W Himalaya

INTRODUCTION

Anthropogenic activities (*e.g.* burning of fossil fuels, deforestation and land use practices) have increased concentration of Green House Gases (GHGs) in the Earth's atmosphere [IPCC, 2007]. GHGs absorb solar radiation reflected by the Earth surface and have attributed to global warming [Loaiciga *et al.*, 1996; Srinivas *et al.*, 2013]. Some authors have claimed that increase in temperature may enhance rates of evapotranspiration and precipitation, which will in turn may intensify hydrological cycle and affect water resources systems [Arnell, 1999; Xu *et al.*, 2011]. These impacts will vary spatially as well as temporally for different regions of the earth. This has been affirmed by recent regional studies undertaken across the globe [Parry *et al.*, 2007]. Generally, results derived from these studies have indicated negative impacts of climate change on water resources (in long-term) however some regions may be benefited.

Effect of climate change on discharges and snow cover in Finland has been studied by Vehvilâinen and Lohvansuu [1991] under hypothetical scenario (doubling CO_2 concentration). Their study has predicted increase in mean discharge by 20–50% and vanishing of winter snow cover in Southern Finland. Whitfield and Cannon [2000] examined climatic and hydrologic variations over Canada for the decades of 1976–1985 and 1986–95 and revealed mixed patterns of change in river discharge. Mimikou and Fotopoulos [2005] have inspected impacts of climate change on the water cycle of the Aliakmon river basin in Western Macedonia and predicted reduction in mean monthly runoff for future period. A similar pattern of change in stream flow has also been observed in upper watershed of the snow-melt driven Limari river basin in North-Central Chile [Vicuna *et al.*, 2011]. In this line of study, impacts of climate change on headstream runoff in the Tarim river basin have been scrutinized by Xu *et al.* [2011]. Their results have revealed rise in temperature which has caused melting of glaciers and resulted increase in runoff. However, glacier melt water would be exhausted due to continual glacier shrinkage and increased trend of runoff in the headstream may also slow or lessen. These could result in increased water stress on both agricultural and natural ecosystems [Gao and Giorgi, 2008].

From the study of Vicuna and Dracup [2007], it has been concluded that snow and glacier-fed rivers of the world are more inclined to changes in temperature because it determines snow accumulation and snow melt processes *i.e.* timing of snow melt runoff. Indus, Ganga and Brahmaputra rivers which originate from the glaciers of the Himalaya have great potential to suffer from the effects of global warming [IPCC, 2007]. Such concerns have been supported by reports of significant retreat and depletion of glacier volume across the Himalayan region [Singh and Kumar, 1997; Naithani *et al.*, 2001; Shrestha *et al.*, 2004; Berthier, 2007; Eriksson, 2009]. The temperature driven snow and glacier-melt would have profound impacts on annual and seasonal runoff of the rivers. Initially, increase in runoff will occur with increase in temperature but for prolonged period of warming, runoff will fall sharply due to shrinkage in glacial mass [Rees and Collins, 2005]. It is predicted that at this present rate of retreat, glaciers in the region will vanish within 40 years [WWF Nepal Program, 2005]. This will lead to significant decline in discharge of major river systems flowing through this region and widespread water shortages.

Thus, the study of long-term trends in stream runoff is highly required for understanding implications of climate change on water resources in the Himalayan river basins. However, lack in monitoring stations, poor data availability in addition to physical inaccessibility has limited number of studies in the region. Recently, Bhutiyani *et al.* [2008] examined trends in annual and seasonal discharge of four rivers in North-West Himalaya (NWH). Their results have indicated insignificant increase in annual and monsoonal discharge of Chenab river during 1969–1998 and Ravi river during 1965–1992. Opposite to this, significant decrease in annual and monsoonal discharge has been reported for Beas river during 1961–1995 followed by insignificant decrease in discharge of Sutlej River during 1961–2004 respectively. However, for Sutlej River, the trend in annual and seasonal discharge has been measured at Bhakara downstream of the Sutlej River.

Sutlej basin, formed by Sutlej River is blessed with huge hydropower generation potential due to its unique topographical setting and availability of abundant water. Hence, several hydropower projects have been installed on this river. The variability in patterns of river discharge triggered by global climate change may affect production of electricity and agricultural practices in the basin. Keeping the above in mind, the main objective of this paper is to study annual and seasonal patterns of discharge in Sutlej River at different gauging sites (upstream from Bhakara) in NWH region, India.

MATERIALS & METHODS

Study Area

The present study has been carried out in a part of Sutlej River basin that is confined in the hilly State of Himachal Pradesh, India. The State shares its boundary with four Indian States namely, Jammu and Kashmir from North, Punjab from West, Haryana from South, Uttarakhand from South-East and has international border with China (Tibet). It covers parts of Simala, Kullu, Mandi, Bilaspur and Solan districts of Himachal Pradesh. This has a spread of 2457 km^2 and lies between 31°05′00″N and 31°39′26″N latitudes and 76°51′11″E and 77°45′17″E longitudes (Figure 1). Sutlej River basin is drained by the Sutlej River which originates from Mansarovar- Rakastal lakes near Darma pass in the western Tibet at an elevation of 4,570 m. The basin is characterized by steep slope, dissected topography and high relief features. The mean annual temperature and precipitation has been recorded 21,23°C and 103 cm respectively. The identified hydropower potential in this basin is 9226,75MW (megawatt). The major hydropower projects installed on the Sutlej River within the study area are Sunni Dam Project of 1080MW, Rampur Hydro-electric Power Project (RHEP) of 412MW and Nathpa Jhakari Hydro-electric Power Project (NJHEP) of 1500MW.

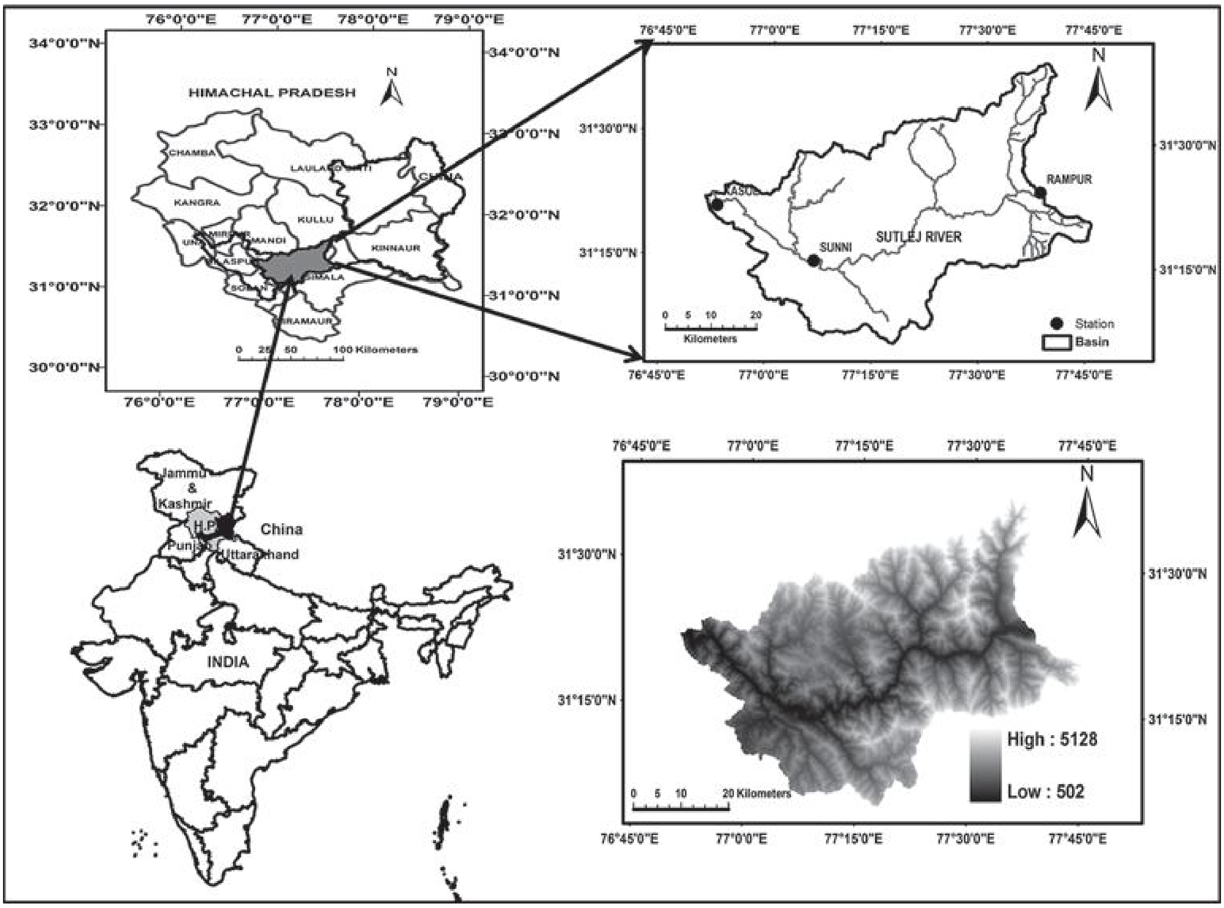

Fig. 1. Location map of the study region.

Table 1. Location details of the stations considered for the study in Sutlej basin

Station	Latitude	Longitude	Elevation (m)	Mean Annual Discharge (cumec)	Standard Deviation (cumec)
Kasol (1970–2005)	31°21′25″	76°52′42″	662	12636.6	1976.9
Sunni (1970–2005)	31°14′15″	77°06′30″	655	1177.5	1933.6
Rampur (1970–2005)	31°27′15″	77°38′40″	976	10331.7	1903.4

Data Availability and Sources

The long-term discharge data used in the present study has been collected and supplied by Bhakra Beas Management Board (BBMB) for three gauging sites; Kasol, Sunni and Rampur. These data are available from 1970 to 2010 for the period of 41 years on daily time step. The locations of given stations have been shown in Fig. 1 earlier while the details of the data have been described in Table 1. For the analysis, daily values of discharge are summed to obtain annual and seasonal values at each site.

Methodology

Standardized Discharge Indices (SDI). The concept of Standardized Discharge Indices (SDI) has been adopted from the study of Bhutiyani *et al.* [2008]. This has been used to bring uniformity and facilitate comparison between the hydrological responses (flows) of Sutlej River at different gauging sites. The monthly (for seasonal analysis) and yearly (for annual analysis) discharge data has been standardized by subtracting their mean and dividing by their standard deviation averaged over period 1970–2010 from the time series as shown in equation 1.

$$X_{SDI}\left(\frac{X_i - X_{mean}}{SD}\right), \tag{1}$$

Where, X_i is observed time series of discharge, X_{mean} is mean discharge averaged over period 1970–2010 and SD is standard deviation of discharge during this period. In this way, annual and seasonal SDI for each site has been computed.

Mann-Kendall (MK) Trend Analysis Method. MK test is a non-parametric rank based test and has been used widely for analyzing trend in hydrologic and climatologic variables [Mann, 1945]. It has advantage over other tests as it is distribution-free and robust against outliers [Hess *et al.*, 2001]. It assumes that the time series under research are stable, independent and random with equal probability distribution [Zhang *et al.*, 2005].

In MK test, null hypothesis (H_o) of no trend is checked with the alternative hypothesis (H_i) of increasing or decreasing trend. The S statistics of MK test is defined as [Jain and Kumar, 2012]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right), \tag{2}$$

where n is the number of data points, x_j is observed value at time *j* and x_i is observed value at time *i*. The value of $\operatorname{sgn}(x_j - x_i)$ is computed as shown in equation 3:

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} +1, & \left(x_j - x_i\right) > 0 \\ 0, & \left(x_j - x_i\right) = 0 \\ -1, & \left(x_j - x_i\right) < 0. \end{cases} \tag{3}$$

For samples ($n \geqslant 10$), MK test is conducted using a normal distribution and variance of *S* statistic is defined by:

$$Var\left(S\right) = \\ = \frac{m\left(n-1\right)\left(2n+5\right) - \sum_{i=1}^{n} t_i\left(i\right)\left(i-1\right)\left(2i+5\right)}{18} \tag{4}$$

in which t_i denote the number of ties to extent *i*.

The test statistic Z is estimated as:

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & S>0 \\ 0, & S=0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & S<0. \end{cases} \qquad (5)$$

Ho is rejected at α level of significance in a two-sided test if the value of $|Z|$ is greater than $Z_{\alpha/2}$ [Xu *et al.*, 2008]. The statistical interpretation of the rejection of Ho at given α level of significance implies a probability α that a trend is falsely identified. The significance level is taken as a criterion in hypothesis testing for rejection of Ho. The level of significance is a subjective issue and has been found between 1% to 10% level (mostly 5% level) in several research studies [Patra *et al.*, 2012]. In this study, Ho is tested at 5% level of significance (Z0.025 = 1.96).

Sen's slope method is used to compute magnitude of trend line. This is defined as the median of all combination of data pairs for the whole data set. It is given as follows [Xu *et al.*, 2008]:

$$Q = Median\left(\frac{x_j - x_i}{j-i}\right) \quad \text{for } i = 1, 2, ..., n, \qquad (6)$$

where x_i and x_j are data values at time i and j respectively.

Q is an estimate of the trend magnitude. Positive value of Q indicates an upward (increasing) trend and negative value of Q indicates a downward (decreasing) trend in time series.

RESULTS

Site Wise Trends in Annual and Seasonal SDI Using MK Test for 1970–2010

The annual pattern of trend in SDI for period of 1970–2010 has been shown in Fig. 2. The decreasing trend in SDI has been reported at Kasol followed by Sunni and Rampur. The trend is statistically insignificant at 95% level of confidence at Kasol and Sunni but it is statistically significant at Rampur. The rate of decrease is 0,02 cumec/year (Kasol), 0,01 cumec/year (Sunni) and 0,04 cumec/year (Rampur) respectively. In this way, highest decrease in annual discharge has been found at Rampur and minimum at Sunni.

Table 2 provides the summary of seasonal trend analysis of SDI for 1970–2010.

Generally, decreasing trends in SDI have been found at all sites. The trends are statistically significant at Sunni and Rampur during summer (June, July and August) and autumn (September, October and November) seasons. The rate of change is 0,32 cumec/year, 0,031 cumec/year at Sunni and 0,47 cumec/year, 0,034 cumec/year at Rampur respectively. The winter (December, January and February) and spring (March, April and May) seasons are characterized by statistically insignificant decreasing trends in SDI at all the sites. The rate of decrease is highest during summer season.

Decadal Change in Annual and Seasonal SDI for 1970–2010

Decadal (annual and season wise) change in SDI has been computed for the period of 1970–2010 to determine whether the rate

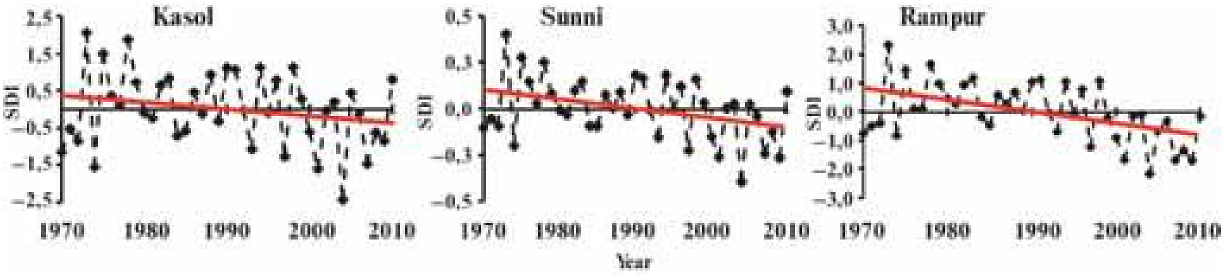

Fig. 2. Annual trends in SDI at Kasol, Sunni and Rampur for 1970–2010.

Table 2. Seasonal trend analysis of SDI for 1970–2010 performed at all sites

Station	Season	Z_s	*Q* (°C/year)	Remarks
Kasol	Winter	(–)	–0,002	Decreasing
	Spring	(–)	–0,007	Decreasing
	Summer	(–)	–0,021	Decreasing
	Autumn	(–)	–0,013	Decreasing
Sunni	Winter	(–)	–0,008	Decreasing
	Spring	(–)	–0,012	Decreasing
	Summer	(–)*	–0,032	Decreasing
	Autumn	(–)*	–0,031	Decreasing
Rampur	Winter	(–)	–0,015	Decreasing
	Spring	(–)	–0,015	Decreasing
	Summer	(–)*	–0,047	Decreasing
	Autumn	(–)*	–0,034	Decreasing

(* indicates that values are statistically significant at 5% level of significance).

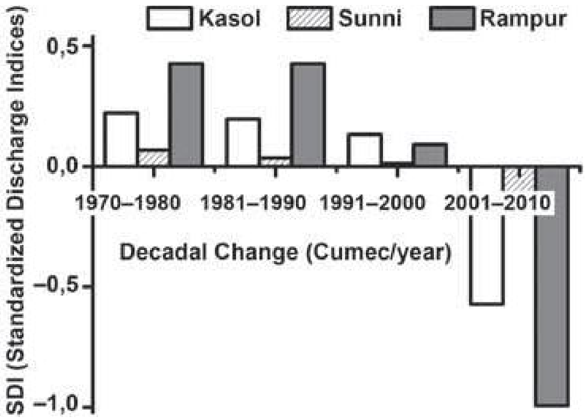

Fig. 3. Annual decadal change in SDI (cumec/year) at Kasol, Sunni and Rampur for 1970–2010.

of change at a particular station is uniform or not. The results of annual decadal change in SDI for all the sites have been shown in Fig. 3. There is a continuous reduction in river discharge in long-term. The rise in annual discharge with varying rates has been observed in decades of 1970–1980, 1981–1990 and 1991–2000 followed by an abrupt fall in 2001–2010 for Kasol, Sunni and Rampur sites respectively. The maximum rise and fall in river discharge has been reported at Rampur site. The recent (2001–2010) reduction in river discharge is solely responsible for having decreased annual trends in SDI observed at different gauging sites of Sutlej River.

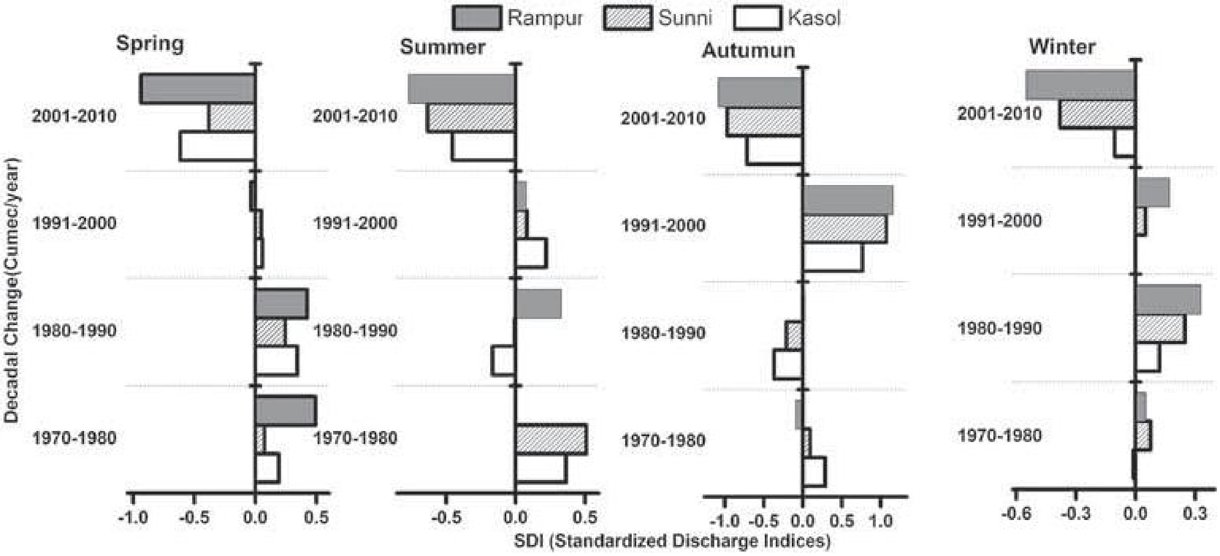

Fig. 4. Inter-decadal (seasonal) change in SDI (cumec/year) at Kasol, Sunni and Rampur for 1970–2010.

Fig. 4 shows results of inter-decadal change in SDI at Kasol, Sunni and Rampur sites respectively. A substantial fall in SDI has been observed at each site throughout all seasons during the decade of 2001–2010. The decrease in SDI informs about reduction in flow of river water. However, more or less rise in SDI has been noticed during spring and winter seasons from 1970–1980 to 1991–2000. The nature of change in patterns of SDI is not uniform during summer and autumn seasons.

DISCUSSIONS AND CONCLUSIONS

The analysis of MK test reveals decreasing annual and seasonal trends in SDI at different gauging sites of Sutlej River for the period of 1970–2010. The annual trends are statistically significant at Rampur and insignificant at Kasol and Sunni respectively. Similarly, statistically significant decreasing trends in SDI have been observed at Sunni and Rampur during summer and autumn seasons. The decreasing trends in SDI reflect the decline in river discharge.

In the present study, a continuous rise in annual discharge has been observed at all the sites from decades 1970–1980 to the last decade of 20th century (1991–2000). However, the results of the study of annual decadal change in SDI at all the sites shows a reduction in river discharge in the decade of 2001–2010. The decline in flow of Sutlej River may be attributed to rise in surface mean temperature over NWH. The increase in the surface mean temperature over NWH has also been confirmed in the study of Bhutiyani et al [2009].

The initial increase in the annual discharge from 1970–1980 and then from 1991–2000 may be attributed to fact that there has been an increase in the mean surface temperature during the corresponding period which resulted in the increase of discharge due to accelerated melting of glaciers. However, during the later stage, due to shrinkage in the volume of glaciers, there is a significant decrease in the discharge of river Sutlej during the period 2001–2010 even though there was an increase in mean surface temperature during this period also. The present study thus shows the pattern of alteration in the behaviour of discharge of Sutlej River basin. Therefore, it is the need of the hour to adopt of an appropriate strategy for proper monitoring and management of water resources in the Sutlej basin in respect of global climate change. ■

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