Paper No. 714

RECENT TRENDS IN HIGH ALTITUDE TEMPERATURES AND RIVER FLOWS IN UPPER INDUS BASIN

DR. MUHAMMAD SIDDIQUE, DANIAL HASHMI

RECENT TRENDS IN HIGH ALTITUDE TEMPERATURES AND RIVER FLOWS IN UPPER INDUS BASIN

By

Dr. Muhammad Siddique

Advisor to Authority on Hydrology and Sedimentation, WAPDA, Lahore

Danial Hashmi

Senior Engineer; Pakistan Snow and Ice Hydrology Project, WAPDA, Lahore

Abstract:

Upper Indus Basin is the abode of more than 11000 glaciers and perennial snow fields that support more than 85 percent of the flow to the River Indus at Tarbela. Any abnormal change in the temperatures will have impact on the flows of the River Indus at Tarbela. The analysis of Positive Degree Days worked out from the automatic high altitude meteorological data collection network established by WAPDA in 1995 in Hindu Kush-Himalayan (HKH) region in the elevation zone of 2500 to 5000 meters above sea level in the vicinity of glaciated basins shows that there is a significant falling trend in the available sensible heat, determined by the total monthly Positive Degree Days for the melting of glaciers during the months of July, August and September i.e. glacier melting period, but rising trends in Positive Degree Days were observed during the months of May and June from 1995 to 2009 i.e. snow melt period, indicating anomalous climatic conditions in Upper Indus Basin. The trends in temperatures are inline with the corresponding trends in river flows observed at three different locations on the main stem of Upper River Indus during glacier melt season. These preliminary findings do not support the prevailing hypothesis of rapidly melting and receding glaciers in the wake of climate change. However, confirmation of these preliminary findings is necessary by additional data collection and its analysis.

Key words: Upper Indus Basin; HKH Region, Climate Change; Hydrometeorological Data Trends; Positive Degree Days

1. Introduction

Pakistan is a single river system country fed by River Indus that originates from snow and glacier fields of the Himalaya-Karakoram-Hindukush (HKH) region. Glacier melt, snow melt and rain fall runoff accounts for about 65%; 25% and 10 % respectively of the annual flows of River Indus at Tarbela where it averages to 60.17 MAF (1976-2009). Westerlies are the primary source of water for Pakistan. They originate from Mediterranean and nourish Upper Indus Basin (UIB) glaciers and snow fields. They remain active during the months from November to April. Secondary source of water for Pakistan are Monsoons. They originate from Bay of Bengal, obtain moisture input from Arabian Sea and downpour on the Indus Plains and in the upper catchments of Indus, Jhelum, Chenab, Ravi, Sutlej and Kabul. Monsoons remain active from mid June to late September.

Global Climate Change resulting from an increasing concentration of Greenhouse Gases (GHG) in the atmosphere by the use of fossil fuels and other human activities have been observed in most parts of the world. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the average temperature of the earth's surface increased by 0.6 °C over the past century and is projected to increase further by 1.1 to 6.4 °C by the end of the current century (IPCC 2007).

Pakistan is particularly vulnerable to climate change because it has generally a warm climate; it lies in a world region where the temperature increases are expected to be higher than the global

averages; its land area is mostly arid and semi-arid (about 60 per cent of the area receives less than 250 mm of rainfall per year and 24 per cent receives between 250-500 mm); its rivers are predominantly fed by the Hindu Kush-Karakoram-Himalaya (HKH) glaciers which are predicted to be receding rapidly due to global warming; its economy is largely agrarian and hence highly climate sensitive; and so the country faces increasingly larger risks of variability in monsoon rains, large floods and extended droughts. Under the influence of all these factors the Water Security and the Food security of the country are under serious threat. (TFCC 2009)

However there are conflicting views of researchers about melting of Karakoram glaciers as described in section-5 below. The objectives of present study is to carry out a critical appraisal of current hypothesis regarding the snow and ice melting projections in Upper Indus Basin in the light of recent data collected through high altitude Data Collection Platforms Network during 1995 – 2009 and the corresponding flows in Upper River Indus at the selected stations.

2. Hydrometeorological Network in the Study Area

Since its creation in 1958 Pakistan Water & Power Development Authority (WAPDA) has taken various steps to study Upper Indus Basin cryosphere and established Hydro-meteorological networks in 1960's for its monitoring through its Surface Water Hydrology Project, refer Figure 1.

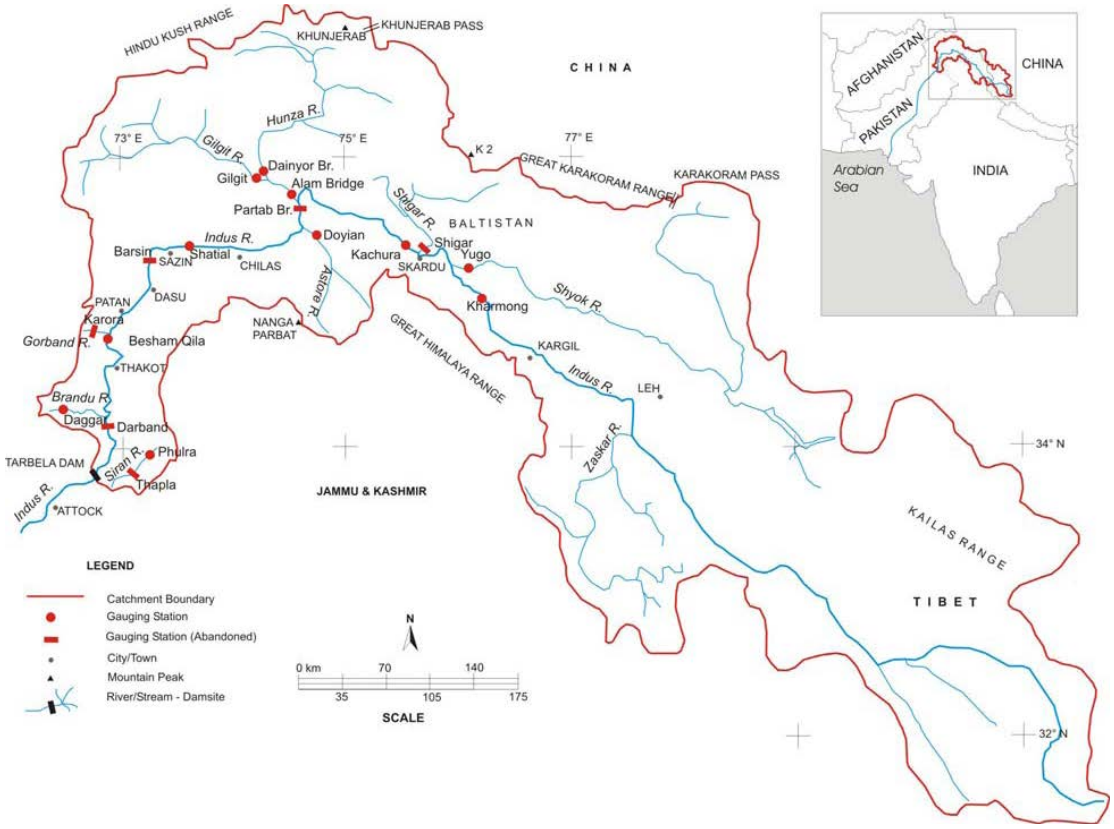


Figure 1: WAPDA Stream Gauging network in Upper Indus Basin

The farthermost station installed at the entry point of River Indus into Pakistan is Kharmong. Six stream gauging stations are installed on main stem of River Indus before it enters Tarbela Reservoir. There are five major tributaries namely, Gilgit, Hunza, Shigar, Shyok and Astore, of Upper River Indus located within Pakistan boundary. One major river gauging station is installed at mouth of these tributaries. Rivers are gauged at each of these stations using current metering technique.

3. Snow and Glacier Fields of Pakistan

Snow and glacier melt contribution to River Indus is about 70 – 80 % but very little effort was made to study snow and glacier fields before 1980's. During 1985-1989 ground based research was carried out by WAPDA with Canadian Universities under its Pakistan Snow and Ice Hydrology Project to understand the cryosphere and hydrologic conditions of UIB. Mass balance studies of selected glaciers of Karakoram and Himalayas were carried out. In addition a high altitude network comprising 20 Data Collection Platforms was installed in the Upper Indus Basin within an elevation zone of 2500 to 5000 meters a.s.l., refer Figure 2. These stations collect hourly data on temperature, precipitation, relative humidity, solar radiation, snow water equivalent, wind (speed, gust and direction) and transmits this data through Meteorburst Communication System to the Flow Forecasting Centre at Lahore since 1995.

The snow surveys were carried out during 1961 to 1968 in Mangla Basin to forecast River Jhelum at Mangla Basin.

It is estimated that there are more than 11000 small, medium and big size glaciers in UIB that cover about 15000 Km^2 of the UIB area, but it is the large size glaciers with surface area of more than 5 Km^2 that hold most (88%) of the estimated ice reserves of 1760 MAF (ICIMOD 2011). This ice reserve is annually nourished by westerlies and contributes about 40 MAF on average to the Indus River inflow volumes above Tarbela Reservoir.

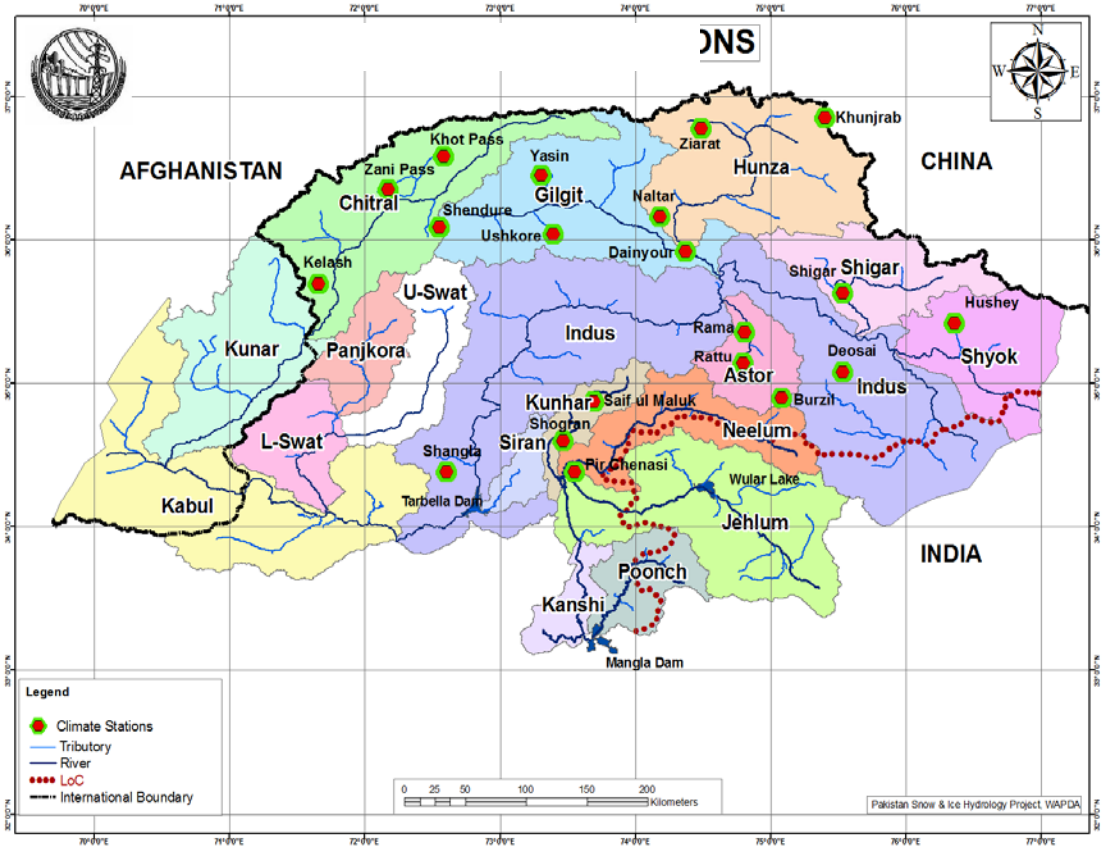


Figure 2: WAPDA high altitude Data Collection Platform Network in Upper Indus Basin

Important glaciers of Upper Indus Basin are: Siachin (1181 Km^2) ; Baltoro (756 Km^2); Biafo (627 Km^2); Batura(290Km^2); Hispar (622 Km^2); Panmah (410 Km^2).

4. Materials and Methods

To identify trends in hydrologic and hydro-meteorological data of UIB stations, the Mann – Kendall trend test has been applied. This is a non - parametric test, suggested by Mann (1945) which can be applied to any time series. It has been extensively used in the analysis of environmental time series data.

Mann-Kendall test is based on statistic S. Each pair of observed values yi, yj (i > j) of random variable is inspected to find out whether $y_i > y_j$ or $y_i < y_j$. Let the number for former type be P (Positive), and the number for later type be N (Negative). Then S is defined as

$$S = P - N \qquad (1)$$

There is a correction factor for ties when $y_i = y_j$ (Salas, 1993).

Under the null hypothesis H_0, that there is no trend displayed by the time series, the distribution of S is then expected to have a zero-mean and variance

$$var(S) = [n (n-1) (2n+5)] / 18 , \qquad (2)$$

where n is the number of values in data set. Then the Kendall Statistics Z_o is given as

$$Z_o = \begin{cases} (S - 1) / \sqrt{var(S)} & \text{if } S > 0, \\ 0 & S = 0, \\ (S + 1)/ \sqrt{var(S)} & \text{if } S < 0 \end{cases} \qquad (3)$$

The magnitude of trend is given as

$$\beta = \text{Median } [(y_i - y_j) / (i - j)] \qquad (4)$$

In which $1 < j < i < n$. A positive value of β indicates an upward trend and a negative value of β indicates a downward trend.

The Mann – Kendall test is given as:

Null Hypothesis Ho: $\beta = 0$, i.e. there is no trend, P = N or S = 0

Rejected H_o : $|Z_o| > Z_{1-\alpha/2}$ there is a trend at significance level, α .

In which + $Z_{1-\alpha/2}$ □□ are the standard normal deviates, and α is the significance level for the test. The hypothesis that there is no trend is rejected when the $|Z_o|$ value computed by above equation is greater than the tabulated value $Z_{1-\alpha/2}$. Conversely α value or confidence level (1 - α) in percentage can be computed at which the hypothesis is rejected and significance of trend is established.

The Mann – Kendall test is expected to be less affected by the outliers because its statistics is based on the sign of differences, not directly on the values of the random variables.

This trend assessment technique has been applied to the world global temperatures, monthly flows on the selected UIB stream gauging stations Kharmong, Kachura and Partab and to the Positive Degree Days of selected high altitude Upper Indus Basin Data Collection Platform Network and is discussed in the study.

The trend with significance level α less than 90% is categorized as low significance level trend, and that with α between 90% - 95% is considered as Moderate Significance level trend, and the trend with α more than 95% is taken as a high significance level trend for the purpose of this study.

5. Climate Change Prediction for Upper Indus Basin

Examination of global temperatures from 1980 – 2009 shows a rising trend in mean annual temperatures, but it is the consistent rising trend since 1995 with Mann-Kendall High Significance level of 98% shown in Figure: 3, which is of great concern for the countries whose economies are sensitive to temperature rise. However there are conflicting reports from different researchers about melting of Karakoram glaciers.

The IPCC assessments based on the projection of future global climate with the help of various Global Circulation Models (GCM) predict somewhat higher temperature increases in the region where Pakistan is located as compared to average global temperature increase. According to the studies carried out by Global Change Impact Study Centre, Islamabad using IPCC high and medium range scenarios, the temperature increase in Northern Pakistan at the end of the time horizons 2020, 2050, and 2080 in each scenario is higher than the corresponding globally averaged temperature increase.

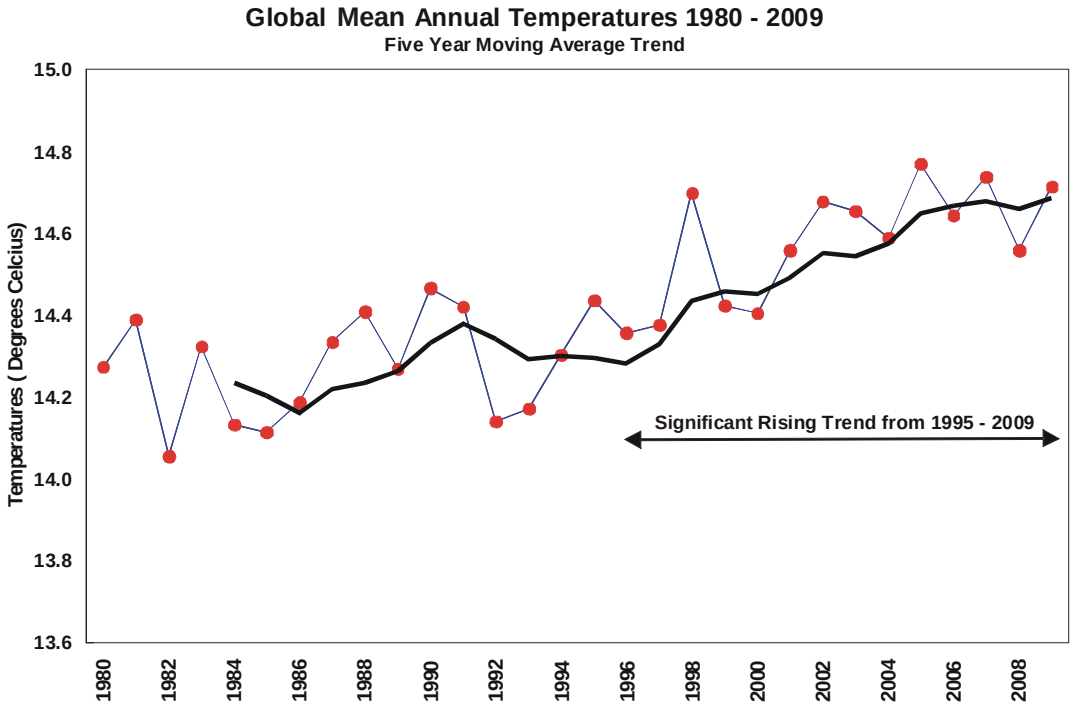


Figure 3: Rising Global mean annual temperature since 1980

According to World Bank (2006), the glacier melting in the Himalayas is expected to increase flooding of Indus and its tributaries for the next two to three decades which will be followed by decreased river flows as the glaciers recede . The western Himalayan glaciers will retreat for next 50 years causing increase in Indus River flows. Then the glacier reservoirs will be empty, resulting in decreases of 30% to 40% in river flows in the Indus Basin. A simulation modeling study by GCISC shows that if the average temperature in the Indus watershed were to rise by 3°C and the HK glaciers to shrink to half their present size, not only the overall annual flow would reduce by about 15%, the monthly flow pattern would also change considerably, with more water coming in spring and early summer and less water in the later part of summer (GCISC 2009c). Although the glaciers all over the world are found to be receding over the past century, those in the HKH region are reported to be receding faster than in any other part of the world (Rees and Collins 2004).

There is some uncertainty about the Karakoram glaciers as they have not been investigated due to difficult terrain and steep slopes for undertaking the comprehensive studies. While the Batura Glacier has been reported to be retreating significantly in recent years (Shroder and Bishop 1999), Hewitt (2005) asserts that some of the Karakoram glaciers are actually surging rather than receding. Fowler and Archer (2006) have observed thickening and expansion of glaciers in the UIB region, in contrast to wide spread retreat and decay in Eastern Himalayans. Preliminary analysis of the time series data on flows of the Indus and its tributary rivers did not indicate any large melting of glaciers so far (GCISC 2009c). A recent study using satellite derived monthly gravity fields for 2003 – 2010 concludes that the world's greatest snow-capped peaks, which run in a chain from the Himalayas to Tian Shan on the border of China and Kyrgyzstan, have lost no ice over the last decades (Jacob et al., 2012).

In the following study the analysis of sensible heat available for melting of snow and glaciers along with corresponding river flows has been carried out to clarify to some extent the actual status of melting in Western Himalayas and Karakorams.

6. Trends in Available Sensible Heat for Melting

Pakistan Water and Power Development Authority installed an automatic high altitude weather monitoring network in the snow and glacier melting zone (2800 – 4800 m.a.s.l) of Upper Indus Basin. Mean daily data for maximum and minimum temperature along with other meteorological parameters is available since 1995 from this network. This data has been analyzed for the trends in the Positive Degree Days (PDD) using Mann-Kendall trend statistics. The number of Positive Degree Days is a measure of sensible heat available for the melting of snow and glaciers. The period of interest was snowmelt (May and June) and glacier melt (July to September) seasons as most of the water in Upper Indus is generated during these seasons. Trends in observed data for 15 years (1995 – 2009) for different Data Collection Platforms are summarized in Table 1.

Table 1: Trends statistics for Positive Degree Days in Upper Indus Basin during 1995 – 2009.

SUB BASINS **DCP Stations**	**Elevation (m.a.s.l.)**	**Snow Melt Period (May + June)**			**Glacier Melt Period (July + August + September)**		
		Mann Kendall Test Z	**Mann Kendall Sig. Level**	**Trend**	**Mann Kendall Test Z**	**Mann Kendall Sig. Level**	**Trend**
SHYOK							
Hushe	2955	0.6928	51%	Rising	-0.9897	68%	Falling
SHINGO							
Burzil	4030	0.0610	5%	Rising	-1.7518	92%	Falling
Deosai	3910	0.3114	24%	Rising	-1.2456	79%	Falling
ASTORE							
Rama	3000	0.8908	63%	Rising	-2.2764	98%	Falling
Rattu	2570	1.2867	80%	Rising	-1.9795	95%	Falling
HUNZA							
Khunjerab	4710	0.3959	31%	Rising	-1.9795	95%	Falling
Ziarat	3669	1.4803	86%	Rising	-3.1752	100%	Falling
Naltar	2810	0.9897	68%	Rising	-1.6826	91%	Falling
GILGIT							
Yasin	3150	1.2867	80%	Rising	-2.6278	99%	Falling
Ushkore	2970	1.0887	72%	Rising	-2.1898	97%	Falling

Shingo Sub-Basin

Shingo sub-basin covers the main Indus River catchment between Kharmong and Kachura. This is mainly a snow basin with vast Plains of Deosai at an average elevation of 4000 meters above sea level. High altitude temperatures in this sub catchment are represented by DCP stations Deosai (El 3910 m) and Burzil (El 4030 m), the later being located at the catchment boundary. During snow melt period (May & June) Burzil shows practically no trend in sensible heat, whereas Deosai shows a little rising trend. However, during glacier melt seasons both these stations show falling trends with low to moderate significance levels, refer Figure 4.

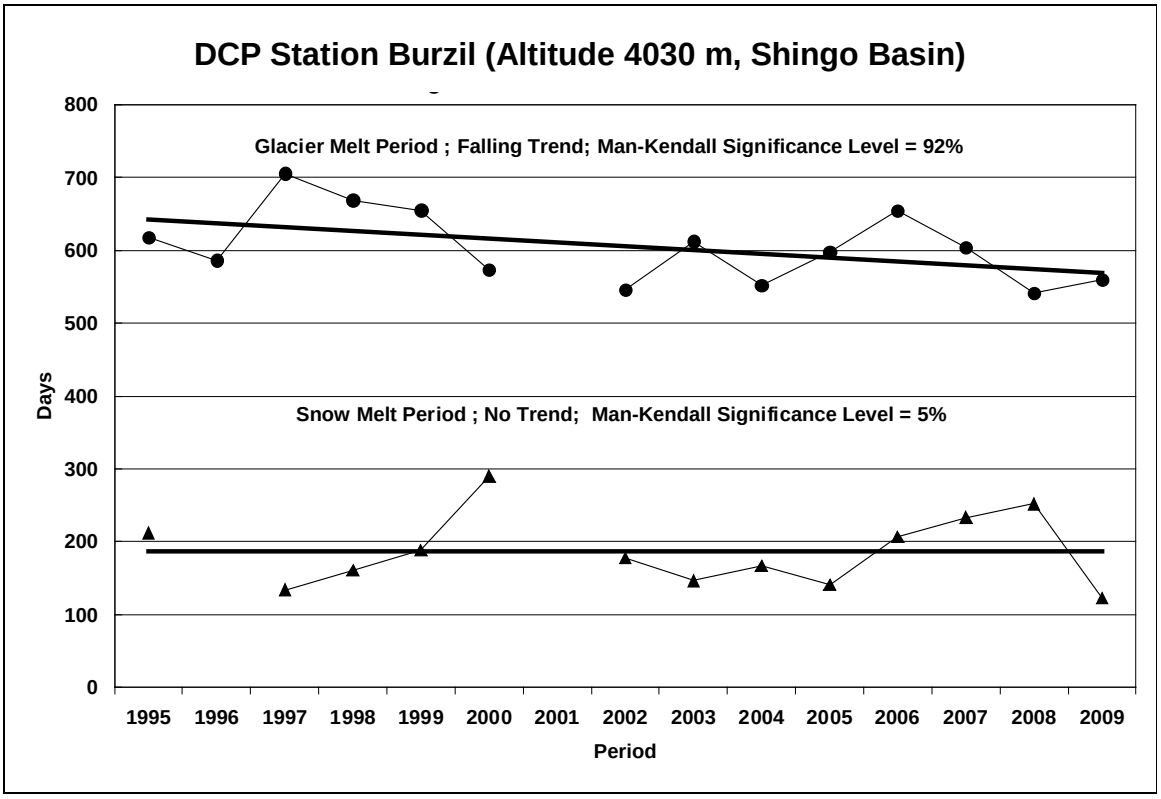


Figure 4 : Positive Degree Days Trend at DCP Station Burzil for Snow and Glacier melt periods during 1995 – 2009.

Shyok Sub-Basin

It is a huge glaciated basin with numerous small to medium size glaciers including the giant 75 Km long Siachin Glacier. Most of the basin is in Indian Held Kashmir. Only a single DCP station at Hushey monitors temperatures at El 2955 in Shyok sub-basin. During snow melt season this station shows slight rising trend (Significance level 51%) in sensible heat but a falling trend (Significance level 68%) during glacier melt season as shown in Figure 5.

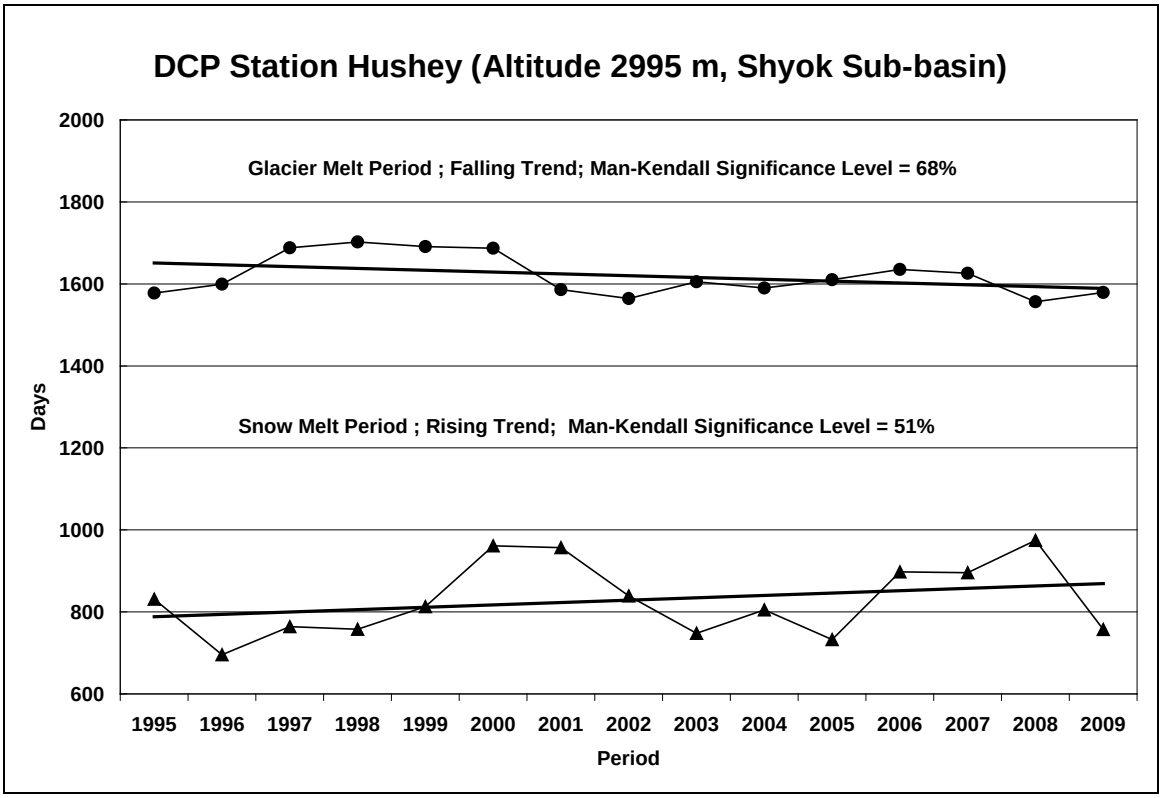


Figure 5: Positive Degree Days Trend at DCP Station Hushey for Snow and Glacier melt periods during 1995 – 2009.

Astore Sub-Basin

It is a north facing glaciated basin in Himalaya Range and is nourished both by Westerlies and Monsoons. There are two DCP stations to monitor cryosphere conditions in this sub basin; these are Rattu (El.2570 m) and Ramma (El. 3000 m). Both these stations show weak rising trends in sensible heat availability during snow melt period, but falling trends with high significance levels in glacier melt period.

Figure 6 below shows trends of Positive Degree Days for DCP Station Rattu for the Snow and Glacier melt periods during 1995 – 2009

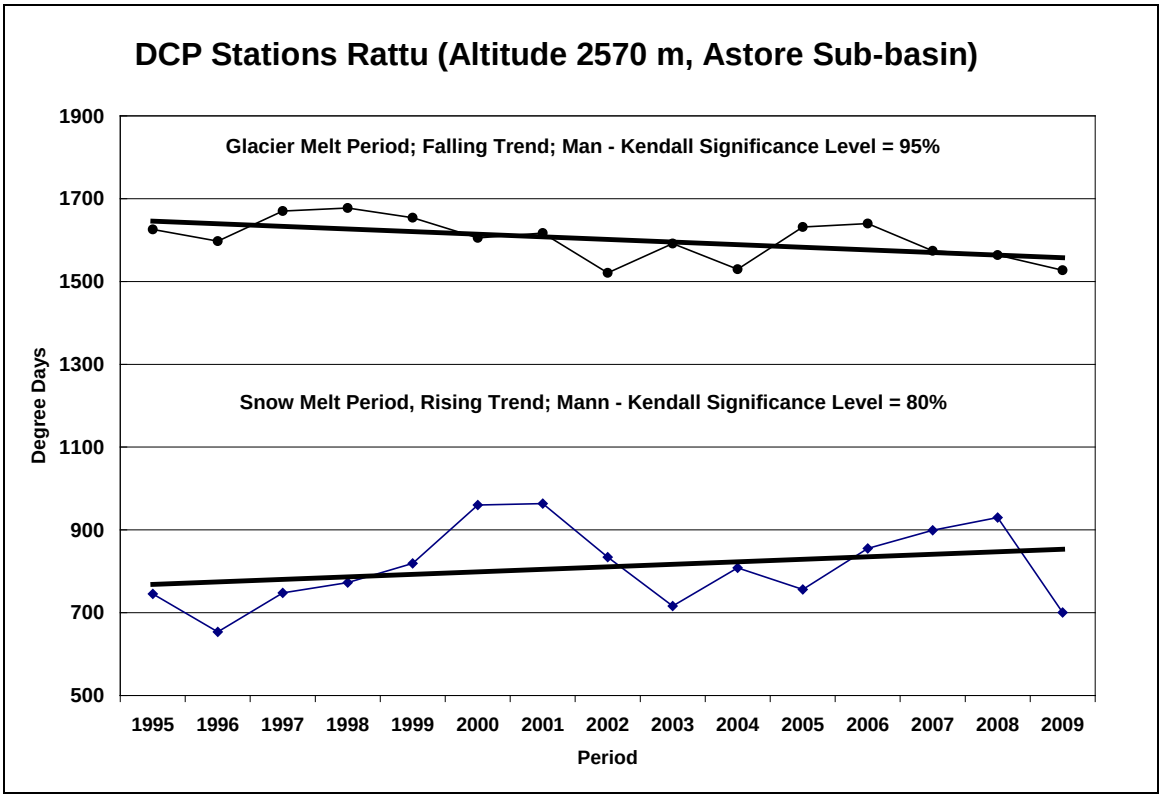


Figure 6: Positive Degree Days Trend at DCP Station Rattu for Snow and Glacier melt periods during 1995 – 2009.

This automatic weather station is located in Western Himalayas in a north facing sub-basin. Whereas during snow melt period i.e. May and June a weak rising trend with Mann - Kendall Significance Level of 80% is noted at this station, a reverse significant falling trend is observed during glacier melt period i.e. July to September with Mann - Kendall Significance Level of 95%.

Hunza Sub-Basin

This is highly glaciated basin in Karakorams with catchment of 13925 Km^2 with glacier cover of about 35%. It has many glaciers including 68 Km Batura glaciers. Three DCP stations are installed in Hunza sub basin i.e Khunjerab (El.4710m), Ziarat (El.3669 m) and Naltar (El.2810 m). The analysis of data for these stations shows that there are weak rising trends in sensible heat during snow melt period but there are falling trends for glacier melt season at moderate to high significance level.

Figure 7 below shows trends of Positive Degree Days for DCP Station Ziarat. This automatic weather station is located in Hunza Basin, Karakorams. Whereas during snow melt period i.e. May and June a moderate rising trend with Mann - Kendall Significance Level of 86% is noted at this station, a reverse significant falling trend is observed during glacier melt period i.e. July to September with Mann - Kendall Significance Level of 100%.

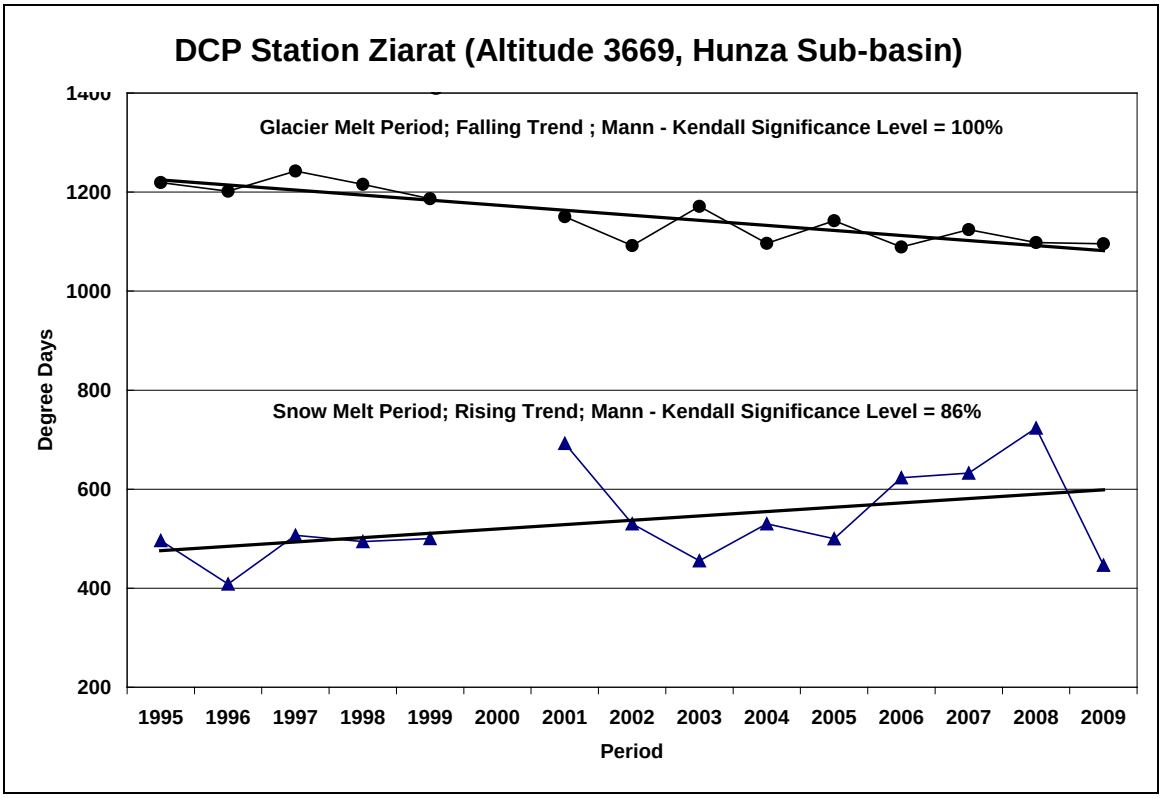


Figure 7: Rising and Falling Trends of Positive Degree Days at DCP Station Ziarat for Snow and Glacier melt periods during 1995 – 2009.

Gilgit Sub-Basin

This glaciated basin with catchment of 12800 Km^2 is at the extreme west of Karakoram and shares common border with Hindukush Mountains. It is mainly influenced by Westerlies which are active during November to April. Two DCP stations, i.e. Yasin (El;.3150) and Ushkore (El.2970 m) to monitor cryosphere conditions in Gilgit sub basin are available. Both these stations show weak rising trends in sensible heat during snow melt season but falling trends with high significance level during glacier melt season.

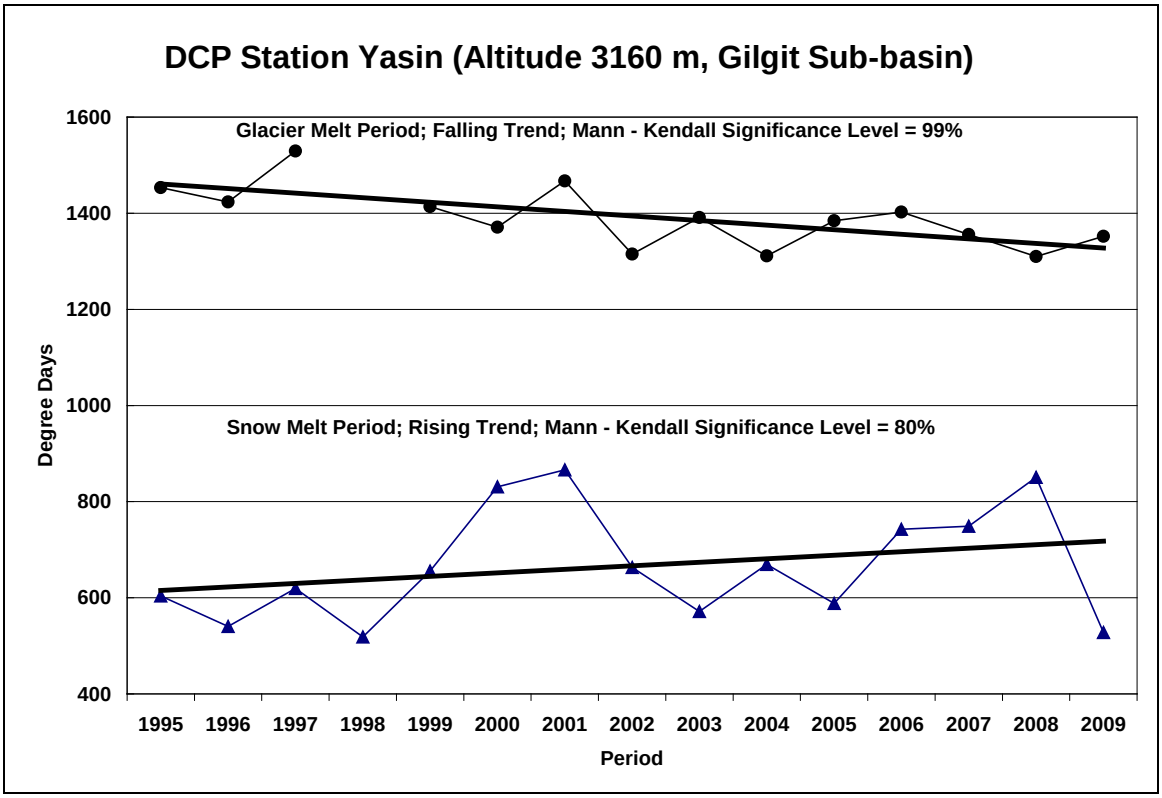


Figure 8: Rising and Falling Trends of Positive Degree Days at DCP Station Yasin for Snow melt and Glacier melt periods during 1995 – 2009.

Figure 8 shows trends in positive degree days at DCP station Yasin which is located at the border of Hindukush and Karakoram Ranges. This station showed a rising trend during snow melt period i.e. May and June with Mann - Kendall Significance Level of 80% but a reverse significant falling trend during glacier melt period i.e. July to September with Mann - Kendall Significance Level of 99%.

7. Trends in Stream Flow of Main Indus

Stream flows in Upper Indus Basin are mainly driven by summer temperature and winter precipitation. Three stream gauging stations on River Indus i.e. Kharmong, Kachura and Partab Bridge are selected for trend analysis in stream flows observed during 1995 – 2009. Long term flows of Indus River at Partab Bridge have been estimated to be 46.021 maf (1982 to 2005). Of these flows the contribution up to Kharmong is approximately 25 % and that up to Kachura is 58 %. Trends Statistics for these three stations are summarized in Table 3.

Table 3: Trends of flows at selected gauging stations on upper Indus River during snow and glacier melting period during 1995 -2009

Station Name	Average Annual Flows during 1995-2009 (MAF)	Snow Melt Period			Glacier Melt Period		
		Mann Kendall Test Z values	Mann Kendall Sig. Level	Trend	Mann Kendall Test Z values	Mann Kendall Sig. Level	Trend
River Indus at Kharmong	11.112	-0.7918	57%	Falling	-0.69282	51%	Falling
River Indus at Kachura	29.65	-0.1979	16%	Falling	-1.78154	93%	Falling
River Indus at Partab Bridge	48.56	0.061	5%	Rising	-1.64724	90%	Falling

Indus River at Kharmong

Kharmong is the first gauging station on Indus as it enters Pakistan. The station gauges the stream flows generated by higher Tibetan and Leh areas located at lower latitude in Eastern Karakoram, which are mainly influenced by Monsoon. For both snow melt and glacier melt seasons, stream flows for this station show weak falling trends as shown in the Figure 9.

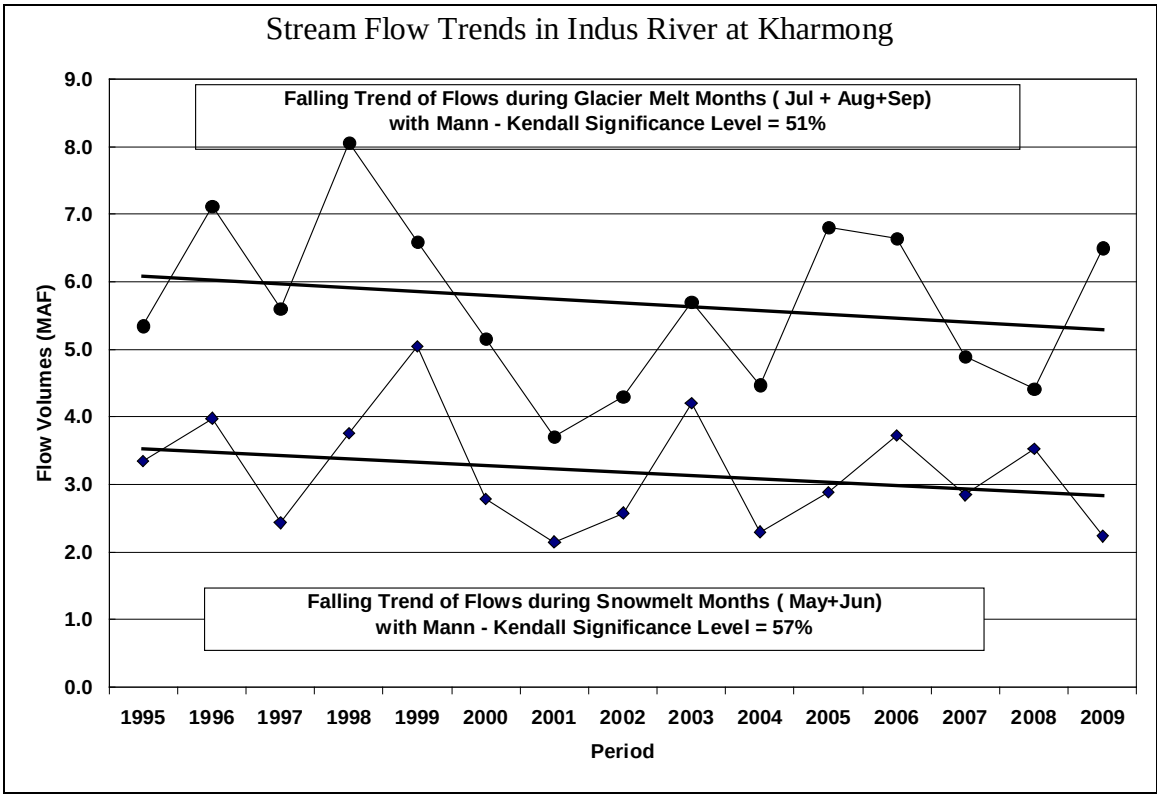


Figure 9: Stream Flow Trends for Indus River at Kharmong for Snow and Glacier melt periods during 1995 – 2009

Average annual flows of Indus at Kharmong during (1995 – 2009) are 11.112 MAF; during May to September the river flows amount to 8.871 MAF, of which 36 % come from snowmelt and 64 % from glacier melt.

Indus river at Kachura

The second major stream gauging station of UIB is at Kachura. Upto Kachura, flow contributions from Shyok, Shigar and the river segment between Kharmong and Kachura are added to the Main Indus. The average annual flows at Kachura for study period are 29.65 MAF; during May to September the river flows amount to 18.48 MAF, of which 27% come from snow melt and 73% from glacier melt. During glacier melt period the falling trends in stream flow are well established at Kachura with moderate significance level of 93%, following the trend in sensible heat. However, during snow melt period the stream flows display only a slightly falling trend, refer Figure 10.

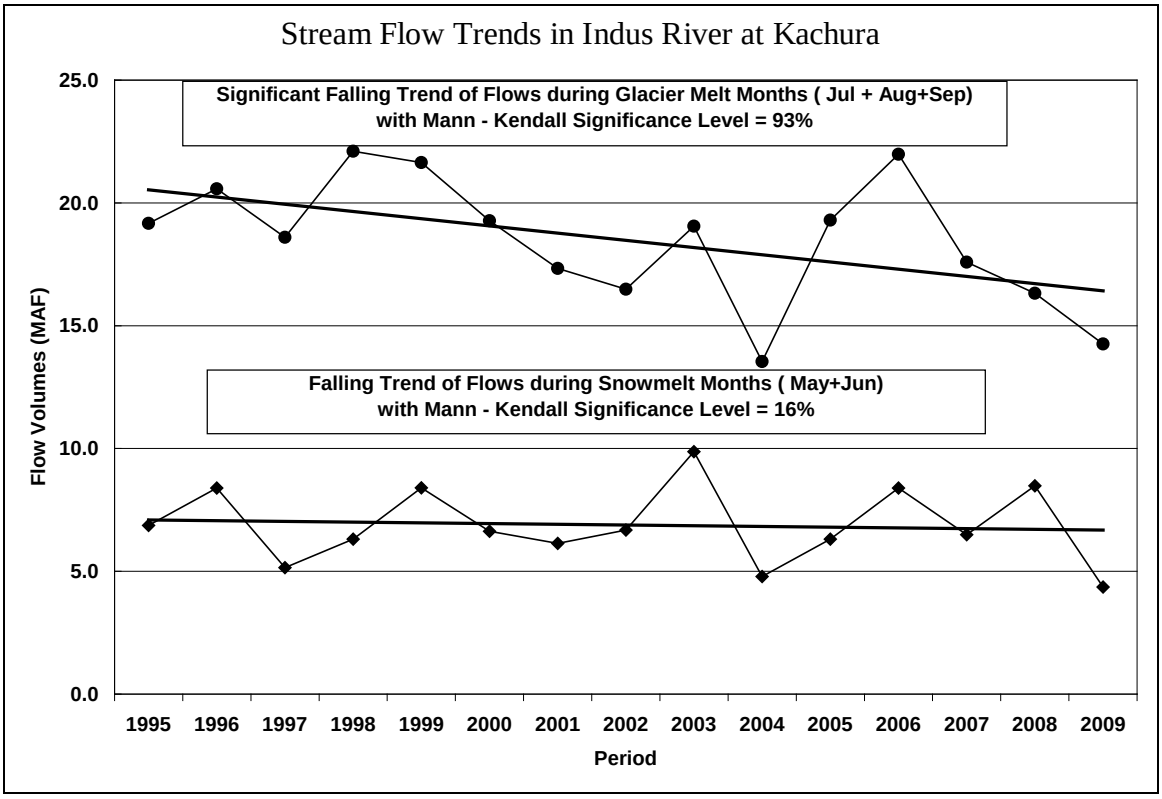


Figure 10: Stream Flow Trends for Indus River at Kachura for Snow and Glacier melt periods during 1995 – 2009

Indus River at Partab Bridge

The third major stream gauging station at main stem of Indus River is Partab Bridge. At Partab Bridge, flow contributions from Gilgit and Hunza sub-basins are added to main Indus. The average annual flows at Partab Bridge for study period are 48.56 MAF; during May to September the river flows amount to 29.3 MAF, of which 29 % come from snowmelt and 71 % from glacier melt. Upper Indus flows measured at Partab Bridge indicates a falling trend during glacier melt season at significance level of 90%, following the trend in sensible heat. However, during snow melt season there is almost no trend in stream flow data, refer Figure 11.

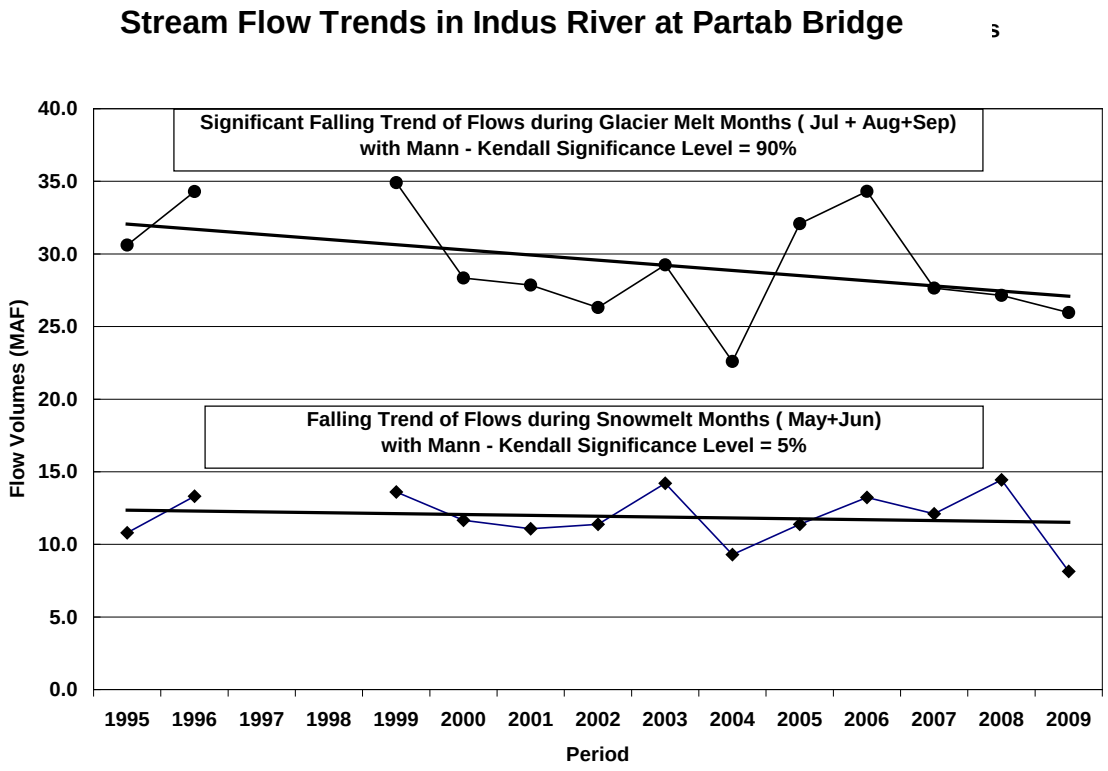


Figure 11: Stream Flow Trends for Indus River at Partab Bridge for Snow and Glacier melt periods during 1995 – 2009

8. Conclusions

Trend analysis for the Monthly Positive Degree Days for the period 1995 – 2009 indicates that while the available sensible heat required for melting of snow during May and June is increasing, that for glacier melt during July, August and September is decreasing significantly for all the DCP Stations installed in the ablation zone of Upper Indus Basin. This represents an anomalous climatic conditions during snow melt and glacier melt periods in Upper Indus Basin.

As a result of falling trends in sensible heat during glacier melt season, the corresponding flows for 1995-2009 at Kachura and Partab Bridge are also displaying significant falling trends. However, flows generated during snow melt season in Western Himalayas show only weak trends, with mixed directions, which do not necessarily correspond with the rising trends in sensible heat in this season.

The present analysis of fifteen years data does not support the prevailing hypothesis of rapidly melting or receding glaciers in Upper Indus Basin in the wake of global warming. On the other hand the study indicates a reduction in sensible heat which implies reduced ablation and enhance stability of glaciers which is also reported by Jacob et al. (2012) and Hewitt (2005). However, confirmation of these preliminary findings is necessary by additional data collection and its analysis.

9. References

- Fowler H. J. and Archer D. R. (2006) Conflicting Signals of Climatic Change in the Upper Indus Basin, Journal of Climate, Volume (19), American Meteorological Society.

- GCISC (2009 c): Ali, G., S. Hasson, and A.M. Khan, Climate Change: Implications and Adaptation of Water Resources in Pakistan, Research Report No.GCISC-RR-13, Global Change Impact Studies Centre, Islamabad.
- GCISC (2009a): Sheikh, M. M., N. Manzoor, M. Adnan, J. Ashraf and Arshad M. Khan, Climate Profile and Past Climate Changes in Pakistan, Research Report No.GCISC-RR-01, Global Change Impact Studies Centre, Islamabad.
- GCISC (2009b): Islam, S., N. Rehman, M. M. Sheikh and Arshad M. Khan, Climate Change Projections for Pakistan, Nepal and Bangladesh for SRES A2 and A1B Scenarios using outputs of 17 GCMs used in IPCC-AR4, Research Report No.GCISC-RR-03, Global Change Impact Studies Centre, Islamabad.
- Hewitt, K. (2005), The Karakoram Anomaly? Glacier expansion and the "Elevation Effect", Karakoram Himalaya, Mountain Research and Development, Vol. 25 (4): 332-340.
- ICIMOD (2011), Glacier Report November 2011
- IPCC (2007): Fourth Assessment Report (AR4), Climate Change 2007, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge.
- PMD (2009): Qamar-uz-Zaman Chaudhry, Arif Mahmood, Ghulam Rasul, Muhammad Afzaal, Technical Report No. PMD 22/2009, Climate Change Indicators of Pakistan, Pakistan Meteorological Department, Islamabad
- Rees, G. and D. N. Collins (2004), An assessment of the Potential Impacts of Deglaciation on the Water Resources of the Himalaya, Technical Report, DFID KAR Project No. R7890, Centre for Ecology and Hydrology, Oxfordshire, UK.
- Shroder, J. , R. A. Scheppy, and M. P. Bishop (1999), Denudation of small Alpine Basins, Nanga Parbat Himalya, Pakistan. Arctic, Antarctic and Alpine Research, 31: 99-105.
- TFCC (2009): Pakistan's Climate Change Policies and Actions, Task Force on Climate Change Planning Commission, Planning and Development Division Government of Pakistan, Islamabad
- Thomas Jacob, John Wahr, W. Tad Pfeffer & Sean Swenson, Recent contributions of glaciers and ice caps to sea level rise, Nature (2012) doi:10.1038/nature10847, Published online 08 February 2012
- World Bank (2006): Pakistan Water Economy Running Dry, World Bank.