WORKING PAPER 23

Pakistan Country Series Number 7

Searching Evidence for Climatic Change

Analysis of Hydro-meteorological Time Series in the Upper Indus Basin

Asim Rauf Khan

International Water Management Institute

FUTURE HARVEST
IWMI is a Future Harvest Center
Supported by the CGIAR

Working Paper 23

Searching Evidence for Climatic Change

Analysis of Hydro-meteorological Time Series in the Upper Indus Basin

Asim Rauf Khan

International Water Management Institute

IWMI receives its principal funding from 58 governments, private foundations, and international and regional organizations known as the Consultative Group on International Agricultural Research (CGIAR). Support is also given by the Governments of Pakistan, South Africa, and Sri Lanka.

Cover photograph: Biafo Glacier, The Upper Indus Basin, courtesy of the Pakistan Snow & Ice Hydrology Project, WAPDA.

The authors: Asim Rauf Khan, Civil Engineer IWMI

Khan, A. R. 2001. *Analysis of hydro-meteorological time series: Searching evidence for climatic change in the Upper Indus Basin*. Lahore, Pakistan: International Water Management Institute. (IWMI working paper 23)

ISBN: 92-9090-205-1

water resources management / river basins / analysis / catchment areas / stream flow / data collection / models / time series / models / hydrology / meteorology / Pakistan

Please direct inquiries and comments to: IWMI 12 Km, Multan Road, Chowk Thokar Niaz Baig, Lahore 53700 Pakistan.

CONTENTS

ACRONYMS

DMA	Double Mass Analysis
GCM	General Circulation Model
IBIS	Indus Basin Irrigation System
ICSI	International Commission on Snow and Ice
IPCC	Intergovernmental Panel on Climate Change
m.a.s.l	Meters above sea level
Met.	Meteorological
PMD	Pakistan Meteorological Department
PSIHP	Pakistan Snow and Ice Hydrology Project
T_{MAX}	Maximum Temperature
T_{MIN}	Minimum Temperature
UIB	Upper Indus Basin
UK	United Kingdom
WAPDA	Water And Power Development Authority
WMO	World Meteorological Organization

ACKNOWLEDGMENT

I wish to acknowledge the Pakistan Meteorological Department (PMD), Lahore, and the Water and Power Development Authority (WAPDA), who provided wonderful support during the course of this study.

A very special thanks to Ramya De Silva in getting the ICSI report on Himalayan Glaciers. I am also very grateful to Dr. G. W. Kite for his guidance and intellectual input. Dr. Hammond Murray-Rust (Principal Researcher, IWMI) and Vilma M. Horinkova (Regional Director, IWMI) were kind enough to review the final draft.

Special thanks are due to Ms. Sofiya Saeed for editing this report and also thanks to Ms. Shahnaz Akhtar for formatting the report

Lastly, I would like to acknowledge the support of Dr. S. A. Prathapar (former Director, IWMI-Pakistan) who was always very keen to look into different issues that could possibly have a bearing on water resources in the Indus Basin.

SUMMARY

The study examines some of the major components of water cycle in the Upper Indus Basin (UIB) to look for evidence of climate change. An analysis of hydrometeorological data has been performed for UIB. An Additive Decomposition Model was used for analyzing the time series data from ten meteorological stations in the Mangla (Jhelum River) and the Tarbela (Indus River) catchments and the long-term flow data for the three major rivers, the Indus, Jhelum and Chenab. The model decomposes a time series into trend, cyclical or periodic, autoregressive and irregular components. Furthermore, spectral analysis is done in order to display these components of the time series and examine the results of the removal of the components. This approach makes use of the fact that a change in climate, if it has occurred, will have a magnified effect on hydrologic time series. By detecting trends in such series, it should be possible to work backwards and identify the causative climatic change. In case of flow data for the three rivers, which was available for a longer period than the meteorological data, the 'F' and 't' tests for stability of variance and mean, respectively, were also performed.

The annual cycle dominated all the temperature series i.e., large periodic components, and none of other three components were significant. For precipitation, the variance in time series was explained by the periodic component and a dominant random component. In case of stream-flow data, the annual temperature cycle was dominant and no trend components were found in any of the flow series. The F-test and the t-test indicated the variances and means for different sub-periods of each flow series to be stable at 5% level of significance. The analysis of time series of river flows and associated climatic data did not find any pattern of trends likely to be caused by 'greenhouse warming' in the Upper Indus Basin.

SEARCHING EVIDENCE OF CLIMATIC CHANGE: AN ANALYSIS OF HYDRO-METEOROLOGICAL TIME SERIES IN THE UPPER INDUS BASIN

INTRODUCTION

The Upper Indus Basin

The Upper Indus Basin (UIB) is home to three of the world's mightiest mountain ranges. The Karakoram and the Himalayan Mountain Ranges are in the north and northeast of Pakistan while the Hindukush Mountain Range guards the northwestern frontiers of the country (Figure 1). The Indus River and many of its major tributaries originate in these mountains. The Indus River System forms a link between two great natural reservoirs, the snow and glaciers in the mountain ranges of UIB and the groundwater contained by the alluvium in the Indus Plains of the Punjab and Sindh Provinces of Pakistan. Barring the Polar Regions, UIB contains the world's largest glaciers. The Upper Indus Basin lies within the variable influence of three major weather systems: the sub-Mediterranean regime of mainly winter, westerly storms; the summer monsoon; and the Tibetan anticyclone.

Perspective for the Study

A lot of research is being carried out to look into the effects of increased concentrations of CO_2 and other greenhouse gases in the atmosphere. Whether the reported increase in the earth's mean temperature by about 0.6^{o}C over the past 120 years is due to the effects of greenhouse gases or the natural swings of climate and changes in the sun's luminosity, the debate goes on. Scientists and researchers are studying the behaviour of the hydro-meteorological regimes of the Polar Regions. According to scientific reports (Hodges, 2000), the Arctic has warmed considerably in the past two decades and the ocean's ice cover has thinned by about 40 percent since the 1960s. Some have suggested that the shrinking ice lakes in the Andes (South America) are a consequence of global warming (Nash, 1999). It has also been reported that there is a worldwide decline in glaciers and alpine glaciers have retreated by 25 percent over the past hundred years. A four-year study recently completed by the International Commission on Snow and Ice (ICSI) predicts that all the glaciers in the central and eastern Himalayas could disappear by the year 2035.

The findings of the ICSI studies, in particular, are quite alarming for Pakistan since the Indus Basin Irrigation System (IBIS) relies heavily on the runoff generated by melting of snow and ice in the Upper Indus Basin. The irrigation canals of IBIS withdraw almost seventy five percent of the mean annual runoff available in all the major rivers of the Indus Basin. The suspected climate change, if it has occurred, must have a bearing on water resources. In this context, it would be quite opportune to examine some of the major components of water cycle in UIB for evidence of climate change.

Objective of the Study

The objective of this study is to look for evidence suggesting climatic change, through a time series analysis of hydro-meteorological data from various locations in the Upper Indus Basin.

Figure 1. The Indus Basin, Pakistan.

CLIMATE CHANGE

Climate describes the average weather conditions of a certain area. Maunder (1994) has defined climate change as: "a significant change in the mean values of a meteorological element (…) during the course of a certain period of time, where the means are generally taken over periods of a decade or more". Like weather, climate also changes over time. Some changes occur naturally because of global climate cycles due to changes in sun's luminosity, earth's shifts in its orbit and the tilt of its axis, etc. Changes in climate may also take place due to anthropogenic factors such as the burning of fossil fuels resulting in increased concentrations of greenhouse gases (carbon dioxide, methane etc.). Recently, scientific attention has been focused on the idea of a changing climate as a result of suspected 'greenhouse warming' of the atmosphere and its consequent effects on our way of life.

Impacts on Water Resources

Water resources and the hydrologic cycle are largely controlled by climatic factors including precipitation, humidity, temperature, wind speed, and solar radiation. Therefore, any change in any of these climate variables may affect the quantity, quality and spatial distribution of water on land. The scenarios for future climate change indicate the possibility of sharpening of extremes (e.g., droughts, floods etc.) and changes in seasonal and areal distribution of water resources.

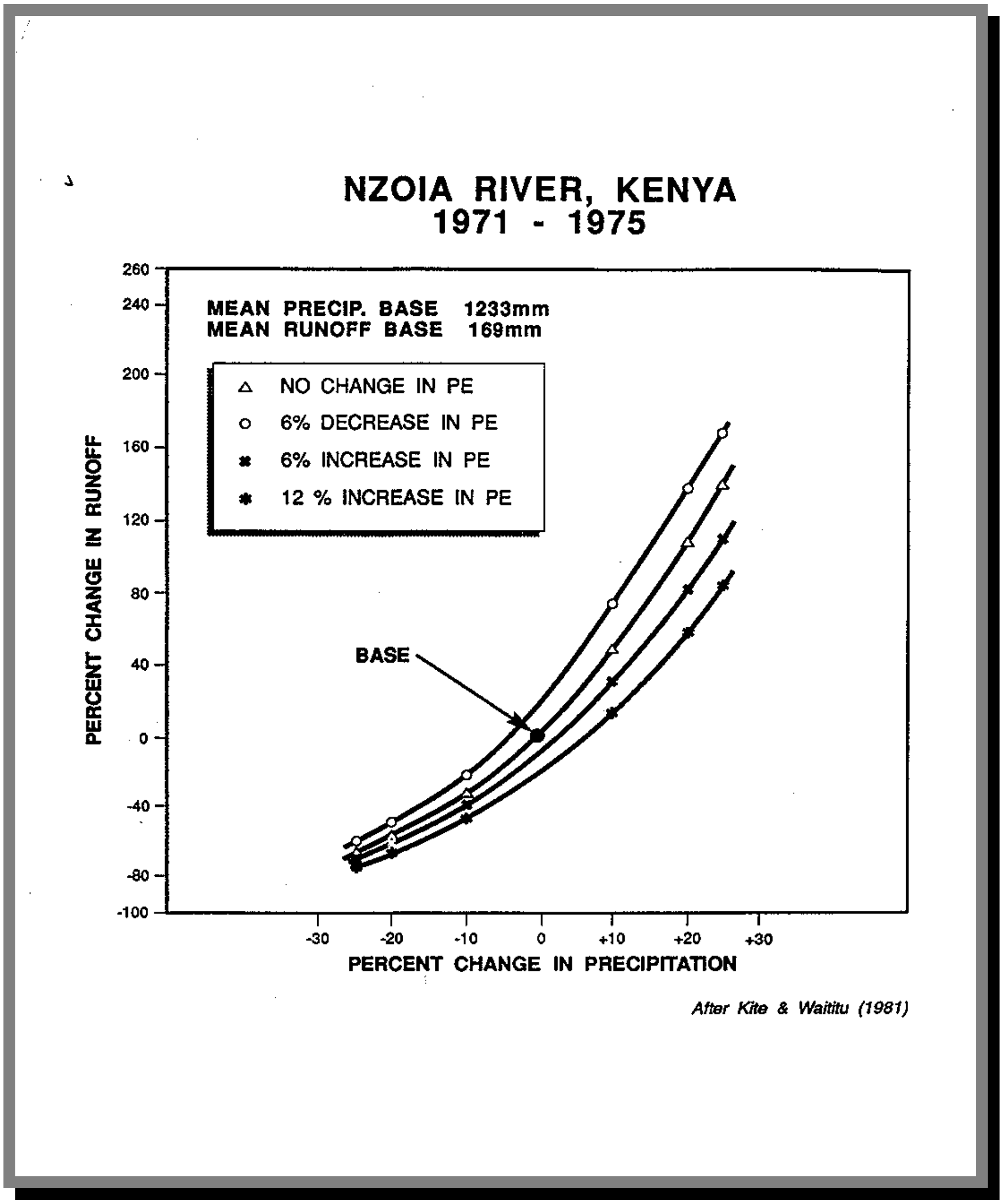
Many studies have anticipated the effects of a doubling of radiatively active gases on water resources. Wigley and Jones (1985) showed that changes in precipitation always have an amplified effect on runoff. A 10% change in precipitation over a basin with a runoff ratio (runoff/precipitation) of 0.2 would result in a 50% change in runoff, assuming no change in evaporation.

$$\frac{R_1}{R_0} = \frac{\alpha - (1-\tau)\beta}{\tau}$$

Where, R_1 is the runoff after climatic change
R_0 is the runoff before climatic change
α is the change in precipitation due to climatic change
β is the change in evaporation due to climatic change
τ is the runoff ratio of the basin (runoff/precipitation)

Similarly, Kite and Waititu (1981), studied the effects of varying precipitation and evaporation/evapotranspiration on river flow in Nzoia River and Lake Victoria in Africa. They have shown that the rainfall-runoff process is extremely sensitive to changes in input (Figure 2). The results of climate change impact studies using General Circulation Models (GCMs), apparently suggest that the accumulation of CO_2 and other 'greenhouse' gases in the atmosphere is creating trend components such as increasing temperatures and precipitation. Evidence of a climate change might therefore appear as positive or negative trends in natural time series.

Figure 2. Changes in Streamflow as a Result of Changes in Precipitation and Evapotranspiration (adopted from Kite and Waititu, 1981).



STUDY AREA

The Upper Indus Basin (UIB), with particular focus on the catchments of Mangla and Tarbela reservoirs, was the area under study. The Upper Indus Basin (UIB) has been marked as the area above *Rim Stations*. A rim station, in the Indus Basin, is defined as a control structure (reservoir, barrage, etc.) on the river just when it enters into Pakistani territory or upstream of the canal-irrigated Indus Plains of the Punjab and Sind Provinces (Khan, 1999). The rim stations for the main Indus, the Jhelum and the Chenab Rivers are the Kalabagh Barrage, Mangla Reservoir and Marala Barrage, respectively (Figures 1 and 3).

Most of the runoff generated in the Indus River catchment above the Kalabagh rim station comes from snow and ice melt. About 37% area in the Karakorams and 17% in the Himalayas is covered with glaciers (Tarar, 1982). The catchments of Jhelum and Chenab Rivers above Mangla and Marala, respectively, receive the summer monsoons and thus, have a considerable rainfall component in addition to snow and ice melt. These three rivers (also called as the Western Rivers); namely the Indus, Jhelum and Chenab, are the major source of water supply to the Indus Basin Irrigation System. The other two major rivers originating in the Indus Basin (also called as the Eastern Rivers) are Ravi and Sutlej. The entire water rights of these two rivers have been granted to India (The Indus Waters Treaty 1960) and, therefore, are not of a great consequence to Pakistan except from a flood management perspective. Furthermore, the time series data for these two rivers, available in Pakistan, carry influences of direct anthropogenic activities on the upstream side within India — large-scale irrigation projects, e.g., storages, canal withdrawals etc.

DATA AND METHODOLOGY

Data

Meteorological data from ten climate stations, seven in the Tarbela catchment and three in the Mangla catchment, have been used in the analysis (Figure 3). This data, which was available for a period of 40 years (1955-95) for the Mangla catchment and 30 years (1966-95) for the Tarbela catchment, included: mean monthly maximum temperature, mean monthly minimum temperature and monthly precipitation. Although data for an over 40-year length of period from 1953 to 1995 was available for climate stations in the Tarbela catchment, there were gaps as the data was missing for a longer period (6 months, an year), in the earlier years. In addition, the data on inflows to Tarbela reservoir were not available prior to 1962. Therefore, data for the 10-year period from 1955 to 1965 was not used in the analysis for climate stations in the Tarbela catchment. The meteorological data was obtained from the Pakistan Meteorological Department (PMD) (Annex 1 and 2).

In addition to meteorological data, the following time series data on river flows was also analyzed:

- Indus River at Tarbela (Monthly inflows, 1962-98);
- Indus River at Kalabagh (Monthly inflows, 1923-97);
- Jhelum river at Mangla (Monthly inflows, 1923-97); and
- Chenab River at Marala (Monthly inflows, 1923-97).

Figure 3. The Upper Indus Basin Showing Catchments of Tarbela and Mangla Reservoirs.

This data was acquired from the Pakistan Water and Power Development Authority (WAPDA). A small database (five years[1]) of high altitude meteorological data, from three climate stations located at elevations of over 3000 m.a.s.l in the Tarbela catchment, was also available with WAPDA. The data from these climate stations was used for making comparisons with the data from three of the PMD valley-bottom climate stations.

Meteorological observations for longer periods of time are the most desirable form of data for time series analyses. But they suffer from several disadvantages (Kite, 1989); some of which are:

1. Meteorological observations are measurements at a point and may be representative of only a small area;
2. They are highly susceptible to external influences such as urbanization and to unintended changes in the environment (e.g., rain gauges surrounded by growing trees); and
3. They generally have large fluctuations.

The hydrologic time series such as river flow and lake-levels, on the other hand, measure areally integrated effects and are more highly damped. While atmospheric processes induce randomness into precipitation and temperature series, the storage effect of the river basins replaces some of this randomness with autoregression in the river flow series. Furthermore, it is easier to distinguish, in hydrologic time series, the ones that are affected directly by man's activities (e.g., dams or diversions).

Methodology

Although it may vary in magnitude and direction, the climatic change referred to these days is of a much shorter time scale and is assumed to be the consequence of the 'greenhouse' gases. Therefore, it would be of some relevance to look for any signals suggesting a change in climate in the natural time series. The methodology adopted for time series analysis in this study makes use of the fact that a change in climate, if it has occurred, will have a magnified effect on hydrologic time series. The hypothesis is that a linear additive decomposition model (Kite, 1989 & 1992) can adequately represent a time series X:

$$X_t = P_t + T_t + R_t$$

Where, P_t is the periodic or cyclic component
T_t a trend component, and
R_t a stochastic component

The model decomposes the time series into trend, cyclical or periodic, auto-regressive and irregular components (Figure 4). Spectral analysis is done to display these components of the

[1] These high-altitude climate stations were commissioned in the mid-nineties and are owned and operated by the Hydrology and Research Directorate of Pakistan WAPDA.

time series and examine the results of the removal of the components (Figure 5). Converting the data from time domain to frequency domain aids in detecting significant components. The relative importance of these components can then be expressed as percentages of the total variance of time series. Thereafter, attempts are made to provide physical explanations for the presence of these components. In this process the time series, instead of being split into sub periods, is analyzed as a whole.

The results of impact studies using general circulation models apparently suggest that the accumulation of 'greenhouse' gases in the atmosphere is creating trend components (Marchand et al., 1988; IPCC, 1997; UK Met. Office, 1999). By detecting trends in such series, it is possible to work backwards and identify the causative climatic change. A pattern of significant trends might provide an indication that some form of climatic change was occurring. If the statistical analysis suggested the presence of a trend component in a particular time series, then its significance was checked by the Spearman's rank correlation method. This method is simple and distribution-free, i.e., it does not require the assumption of an underlying statistical distribution. Another advantage of this method is its nearly uniform power for linear and non-linear trends (WMO, 1966; Dahmen and Hall, 1990).

Scenarios of future climate indicate the possibility of sharpening of extremes and changes of seasonality. This would have a significant impact on river flow, one of the most important hydrological variables. Beran and Arnell (1995) have found that a ten percent increase of the mean would cause a ten-year flood to occur on average every seven years. If such circumstances of a significant increase in the severity of hydrological extremes in the 'warmer' world, the consequences for design codes could be severe (Kundzewicz and Kaczmarek, 2000). It would be necessary to design bigger water storage volumes at higher costs to accommodate larger flood waves and to fulfill the growing demand for water during the prolonged and more frequent droughts of increasing severity.

In this perspective, split-record tests for stability of the variance and mean of the long-term stream-flow data were carried out. As stated earlier, hydrologic time series measure areally integrated effects; and, fortunately enough, the streamflow records for this study were available for a period of over seventy years for all the three major rivers (Annex 1). Thus, in case of streamflows, we had the advantage of a more detailed statistical analysis. The time series for Indus, Jhelum and Chenab rivers were split into different non-overlapping sub periods.

The F-test, used for checking the stability of variance, determines the ratio of the variances of two split, non-overlapping, sub-sets of the time series. The distribution of the variance-ratio of samples from a normal distribution is known as the F, or Fisher, distribution. Even if the samples are not from a normal distribution, the F-test will give an acceptable indication of stability of variance. The t-test for stability of mean involves computing and then comparing the means of two non-overlapping sub-sets of the time series (the same sub-sets from the F-test for stability of variance).

Figure 4. Time (left-hand side) and Frequency (right-hand side) Domain Plots of Sample Data (adopted from Kite, 1992).

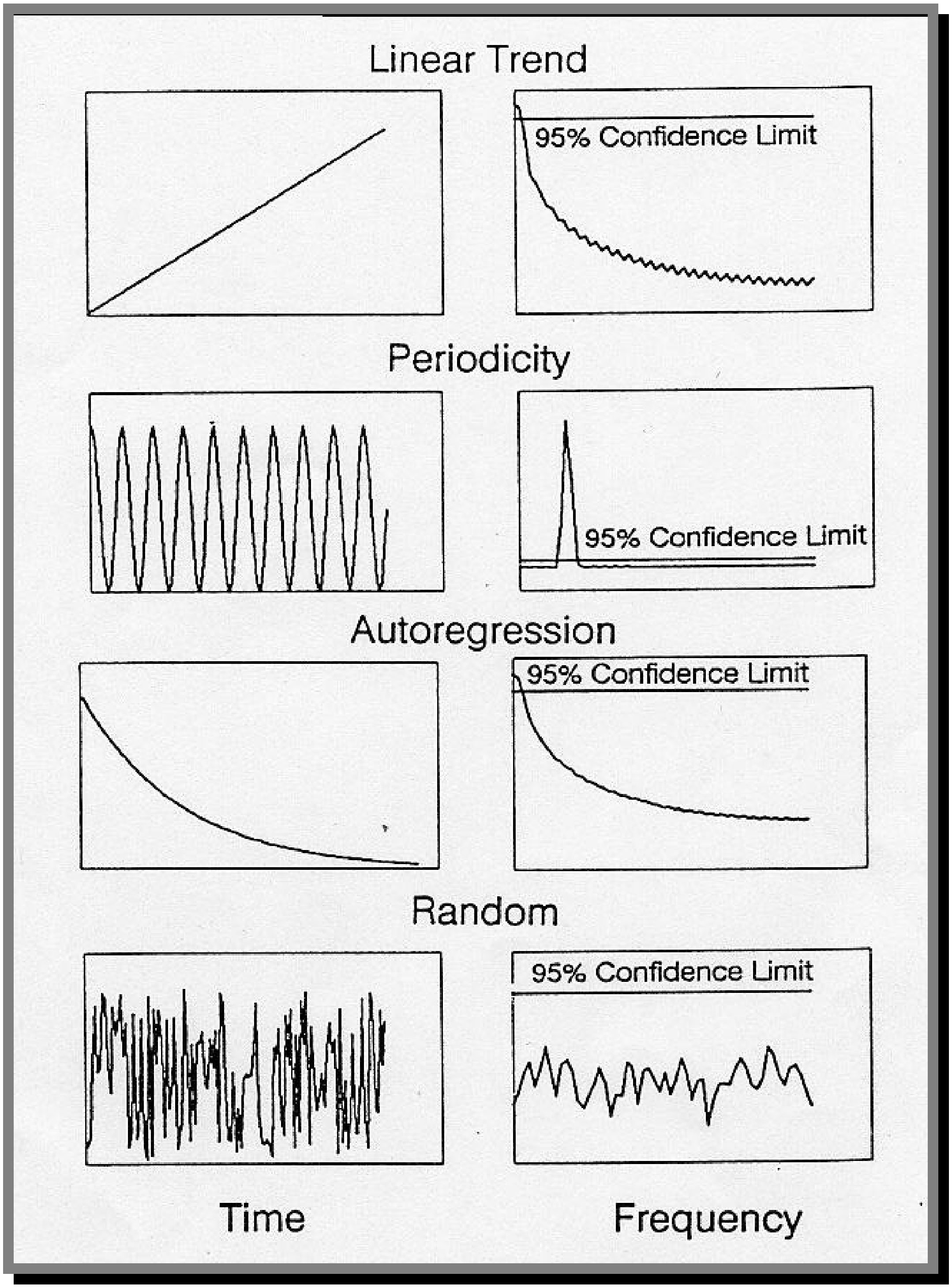
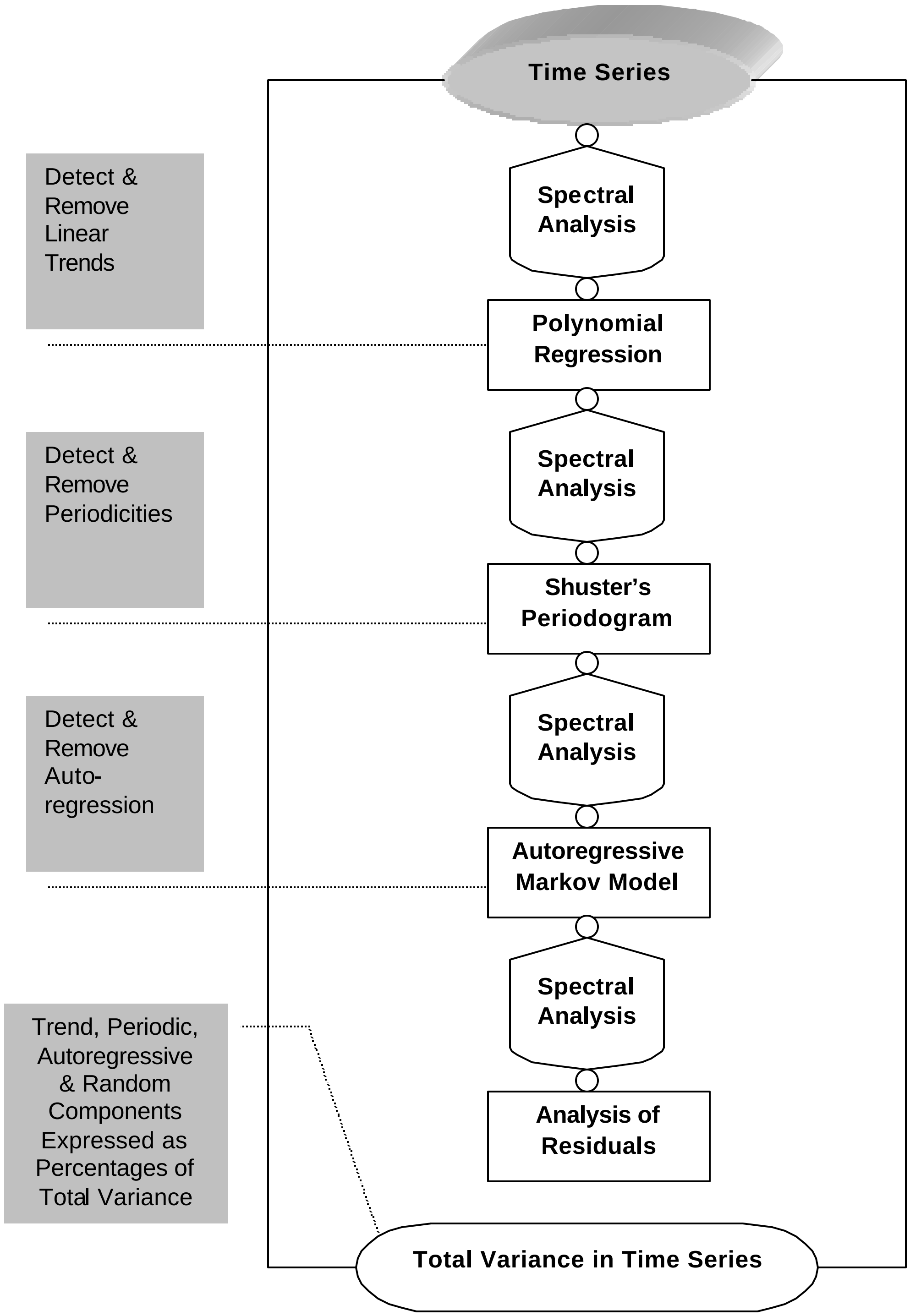


Figure 5. Time Series Analysis Performed by the Linear Additive Decomposition Model.



RESULTS OF TIME SERIES ANALYSIS

Tarbela Catchment

The temperature and precipitation data for a 30-year period, at a monthly time step, from seven climate stations in the Indus River catchment upstream of Tarbela Reservoir were analyzed. Similarly, monthly inflows to Tarbela Reservoir for the same period were also analyzed. The results are given in Table 1. The percentages given in the table have been rounded off and do not always add up to 100%.

All the temperature series (T_{MAX} and T_{MIN}) have large periodic component due to the annual cycle. In case of T_{MIN} for Kakul meteorological station, 1% of the total variance in the time series is explained by the trend component. Using the Spearman's Rank Correlation method, this trend component was found to be significant. This test was performed by aggregating the mean monthly minimum temperatures for Kakul to the annual level (one value of T_{MIN} for each year: 1966–1995). A look at the time series plot of the Kakul T_{MIN} indicates a downward trend during 1972–73. The series stabilizes after 1973 and then there is another dip towards the end of the time series in 1994 (Figure 6).

In case of the precipitation series, except for Kakul, almost two thirds of the total variance is unexplained as random residual. The precipitation data at Kakul meteorological station shows that two thirds of the total variance may be explained by the periodic component and one third is the random residual. The reason for Kakul precipitation data showing different characteristics than the rest of the Tarbela catchments weather stations is that Kakul is located in a region (commonly referred to as the Tarbela-Local sub catchment) where the activities of both the major weather systems i.e., the summer monsoons and the winter western disturbances, are quite pronounced thereby inducing periodicity in precipitation data. As we move north and east towards the upper catchment of Tarbela Dam, it is only the winter precipitation caused by the western disturbances from the Mediterranean, which accounts for most of the annual precipitation. There is, however, some spillover of the summer monsoons across the Himalayan ridge but as the data shows its influence is not that pronounced in the precipitation time series. There were no trend components in any of the precipitation time series.

The monthly inflow data of Tarbela Reservoir for the same period as that of the meteorological time series shows a large periodic component due to the annual temperature cycle, and relatively small autoregressive and random components. There was no trend component in this time series either. The results of the analyses of precipitation data may be considered simultaneously with the streamflow data. The Indus River (Tarbela catchment) being predominantly glacier fed; 96% of the total variance is explained by the annual temperature cycle, there is no trend component, and a very small (1%) auto regressive component. Only 2% of the variance remains as unexplained residual. In comparison, an analysis of the monthly precipitation recorded at all the PMD stations, except Kakul (in the Tarbela-Local sub catchment), shows almost 60–70% of the variance to be unexplained residual and 30–40% explained by periodicities. The storage effect of the catchment (glacial ice-pack) damps the random component in precipitation and introduces a strong periodic component in streamflow due to the annual temperature cycle.

There is an interesting aspect of Tarbela Reservoir inflows that may be examined from a climate change perspective. If we look at the ten-daily inflow hydrograph of Tarbela Reservoir, two distinct features of the hydrograph may be observed (Figure 7). The Indus River starts to rise in early May due to the melting of snow. When all the snow cover (below the snow line ~5500 m.a.s.l) has depleted, glacial melt begins to contribute towards river runoff from July onwards. The annual flow peak in the Indus can occur as early as 30^{th} of June and as late as 20^{th} of August (PSIHP, 1992). The river flows during the months of May and June are, therefore, a result of snowmelt whereas glacial melt accounts for a dominant part of the Indus River flows during July and August.

With this viewpoint, the two-monthly inflows for Tarbela Reservoir May–June representing snowmelt and July–August representing glacial melt, were analyzed for the entire length of the time series available for Tarbela Reservoir (1962–1998). In this way the annual cycle (the major cause of periodicity) is removed and consequently, we do not see any periodic component (Table 1). This data, also, did not indicate the presence of any trend component. The random component expounded the total variance in both the time series i.e., the snowmelt and glacial melt components of the river runoff.

The Kakul Time Series

The T_{MIN} series for Kakul, was also analyzed for the entire length of record available (1953–95, Annex 3-a). The relative proportions of the trend, periodic, auto-regressive and residual components were found to be 2%, 94%, 0%and 3%, respectively. The split-record t-test for stability of mean indicated a break in the time series after 1970-73 to be real. The variance, however, was stable among the sub periods (1960-69, 1973-82, 1983-92). The time series analyses, including the F-test and the t-test, for T_{MAX} and precipitation series did not indicate the presence of any significant change in these time series data.

The temperature and precipitation records for Kakul were double-checked and the matter discussed with PMD officials. According to them, there has neither been a change in observation/calculation procedures nor a change in the location of the weather stations or replacement of new sensors/instruments. All the sensors/instruments are calibrated at the PMD regional office at Lahore before installation. The relative consistency of post-1973 Kakul data (1973 to 1990) was also checked using Double Mass Analysis (DMA) technique, to determine if other stations in the same hydrologic region (the Tarbela-Local sub catchment) as Kakul experienced the same meteorological conditions. Data from two of the WAPDA weather stations at Shinkiari and Oghi was used for this comparison. As indicated by DMA (Annex 3-b), the post-1973 data (1973 to 1990) from Kakul does not appear to be influenced by some errors in observation or instrumentation. Unfortunately, there was not enough data for Shinkiari and Oghi (i.e., data for period prior to 1973), to check the accuracy (rather relative consistency) of the Kakul temperature records for the two earlier decades.

If we look at the monthly series for all the Kakul meteorological data, the following observations may be made by comparing the data for sub-periods 1953–1971(sub-period A) and 1974–95 (sub-period B):

1. In comparison to sub-period A, the mean monthly precipitation for sub-period B (1974–95) was 36 and 50 percent higher during March and June respectively; 16% higher during July and 8% higher during August. There was no change in the other months. On an overall basis, the sub-period B (1973–95) was 12% wetter and the evenings and nights were cooler during the winter months than in sub-period A (1953–71). The increased precipitation in March and June suggests more pronounced westerly activities (rainfall brought in by the western disturbances). This is also confirmed by the rainfall recorded at Tarbela Dam (Tate and Farquharson, 2000) and the observed flows of the Siran River; one of the two major streams in the Tarbela-Local sub catchment (Kakul, Shinkiari and Oghi meteorological stations also fall in Siran River catchment).
2. The mean monthly maximums in sub-period B were 11–12% lower than in sub-period A during February and March. For the remaining months the decrease in sub-period B was 3–6%. This slight, statistically insignificant, decline in mean monthly maximum temperatures (T_{MAX}), may be explained by the occurrence of more rain (or of the cloud cover required for rain) during sub-period B that caused a lowering of day-time maximums.
3. In contrast, the mean monthly T_{MIN} for sub-period B was 2.4 ^{O}C lower than that in sub-period A. The mean values for T_{MIN} series in sub-period B were lower than those in sub-period A by the following ratios: January, February, and December 55–75% lower; March and November, 30–34% lower; April, May, June, September, and October, 13–22% lower; and July and August, 8-9% lower. The occurrence of more rainfall in sub-period B did not raise the daily minimums at Kakul; which was the effect one would have normally expected. Instead it is quite the opposite that happened. However, the reduction in mean monthly T_{MIN} took place during a course of a two-year time period of 1972–73 and in the period between 1973 and 1993, the time series has remained stable. Whether, the step trend of 1972–73 was induced due to an error in calibration of the temperature sensors, it could not be confirmed from PMD's records.

Table 1. Tarbela Catchment: Time Series Components As Percentage of Total Variance for Hydrometeorological Data (30-Years Data).

	Trend	Periodicity	Auto-regressior	Residual
Temperature (T_{MAX})				
Kakul	0	95	0	4
Chilas	0	96	0	3
Bunji	0	96	0	3
Astore	0	96	0	3
Gilgit	0	97	0	2
Gupis	0	96	0	3
Skardu	0	96	0	3
Temperature (T_{MIN})				
Kakul	1	95	0	3
Chilas	0	97	0	2
Bunji	0	96	1	2
Astore	0	96	0	3
Gilgit	0	97	0	2
Gupis	0	96	1	2
Skardu	0	96	0	3
Precipitation				
Kakul	0	62	0	37
Chilas	0	27	0	72
Bunji	0	32	0	67
Astore	0	41	0	58
Gilgit	0	38	0	61
Gupis	0	40	3	55
Skardu	0	31	0	68
Streamflow				
Tarbela Inflows	0	96	1	2
Partial Duration Serie				
Snow Component	0	0	0	100
Glacier Component	0	0	0	100

Figure 6. Ten-Daily Inflow Hydro-graphs for Tarbela Reservoir.

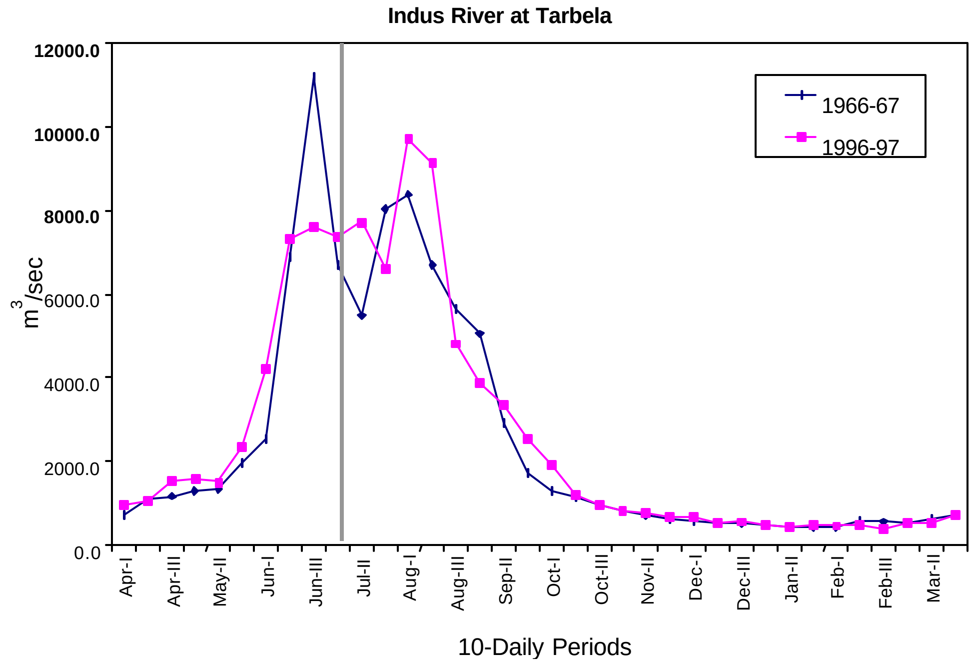


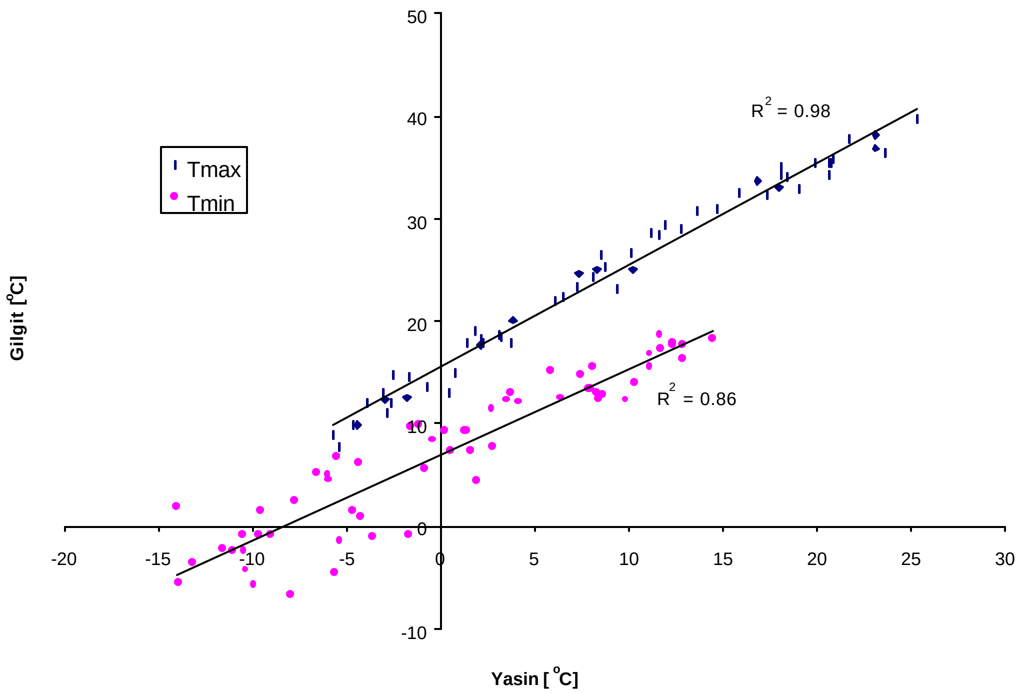
Figure 7. Time Series Plot of T_{MIN} of Kakul Meteorological Station in Tarbela Catchment.

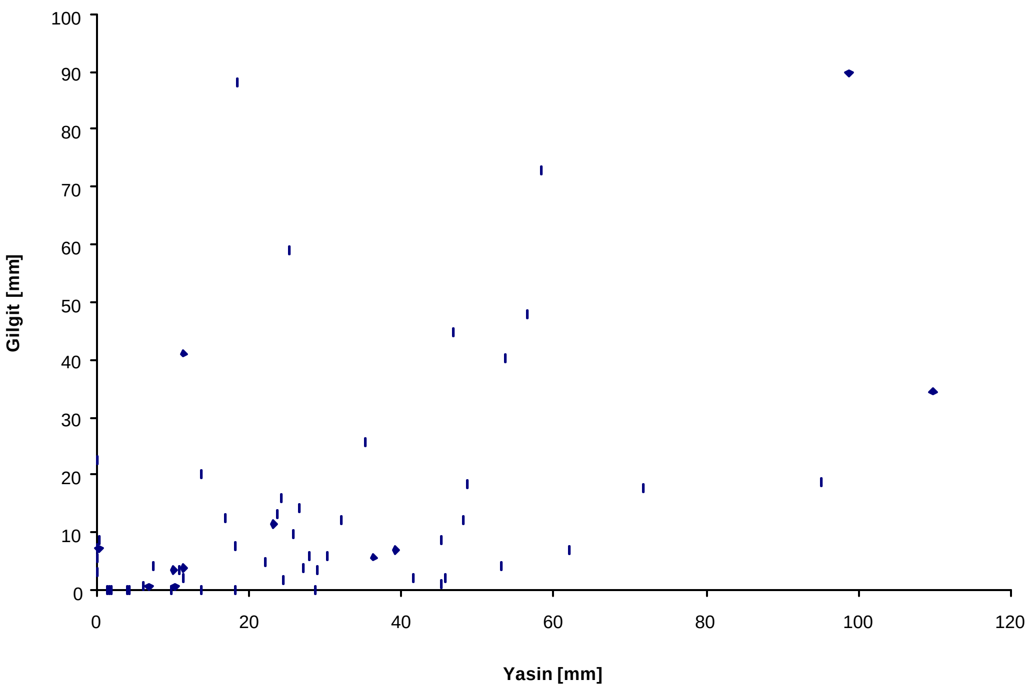
High-Altitude Meteorological Data: Tarbela Catchment

Glacial melt is one of the major sources of inflow in the Upper Indus Basin, and the Tarbela drainage basin in particular. Most of the winter precipitation, which provides nourishment to the Indus glaciers, occurs at higher altitudes. The active hydrologic zone for the Indus River lies between the elevations of 3000 m.a.s.l to 5500 m.a.s.l. Unfortunately, all PMD meteorological stations are located below the elevation of 3000 m.a.s.l. In the mid-nineties, however, Pakistan WAPDA installed some high-altitude weather stations in the Upper Indus Basin. A five-year database is also available for these weather stations. This data, no matter how short the length of time series, may provide some insight if examined in relation to the PMD valley-bottom climatic data (i.e., below an elevation of ~ 3000 m.a.s.l).

Meteorological data from three of the high-altitude stations namely, Yasin, Rama, and Hushe (Figure 3, Annex 2) was examined in relation with the data from their respective nearby valley-bottom stations, Gilgit, Bunji and Skardu i.e, a sort of double mass analysis for common data period (Figure 8). Both the temperature series (T_{MAX} and T_{MIN}) for high-altitude data had very strong correlations with the valley-bottom data in all three cases. The slightly weaker correlation for T_{MIN} was due to the valley effects during night hours. A valley can pick up cold air during night lowering the daily minimums thereby increasing the daily temperature range. For precipitation data, there was no correlation since the phenomenon is highly variable in general and in mountainous regions, such as the Upper Indus Basin, in particular.

Figure 8. Correlation of High-Altitude Meteorological Data (Yasin) with Valley-Bottom Data (Gilgit), in the Indus River Catchment.





Mangla Catchment

The temperature and precipitation data for a 40-year period, at a monthly time step, from three climate stations in the Jhelum River catchment upstream of Mangla Reservoir were analyzed. Similarly, monthly inflows to Mangla Reservoir for the same period were also analyzed. The results are given in Table 2. All the temperature series (T_{MAX} and T_{MIN}) have large periodic component due to the annual cycle; and there were no trend components in any of the temperature series. The periodic component explained 50–65% of the total variance in the precipitation data for all the three climate stations. The remaining was the random residual and here also, there was no trend component to be found in any of the time series.

The annual cycle dominated the streamflow data with the periodic component explaining 81% of the total variance. The autoregressive component was 5%, higher than that for Tarbela inflows. This slightly higher autoregressive component was induced due to the regulation provided by the Wular Lake in the drainage area of the Jhelum River upstream of Mangla Reservoir. Similarly, the random residual for Mangla inflows was 12%, again higher than that for Tarbela — the monsoon effects in the Mangla catchment inducing a relatively higher degree of randomness.

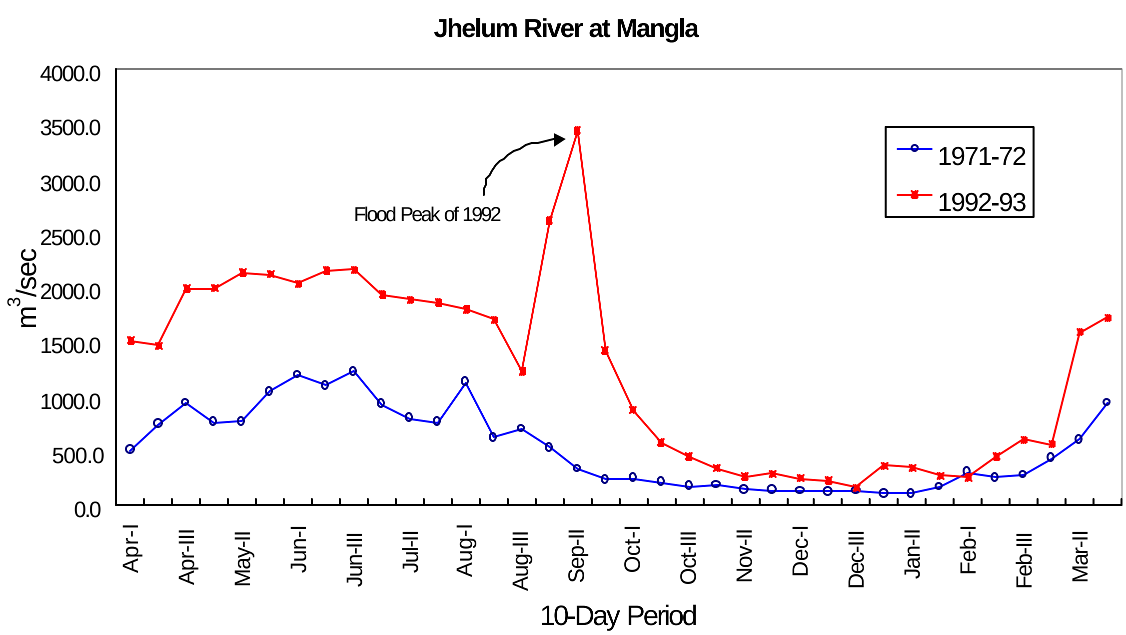
The results of the analysis of precipitation data may be considered at the same time as those of the Mangla inflow series. The Jhelum River inflows at Mangla show a slightly lower periodic component than for the Indus River at Tarbela; the autoregressive and random components are higher. The monthly precipitation records at all the three climate stations in Mangla catchment show a larger periodic component indicating the cyclic distribution of the annual precipitation (monsoons and the western disturbances).

In contrast to Tarbela, due to the more southern position of the contributing drainages, Mangla starts to rise a month earlier (Figure 9). The summer monsoons provide substantial runoff late July and August; and some times even during September. Some of the highest floods in the Jhelum River have been the result of heavy monsoon rains in the Mangla catchment late in the summer. Therefore, the three-monthly (July–September) Mangla Reservoir inflows, dependent mostly on the monsoonal rainfall, were also analyzed to look for any signals of 'change' in the monsoon weather systems appearing in the river runoff. No trend was found in this partial duration series either; as in the case of Tarbela, the random component was 100% for Mangla as well (Table 2).

Table 2. Mangla Catchment: Time Series Components as Percentage of Total Variance for Hydrometeorological Data (40-Years Data).

	Trend	Periodicities	Auto-regression	Residual
Temperature (T_{MAX})				
Kotli	0	94	0	5
Muzafferabad	0	94	0	5
Garhi Doputta	0	95	0	4
Temperature (T_{MIN})				
Kotli	0	96	0	3
Muzafferabad	0	97	0	2
Garhi Doputta	0	95	1	3
Precipitation				
Kotli	0	66	0	33
Muzafferabad	0	57	0	42
Garhi Doputta	0	48	0	51
Streamflow				
Mangla Inflows	0	81	5	12
Partial Duration Series				
Monsoon Component	0	0	0	100

Figure 9. Ten-Daily Inflow Hydro-graphs for Mangla Reservoir.



Stream flows: Indus, Jhelum, and Chenab

The three western rivers, the Indus, Jhelum and Chenab, are important to Pakistan since they provide major portion of irrigation water to the Indus Basin Irrigation System (IBIS). The gauging stations for observing discharge rates were set up on these rivers in 1922-23. Therefore, longer streamflow series (over 75 years) are available for analysis. The results of the analysis for monthly streamflows for the Indus, Jhelum and Chenab rivers at Kalabagh, Mangla and Marala, show the presence of a dominant periodic component — the annual temperature cycle, of course, being the basis for it (Table 3). The Indus and Chenab flow data show higher periodic component than that for the Jhelum River. Both the Indus and Chenab rivers rise at very high elevations (over 4500 m.a.s.l) and have a much bigger snow/glacial-melt component relative to the Jhelum River (Kashmir Valley). The Chenab catchment, however, also witnesses the monsoon activity and as such, the Chenab River flow series has a higher random component than the Indus.

Table 3. Long-Term River Inflows: Time Series Components as Percentage of Total Variance for Hydrological Data (75-Years Data).

	Trend	Periodicities	Auto-regression	Residual
Streamflow				
Indus River	0	94	1	3
Jhelum River	0	82	4	12
Chenab River	0	90	1	7

The 75-year time series of the Indus River streamflow records for the Kalabagh Rim Station used in this analysis, do not seem to be influenced by the operation of Tarbela Reservoir located approximately 200 Km upstream. The break-up of the time series into pre-Tarbela (1923-75) and post-Tarbela (1976-97) did not indicate any significant difference in the relative proportions of the four components of total variance in time series i.e., trend, periodicity, autoregression and random residual. This may be explained on the basis that, firstly, the live storage capacity of Tarbela is only 15% (presently less than 13%) of the mean annual runoff of the Indus River at Tarbela; and secondly, this storage is utilized within the same year. There is not any carry-over of one year's storage to the following year and the annual inflows and outflows from Tarbela are almost equal.

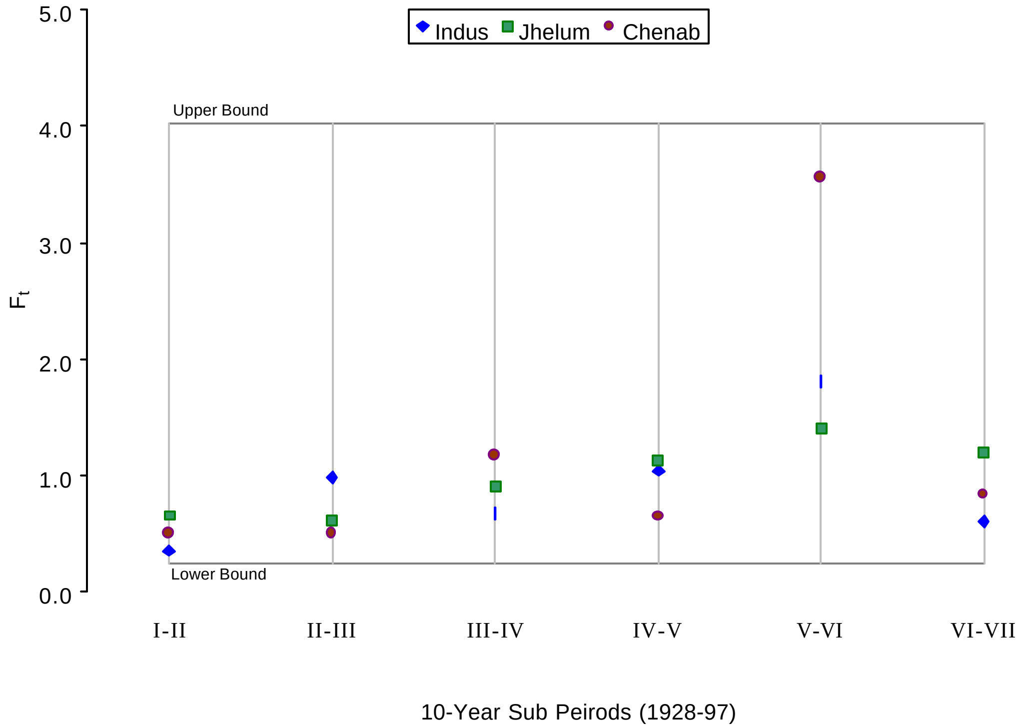
As described earlier, the flow series for the three major rivers, Indus, Jhelum and Chenab, were split into sub-sets, each of 10-year period duration. These successive, non-overlapping sub-sets of flow data were tested for stability of variance and mean by using the F-test and the t-test, respectively. The series were initially divided into the following sub-periods: (I) 1928 to 1937; (II) 1938 to 1947; (III) 1948 to 1957; (IV) 1958 to 1967; (V) 1968 to 1977; (VI) 1978 to 1987; and (VII) 1988 to 1997.

The results indicate that both the variance and the mean were stable, at a 5% level of significance, during the 70-year period from 1928 to 1997 for all the three major rivers in Pakistan (Figure 10). The Indus River flow records are, however, an exception. In case of the Indus flow series, although the variance is stable, the means of the series for sub-periods I and II (1928-47), IV and V (1958-77), and VI and VII (1978-97), apparently are not — the test statistics (T_t) falling in the critical region. A graphical display of the time series along with the means for different sub-periods (Figure 11), however, shows that the mean for sub-period VII (1988-97) is, apparently the only one not having a comparable mean value amongst the means of any of the preceding sub-periods suggesting a step-trend in the time series.

To determine the singularity of the mean for sub-period VII, it was compared with all sub-periods of 10-year duration prior to 1987 by shifting the splitting point between sub-periods. The sub-periods 1933-42, 1943-52 and 1953-62 had mean values comparable to the one for sub-period 1988-97. Thus, the streamflows in the Indus River during the period from 1988 to 1997, although representing a wet sequence, are also a part of the long-term stochastic hydrologic phenomena. Similarly, by breaking and analyzing the time series into two non-overlapping pairs of 30-year each, the F-test and the t-test indicate the variances and means of the different sub-periods to be stable at 5% level of significance.

These variations in the Indus flows may also be looked into from another perspective — the glacier movements. In the last 100 years, 26 sudden, rapid advances have been reported involving 17 glaciers and at least 12 other glaciers have features associated with surge behavior (Hewitt, 1969 & 1998). We tried to establish some kind of link between these reported surges and variations in the Indus flows. Most of these glacier surges occurred in the time period from 1928 to 1937 and from 1988 to 1997. However, there were no distinct patterns found. The reason is that UIB is not an intensively monitored region like the Alaska-Yukon ranges, Svalbard, or Iceland. The glacier advances and retreats are underreported. Furthermore, glacier response to weather and climate and their impacts on river runoff is a very complex phenomenon and could only be dealt with effectively in an independent study on the subject.

Figure 10. Results of F-test and t-test on Flow Series for Indus, Jhelum and Chenab Rivers.



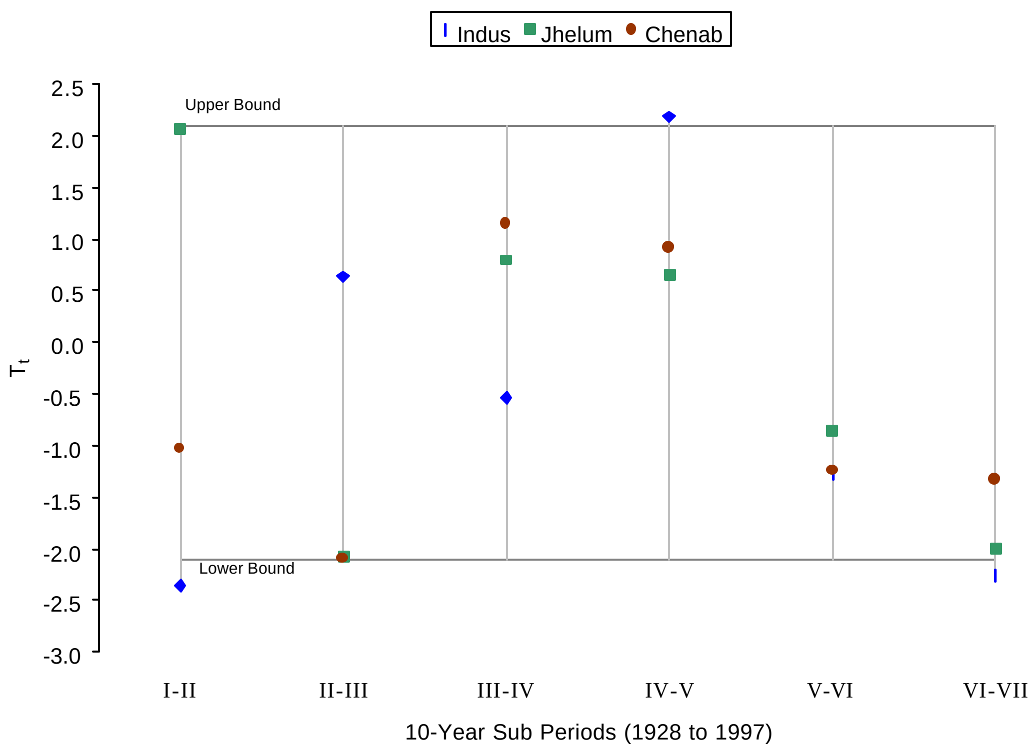
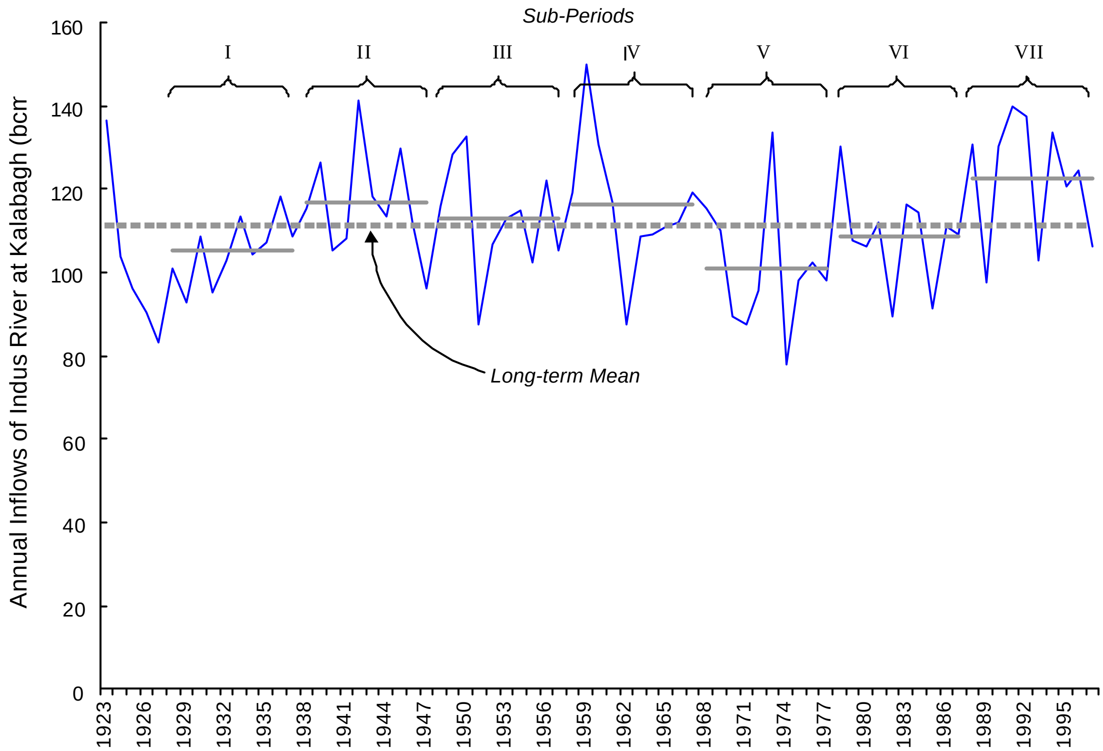


Figure 11. Annual Indus River Inflows at Kalabagh (Rim Station) and Annual Precipitation at a PMD Weather Station (Skardu).



DISCUSSION ON RESULTS

The results of the time series analysis may be summarized as follows:

1. Annual cycle dominated all the temperature series i.e., large periodic components, and none of other three components were significant. The mean monthly minimum temperature series (T_{MIN}) for one of the meteorological stations in Tarbela catchment did indicate the presence of a statistically significant trend. However, there were no patterns.
2. For precipitation, the periodic component and a dominant random component explained the variance in time series.
3. In case of stream-flow data, again the periodic component, as a consequence of the annual temperature cycle, dominated all the streamflow time series.
4. The analysis of all meteorological and hydrological time series did not indicate any pattern of trends likely to be caused by 'greenhouse warming' in the Upper Indus Basin.
5. The comparison of high-altitude temperature data with the valley-bottom data, although for a very short time period (5 years), indicated that a very high degree of correlation

> exists between the two data sets. Therefore, the results of the time series analysis for valley-bottom data may be extended, with reservations of course on the complex glacier behavior, to the hydrometeorological data at higher elevations and close to the permanent ice cover of the Upper Indus Basin.

Time series analysis and spectral analysis can show the relative magnitude of apparent components such trends, jumps, periodicities and autoregression within climate-related time series. Any such components suggested by statistical analysis must have a valid physical explanation. There are two problems: signals must first be detected and then they must be linked by meaningful, i.e., causal relationships. Sometimes the signal itself is self-evident, for example, the seasons of the year; sometimes it is very faint, buried in noise and hard to detect, like that of the luni-solar and solar cycles in air temperature records. Sometimes pattern seems clear to us but we are not sure of its mechanism, such as the 11-year sunspot cycle (Klemes, 1998). Another limitation in time series analysis may be that the effects of instrumentation and changes in observational/computational methods may be similar to those caused by climatic change. The apparent components of a time series may also change with time; what appears to be a trend now, may turn out to be part of a periodicity when looked at over a longer time span.

In this study, no time series components were found that would be compatible with a climatic change induced by the 'greenhouse effect'. Trends in time series are generally presented as evidence of climatic change – we have demonstrated that it has not been detected in the hydrometeorological time series pertaining to the UIB. This does not necessarily mean that such a change is not occurring; this could be because the sample size is small, the data are not sensitive enough (or contain errors) or, as discussed earlier, time series analysis techniques are not yet good enough to tackle the complex climate-related issues. Another reason, and which may be unique to the Upper Indus Basin, is that since climate has sufficient inertia, the glaciers of this region may be buffering it against climate change.

The 'Ice' Factor

In regions with surging glaciers, of which Karakoram and Himalayas are one, surges complicate the normally sensitive relations between glaciers and climate. Surges tend to recur in cycles peculiar to each glacier and are out of phase with the general patterns of glacier advance and retreat. The UIB glaciers lie between 3000 and 7500 m above sea level. They lie in subtropical latitudes similar to examples in Andean Argentina and have an extreme continental location comparable to the nearby Pamir surging glaciers. However, there is heavy snowfall and year-round avalanching at high elevations, which promotes rates of flow and throughput of ice comparable to more humid conditions and maritime glacier (Mercer, 1975; ed. Hewitt, 1990; Hewitt et al, 1989).

Furthermore, approximately 25% to 90% of the ablation zones of Karakoram glaciers are covered with variable amounts of ablation moraine (Wake, 1985). This debris cover largely controls the rates of ice melt. The critical thickness of debris cover for acceleration and retardation of ablation is about 3 cm and the most effective thickness about 1 cm (Khan, 1989). This means that the debris depth of less than 3 cm enhances ablation of the glacier. In light of the foregoing, it is quite evident that, even if a change in climate might be taking place, because of the masking effects of glaciers, we may not be able to detect it.

If the rate of de-glaciation is high, as indicated by the ICSI studies on east-Himalayan glaciers and the third assessment report by IPCC (Shanghai Draft, 2001), then the flows into the rivers would increase. However, whether the increase in annual runoff would be sufficient to get noticed in the overall volume, is the main question. In our analysis, the river flow series for the Indus River which has a dominant glacial melt component, did not, however, indicate the presence of a trend component both in the Indus River flows at Tarbela (1962 to 1998) and Kalabagh (1923 to 1997). Glaciers act as large and slow reservoirs that smooth out the inter-annual variations in precipitation resulting in a relatively stable flood in the Indus. Without the glaciers, the high altitude precipitation would still freeze in winter and be released in summer – what would be lost is, a large part of the over-year balancing of the ice-pack.

Concluding Remarks

The term "climate change" has a negative connotation these days. It is something that must be minimized. The results of this particular study, therefore, may put us in a politically 'unfavorable' corner of the climate change debate. Considerable resources are being spent to identify the effects of a possible climatic change in different regions of the world. However, the results of these impact assessment studies, using a number of sophisticated General Circulation Model (GCMs), have found very large variations in global climate sensitivity. Notwithstanding the uncertainties in the projected climatic change, there is a great deal of certainty in this predictive information.

Climate questions are hard to entangle since landscape and other atmosphere–surface interactions involve complex, non-linear feedbacks, which makes it very hard to accurately predict future climate. Therefore, there is a need to balance the amount of attention given to impact studies by focusing on search for present–day evidence of climatic change. There are, however, certain limitations regarding the suitability of the statistical techniques and the number of data needed to identify changes in climate. Furthermore, as we have seen in a particular time series in Tarbela catchment, it may be difficult to differentiate between changes brought in a climate related time series due to instrumentation errors and 'greenhouse' effect. Nevertheless, time series analysis is one technique, which can help in the search of evidence of climatic change by defining the relative magnitude of trends, periodicities and autoregression within data sets and provide some insight into questions on climate change. Any components indicated by such statistical analysis must then be examined for their physical causes.

REFERENCES

Beran, M.; N. Arnell. 1995. *Climate Change and Hydrological Disasters. Hydrology of Disasters*. V.P. Singh, ed. Dordecht, The Netherlands: Kluwer.

Dahmen, E. R., M. J. Hall. 1990. *Screening of Hydrological Data*. ILRI Publication No. 49, Wageningen, The Netherlands.

Hewitt, K. 1969. *Glacier Surges in the Karakoram Himalaya (Central Asia)*, Canadian Journal of Earth Sciences, 6, 1, 009B1, 018.

Hewitt, K., C. P. Wake, G. J. Young, C. David. 1989. Hydrological Investigations at Biafo Glacier, Karakoram Himalaya: An Important Source of Water for the Indus River, Ann. Glaciol., 13, 103B108.

Hewitt, K. (Ed.). 1990. *Overall Report: Pakistan Snow and Ice Hydrology Project*, Upper Indus Basin SIHP, Cold Regions Research Center, Wilfred Laurier University, 179p.

Hewitt, K. 1998. *Recent Surges in the Karakoram Himalaya, South Central Asia*. http://www.agu.org/eos_elec/97016e.html, American Geophysical Union.

Hodges, G. 2000. The New Cold War – Stalking Arctic Climate Change by Submarine. National Geographic, Volume 97 No.3.

IPCC. 1997. *An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report*. J. T. Houghton et al (Editors), Technical Paper II, Intergovernmental Panel on Climate Change.

IPCC 2001. *Summary for Policymakers*. IPCC WGI Third Assessment Report, Shanghai Draft.

Khan, A. R. 1999. An Analysis of Surface Water Resources and Water Delivery Systems In the Indus Basin. IWMI Report R-93, Lahore, Pakistan.

Khan, M. I. 1989. Ablation on Barpu Glacier. Karakoram, Himalaya, Pakistan: A Study of Melt Processes on a Faceted, Debris-Covered Ice Surface, Wilfrid Laurier University, Ontario, Canada.

Kite, G. W.; J. K. Waititu. 1981. Effects of Changing Precipitation and Evaporation on Nzoia River Flows and Lake Victoria Levels. A Contribution to the World Climate Program. Nairobi.

Kite, G. W. 1989. *Use of Time Series to Detect Climatic Change*. Journal of Hydrology, 111 pp. 259-279.

Kite, G. W. 1993. *Analysing Hydrometeorological Time Series for Evidence of Climatic Change*. Nordic Hydrology, 24 pp. 135-150, National Hydrology Research Institute, Saskatoon, Canada.

Klemes, V. 1998. *Geophysical Time Series and Climatic Change*. Time and The River. G. W. Kite (Editor). Water Resources Publications, USA.

Kundzewicz, Z. W.; Z. Kaczmarek. 2000. *Coping with Hydrological Extremes*. Water International, Vol. 25 (1): 66-75, International Water Resources Association.

Linacre, E. 1992. Climate Data And Resources: A reference And Guide. Routledge, London/New York.

Marchand, D.; M. Sanderson; D. Howe; C. Albauch. 1988. *Climate Change and Great Lake Levels — The impact on Shipping*. Climate Change, 12(2): 107-134.

Maunder, W. J. 1994. *Dictionary of Global Climatic Change*. 2nd Revised Edition. UCL press, London, 257 pp.

Mercer, J. H. 1975. *Glaciers of the Karakoram*, Mountain Glaciers of the Northern Hemisphere 1, Chapter 3, 371B40, edited by O. W. Field.

Nash, J. M. 1999. The Case for a Shifting Climate is Heating Up. Time. August 9.

PSIHP. 1992. *Pakistan Snow and Ice Hydrology Project*, Project Direction and Review Report, BCHIL-WAPDA.

Tarar, R. N. 1982. *Water Resources Investigation in Pakistan with the help of LANDSAT Imagery – Snow Surveys 1975-1978*. Hydrological Aspects of Alpine and High Mountain Areas. Proceedings of the Exeter Symposium, IAHS Publication No.138, 177-190.

Tate, E. L., F. A. K. Farquharson. 2000. *Simulating Reservoir Management Under The Threat of Sedimentation: The Case of Tarbela Dam on the River Indus*. Water Resources Management, No.3 14: 191-208, Kluwer Academic Publishers. The Netherlands.

UK Met. Office. 1999. *Climate Change and its Impact.* Hadley Centre for Climate Prediction and Research, The Met. Office, Bracknell, UK.

Wake, C. 1985. Preliminary Work Towards a Geographic Information Systems Approach to Predicting Runoff from the Upper Indus Basin. PSIHP, Annual Report, 77-89.

Wigley, T. M. L.; P. D. Jones. 1985. *Influences of Precipitation and Direct CO_2 Effects on Streamflow.* Nature, Vol. 314, pp. 149-152.

WMO. 1966. *Climate Change*. J. M. Mitchel (Editor), WMO No. 195, TP. 100, World Meteorological Organization, Geneva.

ANNEXURES

Annex 1. Time Series Hydro-meteorological Data from the Upper Indus Basin.

No.	Type of Time Series Data	Time Step	Length[2] of Time Series	Data Acquired from
1.	*Tarbela Catchment*			
	Maximum Temperature (T_{MAX})	(Mean) Monthly	30	PMD
	Minimum Temperature (T_{MIN})	(Mean) Monthly	30	PMD
	Precipitation (Precip)	Monthly (Totals)	30	PMD
	Tarbela Inflows	Monthly	30	WAPDA
	Tarbela Inflows, Snow-melt Component (May-June)	Yearly	30	
	Tarbela Inflows, Glacial-melt Component (July-August)	Yearly	30	
	High-Altitude Data (T_{MAX}, T_{MIN}, Precip)	Monthly	5	WAPDA
2.	*Mangla Catchment*			
	Maximum Temperature (T_{MAX})	(Mean) Monthly	40	PMD
	Minimum Temperature (T_{MIN})	(Mean) Monthly	40	PMD
	Precipitation (Precip)	Monthly (Totals)	40	PMD
	Mangla Inflows	Monthly	40	WAPDA
	Mangla Inflows, Monsoon Component (July-September)	Yearly	40	
3.	*Long-term River Inflows*			
	Indus River at Kalabagh	Monthly/Annual	75	WAPDA
	Jhelum River at Mangla	Monthly/Annual	75	WAPDA
	Chenab River at Marala	Monthly/Annual	75	WAPDA

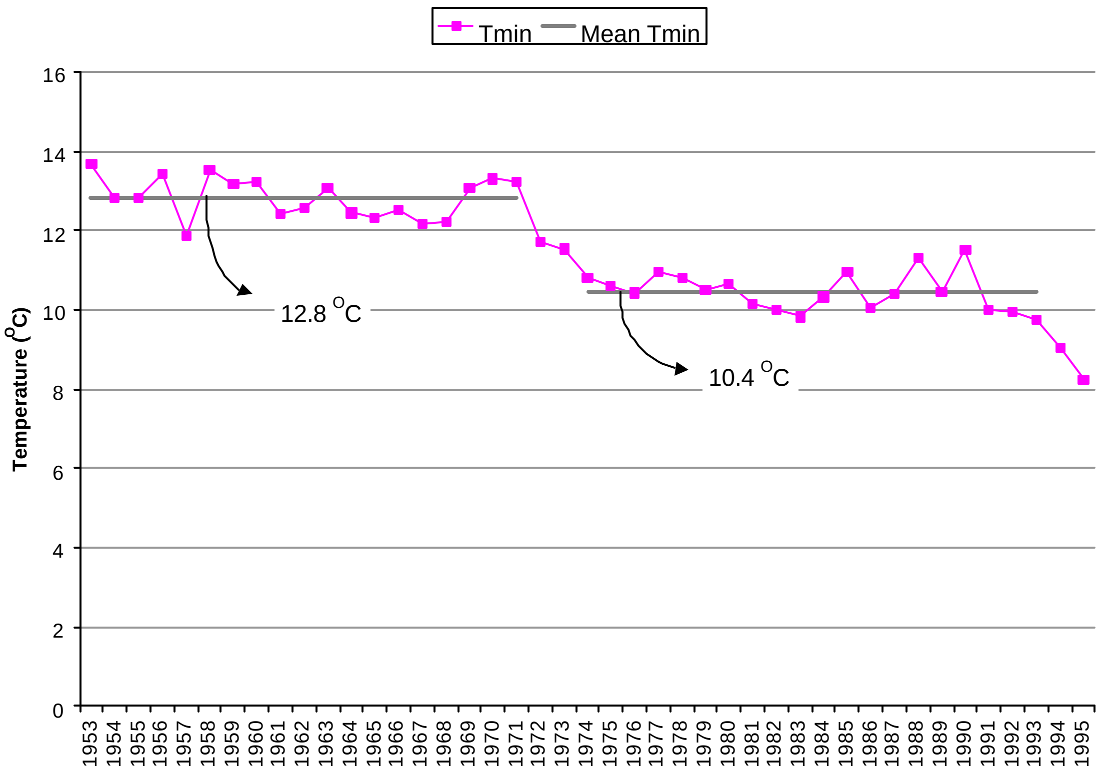
[2] Uninterrupted length of time series i.e., without any gaps in the data of six months or more.

Annex 2. Names and Coordinates of Hydro-meteorological Stations in the Upper Indus Basin.

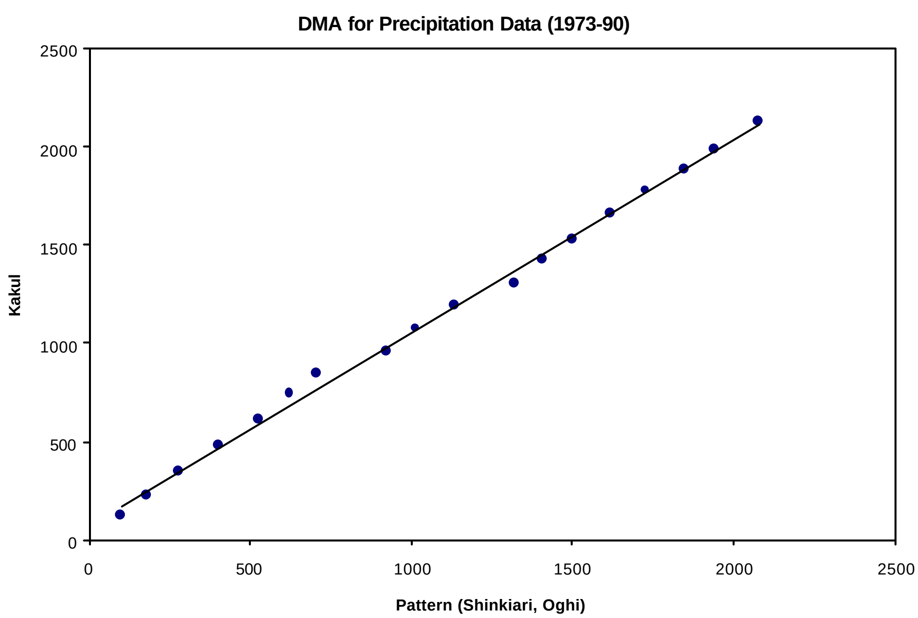
Name	Latitude	Longitude	Elevation (m.a.s.l)
Skardu	35.3	75.7	2210
Bunji	35.7	74.6	1372
Astore	35.4	74.9	2169
Gupis	36.2	73.7	2157
Gilgit	35.9	74.3	1460
Chillas	35.4	74.1	1250
Kakul	34.2	73.3	1309
Shinkiari	34.5	73.2	991
Oghi	34.5	73.0	1128
Yasin	36.3	73.3	3353
Hushe	35.4	76.4	3010
Rama	35.4	74.8	3140
Tarbela Dam	34.1	72.7	610
Muzafferabad	34.4	73.5	702
Garhi Doputta	34.2	73.6	813
Kotli	33.5	73.9	615
Mangla Dam	33.1	73.6	282

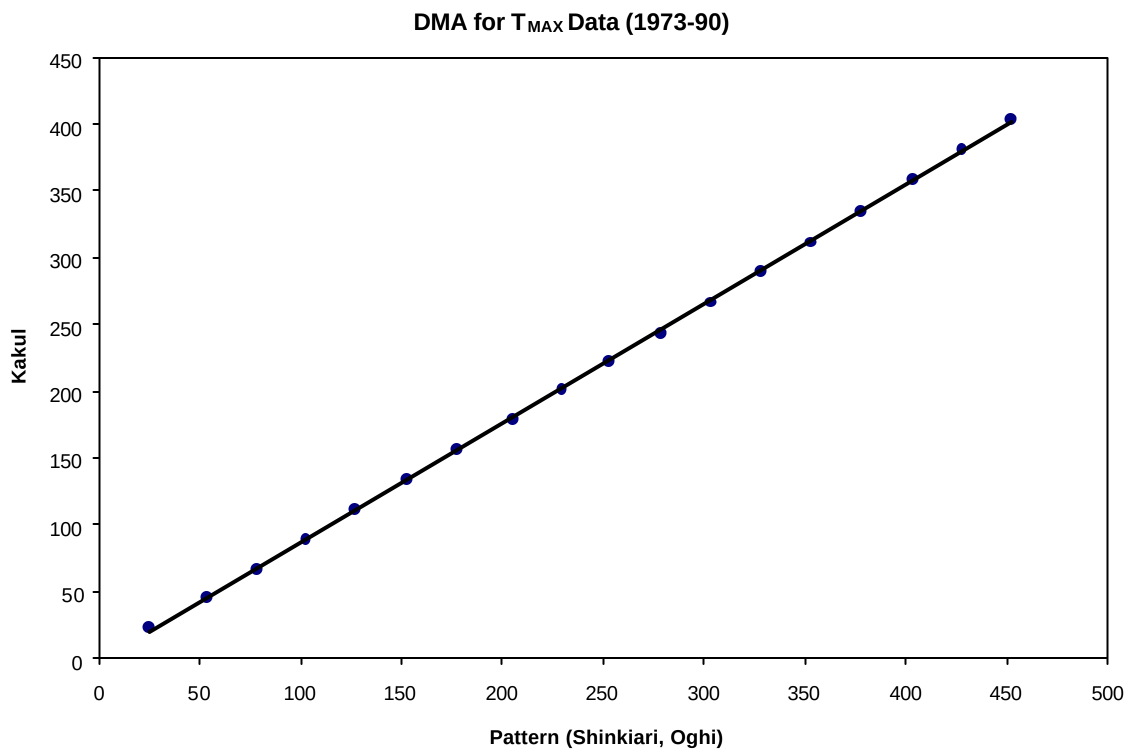
Annex 3. Meteorological Time Series for Kakul, Shikiari and Oghi Weather Stations.

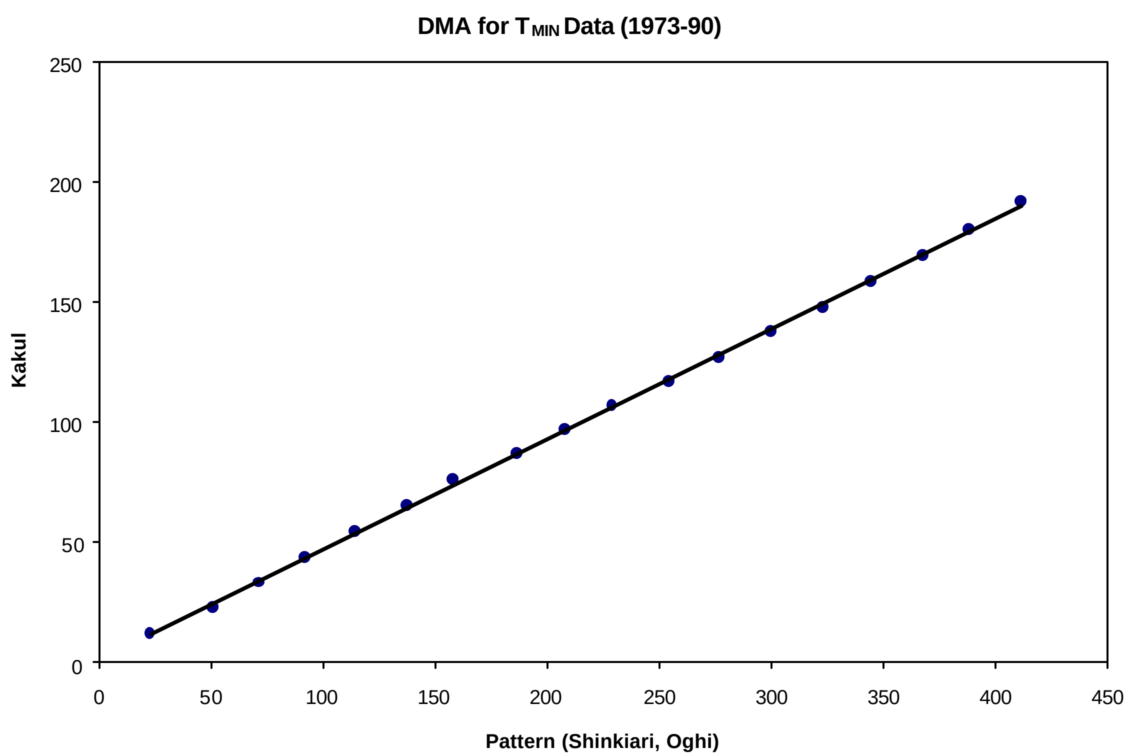
(a) Plot of Kakul T_{MIN} series for the entire length of available record.



(b) Double Mass Analysis (DMA): Kakul Precipitation, T_{MAX} and T_{MIN} Series with Pattern (corresponding data from Shinkiari and Oghi weather stations).




DMA for T_{MAX} Data (1973-90)
Kakul
Pattern (Shinkiari, Oghi)
0
50
100
150
200
250
300
350
400
450
500


DMA for T_{MIN} Data (1973-90)
Kakul
Pattern (Shinkiari, Oghi)
0
50
100
150
200
250
300
350
400
450

IWMI Pakistan
Regional Office
12km
Multan Road
Chowk Thokar Niaz Baig
Lahore 53700
Pakistan

Headquarters
127, Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Mailing Address
P O Box 2075
Colombo
Sri Lanka

Tel.
94-1-867404, 869080

Fax
94-1-866854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

IWMI
International
Water Management
Institute

FUTURE HARVEST
IWMI is a Future Harvest Center
Supported by the CGIAR