Pakistan-U.S. Science and Technology Cooperation Program
Final Report Form

Reports should be prepared jointly by the Pakistani and U.S. principal investigators and should cover all project-related activities carried out during the entire period on both sides. Please expand the boxes below to accommodate all the information you need to include.

Project Title: Upper Indus River-flow reconstruction using tree-rings: Implications for agriculture and hydroelectricity.	
Pakistani Principal Investigator: Dr Moinuddin Ahmed	**U.S. Principal Investigator:** Dr Edward Cook
Reporting Period: 1 April 2008 – 31 March 2011 (3 Years)	

Summary of Activities During Reporting Period: Please describe what has been accomplished under your grant during the reporting period, outlining the activities that were undertaken and specifically discussing achievements in relation to the milestones or targets set in the original work plan. For project-related events such as workshops, conferences, exchange visits, etc., please be sure to include exact dates and locations.

Introduction:

The concept for this project arose after discussions about successful studies using tree-rings to reconstruct past flow-rates of the Colorado River in order to assist with water management decisions (an interested reader should visit http://treeflow.info/). Our intention was to initiate similar studies in Pakistan based on the short discharge records of the Upper Indus Basin (UIB). The lack of any prior studies in the region meant the scope of our objectives needed to be both realistic and cautious. Consequently, our three main objectives for this project were:

1. The development of a network of tree-ring chronologies from major catchments within the UIB.
2. The reconstruction of Indus River flow derived from the network of tree-ring chronologies.
3. The dissemination of the key findings to relevant agencies/groups through workshops and publications (both local and international journals).

This report covers the full duration of the research program and we are pleased to be able to report that we have been able to accomplish all of the main objectives.

Specific activities/outcomes:

1. Tree-ring network development.

The sampling of forests in the Upper Indus Basin (UIB) was the early focus of our program with the emphasis later being directed towards completing the processing and compiling of the tree-ring data into site chronologies. Even though there was a progressive change from sampling to analysis, five new sites were added in the last year bringing the total to 39 tree-ring sites being developed (details in **Figure 1** and **Table 1**). Most of the network was used to investigate the strength of any climate signals and the results published (Ahmed et al., 2011). Of the 39, 24 of the sites are new and due solely to this project, while the remaining 15 (all *Juniperus excelsa*) had been developed by Esper et al. (1995) over a decade ago. Several species had trees attaining ages of around 700 years (*Cedrus deodara*, *Pinus gerardiana*, *P. wallichiana* and *Picea smithiana*, but the juniper was clearly the oldest with some trees greater than 1,000 years of age.

Ahmed et al. (2011) found that correlations between the site chronologies declined with increasing separation distance. This was consistently seen both between sites of the same species and between sites composed of different species. It also led to a situation where a much stronger correlation was sometimes found between two different species growing at the same site than between sites of the same species, but separated by as little as 0.5 km. These findings support the practice of developing a dense multi-species tree-ring network for better spatial and temporal coverage in complex terrain, which is exactly the approach taken in this study. The best prospect for this in the Karakoram appears to be with *Cedrus deodara* and *Pinus gerardiana* and is consistent with reported studies from neighboring India.

The heterogeneous nature of the tree-ring network with respect to distance between chronologies is consistent with the findings of Archer and Blenkinsop (2010) who found high heterogeneity between climate station data in the Karakoram. Such results again highlight the obvious strong elevational and orographic gradients present in this mountainous region (where some elevations are over 7,000 m). However, in the case of Archer and Blenkinsop (2010), they argued that the climate station data heterogeneity found by them would make a successful reconstruction of hydroclimate over the Karakoram unlikely. As we will show, this interpretation is unduly pessimistic if a sufficiently dense mult-species tree-ring network is developed.

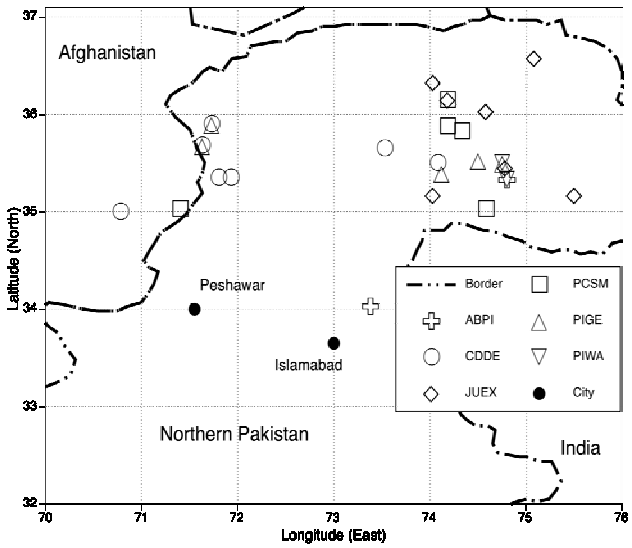

Figure 1. Map of northern Pakistan showing the tree-ring sites. Species codes are *Abies pindrow* (ABPI), *Cedrus deodara* (CDDE), *Juniperus excelsa* (JUEX), *Picea smithiana* (PCSM), *Pinus gerardiana* (PIGE), and *P. wallichiana* (PIWA). See **Table 1** for further details.

Table 1. Summary of the 39 tree-ring chronologies from northern Pakistan (modified from Ahmed et al. 2011).

	Site Code	Species	Start	End	Latitude		Longitude		Site Name
1	ASTABP	ABPI	1505	2005	35	20	74	48	Astore-Rama
2	ASTPIW	PIWA	1317	2005	35	20	74	48	Astore-Rama
3	BABJUE	JUEX	1646	2007	35	10	74	2	Babusar (Daimer District)
4	BAG1JU	JUEX	1593	1993	36	2	74	35	Bagrot site 1 Esper
5	BAG2JU	JUEX	1369	1993	36	2	74	35	Bagrot site 2 Esper
6	BAG3JU	JUEX	1679	1993	36	2	74	35	Bagrot site 3 Esper
7	BAG4JU	JUEX	1438	1993	36	2	74	35	Bagrot site 4 Esper
8	BAG5JU	JUEX	1240	1993	36	2	74	35	Bagrot site 5 Esper
9	BUKCDD	CDDE	1411	2006	35	41	71	38	Kalash Valley, Bamburet
10	BUKPIG	PIGE	1403	2006	35	41	71	38	Kalash Valley, Bamburet
11	CGPCDD	CDDE	1537	2006	35	54	71	44	Chitral-Gol National Park
12	CGPPIG	PIGE	1260	2006	35	54	71	44	Chitral-Gol National Park
13	CHEPCS	PCSM	1394	2005	35	2	74	35	Chera (Gilgit)
14	CHP1JU	JUEX	1640	1993	36	20	74	2	Chaprot site 1 Esper
15	CHP2JU	JUEX	1032	1993	36	20	74	2	Chaprot site 2 Esper
16	CHP3JU	JUEX	1141	1993	36	20	74	2	Chaprot site 3 Esper
17	DskJUE	JUEX	1290	2007	35	27	74	47	Dashkin
18	GOAPIG	PIGE	1738	2007	35	32	74	30	Gohar Abad (Diamer)
19	ISBCDD	CDDE	1511	2006	35	21	71	56	Islam Baiky
20	JOTPIG	PIGE	1559	2007	35	24	74	7	Joti (Chilas)
21	JUTPCS	PCSM	1523	2008	35	50	74	20	Jutial (Gilgit)
22	KARPCS	PCSM	1574	2008	35	53	74	11	Kargah (Gilgit)
23	MOR1JU	JUEX	476	1990	36	35	75	5	Morkhum Site 1 Esper
24	MOR2JU	JUEX	968	1990	36	35	75	5	Morkhum Site 2 Esper
25	MOR3JU	JUEX	554	1990	36	35	75	5	Morkhum Site 3 Esper
26	MOR4JU	JUEX	1069	1990	36	35	75	5	Morkhum Site 4 Esper
27	MSFCDD	CDDE	1296	2007	35	30	74	5	Mushfar (Gilgit)
28	MUAABP	ABPI	1678	2005	34	2	73	23	Murree-Ayubia

28	MUAABP	ABPI	1678	2005	34	2	73	23	Muree-Ayubia
29	MUSPIG	PIGE	1362	2007	35	30	74	45	Mushkin
30	MUSPIW	PIWA	1730	2007	35	30	74	45	Mushkin
31	NLTJUE	JUEX	1523	2009	36	9	74	11	Naltar (Gilgit)
32	NLTPCS	PCSM	1387	2005	36	9	74	11	Naltar (Gilgit)
33	SAT1JU	JUEX	1412	1993	35	10	75	30	Satpara site 1 Esper
34	SAT2JU	JUEX	736	1993	35	10	75	30	Satpara site 2 Esper
35	SAT3JU	JUEX	388	1993	35	10	75	30	Satpara site 3 Esper
36	SHEPCS	PCSM	1663	2006	35	2	71	32	Sheshan (Afghanistan)
37	TANCDD	CDDE	1661	2008	35	39	73	32	Tangir (Diamer)
38	TKACDD	CDDE	1569	2007	35	0	70	47	Tangi-Kamdesh (Afghan.)
39	ZACCDD	CDDE	1472	2005	35	21	71	48	Zairat (Chitral)

Note: Species codes are *Abies pindrow* (ABPI), *Cedrus deodara* (CDDE), *Juniperus excelsa* (JUEX), *Picea smithiana* (PCSM), *Pinus gerardiana* (PIGE) and *P. wallichiana* (PIWA).

2. Reconstruction of Indus River flow.

As the title of our project indicates, our goal has been the reconstruction of Upper Indus Basin (UIB) discharge from long tree-ring records. Here we demonstrate the feasibility of doing so through an example reconstruction of May-September discharge as measured at Partab Bridge (34°43'N, 74°38'E). The gauged flow data was kindly provided by David Archer (JBA Consulting Engineers and Scientists) and the Pakistan Water and Power Development Authority (WAPDA) from 1962 to 1996. It was subsequently updated from 1997 to 2008 by Connie Woodhouse (University of Arizona) using gauged data from three upstream station records. The Partab Bridge record represents the majority of the UIB runoff that flows into Tarbela Reservoir, a major hydroelectric power generation facility (Archer, 2003). It also provides canal irrigation water for approximately 50 percent of Pakistan's agricultural land. Archer (2003) showed that UIB runoff is a complex combination of summer and winter precipitation, seasonal snowmelt, and glacier melt water coming from a variety of sub-basin hydrological regimes. This would appear to make a skillful discharge reconstruction from tree rings difficult to produce, as argued by Archer and Blenkinsop (2010). Yet as we show here, the development of a dense multi-species network of tree-ring chronologies in northern Pakistan has enabled us to produce just that, a skillful reconstruction of May-September discharge for the UIB at Partab Bridge covering the period 1470-2008.

As described earlier in this Final Report, a total of 39 annual tree-ring chronologies have been developed by this project (Ahmed et al., 2011), including some from earlier tree-ring collections made by Moinuddin Ahmed (e.g. Ahmed, 1989) and Jan Esper (e.g. Esper et al., 1995). However, only those tree-ring chronologies that end no earlier than 2005 have been used here as candidate predictors for reconstruction (24 in all), with all of them being based on field collections made by this project. The need to restrict ourselves to using only these most recently developed tree-ring chronologies in Pakistan is because the Partab Bridge discharge record only covers the period 1962-2008, a very short period for both calibration and verification of the reconstruction we present below. A large number of long *Juniperus* chronologies collected in the 1990s by Jan Esper could not be updated in time by this project and have therefore been left out of the reconstruction. Updating those records in the future will be a very high priority if this research is continued as we hope.

The choice of the May-September reconstruction season was determined in part by the properties of the Indus River monthly flow data at Partab Bridge. The hydrograph is highly seasonal with 85% of the annual discharge coming during those months on average (**Figure 2A**). Thus, any useful reconstruction of UIB discharge needs to include these months. The rapid increase in discharge beginning in May reflects the contributions of seasonal snowmelt and glacier melt water during the warm-season months. These contributions are estimated to account for ~70% of the total annual UIB discharge (Immerzeel et al., 2009) and represent the highest contribution of melt water to total runoff of any major river system in the world (Immerzeel et al., 2010; Kaser et al., 2010). The May-September season also matches the warm-season period of tree growth in the Karakoram. However, because a significant proportion (~40%; Immerzeel et al., 2009) of UIB runoff derives from cold-season precipitation, tree growth there must also be dependent on antecedent wintertime precipitation if May-Septermber discharge is to be successfully reconstructed from tree rings. To this end, Ahmed et al. (2011) has demonstrated this necessary dependence between warm-season tree growth and cold-season precipitation in the

Karakoram. It is a commonly found association in such arid environments where soil moisture recharge needed for tree growth depends heavily on the relatively high effectiveness of cold-season precipitation, both in liquid and solid forms.

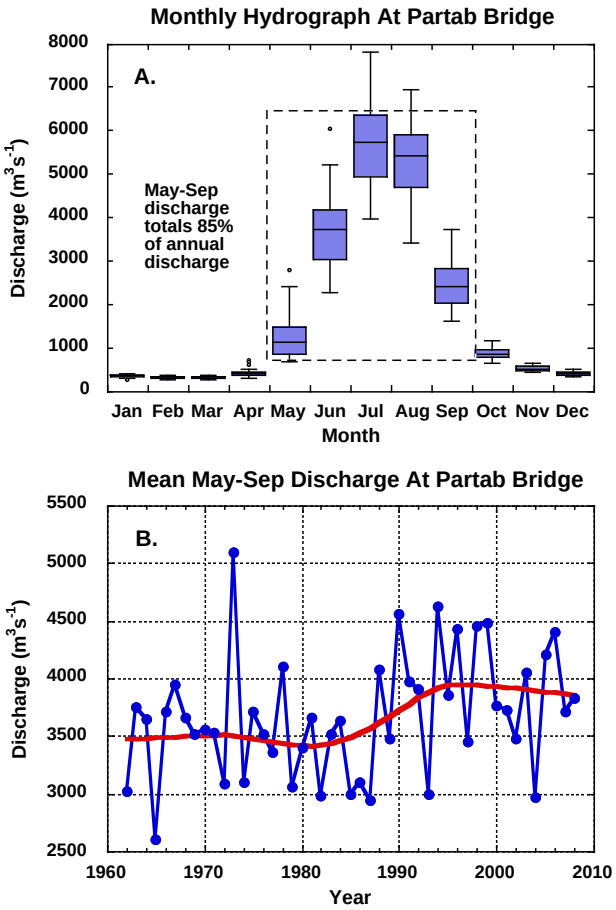

Figure 2. The monthly hydrograph of upper Indus River discharge at Partab Bridge for the period 1962-2008 (top) and the cumulative discharge series for the May-September months (bottom) that collectively account for about 85% of the annual discharge on average. The red curve is a 50% LOWESS robust smooth of the yearly discharge data. Data courtesy of David Archer and WAPDA. Updated from 1997 to 2008 by Connie Woodhouse using gauged data from three upstream stations.

Figure 2B shows the times series of May-September discharge that will be used for reconstruction. It has a median discharge of 3,658 m^3s^{-1}, but also the appearance of two flow regimes: 3,519 m^3s^{-1} from 1962-1987 and 3,902 m^3s^{-1} from 1988-2008, an ~11% increase from early to late. These two periods are reasonably consistent with periods of observed glacier recession in 1985-1995 and expansion in 1997-2002 in the Karakoram (Hewitt, 2005). So is either of these flow periods more characteristic of long-term UIB discharge or are they random decadal-scale fluctuations around the overall longer-term median? The UIB record at Partab Bridge is too short to tell, hence the value of producing a much longer May-September river flow reconstruction from tree rings.

The 24 tree-ring chronologies used here for UIB streamflow reconstruction begin anywhere from 1321 to 1738 and all end on or after 2005. However, after restricting ourselves to using only those more reliable portions of the tree-ring chronologies based on at least 5 samples per year, the range of starting years was reduced to 1452-1801. These truncated chronologies were then used in a principal components regression (PCR) program written specifically to reconstruct climate from tree rings (Cook et al., 1999, 2004, 2010). The calibration period chosen to develop the regression model was 1975-2004 (30 years), with the 1962-1974 period (13 years) withheld for validating the tree-ring estimates. Each chronology was evaluated for correlation with May-September discharge for both year *t* and *t+1* (a total of 48 candidate predictors) and only those chronologies that correlated significantly ($p<0.10$, 2-tailed) were retained as predictors in PCR. This screening procedure reduced the predictor set to 15 tree-ring variables. All but two were positively correlated with discharge in year *t*, a strongly consistent relationship between tree growth and runoff provided by the cold-season precipitation bridge that links them. The geographic distribution of chronologies used, size-coded by strength of correlation with discharge, is shown in **Figure 3**. It can be seen that the distribution of sites covers a large geographic portion of the upper Indus River Basin.

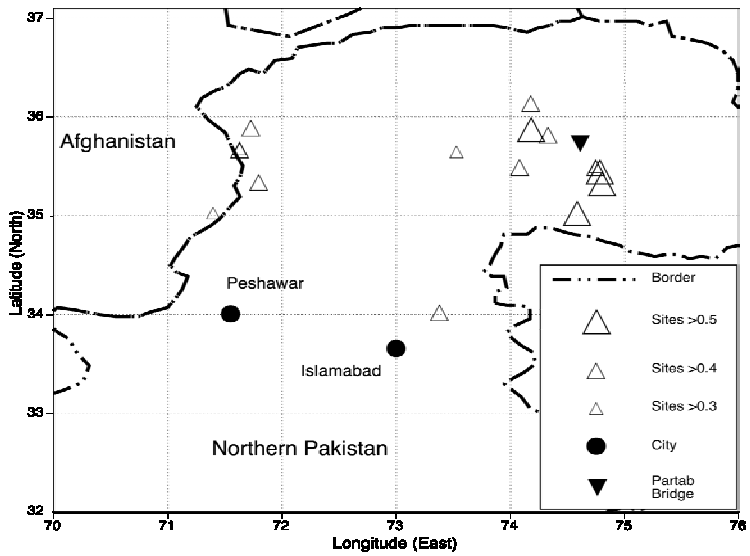

Figure 3. Map showing the locations of tree-ring chronologies used for reconstructing annual discharge at Partab Bridge (inverted solid triangle). The tree-ring locations (open triangles) are coded by the magnitude of the correlation with discharge.

The 15 screened tree-ring chronologies produced a total of 13 discharge reconstructions, each created by sequentially running PCR on decreasing subsets of chronologies having progressively earlier starting years. This produced a sequence of 13 progressively longer reconstructions, with each longer one based on fewer chronologies. The full 'nested' reconstruction was then created by appending each subset-reconstruction extension back in time to the beginning of pre-existing shorter reconstruction after appropriate scaling to recover lost variance due to regression. This reconstruction, along with the changing number of chronologies used, is shown in **Figure 4A**. It includes 2-tailed 90% prediction intervals around each reconstructed value Y_f of the general form (Seber and Lee, 2003; Olive, 2007)

$$\hat{Y}_f \pm t_{n-p,1-\alpha/2}\sqrt{MSE}\sqrt{(1+h_f)}$$

where t is the 1-α/2 t-statistic with n-p degrees of freedom, MSE is the mean square error of the fitted calibration model, and h_f is the "leverage" from the hat-matrix of predictors for each year calculated as

$$h_f = \boldsymbol{x}_f^T(\boldsymbol{X}^T\boldsymbol{X})^{-1}\boldsymbol{x}_f.$$

The primary difference here is that the usual regression-based Y_f estimates and the t-statistic have been replaced by the 50th (median) and 5th and 95th quantiles (90% 2-tailed limits) from a suite of pseudo-reconstructions produced after applying the maximum entropy bootstrap (MEBoot; Vinod, 2006, Vinod and López-de-Lacalle, 2009) to the predictor and predictand data prior to regression. This includes any pre-processing steps up to the final regression model (e.g., prewhitening and predictor variable screening; e.g., Cook et al., 1999). So, except for the selection of the original pool of candidate predictors, all steps in the reconstruction procedure have been accounted for by the MEBoot procedure used here.

The application of MEBoot to both the tree-ring predictors and steamflow predictand explicitly admits that there is some error on both sides of the regression model to consider, but these errors are either unknown or difficult to estimate. This makes the use of more formal "total least squares" methods (e.g. Hegerl et al., 2007) difficult to use because the error variances of the predictors and predictand are assumed known or at least estimated in an unbiased way. In lieu of estimating those error variances, we use MEBoot as a perturbation procedure that imparts a realistic level of random error to each series datum prior to modeling. The MEBoot algorithm preserves the overall shape (i.e., temporal form) of the data, thus allowing for direct estimates of uncertainty to be made from an ensemble of pseudo-reconstructions. It also preserves the persistence structure of any arbitrary

stochastic process, including non-stationary ones, which can be difficult or impossible to do with block bootstrapping. In so doing, MEBoot satisfies both the ergodic theorem and central limit theorem (Vinod and López-de-Lacalle, 2009). Collectively, this guarantees that the stochastic properties of the original time series used in regression are preserved in the ensemble of MEBoot pseudo-series. Thus, MEBoot adds a natural element of randomness to each pseudo-reconstruction, and this was done 300 times to produce empirical probability density functions for each year as a replacement for the *t*-distribution. This non-parametric part of the prediction intervals allows them to be both variable and asymmetric each year as dictated by the data. Coupling these quantile uncertainties with the MEBoot 95th quantile of *MSE* (fixed over each reconstruction 'nest') and the leverage estimates of the predictors (which also introduces variation to the intervals) completes the 90% prediction intervals shown in **Figure 4A**. The original parametric form of the prediction intervals equation has been preserved, but it now estimates those intervals in a significantly non-parametric, data-adaptive way. The leverage terms can also used to identify those years that fall outside the range of the calibration period data and thus behave as extrapolations (Weisberg, 2005). The prediction intervals for such values are far less reliable (Olive, 2007).

In terms of model calibration and verification, five statistics are shown in **Figure 4B-H** for each of the 14 nested reconstructions: CRSQ (coefficient of determination - a measure of explained variance in the calibration period), CVRE (the leave-one-out cross-validation estimate of CRSQ based on the reduction of error statistic – a more conservative measure of calibrated variance), VRSQ (verification period square of the Pearson correlation - a measure of explained variance in the verification period), VRE (reduction of error – a test to determine if the tree-ring estimates in the verification period have more skill than the calibration period mean of the actual data – VRE>0 means more skill), and VCE (coefficient of efficiency – a test to determine if the tree-ring estimates in the verification period have more skill than the verification period mean of the actual data – VCE>0 means more skill). See Cook et al. (1999) for detailed descriptions of CRSQ, VRSQ, VRE, and VCE and their interpretations. These statistics are shown in **Figures 4B-F** as medians with their 5th and 95th quantile limits as estimated from the 300-member ensemble of nested pseudo-reconstructions. Thus, the novel use of MEBoot here automatically provides a series of confidence intervals for these statistics as well, including those for VRE and VCE which cannot be estimated analytically. The 'nested' calibration and verification statistics in **Figures 4B-F** are all significant at the 2-tailed 90% significance level back to 1470, although the earliest segment based on only one tree-ring chronology is weaker. This is a remarkably strong result should lay to rest the concerns raised by Archer and Blenkinsop (2010) that tree rings may not be able to reliably reconstruct UIB discharge.

The May-September streamflow reconstruction at Partab Bridge has many important things to say about the long-term flow characteristics of the UIB. The long-term median flow estimated from the reconstruction from 1470 to 2008 (including the 2005-2008 instrumental-only data) is 3,575 m^3s^{-1}, which is below the 1962-2008 gauged median discharge of 3,658 m^3s^{-1} by 2.3%. It is also closer to the median for the early 1962-1987 period (3,519 m^3s^{-1}) than for the late 1988-2008 period (3,902 m^3s^{-1}). These differences are unlikely to be statistically significant, but they do suggest that 1988-2008 streamflow has been anomalously high nonetheless. This suggestion is further supported by the reconstruction - it is necessary to go back 318 years in the past to 1690 to find a comparable high-flow period as seen since 1988. Thus, the long-term reconstructed median should be used as the best estimate of expected May-September discharge at Partab Bridge.

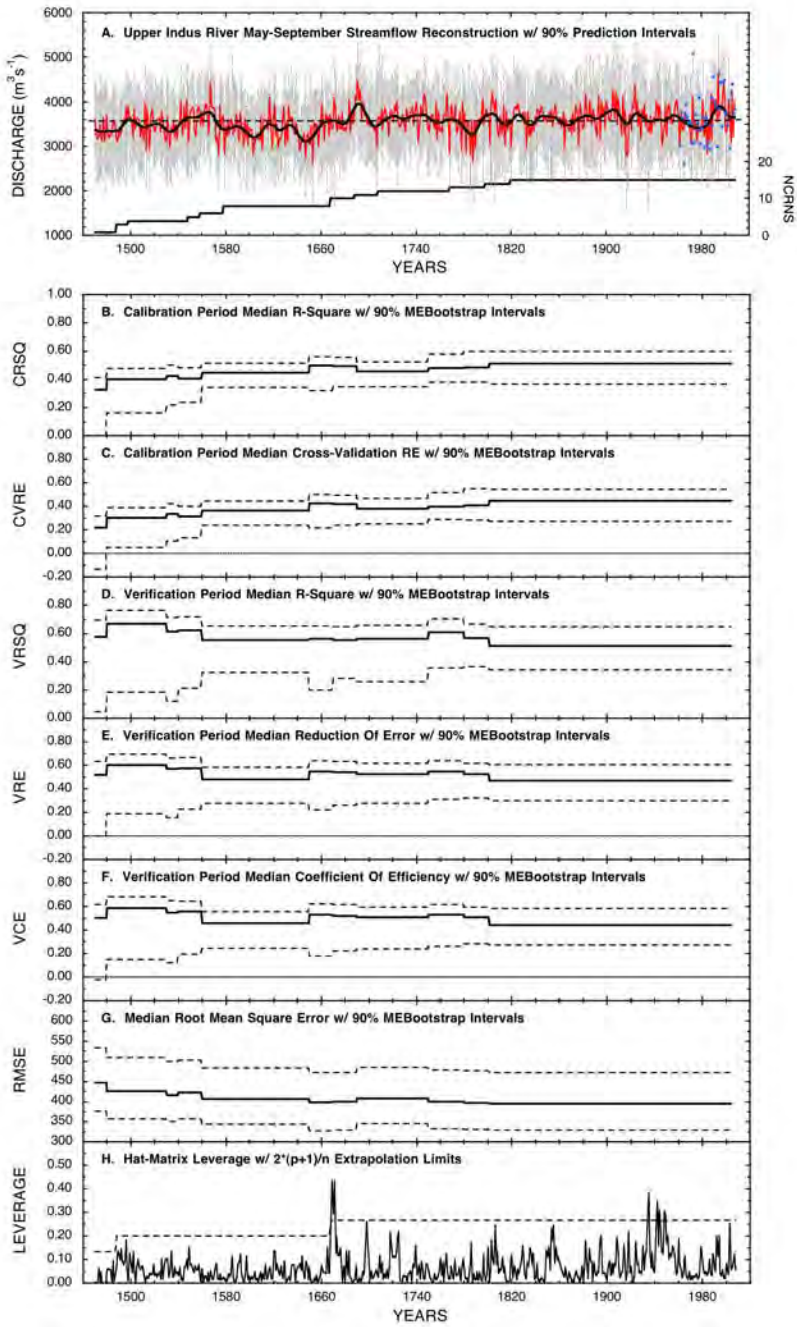

Figure 4. Tree-ring reconstruction of May-September Upper Indus Basin discharge at Partab Bridge. The top plot (**A**) shows the reconstruction itself covering the period 1470-2008. A 20-year spline (thick smooth curve) has been added to emphasize the multi-decadal fluctuations apparent in the yearly record. The short outermost plot with solid dots shows the actual annual discharge data for comparison. Plots **B** and **C** show the calibration (coefficient of determination - CRSQ) and cross-validation reduction of error (CVRE) based on a leave-one-out calibration procedure. Plots **D-F** show the verification statistics (VRSQ – square of the Pearson correlation – VRSQ, reduction of error – VRE, coefficient of efficiency – VCE) results for the various nested reconstruction models. VRE and VCE stand out as especially noteworthy because, except for the earliest reconstruction nest based on one chronology, they are all strongly positive, a clear indication of reconstruction skill. Plot **G** shows the changing root mean square error (RMSE) for the nested reconstruction and plot **H** the leverage estimates from the hat-matrix. These latter two terms are used in calculating the 90% prediction intervals shown in plot **A**.

Whether or not the current high flow period is due to more seasonal snowmelt from increased wintertime snow accumulation or warmer summertime temperatures resulting in more glacier meltwater cannot be answered definitively at this time. However, in terms of 'global warming', the Karakoram appears to be anomalous. Glaciers there are not retreating in any consistent way (Hewitt, 2005; Armstrong, 2010). In addition, summer temperatures over the UIB have recently decreased (Fowler and Archer, 2006; Shekhar et al., 2010), although Immerzeel et al. (2009) claim just the opposite. So it is doubtful that increased glacier meltwater is the cause of the recent flow increase. Instead, there is evidence for a recent increase in winter precipitation over the UIB (Fowler and Archer, 2006), which would add to summer runoff. Maps of correlations between May-September reconstructed flow and both December-April precipitation total and May-September temperature (**Figure 5**) support this argument. There is a stronger correlation between UIB discharge and cold-season precipitation than that with warm-season temperature. This suggests that seasonal snowfall/snowmelt is the more important contributor to observed variations in UIB discharge at this time.

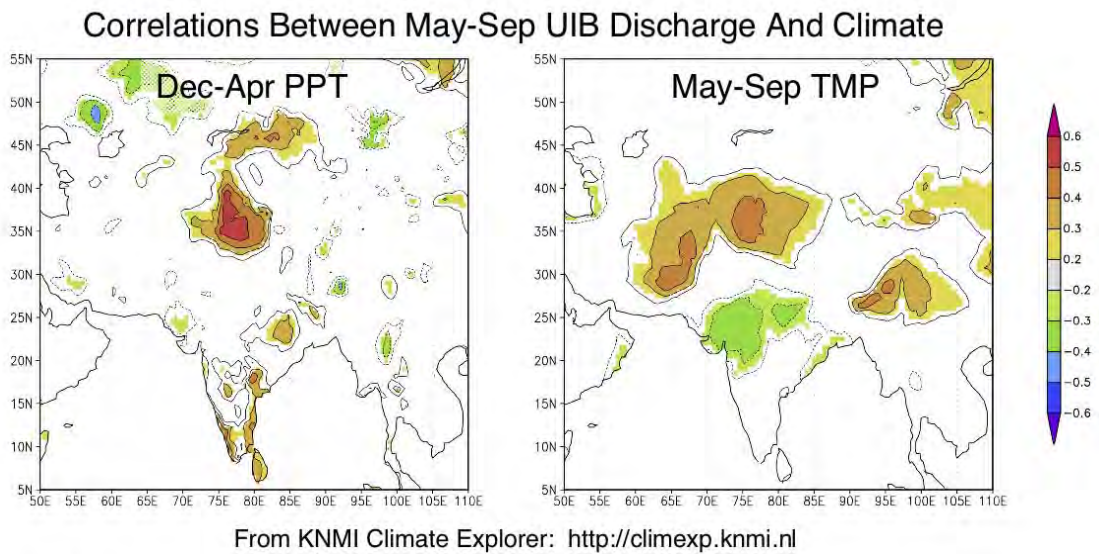

Figure 5. Maps showing the correlations between May-September UIB discharge and climate over the 1950-2004 time period. Only those correlations significant at the 90% level (2-tailed) are shown. The correlations with December-April total precipitation reflect the importance of antecedent seasonal snowfall accumulation and subsequent snowmelt to runoff. The correlations with concurrent May-September temperature reflects the importance of air temperatures in promoting both snow and glacier melt water contributions to UIB runoff. The higher correlations (r>0.50) with precipitation over the core accumulation region of the Karakoram imply that snowfall accumulation/melt is the most important contributor to May-September UIB runoff.

Perhaps the most worrying feature in the streamflow reconstruction is the occurrence of a pronounced and prolonged 112 year low-flow period from 1572 to 1683 (median: 3,404 m^3s^{-1}) and a shorter but much drier 27 year period from 1637 to 1663 (median: 3,292 m^3s^{-1}). The former is ~7% below and the latter ~10% below the median of the observed discharge record. Should either period of low-flow repeat itself in the future, the results could be devastating to Pakistan irrigation and hydroelectric power generation provided by the Tarbela Reservoir and Dam.

Acknowledgements:

We gratefully acknowledge the help of the Pakistan Water and Power Development Authority, Higher Education Commission of Pakistan, and the Pakistan Meterological Department in conducting our research in Pakistan.

References:

Ahmed, M. 1989. Tree-ring chronologies of Abies pindrow (Royle) Spach, from the Himalayan region of Pakistan. *Pakistan Journal of Botany* 21(2):347-354.

Ahmed, M., Palmer, J., Khan, N., Wahab, M., Fenwick, P., Esper, J., and Cook, E. 2011. The dendroclimatic potential of conifers from northern Pakistan. *Dendrochronologia* 29:77-88.

Archer, D. 2003. Contrasting hydrological regimes in the upper Indus Basin. *Journal of Hydrology* 274:198-210.

Archer, D. and Blenkinsop, S. 2010. Heterogeneity and spatial representativeness of station climate and tree-ring records as climate change indicators in the upper Indus Basin. Talk presented at *International Conference/Workshop on Dendrochronology* held at Federal Urdu University, Karachi, November 15, 2010.

Armstrong, R. 2010. *The Glaciers of the Hindu Kush-Himalayan Region: A summary of the science regarding glacier melt/retreat in the Himalayan, Hindu Kush, Karakoram, Pamir, and Tien Shan mountain ranges*. Kathmandu: ICIMOD.

Cook, E.R., Meko, D.M., Stahle, D.W., and Cleaveland, M.K. 1999. Drought reconstructions for the continental United States. *Journal of Climate* 12:1145-1162.

Cook, E.R., Woodhouse, C., Eakin, C.M., Meko, D.M. and Stahle, D.W. 2004. Long-term aridity changes in the western United States. *Science* 306:1015-1018.

Cook, E.R., Anchukaitis, K.J. Buckley, B.M., D'Arrigo, R.D., Jacoby, G.C. and Wright, W.E. 2010. Asian monsoon failure and megadrought during the last millennium. *Science* 328(5977): 486-489.

Esper, J., Bosshard, A., Schweingruber, F.H., and Winiger, M. 1995. Tree-rings from the upper timberline in the Karakorum as climatic indicators for the last 1000 years. *Dendrochronologia* 13:79-88.

Fowler, H.J. and Archer, D.R. 2006. Conflicting signals of climate change in the Upper Indus Basin. *Journal of Climate* 19(17):4276-4293.

Hegerl, G.C., Crowley, T.J., Allen, M., Hyde, W.T., Pollack, H.N., Smerdon, J., and Zorita, E. 2007. Detection of Human Influence on a New, Validated 1500-Year Temperature Reconstruction. *Journal of Climate* 20:650-666.

Hewitt, K. 2005. The Karakoram anomaly? Glacier expansion and the 'elevation effect,' Karakoram, Himalaya. *Mountain Research and Development* 25(4):332-340.

Immerzeel, W.W, Droogers, P., de Jong, S.M., and Bierkens, M.F.P. 2009. Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing. *Remote Sensing of Environment* 113:40-49.

Immerzeel, W.W., van Beek, L.P.H., and Bierkens, M.F.P. 2010. Climate change will affect the Asian water towers. *Science* 328:1382-1385.

Kaser, G., Grosshauser, M., and Marzeion, B. 2010. Contribution potential of glaciers to water availability in different climate regimes. *Proceedings of the National Academy of Sciences* 107(47):20223-20227.

Olive, D.J. 2007. Prediction intervals for regression models. *Computational Statistics & Data Analysis* 51:3115-3122.

Seber, G.A.F. and Lee, A.J. 2003. *Linear Regression Analysis*, 2nd Edition. Wiley, New York.

Shekhar, M.S., Chand, H., Kumar, S., Srinivasan, K., and Ganju, A. 2010. Climate change studies in the western Himalaya. *Annals of Glaciology* 51(54):105-112

Vinod, H.D. 2006. Maximum entropy ensembles for time series inference in economics. *Journal of Asian Economics* 17(6):955–978.

Vinod H.D. and López-de-Lacalle, J. 2009. Maximum entropy bootstrap for time series: the meboot R package. *Journal of Statistical Software* 29(5):1–19.

Weisberg, S. 2005. *Applied Linear Regression*, 3rd Edition. John Wiley, New Jersey.

3. Dissemination of findings:

A range of activities have been undertaken to help inform people about the project. These have mainly been in the form of publications (listed later), training courses and workshops as well as articles in local newspapers. A yearly summary is as follows:

2008:

1. "Applications of tree_ring research in Pakistan" was presented by Prof Ahmed at the New Zealand Ecological Society Conference on 30th September.
2. Dr Jonathan Palmer presented a seminar on 9th November at the request of Prof. Dr. Zaheeruddin Khan, Chairman Department of Botany, G.C University, Lahore, on "Application of tree rings in Pakistan".
3. A case study of "Drought reconstruction of River Indus" was presented by Prof Ahmed during "The National Conference of Ecology" at Federal Urdu University, Karachi on 24th November 2008.

4. "Dendrochronological Research in Pakistan" was presented by Prof Ahmed at the "35th All Pakistan Science Conference" on 21st December at Karachi University.

2009:

1. Organization by Prof Ahmed of a 4-day seminar/workshop on World Earth Day (22nd to 25th April, 2009) at Federal Urdu University, Karachi
2. Organization and seminar presentation by Prof Ahmed on the "Water Crisis in Pakistan" funded by HEC, 19th May, 2009 at Dr. Abdul Qadir Auditorium, Fed. Urdu University, Karachi
3. Seminar presented by Prof Ahmed on "World Environment Day" at Arts Council Karachi, 5th June, 2009.
4. A presentation by Prof Ahmed on related topic at Liaquat Medical College Karachi on 7th August, 2009.
5. Collaboration with G.C. University Lahore, and Env. Dept. Govt. of Punjab (5th to 7th October, 2009) an arrangement of a seminar/workshop "Bio-diversity: applications of Tree-Rings in Pakistan. Dr Palmer presented a talk "Dendrochronology, a case study of the River Indus". Dr. Moinuddin Ahmed organized and ran a workshop on tree-ring methods.
6. Seminar presented on the "Applications of tree-ring research in Pakistan" by Dr Palmer at F.C. College University Lahore, on 8th October, 2009.
7. A talk by Prof Ahmed on the "Potential of tree-ring studies in Pakistan" Department of Botany, University of Azad Jammu and Kashmir (1st November, 2009).

2010/11:

1. Exhibition at Islamabad under the Pak/US Program "Showcasing Pak/US Research Collaboration" held on the 9th June, 2010.
2. Prof Ahmed presented a paper at the World-Dendro Conference (held only once every four years) at Lapland University, Roveniemi, Finland 17-22 June.
3. The 2nd International Conference / Workshop on Dendrochronology was held at the Federal Urdu University of Arts Science and Technology (Karachi) from 14th to 19th November 2010. There were at least 50 students (both men and women) from various colleges and universities from around Karachi and beyond who attended the conference. More importantly, about 25 students (male and female) participated in the subsequent training workshop.
4. Seminar presented by Prof Ahmed on Tree_Rings in Pakistan 14th Feb. 2011 at FUUAST (highlighted in HEC News and Views).
5. Conducted a tree-ring training program by Prof. Ahmed for M.Phil students at the Botany Department, University of Baluchistan (9-14 May, 2011).

Educational Impacts: Please provide information on the numbers of students and other junior collaborators (graduate and undergraduate students, healthcare workers, laboratory technicians, data collectors, etc.) involved in the projects, and discuss new courses or degree programs created (if any) or changes to existing course curricula as a result of your project.

We believe there has been a continuous range of educational impacts throughout the duration of the project. One of the most significant was the 2nd International Conference / Workshop on Dendrochronology from 14th to 19th November 2010 that was opened by no less than the Federal Minister for Science and Education (mentioned above). Other educational developments include:

- A three-credit course on Dendrochronology is now included in B.S, M.Phil and Ph.D course work programs for students attending the Federal Urdu University of Arts, Sciences and Technology (Karachi).
- The training and involvement of three postgraduate students along with two laboratory assistants and a computer technician.

During the past year, field trips focusing on sampling methods were undertaken with 8 undergraduate students from GC University Lahore, two students of Balochistan University and four students of Federal Urdu University. We are intending to further extend training about the science of dendrochronology to two further universities - at the International University of Karakorum (Gilgit) and University of Hazara.

Infrastructure Development: Please list any equipment acquired during this reporting period with grant funds and discuss the impact the new equipment will have on research and educational activities.

All the items listed in the proposal have been acquired. Of major benefit has been the stand-by generator that has enabled the continuation of research activities during power outages. This has been of tremendous help to both staff and students in causing minimal disruption.

Publications: Please provide citations for any papers published or conference presentations made as a result of your project.

At least a further couple of papers are hoping to be submitted before the end of 2011 specifically about the river-flow reconstructions. However the following list is a summary of what has been accomplished to date.

A: International

Ahmed, et al (2011). The dendroclimatic potential of conifers from northern Pakistan. *Dendrochronologia* 29:77-88.

Ahmed et al (2011). Climate response function analysis of tree species from Indus Basin of Karakorum Range of Pakistan. *International Association of Wood Anatomists (IAWA)* (submitted).

B: Pakistan national journals

Ahmed, M. 2009. *An Introduction to Dendrochronology*. Publication of Federal Urdu University Press, Karachi Pakistan. 106 pp. Published in the national language Urdu .

Ahmed et al (2010). Some preliminary results of climate studies based on two pine species of Himalayan area of Pakistan. *Pakistan Journal of Botany* 42(2): 731-738.

Ahmed et al (2010). Climate response function analysis of *Abies pindrow* (Royle) Spach. Preliminary results. *Pakistan Journal of Botany* 42(1):165-171.

Ahmed et al (2010). Tree-Ring chronologies of Indus Basin of Karakorum range of Pakistan. *Pakistan Journal of Botany* 62 (special issue): 285-307.

Ahmed et al (2010). Dendrochronological potential of gymnosperm species in Pakistan. *International Journal of Biology and Biotechnology* 7(3): 159-174.

Ahmed et al (2010) Standardized tree-ring chronologies of *Picea smithiana* from two sites of the Northern Area, Pakistan. *World Applied Sciences Journal* 11(12): 1531-1536.

Bokhari et al (2010). Application of tree-rings to earthquake studies in Pakistan. *International Journal of Biology and Biotechnology* 7(3): 241-248.

Zafar et al. 2010. Standarized tree ring chronologies of Picea smithiana from two sites of the northern areas Pakistan. *World Applied Sciences Journal* 11(12):1531-1536.

Papers presented at Conferences:

Several papers presented by Dr Palmer, Dr Woodhouse and Prof Ahmed focused on the use of tree-ring chronologies for water resource management at the 2nd International Conference / Workshop on Dendrochronology (November 2010) at Karachi, Pakistan.

The Palaeoclimatic potential of conifer species in the Himalayan region of Pakistan. WorldDendro 2010. The 8th International Conference on Dendrochronology, Finland. 15th June 2010.

Additional Funding: Please list any additional funding applied for or received to help support your project during this reporting period.

None.

Linkages with Government or Private Industry: Please describe any linkages developed with government agencies or companies interested in implementing the results of your project.

As a result of the Conference/Workshop in November we have been able to establish a link with WAPDA (Pakistan Water and Power Development Authority) and we are hoping to strengthen this linkage beyond the final phase of the project.

Problems Encountered: Please provide information on any problems you may have encountered in making progress on your project objectives and describe steps you are taking to resolve the problems.

The only real problem encountered was the reduction and late release of funds from HEC. However mitigating circumstances such as the tragic impacts from the widespread flooding have understandably affected available Government funding. The reduction was unsettling and caused hardship on those involved (e.g. students). Prof Ahmed used personal funding to support the continuation of the project while waiting for the release of funds.

Plans for Future Activities: Please provide details on any follow-on activities during the next year, including planned exchange visits, training events, and ongoing research efforts.

We believe the results provide excellent proof of the potential of this type of scientific investigation in Pakistan. Further research effort is needed to expand the network of tree-ring sites and to update some of the ones collected in the 1990s by Jan Esper. A key aspect for further research is the contribution of glacial meltwater to Upper Indus Basin discharge and how it may change in the future.

Supplementary Information: If applicable, please attach copies of project-related workshop or conference agendas, course curricula developed, summaries of research data collected in the course of the project, or articles about the project appearing in newspapers, journals, or Web sites. **Please note that your report will be posted on the program Web site, so please do not include any data you do not wish to make publicly available at this point in your research.**

Indicators	Reporting Period:
1. Number of higher education partnerships between Pakistani and U.S. institutions (see note below)	1
2. Number of journal articles, technical reports, books, or book chapters (published or accepted for publication) resulting from your project during the reporting period	8
3. Number conference presentations resulting from your project during the reporting period	10
4. Number of training events (courses, workshops, seminars, conferences, stakeholders' meetings) conducted on your project during the reporting period	8
5. Total number of Pakistanis making exchange visits on your project during the reporting period	1
Number of women	
Number of men	1
6. Total number of Americans making exchange visits on your project during the reporting period	2
Number of women	1
Number of men	1
7. Total number of exchange visits overall during the reporting period	6
8. Total number of Pakistani PhD students involved in the project	3
Number of women	-
Number of men	3
9. Total number of American PhD students involved in the project	
Number of women	-
Number of men	-

10. Total number of all other Pakistanis not listed above who participated in your project during the reporting period (Include in this total those who were involved as researchers, MS or undergraduate students, technicians, or data collectors, as well as those who received formal training in workshops or courses or participated in conferences or stakeholders' meetings organized as part of the project.)	134
Number of women	62
Number of men	72
11. Total number of all other Americans not listed above who participated in your project during the reporting period (Include in this total those who were involved as researchers, MS or undergraduate students, technicians, or data collectors, as well as those who received formal training in workshops or courses or participated in conferences or stakeholders' meetings organized as part of the project.)	
Number of women	-
Number of men	-

Note on Question 1: For the number of higher education partnerships, please count the partnership between your institution and your Pakistani counterpart's institution as one. If your project also involves collaboration with other Pakistani institutions / US institutions (universities, research institutes, government agencies, or non-governmental organizations), please add each such additional institution to your total.