Application of tree-ring data in development of long-term discharge of River Satluj

Jayendra Singh[1,]* and Ram R. Yadav[2]

[1]Wadia Institute of Himalayan Geology, 33 General Mahadeo Singh Road, Dehra Dun 248 001, India
[2]Birbal Sahni Institute of Palaeobotany, 53 University Road, Lucknow 226 007, India

Variability in water discharge of the rivers originating in high Himalayan ranges affects water availability for domestic, agricultural and other socio-economic needs of local and downstream people. The observational river discharge data are limited and preclude the understanding of natural variability which is needed to evolve sustainable water resource management plans. We explore here the possibility of extending available measured Satluj River discharge data back in time using ring-width chronology of Himalayan cedar (AD 1380–2005) developed from a moisture-stressed site in the Satluj River basin. Tree-ring-width chronology showed direct relationship with monthly river discharge from October of the previous year to September of the current year. The existence of such a relationship revealed that the network of tree-ring-width chronologies from moisture-stressed sites should be useful in developing robust reconstructions of river discharge required to understand its dynamics in the long-term perspective.

Keywords: *Cedrus deodara*, ring-width chronology, Satluj River, water discharge, western Himalaya.

WATER resource availability in rivers is known to have affected the major civilizations in human history. In modern industrial society with the rapid increase in population, the water demand has grown manyfold to meet the regular socio-economic needs. Water discharge in rivers originating in the high Himalayan ranges, dependent on snow/glacier melt and summer monsoon precipitation, shows high year-to-year variation. The high variability in water discharge increases the vulnerability of local and downstream people to water stress. The river discharge data, spanning the past few decades, are not sufficient to understand natural variability and its future predictability. Taking this in view high priority needs to be given to explore the applicability of high-resolution proxies to supplement the observed river discharge data back to the past few centuries and even millennia.

Tree-ring data from river basins in several countries across the globe, where growth is dependent on variations in soil moisture, have been successfully used to reconstruct river discharge[1–6]. In India, several major rivers in the Western Himalaya pass through the semiarid regions where annual growth in trees is known to be affected by variations in precipitation[7–12]. However, thus far, no attempt has been made to explore the feasibility of developing river discharge reconstructions using tree-ring parameters. In the present study tree-ring-width chronology of Himalayan cedar (*Cedrus deodara*) from Kinnaur, Satluj valley has been used to understand the relationship with the Satluj River discharge.

The Satluj River originating from the Mansarovar and Raskal lakes in the Tibetan Plateau at an elevation of ~ 4572 m amsl, flows in the southwesterly direction across Himachal Pradesh and merges with the Chenab River near Bahawalpur in Pakistan. The contribution of snow and glacier melt in annual river discharge over the upper Satluj basin is high, which gradually declines downward and contribution of summer monsoon increases. The contribution of snow/glacier melt in the annual flow of the Satluj River at Bhakra dam is ~ 59%, the rest being from the summer monsoon rainfall[13]. The observational data of Satluj River flow (1922–2004) show a decreasing trend in winter and monsoon season post 1990, despite the increasing trend in temperature which should have resulted in increased glacier/snow melt[14]. The decreasing trend in river flow since 1990s has been hypothesized to be due to the thinning of glaciers[14]. Though the trail of increasing warmth is already apparent on the biospheric system in high ecotonal zones of the Western Himalayan region[15], the state of glaciers needs to be investigated if the thinning is responsible for reduced river discharge in recent decades. We explore here the potential of tree-ring data from the Satluj watershed, where tree growth is severely limited by moisture stress, to assess long-term river discharge. The long-term robust river discharge data developed using high-resolution tree-ring proxy records should be of immense use in evaluating the recent trends in long-term perspective.

Tree-ring samples of Himalayan cedar were collected from living trees growing on steep rocky slopes with very thin soil cover in Purbani, Kinnaur, Himachal Pradesh (Figure 1). The ecological setting is such that the tree growth is likely to be controlled by soil moisture variations. Old, healthy trees without any visible mark of injury were selected for sampling using increment borers. A total of 28 cores from 21 trees were collected and processed in the laboratory using standard dendrochronological techniques[16]. Ring-widths of each tree core were measured with 0.01 mm accuracy using linear encoder attached to a computer. The ring-width measurement sequences were used for the dating of annual growth rings to the level of calendar year of their formation using the TSAP programme[17]. Dating accuracy and measurement errors were cross-checked and confirmed using dating quality check program COFECHA[18].

Each ring-width measurement series was standardized to remove the non-climatic signal and tree growth trends mainly due to increasing age and tree size. Cubic smooth-

*For correspondence. (e-mail: jayendrasingh@wihg.res.in)

ing splines with a 50% frequency-response cut-off at 50 years were used to detrend the ring-width measurement series. The autocorrelations in detrended series were removed using autoregression modelling selected on the basis of minimum Akaike criterion. The individual indices were combined into a single master chronology using a biweight robust estimation of the mean[19]. A set of three ring-width chronologies: standard, residual containing only the high frequency variations and arstan composed of residual chronology with the pooled autoregression reincorporated were developed using the computer program ARSTAN[19].

River discharge data measured at Bhakra dam (1923–2004) and precipitation data from Purbani (1952–1994) were used in tree growth and climate relationship study using cross-correlation functions. Temperature data from the stations close to the sampling site were not available, hence Shimla temperature data (1900–2005), though located in a different climatic regime than the tree-ring sampling site, were used for understanding the preliminary relationship with tree growth. The location of data stations used in the study is shown in Figure 1. Correlation analyses of ring-width chronology with river discharge, temperature and precipitation were performed using Dendroclim 2002 (ref. 20). The correlations were calculated for the period of the respective data records.

The growth ring sequences among various tree samples of Himalayan cedar showed strong common interannual variability, indicating dominant climate forcing on tree growth. The ring-width chronology prepared extends back to AD 1271, however, based on chronology statistics such as expressed population signal (EPS; 0.85 taken as threshold value to decide series length suitable for reconstruction) and r_{bar} (0.6), a measure of signal strength[21], it was truncated at AD 1380 for further studies (Figure 2).

Correlation analyses (Figure 3) indicated that the ring-width chronology has positive relationship with river discharge from October of the previous year to September of the current year. Precipitation also showed a similar relationship, except for the weakly negative relationship observed during December of the previous year and February and July of the current year. The correlations with mean temperature were not consistent, the positive significant relationship was found only for November of the previous year. The weak relationship observed between the ring-width chronology and mean temperature could be possibly due to the temperature data being from a station far from the tree-ring sampling sites. The correlation

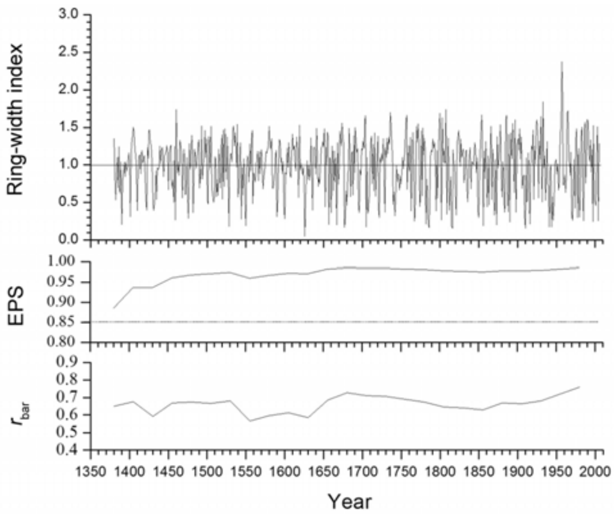

Figure 2. Ring-width chronology of *Cedrus deodara* with running r_{bar} and EPS statistics (AD 1380–2005).

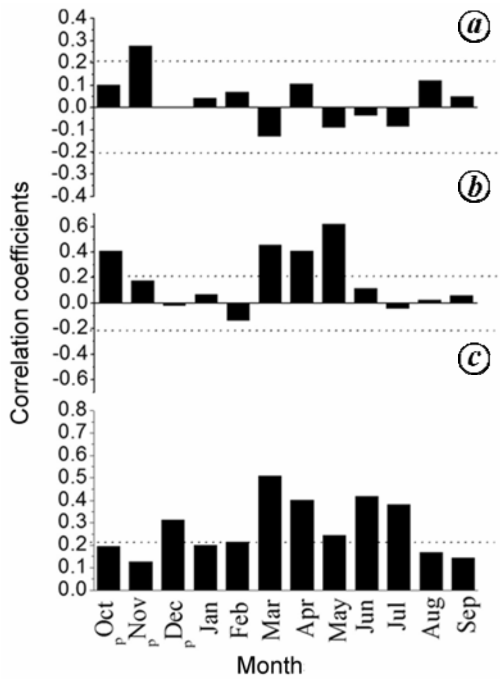

Figure 3. Cross correlation analyses between the residual chronology, Shimla temperature (***a***), Purbani precipitation (***b***) and Satluj River discharge (***c***) from October of the previous year to September of the current year. Bars above dotted lines show significant correlations at 95% confidence level.

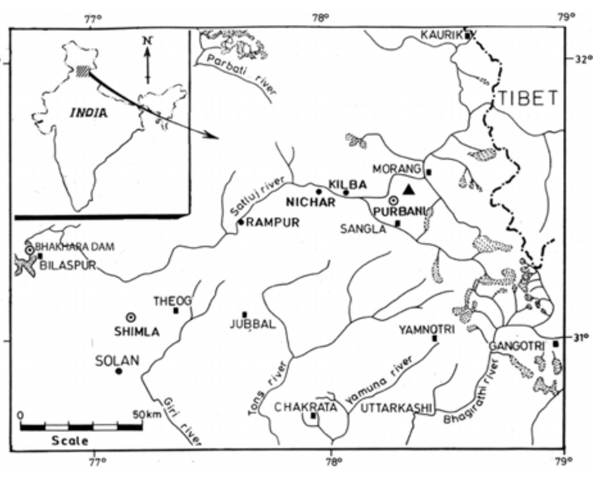

Figure 1. Location of tree-ring sampling site (triangle), meteorological stations and river discharge monitoring point at Bhakra Dam (circle with dot in the centre).

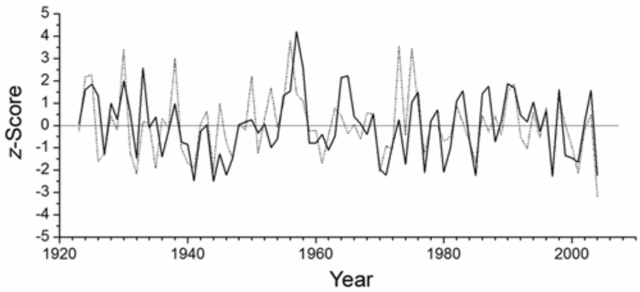

Figure 4. Comparison between ring-width chronology (solid line) and river discharge (dotted line). The river discharge and ring-width chronology were normalized with respect to AD 1923–2004.

analyses revealed that tree growth is usually stressed due to soil moisture deficit. The soil moisture is low over the growing sites of sampled trees used in this study, as water percolation in the soil is low and surface run-off is high due to steep slope gradient and thin soil cover. High soil moisture stress on the growth of trees makes the growth ring variations a sensitive measure of precipitation. As river discharge is closely related to precipitation variations, tree-ring chronologies from such sites could also be taken as a sensitive indicator of river discharge. In conformity with this principle, the tree-ring-width chronology has revealed positive correlation with river discharge from December of the previous year to July of the current year. December–July river discharge is significantly correlated with the tree-ring-width chronology ($r = 0.61$, 1923–2004, $P < 0.0001$). The river discharge (December–July) plotted together with the tree-ring-width chronology also revealed considerably good year-to-year similarity (Figure 4). Significant relationship between the tree-ring-width chronology and river discharge revealed that the moisture-responsive tree-ring chronologies, as the present one, could be successfully used to develop long-term river discharge data. We, at present, restrain to develop the river discharge reconstruction using single-site chronology. We are currently in the process of developing a network of moisture-responsive tree-ring chronologies from the Satluj River basin for incorporation in the predictor chronology model to develop stronger river-discharge reconstruction. The statistically robust reconstructions should be useful in understanding natural variability and predictability of river discharge and to evolve appropriate sustainable water resource management plans.

1. Gou, X., Chen, F., Cook, E., Jacoby, G., Yang, M. and Li, J., Streamflow variations of the Yellow River over the past 593 years in western China reconstructed from tree rings. *Water Resour. Res.*, 2007, **43**, W06434, doi:10.1029/2006WR005705.
2. Lara, A., Villalba, R. and Urrutia, R., A 400-year tree-ring record of the Puelo River summer–fall streamflow in the Valdivian rainforest ecoregion, Chile. *Climate Change*, 2008, **86**, 331–356, doi:10.1007/s10584-007-9287.
3. Axelson, J. N., Sauchyn, D. J. and Barichivich, J., New reconstructions of streamflow variability in the South Saskatchewan River basin from a network of tree ring chronologies, Alberta, Canada. *Water Resour. Res.*, 2009, **45**, W09422, doi:10.1029/2008-WR007639.
4. Wise, E. K., Tree ring record of streamflow and drought in the upper Snake River. *Water Resour. Res.*, 2010, **46**, W11529, doi: 10.1029/2010WR009282.
5. D'Arrigo, R., Abram, N., Ummenhofer, C., Palmer, J. and Mudelsee, M., Reconstructed streamflow for Citarum River, Java, Indonesia: linkages to tropical climate dynamics. *Climate Dyn.*, 2011, **36**, 451–462, doi: 10.1007/s00382-009-0717-2.
6. Urrutia, R. B., Lara, A., Villalba, R., Christie, D. A., Le Quesne, C. and Cuq, A., Multicentury tree ring reconstruction of annual streamflow for the Maule River watershed in south central Chile. *Water Resour. Res.*, 2011, **47**, W06527; doi: 10.1029/2010-WR009562.
7. Yadav, R. R. and Park, W.-K., Precipitation reconstruction using ring-width chronology of Himalayan cedar from western Himalaya: preliminary results. *Proc. Indian Acad. Sci.* (*Earth Planet. Sci.*), 2000, **109**, 339–345.
8. Singh, J. and Yadav, R. R., Spring precipitation variations over the western Himalaya, India since AD 1731 as deduced from tree rings. *J. Geophys. Res.*, 2005, **110**, D01110, doi: 10.1029/2004JD004855.
9. Singh, J., Park, W.-K. and Yadav, R. R., Tree-ring-based hydrological records for western Himalaya, India, since AD 1560. *Climate Dyn.*, 2006, **26**, 295–303, doi: 10.1007/s00382-005-0089-1.
10. Singh, J., Yadav, R. R. and Wilmking, M., A 694-year tree-ring based rainfall reconstruction from Himachal Pradesh, India. *Climate Dyn.*, 2009, **33**, 1149–1158, doi: 10.1007/s00382-009-0528-5.
11. Yadav, R. R., Tree-ring evidence of 20th century precipitation surge in monsoon shadow zone of western Himalaya, India. *J. Geophys. Res.*, 2011, **116**, doi: 10.1029/2010JD014647.
12. Yadav, R. R., Long-term hydroclimatic variability in monsoon shadow zone of western Himalaya, India. *Climate Dyn.*, 2011, doi: 10.1007/s00382-010-0800-8.
13. Singh, P. and Jain, S. K., Snow and glacier melt in the Satluj River at Bhakra Dam in the western Himalayan region. *Hydrol. Sci. J.*, 2002, **47**, 93–106.
14. Bhutiyani, M. R., Kale, V. S. and Pawar, N. J., Changing streamflow patterns in the rivers of northwestern Himalaya: implications of global warming in the 20th century. *Curr. Sci.*, 2008, **95**, 618–626.
15. Dubey, B., Yadav, R. R., Singh, J. and Chaturvedi, R., Upward shift of Himalayan pine in Western Himalaya, India. *Curr. Sci.*, 2003, **85**, 1135–1136.
16. Stokes, M. A. and Smiley, T. L., *An Introduction to Tree-Ring Dating*, The University of Chicago Press, Chicago, London, 1968, p. 73.
17. Rinn, F., TSAP-Win Time series analysis and presentation for dendrochronology and related applications, version 0.53 for Microsoft Windows, Rinn Tech, Heidelberg, Germany, 1991, p. 110.
18. Holmes, R. L., A computer-assisted quality control program. *Tree-Ring Bull*., 1983, **43**, 69–78.
19. Cook, E. R., A time series approach to tree-ring standardization, Ph D thesis, University of Arizona, Tucson, Arizona, USA, 1985.
20. Biondi, F. and Waikul, K., DENDROCLIM2002: a C^{++} program for statistical calibration of climate signals in tree-ring chronologies. *Comput. Geosci*., 2004, **30**, 303–311.
21. Wigley, T. M. L., Briffa, K. R. and Jones, P. D., On the average value of correlated time series, with applications in dendroclimatology and hydrometeorology. *J. Climate Appl. Meteorol.*, 1984, **23**, 201–213.

ACKNOWLEDGEMENTS. J.S. thanks Prof. A. K. Gupta, Director, Wadia Institute of Himalayan Geology, Dehra Dun for extending facilities and encouragement during the course of this work. We thank the forest officials of the Department of Forests, Himachal Pradesh for their help during the fieldwork. The Satluj River discharge data used in the present study were kindly provided by the Bhakra Beas Management Board (BBMB), Chandigarh. J.S. also thanks DST, New Delhi for financial support (SR/FTP/ES-61/2003).

Received 16 April 2012; revised accepted 31 October 2012