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Satluj river flow variations since AD 1660 based on tree-ring network of Himalayan cedar from western Himalaya, India

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ABSTRACT

Water availability is one of the main concerns for future developmental and economic activities in semi-arid to arid western Himalaya. However, the water supply potential of Himalayan rivers, essential for residents living along rivers, is not well understood in long-term perspective largely due to the scarcity of observational data. To fill this void, we developed Satluj river flow reconstruction for October to current year June (OJ) extending back to AD 1660. We used a network of ring-width chronologies of Himalayan cedar (*Cedrus deodara*) from seven moisture stressed, homogeneous sites in Kinnaur, Himachal Pradesh. In this pursuit, a total of 302 increment cores from 212 trees of Himalayan cedar from the Satluj river basin in Kinnaur, Himachal Pradesh were used. The reconstruction capturing 40% of the variance in calibration period (1923–1952) revealed that Satluj river flow, consistent with the decreasing trend in winter precipitation, decreased since the 1990s. The reconstruction spanning over the past 345 years showed 10-year, 20-year high, and low flow records in the 20th century.

1. Introduction

Due to fast growing populations in the Himalayan states and adjoining areas, the demands on water resources for hydropower generation, drinking water, irrigation and tourism are increasing rapidly. Human influence on climate change is one of the most important environmental challenges with profound implications on fresh water supply and natural ecosystems (IPCC, 2013). In view of this, the IPCC in its fifth assessment report raised serious concerns over the availability of water reserves under the changing climate scenario (IPCC, 2014). The Himalaya, the highest and the youngest mountain system of the world, still undergoing structural changes, is the abode of snow, fresh water and glaciers (Kulkarni et al., 2005, 2007; Raina and Srivastava, 2008; Negi et al., 2013; Mehta et al., 2014). The accelerated pace of glacier retreats in Himalayan region with global warming raises doubts over the sustained supply of fresh water to meet the growing needs of society (Kulkarni and Karyakarte, 2014). Developmental activities in this orography dominated region would be immensely affected directly or indirectly due to changes in water resource availability under the background influence of climate. Therefore, long-term river flow records are required to develop suitable water resource management policies. Nonetheless, this is greatly hampered due to the short span of observational river flow records available in India, spanning the past few decades in case of most Himalayan rivers except for the Satluj river, which extends back to the early 1920s (Bhutiyani et al., 2008). The shortness of these records seriously restricts our understanding of the recurrence behavior of extreme events in long-term perspective. The tree-ring data derived from moisture stressed trees growing in river basins provide reliable high-resolution proxy record to extend the available river flow data back to several centuries or even millennium (Gou et al., 2010; Wise, 2010; D'Arrigo et al., 2011; Margolis et al., 2011; Maxwell et al., 2011; Urrutia et al., 2011; Yang et al., 2012; Singh and Yadav, 2013; Sun et al., 2013, and many others cited therein). The tree-ring chronologies of conifers from the western Himalaya have been largely used to develop temperature and precipitation reconstructions (Hughes, 1992; Borgaonkar et al., 1994, 1996; Yadav et al., 1997, 1999, 2004, 2011, 2014; Yadav and Park, 2000; Yadav and Singh, 2002; Singh and Yadav, 2005; Singh et al., 2006, 2009; Yadav, 2011a, 2011b, 2013; Yadav and Bhutiyani, 2013), but river flow studies are very limited. The application of tree rings in assessing long-term Satluj river flow was first attempted by Misra and Yadav (2007), and later more chronologies were used to

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reconstruct Satluj river flow (Misra, 2010). Recently, Singh and Yadav (2013) assessed Satluj river flow for 711 years using three chronologies of Himalayan cedar and one of *Pinus gerardiana*. The present study, with the objective to develop long-term river flow from arid to semi-arid Himalayan region, improves over the others in terms of the large tree-ring data network used for robust Satluj river flow reconstruction. Such long-term river flow records have profound socioeconomic implications for agriculture, hydrological resource management, and tourism of the region.

2. Regional setting

Satluj river, the largest in Himachal Pradesh, is one of the major tributaries of the Indus river system. It is a Trans Himalayan river, which arises from beyond the Indian borders in Tibetan plateau from Mansarover and Rakshastal at an elevation of about 4572 m. It enters in India through a fearsome gorge near Shipki La, Himachal Pradesh. Thereafter, it flows through the arid to semi-arid cold region of Kinnaur. In its course across Kinnaur, the Satluj successively crosses three mountain ranges: Zanskar, Great Himalayan, and Dhauladhar. The topographic setting and abundant availability of water provide a huge hydropower generation potential (Singh et al., 1995, 2000). The river leaves Himachal Pradesh to enter the plains of Punjab at Bhakra, where the world's highest gravity dam has been constructed. The Bhakra dam is considered as a lifeline for Himalayan and adjoining states of India for hydropower and irrigation. Besides this, some major projects are Karchham Wangtu and Nathpa-Jhakri along with several small ones on tributaries. Although the Satluj river basin covers Greater, Lesser and Outer Himalayan ranges, its major part lies in the Greater Himalaya. Due to the wide range of altitude, diverse climate is experienced in the river basin. The lower part of the basin has tropical and warm climate, whereas the middle part has a cold temperate climate. In the upper part, the climate is very cold, with a perpetually frozen (permafrost) uppermost part. In the upper part of the basin, most of the precipitation is produced by the westerly weather disturbances during winter in the form of snow (Martyn, 1992). The lower part of the basin receives only rain, whereas the middle part gets rain and snow. Due to large altitudinal seasonal temperature differences, a highly variable snowline is found in the Satluj valley. The snowline descends to about 2000 m altitude during winter and crosses 5000 m altitude by the end of the summer. The permanent snowline in the Satluj river basin is observed at about 5400 m (Bhakra Beas Management Board (BBMB), 1988). About 65% of the catchment area of Satluj in Himachal Pradesh is covered with snow during winter, which reduced to about 11% after the ablation period (Singh and Bengtsson, 2004). On average, the contribution to annual run off from snow and glaciers is estimated to be about 59%, and the remainder from rains at Bhakra (Singh and Jain, 2002).

The rock substrates which support Himalayan cedar forest in Kinnaur are gneisses, schists, phyllites, quartzites, and granites. Among the members of schistose series, micaceous-schist, talcose rocks and phyllites are common and support good forests of Himalayan cedar at Nichar and Kilba. In Jangi, the exposed rocks are mainly biotite granulite with light coloured granite. Schist and soft-banded gneisses, which decompose rapidly, tend to produce deeper soil than hard fine grained gneiss or quartzite. Fine grained gneiss produce well drained sandy loam when decomposition is slow, to coarse gritty sand when decomposition is rapid. Both soils are suited to the growth of Himalayan cedar. The rapid weathering of granites in some sites, particularly in Akpa and Roghi, appear to be due to very high proportions of feldspar, which disintegrates rapidly under the influence of frost action and extremes of temperatures. The soil profiles are well developed in higher locations under dense forest. Soil over most of the area is formed in situ, and is generally loam to clayey-loam.

3. Data and methods

3.1. Site setting and collection of tree-ring materials

Variability in tree-ring features over a site largely depends on fluctuation in an environmental variable which is limiting for tree growth. The limiting variables might vary from site to site depending on slope, aspect, and soil type. In the present case, where tree-ring data were aimed to develop river flow, moisture stressed sites selected for study are expected to provide suitable materials. Sites with anthropogenic disturbances such as cutting, lopping and fire which add noise in data were avoided for sampling. Open Himalayan cedar forests at seven sites on steep hill slopes with thin soil cover in the Satluj river basin in Kinnaur (31° 05′–32° 05′ N; 77° 45′–79° 00′ E) Himachal Pradesh were selected for the present study (Fig. 1).

Himalayan cedar was selected for present study as it grows very old (Gamble, 1902) and is also widely distributed in the Satluj river basin (Fig. 2). The recorded longevity of this species elsewhere in the Himalaya (Singh et al., 2004) offers very good possibility to develop long chronologies for climate studies. The old trees of Himalayan cedar, easily identifiable by the presence of thick stripped bark, thick lateral branches and umbrella shaped crown were frequently encountered in the Satluj river basin. Healthy undisturbed trees without any visible mark of injury were selected for sampling. A minimum of two core samples were taken from each tree from opposite directions perpendicular to slope at breast height (~1.4 m). The aim was to retrieve the pith of the tree to obtain the longest series of the cored tree. Trees in dense forests were avoided due to competition among closely growing trees which could change the ring pattern leading to high inter tree variations, thus smearing the climate signal. We attempted to take tree core samples from widely spaced trees with no visible mark of injury or disease.

The increment cores were air-dried for a few days and glued to wooden mounts with transverse surfaces up, and wrapped tightly with string. When the glue dried sufficiently, the strings were removed from the core. After this, the cores were cut by sharp blade held at an acute angle to the direction of slicing (Stokes and Smiley, 1968), and sanded with increasingly different grades (220 and 400) of sandpaper so that the cellular details of annual rings became visible under a stereo zoom binocular microscope.

3.2. Crossdating of tree-ring samples

Growth ring sequence of all increment cores were precisely crossdated to the exact calendar year of their formation using the skeleton plotting method (Stokes and Smiley, 1968). Measurement of dated ring-width samples was accomplished using a linear encoder with resolution of 0.01 mm accuracy interfaced with a personal computer. Ring-widths of samples were measured from center to outside along the radial direction. COFECHA, a computer assisted quality control program (Holmes, 1983) was used to verify the dating of crossdated samples and check the accuracy of measurements. The mean correlation coefficient in COFECHA analysis among the samples of all the sites ranged from 0.797 to 0.868. The COFECHA statistics from all the sites showed very strong crossdating. Finally, 302 ring width series of Himalayan cedar from seven sites, which showed high correlation (mean $r = 0.823$) with the master series in COFECHA analyses were combined to prepare a mean ring-width series.

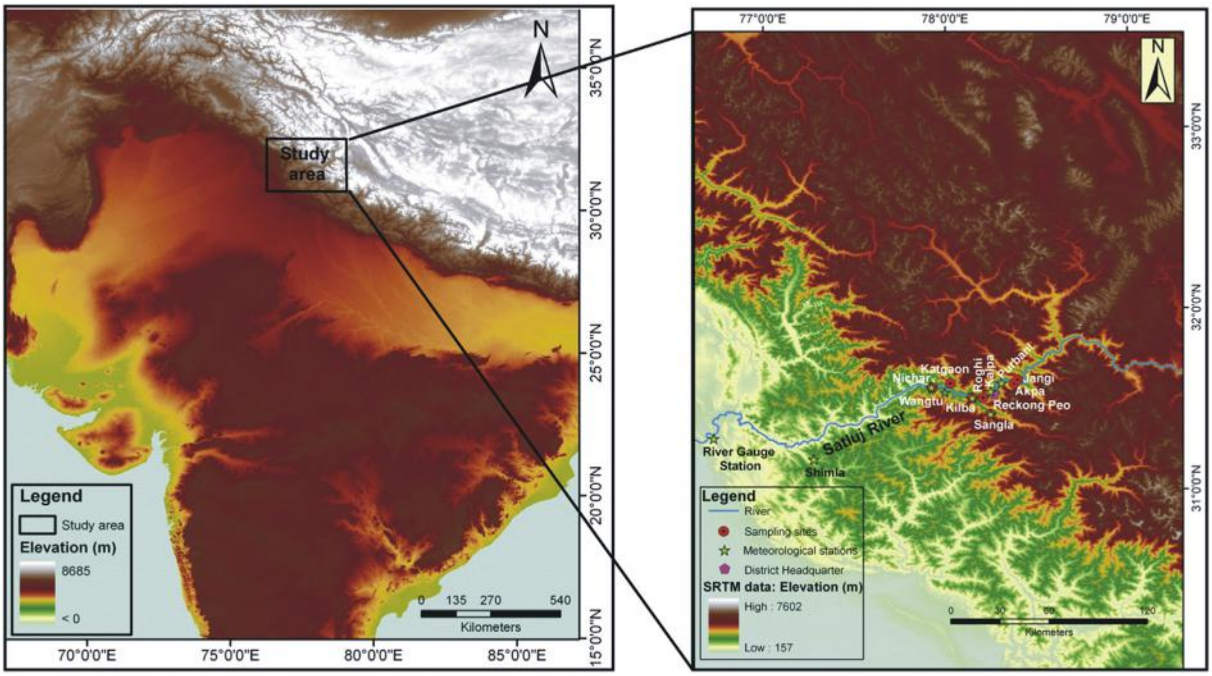

Fig. 1. Map showing the locations of the tree-ring sampling sites of Himalayan cedar (Akpa, Katgaon, Kilba, Nichar, Roghi, Sangla and Jangi), meteorological stations (Kalpa, Kilba, Nichar, Purbani, Sangla, Shimla and Wangtu) and river gauge station near Bhakra used in present reconstruction.

3.3. Chronology development

Annual growth of trees is the aggregate effect of many environmental factors including climate, biological aging, and local endogenous disturbances and competition among the trees. To preserve long-term fluctuations in the series, negative exponential curve has been used for detrending ring-width measurement series (Fritts, 1976; Cook et al., 1990). The negative exponential curve fitting is a very efficient method for removing age/size related growth trend in ring-width series of trees growing in open stands. Such growth trends show an exponential decay as a function of time after the juvenile period of increasing radial increment has passed. However, in the few cases where growth suppression and release due to competition was noted, a cubic spline with 50% frequency-response cutoff equal to 2/3 of the series length was used. The cubic spline is found to be suitable for standardizing tree-ring series from forest interiors, where tree growth is affected by endogenous disturbances such as competition (Cook and Peters, 1981).

The computer program ARSTAN (Cook, 1985) was used to produce a chronology from a set of cross-dated tree-ring measurement

Fig. 2. Pure Himalayan cedar forest growing in Satluj river basin, Kinnaur, Himachal Pradesh.

Table 1
Chronology (standard) statistics of Himalayan cedar from seven sites in Kinnaur. The details of site locations are shown in Fig. 1. SY-start year of the chronology, EPS-expressed population signal, MS-mean sensitivity, SD-standard deviation, AR1-first order autocorrelation.

S. No.	Site	Location	Elevation (m)	Core/trees	SY	Chronology with EPS >0.85	MS	SD	AR1
1.	Akpa	31°35′N, 78°23′E	3127–3266	23/17	1440	1500–2005	0.453	0.401	0.287
2.	Katgaon	31°35′N, 78°02′E	2639–2949	82/55	1480	1540–2005	0.425	0.403	0.335
3.	Kilba	31°30′N, 78°09′E	2260–2500	33/25	1432	1515–2005	0.424	0.430	0.361
4.	Nichar	31°33′N, 77°56′E	2182–2277	48/32	1580	1640–2005	0.353	0.324	0.226
5.	Roghi	31°30′N, 78°13′E	2851–3062	62/45	1388	1440–2005	0.391	0.354	0.281
6.	Sangla	31°25′N, 78°15′E	2345–2590	25/19	1607	1660–2005	0.372	0.363	0.373
7.	Jangi	31°36′N, 78°25′E	3318–3471	29/19	1353	1535–2005	0.350	0.353	0.393

series. ARSTAN detrends each ring-width series and removes the effect of juvenile growth, then computes the chronologies intended to contain maximum common signal and minimum amount of noise. ARSTAN produces three types of chronologies: Standard, capturing low frequency signal and to some extent preserves decadal-scale variation; Residual, capturing high frequency variability; and Arstan chronology composed of residual chronology reincorporated with the pooled autoregression (Cook, 1985). The statistical qualities of the tree-ring chronologies show gradual decay backward in time due to decreasing replication of samples. The expressed population signal (EPS) was taken as a guide to evaluate the most reliable time span of the chronology depicting the population signal (Wigley et al., 1984). The threshold EPS value of 0.85 was used as a cut-off of series length suitable for climatic reconstruction. Various descriptive statistics such as mean sensitivity, standard deviation, and autocorrelation were calculated for each chronology (Table 1) to evaluate their potentiality in river flow reconstruction. The common chronology period AD 1660–2005 was taken to study the coherence among seven site chronologies by computing cross-correlation among the series (Table 2). Highly significant correlation of chronologies indicated strong common forcing i.e., climatic signal. The strong coherence among the chronologies is also clearly visible when all the chronologies are plotted together (Fig. 3).

3.4. Climate and river flow data

For calibration of tree-ring data with climate records, climate data from stations close to the tree-ring sampling sites are required. However, this is the main limitation in the Himalayan region where weather stations with long, homogeneous records are scanty and usually located at lower altitudes, away from the tree-ring sampling sites.

Temperature records from stations close to the sampling sites are not available in the present case. Therefore, temperature records of Shimla (31°10′N, 77°17′E, 1900–1998) meteorological station falling nearest to the tree-ring sampling locations was used for response function analyses. The mean monthly temperature data of Shimla shows that January is the coolest and June the hottest (Fig. 4a).

For precipitation data, regional mean series have been developed by merging six homogeneous data sets from Kilba (31°31′N, 78°09′E, 1901–2000), Nichar (31°35′N, 77°57′E, 1931–2001), Kalpa (31°32′N, 78°15′E, 1951–2004), Sangla (31°25′N, 78°15′E, 1951–2001), Purbani (31°35′N, 78°21′E, 1951–1995) and Wangtu (31°32′N, 78°00′E, 1985–1997), which fall close to sampling sites in Kinnaur, Himachal Pradesh. The mean series were used in response function analyses for the common period 1931–1998 because before 1931 the record was only of one station. The mean monthly precipitation shows that the winter (January, February and March) precipitation is much higher than the monsoon (July, August and September) precipitation (Fig. 4b).

The recorded Satluj river flow data were obtained from Bhakra Beas Management Board (BBMB) and Punjab Irrigation Department, Chandigarh. The gauge of the recorded data is located before Govind Sagar reservoir near Bhakra (Fig. 1). Recorded data of Satluj river flow have been used for calibration with tree-ring data. The data length ranges from 1922 to 2004 and the abnormal values in the data were replaced by mean values. Strong coherence was observed between total monthly precipitation and total monthly river flow (Fig. 5). The coherence between precipitation and river flow was broken during 1953–1968 with correlation dipping to 0.27 as compared to the other periods (1922–1952 and 1969–2004, r = 0.45). Therefore, 1953–1968 values were taken as inconsistent, the cause of which is not known to us at present. In view of this, the river flow records from 1953 to 1968 were excluded from calibration analyses. The mean river flow data shows that the maximum river flow occurred in the monsoon (June, July and August) (Fig. 4c). It could be due to the location of the river gauge station in the monsoon zone.

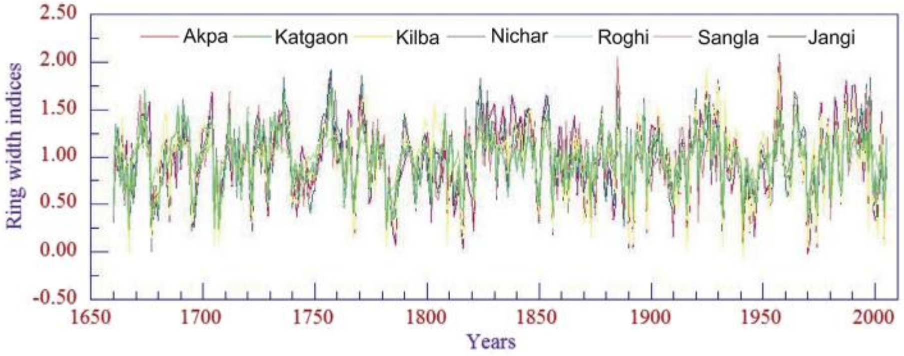

Fig. 3. Ring-width chronologies of Himalayan cedar (common period AD 1660–2005) from seven sites in Kinnaur, Himachal Pradesh overlaid to show similarity in year-to-year departures.

Table 2
Inter correlation among all seven Himalayan cedar ring-width chronologies AD 1660–2005 (significant at the 0.01 level).

Site-chronologies	Akpa	Katgaon	Kilba	Nichar	Roghi	Sangla
Katgaon	0.812					
Kilba	0.805	0.926				
Nichar	0.696	0.919	0.862			
Roghi	0.822	0.879	0.898	0.838		
Sangla	0.815	0.803	0.800	0.739	0.844	
Jangi	0.904	0.782	0.785	0.677	0.826	0.852

3.5. *Response function and correlation analyses*

Response function and correlation analyses of Himalayan cedar chronologies with total monthly precipitation and mean monthly temperature for the common period 1931–1998 showed that the precipitation of previous year October to current year June have positive relationship with tree-growth. Whereas, temperature of the prior year October to current year May, except June, has an inverse relationship with growth. High temperature increases evapotranspiration causing accentuated water stress on tree growth. The correlations between ring-width indices and precipitation and temperature of the monsoon months are not significant, showing that neither precipitation nor temperature is limiting for tree-growth during monsoon months. The response function and correlation analyses revealed that wet and cool springs favour tree-growth. As precipitation of October–June, which has direct relationship with tree-growth, contributes to river flow ($r = 0.45$ (0.003), 1969–2004), this relationship has been taken as a guide to reconstruct the river flow variable. High temperatures during the months of April, May and June, which also promote higher river flow due to added contribution of snow melt water, show an inverse relationship with tree-growth. The quantification of snow melt water contributing to river flow is not possible, as there is no long-term empirical study on the relationship between temperature and snow melt in the upper Satluj basin. In view of this, the present study focuses only on the contribution of precipitation on river flow.

3.6. *Principal component analysis*

Principal component analysis (PCA) was used to reduce multi-dimensional tree-ring data sets to lower dimensions for calibration and reconstruction (Peters et al., 1981). PCA transforms a set of correlated variables to a new set of uncorrelated variables, where the new variables (PCs) are linear combinations of the original variables. To select the significant variables for PCA, lagged variables of tree-ring series ($t-1$ and $t+1$) were also correlated with river flow of previous year October to current year June. However, no significant relationship was found with lagged tree-ring variables. In view of this only t_0 variables were used in PCA. Varimax technique was performed for PCA over the common chronology period of AD 1660–2005. The first principal component (PC#1) explained 84.6% variance with eigenvalue 5.9 and was subsequently selected for further analyses.

4. Results and discussion

4.1. *Calibration and reconstruction of October–June (OJ) river flow*

The observed river flow records of OJ were split into two sub periods (AD 1923–1952 (30 years) and AD 1969–2004 (36 years) to understand fidelity in relationship so that each sub-period could be compared with tree-ring data. Due to inconsistency in river flow data of AD 1953–1968 this part of series was excluded from calibration/verification analyses. The first calibration model (i.e. calibration 1923–1952, verification 1969–2004) explained 40% variance in the observed river flow data (Table 3). However, the second calibration model (i.e. calibration 1969–2004, verification 1923–1952) explained 41% variance (Table 3). The two sub-period calibration models were verified using independent river flow data sets of AD 1969–2004 and AD 1923–1952, respectively. Both the calibration models fail to track the river flow during

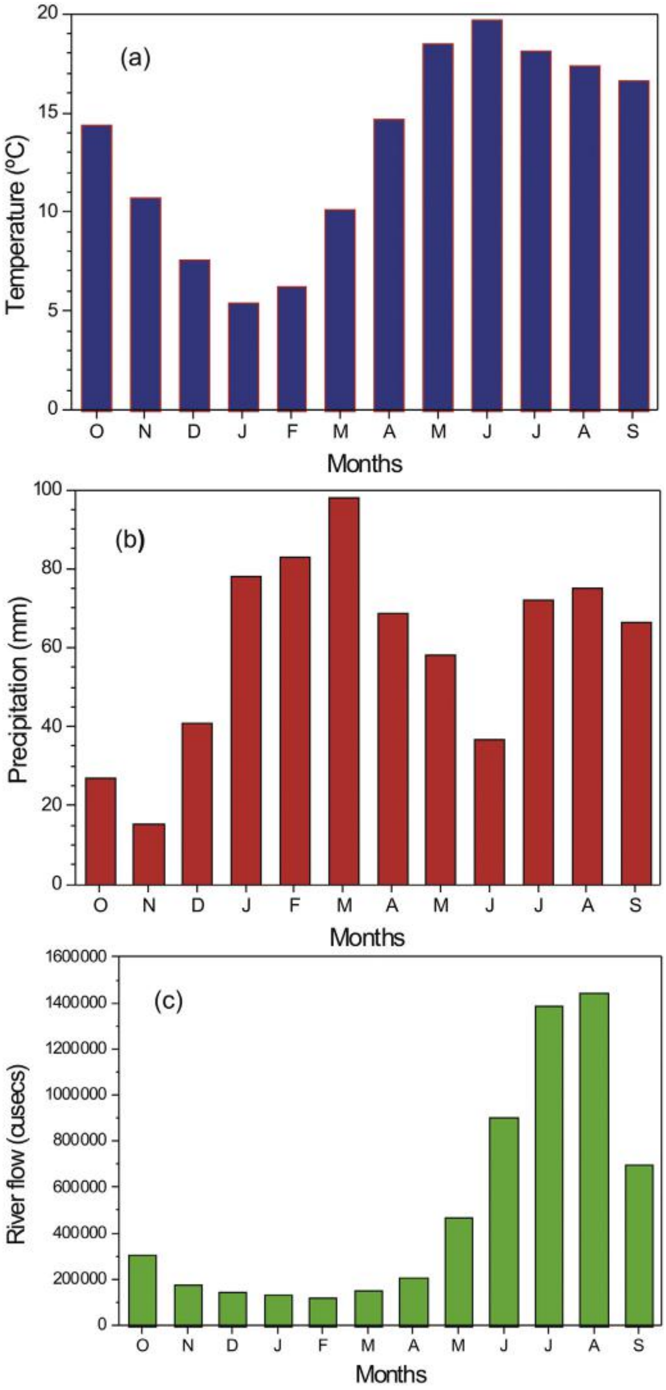

Fig. 4. (a) Mean monthly temperature variations from 1901 to 1998 of Shimla meteorological station. (b) The average monthly precipitation variation from 1901 to 2004 over Kinnaur using six meteorological stations. (c) The average monthly river flow variations from 1922 to 2004 at Bhakra.

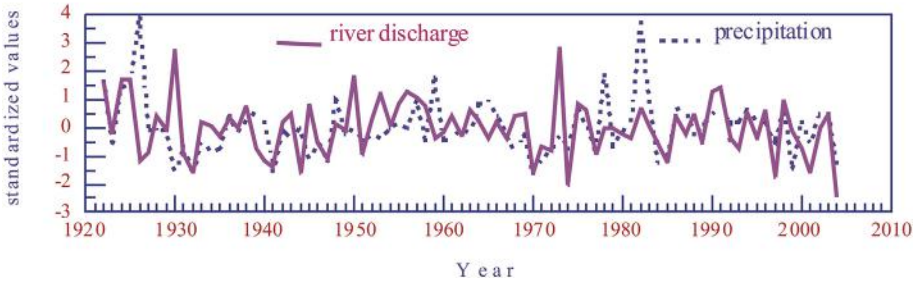

Fig. 5. Relationship between Satluj river flow at Bhakra and regional mean precipitation in Kinnaur, Himachal Pradesh from previous year October to current year June.

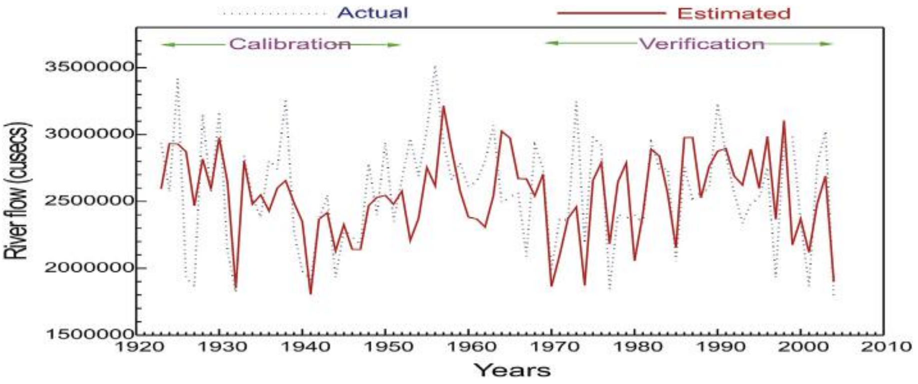

Fig. 6. Instrumental (dotted line) and reconstructed (solid line) OJ river flow plotted together for comparison (AD 1923–1952 Calibration period was used in reconstruction).

1953–1968, indicating inconsistent river flow record during this period. The calibration/verification analysis showed that the PC#1 explained higher variance in second calibration model (AD 1969–2004), but t-value was marginally low. For this reason, the first calibration model (AD 1923–1952) was used for river flow reconstruction (Fig. 6).

4.2. Description and analyses of reconstructed OJ Satluj river flow

The reconstructed OJ Satluj river flow from AD 1660–2004 (345 years) showed annual to multiyear variations (Fig. 7). The thick smooth line superimposed over the reconstruction is a filtered version of reconstruction to emphasize decadal and longer time scale variations (the filter is a cubic spline with a wavelength of 20 years (Cook, 1985). High and low river flow periods were noticed in the whole reconstruction, but extreme annual, 10-year and 20-year periods occurred in the 20th century. Both instrumental and reconstructed data showed decreasing trends since the last decade of the 20th century.

The highest and lowest annual river flow have been recorded in the 1957 (3215446 cusecs) and 1941 (1804058 cusecs), respectively in the 20th century. The highest 10-year mean river flow have been recorded for the period 1987–1996 (2782571 cusecs) followed by 1751–1760, 1922–1931, 1730–1739 and 1822–1831. The lowest 10-year mean river flow were noted for 1939–1948 (2263612 cusecs) followed by 1779–1788, 1812–1821, 1740–1749 and 1907–1916. The 20-year mean reconstructed river flow showed the highest values for 1979–1998 (2698136 cusecs) followed by 1822–1841, 1754–1773 and 1720–1739. The lowest 20-year mean river flow was recorded for 1932–1951 (2377894 cusecs) followed by 1779–1798, 1856–1875 and 1802–1921. In the reconstructed series highest 30-year mean river flow period is 1819–1848 (2649596 cusecs) followed by 1752–1781, 1710–1739 and 1975–2004. The lowest 30-year river flow is recorded for 1887–1916 (2424083 cusecs) followed by 1781–1810, 1855–1884 and 1932–1961.

The reconstructed extreme 10-year high and low flow periods suggest that fluctuations over the modern period of instrumental data are not unusual relative to the previous records. High flow periods occurred more frequently during the 20th century than the preceding centuries, as indicated by high standard deviation. The tree-ring based annual precipitation reconstruction from northern Pakistan also showed intensified pluvial conditions throughout the 20th century (Treydte et al., 2006). The OJ river flow reconstruction showed high flow periods during 1720s–1730s, 1750s, 1820s–1840s, 1920s, 1950s and 1980s, whereas low river flow periods were recorded in 1740s, 1780s–1810s, mid 1850s–late 1890s,

Table 3
Calibration/ verification statistics of previous year October to current year June river flow reconstruction; ar^2–r^2 adjusted after degrees of freedom, R-Pearson correlation coefficient, t-value-derived using the product mean test, Sign test is the sign of paired observed and estimated departures from the mean on the basis of the number of agreements/disagreements, RE-Reduction of Error statistics (Fritts, 1976).

S. No.	Period	Number of series	Calibration		Verification				
			Period	ar^2 (%)	Period	R	Pmt	Sign test	RE
1.	1660–2004	7	1923–1952	40	1969–2004	0.65[a]	2.7[a]	29/7[a]	0.37[a]
			1969–2004	41	1923–1952	0.65[a]	1.5	24/6[a]	0.39[a]

[a] Indicates significance at 0.05 level.

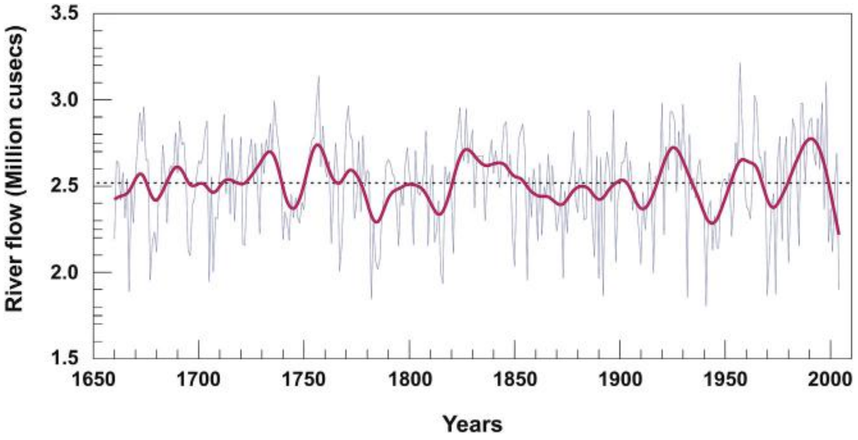

Fig. 7. OJ Satluj river flow reconstruction from Kinnaur (AD 1660–2004), thick smooth line superimposed on the reconstruction is 20-year spline. The middle horizontal line represents the mean river flow.

1900s–1910s, 1930s–1940s, 1970s. The sharp decrease in river flow since last decade of the 20th century could be related to decreasing trend in winter precipitation (Yadav and Bhutiyani, 2013) coupled with the thinning of glaciers in Satluj Basin (Bhutiyani et al., 2008), which contribute to river flow.

Increase in river flow during the 1980s in Satluj as well as increased precipitation in western Himalaya (Yadav and Park, 2000; Singh and Yadav, 2005; Yadav, 2011a,b; 2013) are coherent with the increase in precipitation in Kumaon Himalaya (Yadav et al., 2014) and Tibet (Bräuning and Mantwill, 2004), but for the same period

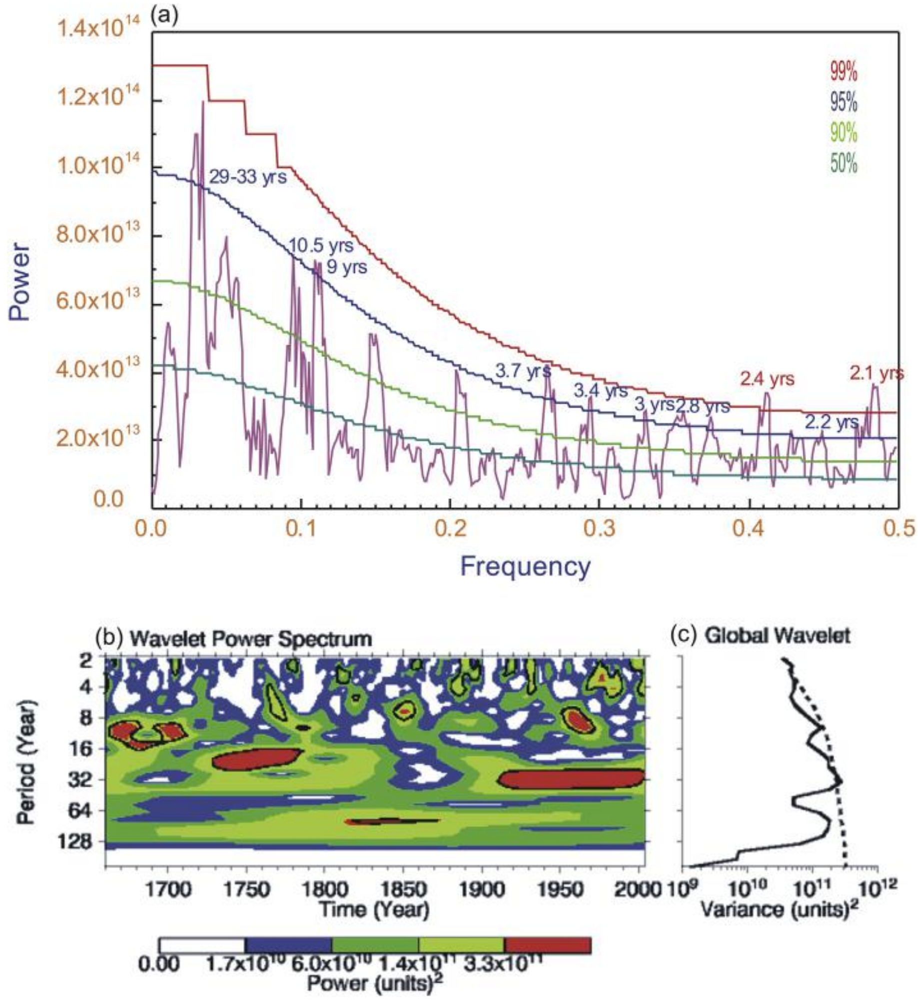

Fig. 8. (a) Multitaper power spectra of the reconstructed Satluj river flow (AD 1660–2004). (b) Wavelet power spectrum for reconstructed Satluj river flow (AD 1660–2004). (c) Global wavelet power spectrum (Torrence and Compo, 1998).

no such increase was observed in precipitation reconstructed for Chandra-Bhaga river basin, Lahul-Spiti (Yadav et al., 2006) and river flow reconstruction from Mongolia (Pederson et al., 2001). High and low flow periods during second half of the 18th to 20th century noticed in the present reconstruction closely match with the March–May precipitation reconstructed for the western Himalaya (Singh et al., 2006). Prolonged low flow period during second half of the 19th century corresponds with the dry spring in western Himalaya (Singh et al., 2006) and low river flow reconstruction in Mongolia (Pederson et al., 2001). The 1790s and 1890s, known as major famine years in India (Anderson et al., 2002) also correspond with low river flow in Satluj, low winter snowfall in Lahul Himalaya (Yadav and Bhutiyani, 2013), amplified winter droughts in Kinnaur Himalaya (Yadav, 2013) and low Indus river flow in northern Pakistan (Cook et al., 2013). Precipitation reconstructions from Kashmir, northwestern Himalaya (Hughes, 1992; Borgaonkar et al., 1994) do not match with the present reconstruction, which could be due to different climatic regimes prevailing in the two regions. The close resemblance in inter decadal variability in Satluj river flow and March–April–May precipitation reconstructions from the western Himalaya (Yadav and Park, 2000; Singh and Yadav, 2005) underscores the importance of precipitation contributing to river flow.

Multi Taper Method (Mann and Lees, 1996) was applied to understand spectral properties of the reconstructed series (Fig. 8a). This showed significant low frequency peaks at 9.0, 10.5 and 29–33 years, whereas high frequency peaks at 2.1–3.7 years. Such biennial periodicities have been recorded in earlier river flow reconstructions (Pederson et al., 2001; Singh and Yadav, 2013) and other precipitation studies (Diaz and Pulwarty, 1994; Briffa et al., 2001; Diaz et al., 2001; Yadav et al., 2014). Biennial periodicities are a dominant feature of the Asia–Pacific tropical climate system, caused by the interaction of atmosphere-ocean-monsoon system and extratropics (Meehl, 1997). The wavelet analysis (Torrence and Compo, 1998) used to understand variability mode in reconstruction (Fig. 8b and c) showed that ~28–33 years periodicity was active during the 20th century and matched with global wavelet. However, the ~16–24 year cycle was dominant in mid 18th century and the ~8–16 years cycle in the early part of the reconstruction. High frequency cycles (~2–8 years) reflecting the ENSO mode of variability are dominant in the later part of 19th century to present.

5. Conclusions

We developed a 345-year long OJ Satluj river flow reconstruction using Himalayan cedar ring-width chronologies from a network of seven moisture stressed sites in Kinnaur, Himachal Pradesh. This reconstruction improves over the previous river flow reconstructions from this part of the Himalayan region in terms of the higher variance captured in the observational river flow data (40%, 1923–1952). The reconstruction revealed high variability in river flow in the 20th century with highest annual river flows in 1957 and lowest in 1941. The reconstructed series showed more frequent high and low flows in recent decades as compared to earlier part of the reconstruction. The spectral analyses of the reconstructed series showed significant frequencies of 2.1–3.7, 9.0, 10.5 and 29–33 years. The identification of significant biennial mode of variability in the reconstructed series reflects the dominant feature over the Asia–Pacific climate system. We are attempting to improve our present river flow reconstruction by adding more tree-ring predictor chronologies in the calibration model. A robust reconstruction should be very useful in understanding of the extreme hydrological events and their recurrence behavior in long-term perspective.

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