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COLUMBIA RIVER FLOW AND DROUGHT SINCE 1750[1]

Ze'ev Gedalof, David L. Peterson, and Nathan J. Mantua[2]

ABSTRACT: A network of 32 drought sensitive tree-ring chronologies is used to reconstruct mean water year flow on the Columbia River at The Dalles, Oregon, since 1750. The reconstruction explains 30 percent of the variability in mean water year (October to September) flow, with a large portion of unexplained variance caused by underestimates of the most severe low flow events. Residual statistics from the tree-ring reconstruction, as well as an identically specified instrumental reconstruction, exhibit positive trends over time. This finding suggests that the relationship between drought and streamflow has changed over time, supporting results from hydrologic models, which suggest that changes in land cover over the 20th Century have had measurable impacts on runoff production. Low pass filtering the flow record suggests that persistent low flows during the 1840s were probably the most severe of the past 250 years, but that flows during the 1930s were nearly as extreme. The period from 1950 to 1987 is anomalous in the context of this record for having no notable multiyear drought events. A comparison of the flow reconstruction to paleorecords of the Pacific Decadal Oscillation (PDO) and El Niño/Southern Oscillation (ENSO) support a strong 20th Century link between large scale circulation and streamflow, but suggests that this link is very weak prior to 1900.

(KEY TERMS: drought; climate change; dendrochronology; Columbia River; Pacific Decadal Oscillation; tree rings; paleohydrology.)

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INTRODUCTION

The Columbia River Basin is the second largest drainage basin in the United States, and supports a diverse range of human and natural interests, including hydroelectric production, agricultural irrigation, navigation, fish stocks (including endangered salmon runs), fisheries, recreation, and human habitation (Bonneville Power Administration *et al.*, 2001). Imposed on these interests is the need to minimize the risk of floods. In many years the demands imposed on the Columbia River system account for more water than flows through the system, leaving managers especially vulnerable to low flow years (Cohen *et al.*, 2000; Miles *et al.*, 2000). The storage potential of the Columbia is already fully exploited, so adaptations to variability or changes in the supply of water need to be driven by reductions in demand rather than through infrastructure developments (Bonneville Power Administration *et al.*, 2001). Additionally, numerical models suggest that future climate change could substantially reduce the capacity of the Columbia River to meet societal water demands (Hamlet and Lettenmaier, 1999b). A longer record of streamflow variability in the Columbia River system would help water planners to develop contingency plans for extreme events by providing a longer context for drought assessment (Stockton, 1990; Loaiciga *et al.*, 1993; Meko *et al.*, 1995). In particular, the gauged record on the Columbia probably does not contain all the relevant low frequency fluctuations, abrupt shifts in flow that might be caused by changing climatic regimes, or multiyear drought events that are relevant to water resource planners (Stockton and Jacoby, 1976).

Climate sensitive tree-ring chronologies provide the opportunity to extend instrumental records of streamflow by exploiting the strong links between climate and runoff (Cayan, 1989, 1996; Moore, 1996;

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[2] Respectively, Department of Geography, University of Guelph, Guelph, Ontario N1G 2W1; USDA Forest Service, Pacific Northwest Research Station, 400 North 34th Street, Suite 201, Seattle, Washington 98103; and Climate Impacts Group, University of Washington, Box 354235, Seattle, Washington 98195-4235 (E-Mail/Gedalof: zgedalof@uoguelph.ca).

Nigam *et al.*, 1999). In particular, the Columbia River system is sensitive to climatic forcing associated with the PDO and ENSO (Hamlet and Lettenmaier, 1999a). Well verified tree-ring based reconstructions have been undertaken for the Sacramento River Basin (Earle, 1991; Meko *et al.*, 2001), the Gila River (Meko and Graybill, 1995), Crater Lake (Peterson *et al.*, 1999), the Colorado River (Stockton and Jacoby, 1976; Hidalgo *et al.*, 2001), and many smaller basins (see reviews in Jones *et al.*, 1984; Stockton, 1990). Trees of the Pacific Northwest are very long lived, often reaching ages that exceed 1,000 years (Brubaker, 1986; Peterson and Peterson, 1994; Laroque and Smith, 1999; Gedalof and Smith, 2001a). Many of these species are sensitive to climatic variability, including Douglas fir (*Pseudotsuga menziesii*) (Wiles *et al.*, 1996; Zhang, 1996; Biondi *et al.*, 2001), subalpine fir (*Abies lasiocarpa*) (Peterson and Peterson, 1994; Ettl and Peterson, 1995), ponderosa pine (*Pinus ponderosa*) (Graumlich, 1987), subalpine larch (*Larix lyallii*) (Colenutt and Luckman, 1991; Peterson and Peterson, 1994; Colenutt and Luckman, 1995), Engelmann spruce (*Picea engelmannii*) (Luckman and Colenutt 1992; Peterson and Peterson 1994), and others (Fritts, 1991; Schweingruber, 1993). The primary objective of this research is to reconstruct streamflow in the Columbia River Basin using dendrohydrological techniques and to use this reconstruction to contextualize the instrumental record.

DATA

Recent efforts to compile tree-ring chronologies into centralized data banks (e.g., Grissino-Mayer and Fritts, 1997) provide the opportunity to compile networks of climate sensitive tree-ring chronologies for the analysis of large scale climatic processes (Minobe, 1997; Kadonaga *et al.*, 1999; Gedalof and Smith, 2001b; McKenzie *et al.*, 2001). Two such data banks were used in this analysis: the International Tree-Ring Data Bank (ITRDB), and the University of Arizona "Past PDO working group" dataset. From these data banks all tree-ring chronologies lying within (or near to) the Columbia River Basin were compiled into a regional dataset. Because the analysis of these data relies on eigenvector techniques, which are limited to the temporal interval common to all sites, all chronologies that were collected prior to 1985 were excluded from further analysis. This screen resulted in a pool of 66 potential chronologies. The choice of a starting year for the analysis involved a tradeoff between a relatively short but data rich reconstruction and a much longer but data sparse reconstruction. By focusing on the post-1750 interval, it was possible to work with the widest range of tree species and locations – thereby providing the best insight into the underlying dynamics. Of the 66 potential chronologies, 57 extend back to 1750 and were retained for further investigation.

Individual ring width series were transformed into stationary, dimensionless, indices in order to remove trends in growth related to tree age and stand dynamics (Cook, 1987). This transformation was undertaken in two steps using the computer program ARSTAN (Cook and Holmes, 1986). First, a negative exponential curve or linear trend was fit to each series, and each observed ring width in the series was divided by this "expected" value. Next, each series was detrended a second time by fitting a cubic smoothing spline with a 50 percent frequency cutoff of 128 years to the residual series (Cook *et al.*, 1990). This frequency cutoff was chosen in order to preserve low frequency information potentially related to the PDO. This filter was sufficiently flexible to effectively remove most of the stand dynamics effects that were encountered, but still preserves 90 percent of the variance at periods shorter than 75 years (Cook and Peters, 1981; Cook *et al.*, 1990). Each ring width index series was prewhitened using autoregressive moving average (ARMA) models, to remove any autocorrelation effects (Biondi and Swetnam, 1987; Cook, 1987), before being combined into a single representative site chronology using a robust mean (Mosteller and Tukey, 1977). Prewhitening is necessary because tree-ring records often exhibit year-to-year persistence due to nutrient storage, foliage production, recovery from disturbance, and other biological processes (Fritts, 1976).

Streamflow data for the Columbia River were provided by the Bonneville Power Administration. These data have been "naturalized" to remove the influences of water diversion and storage and changes in evaporation (A.G. Crook Company, 1993; A.F. Hamlet, P.W. Mote, A.K. Snover, and E.L. Miles, unpublished manuscript). This procedure uses an empirical flow model to incorporate records of reservoir volume, water withdrawal, and theoretical evaporative losses from reservoir surfaces, and derive a record of what flow at The Dalles would have been in the absence of regulatory structures. While it is impossible to verify the representativeness of this record, the naturalization procedure employed is physically defensible and the resulting record is consistent with several independent estimates of past flow (A.F. Hamlet, P.W. Mote, A.K. Snover, and E.L. Miles, unpublished manuscript; A.F. Hamlet, personal communication, March 3, 2004). The analysis focused on reconstructing mean water year (October to September) flow at The Dalles, Oregon, for three principal reasons: (1) the flow record at The Dalles integrates variability over a large portion of the Columbia River drainage basin and is therefore representative of the large scale processes occurring within the system; (2) water resources managers use flow at The Dalles to develop a number of operational applications, so statistics for this location are likely to be of practical utility; and (3) flow at The Dalles has been the focus of other investigations, so the results of this study will provide a direct basis for comparison. Flow at The Dalles has been routinely gauged since 1878, but "naturalized" records extend back only to 1931 due to quality assurance concerns in the early portion of the record. A base 10 log transformation was applied to induce normality in the water year average flow data.

The U.S. "Time Bias Corrected" state climatic divisional dataset (Guttman and Quayle, 1996) was used to investigate relationships between radial growth and climate and between streamflow and climate. Because the divisional data are developed from area weighted averages of temperature and precipitation over regions of relatively homogeneous climate they are often considered preferable for dendroclimatic analyses (Brubaker, 1980; Blasing *et al.*, 1981; Heikkinen, 1985; Ettl and Peterson, 1995). Monthly values of temperature, precipitation, and Palmer drought severity index (PDSI) data are available for the interval 1895 to present.

METHODS

The pool of available chronologies was screened for sensitivity to drought in order to restrict the pool of predictors to candidates exhibiting a physically consistent relationship to hydrologic variability. Pearson correlation coefficients were calculated between annual radial growth index and monthly PDSI values within the pertinent climate division over the interval from December of the year preceding growth to August of the year of growth. Sites that did not exhibit a significant correlation to drought during at least one month were removed from the analysis. Because PDSI is not calculated in Canada, an alternative screening process was required. For sites close to the United States border, nearby representative climate divisions were identified. For more distant sites the correlation to precipitation was used as a guide.

Principal components analysis (PCA) was applied to the subset of screened chronologies to derive a reduced set of independent predictors. From this analysis, only the eigenvectors that exhibited physically meaningful loadings and had eigenvalues that were statistically greater than 1.0 were retained for further investigation (North *et al.*, 1982). This approach is distinct from most other dendrohydrological reconstructions that typically include nonzero lags of radial growth increment and retain a large number of principal components as regressors (but see Hidalgo *et al.*, 2001). Limiting the number of statistical predictors considered minimizes the probability of identifying spurious relationships or of overfitting the regression model. Each principal component (PC) was tested for significant autocorrelation and, where needed, was prewhitened using the appropriate ARMA model. This second prewhitening may be required if the common between site variability is characterized by a red noise process, but is obscured due to site specific noise. In this case, the principal component solution may capture the common, autocorrelated, variability in a high order eigenvector and defer the site specific "noise" to lower eigenvectors (Gauch, 1980). In all cases an AR(1) or AR(0) model was sufficient to describe the autocorrelative structure of the series. The water year average streamflow record exhibited no serial autocorrelation.

Many regression models are possible given the large number of potential predictors. In order to identify the most appropriate model a bootstrapping technique was applied to assess the stability of regression coefficients. Bootstrapping is a method of estimating the standard errors of statistical estimators and related parameters in cases where the dataset is small, or where no theory exists for its underlying distribution (Efron and Tibshirani, 1997). The method proceeds by developing many subsets of the data (termed pseudodatasets) using random sampling with replacement. Each pseudo/dataset is used to estimate a set of regression coefficients. This set of estimates can then be used to derive the frequency distribution of the actual regression parameters. Bootstrapped statistics have been shown to be robust even when residuals are nonnormative, autocorrelated, or when the dataset is too short for normal statistical estimators (Fritts *et al.*, 1990). In this application, regression models were estimated from each pseudo/dataset, with PCs entered stepwise in descending order of eigenvalue (i.e., PC1 then PC2, etc.). This process was replicated 10,000 times in order to derive summary statistics. Regression coefficients whose value exhibited the same sign more than 9,500 times were considered significantly different from zero at the 95 percent confidence level.

Cross-validation statistics were generated by iteratively removing every third year from the data input to the regression model and using the remaining two-thirds of the years to predict the withheld years. This process was repeated three times, incrementing the starting position by one year each time, to develop a reconstruction for the full calibration interval (1931 through 1987) that does not use data from any given year to predict that year's streamflow value. The Pearson correlation coefficient and the reduction of error (RE) statistic (Fritts *et al.*, 1990) were generated from this cross-validated record as indicators of model performance. A second regression model, using the entire calibration interval to estimate the regression coefficients, was developed in order to reconstruct flow since 1750. For comparative purposes the performance statistics for this model were also calculated.

Two additional tests of regression stability were also undertaken to assess the possible violation of regression assumptions. The gauged record of streamflow at The Dalles appears to be nonstationary in two respects: (1) the mean appears to be increasing over the calibration interval used in this analysis; and (2) the variance appears to be reduced over the interval from circa 1950 to 1970. As it turns out, the apparent trend in the gauged flow record is not significant ($p = 0.10$), and in fact is *negative* rather than positive if the recent (post-1987) portion of the gauged record is included – due to a sequence of particularly low flow years in the 1990s. Furthermore, if this trend is linearly removed from the gauged record the results presented below are not changed in any meaningful way. In contrast, the interval of reduced variance is significant using *a priori* statistical tests. Because the variance does not change in proportion to the magnitude of the flow record, though, it is difficult to assess how this feature might bias the analysis. To ensure that this bias is not problematic a constant variance was imposed on each of the three segments, identified visually as 1931 through 1949, 1950 through 1970, and 1971 through 1987, and reran the analysis using this alternative calibration dataset. Again, the results presented below were not changed in any meaningful way; specifically the same set of predictors was chosen, and the regression coefficients were of the same sign and approximate magnitude. Lastly, in the results below the reconstructed streamflow also exhibits reduced variance over this interval, suggesting that the feature is not an artifact of the naturalization and is captured in the reconstruction. While intriguing, it is difficult to justify treating this period differently given current understanding of hydroclimatic variability (see Wunsch, 1999).

RESULTS

Model Development

Of the 57 potential tree-ring chronologies 32 exhibited a significant correlation to at least one month's PDSI (Figure 1, Table1). Two general trends were evident in the calculation of the drought correlations. First, species that are characteristic of subalpine environments exhibited an inverse correlation to PDSI (or precipitation for the Canadian chronologies). This result indicates that lower moisture availability is associated with higher radial growth. In contrast to this result, all but two of the typically low-elevation species generally exhibited a positive correlation. Second, subalpine sites exhibited the strongest association to PDSI (or precipitation) during winter and spring months, and low elevation sites typically exhibited the strongest correlation during summer months. These results corroborate previous studies that have found that radial growth at subalpine locations is often limited by the length of the growing season, which is in turn largely a function of the snow-free interval (Peterson and Peterson, 1994; Ettl and Peterson, 1995; Gedalof and Smith, 2001a; Peterson and Peterson, 2001; Peterson *et al.*, 2002). In contrast, growth at low elevation sites is often limited by moisture availability during the growing season (Graumlich, 1987; Cook *et al.*, 1999; Stahle *et al.*, 2000).

Five eigenvectors were retained from the PCA. Bootstrapping of the regression coefficients suggested that PCs 1, 2, and 4 are stable predictors of mean flow at The Dalles. The cross-validated correlation between observed and reconstructed flow is 0.50, and the reduction of error statistic is 0.24. The statistics from the full calibration model, using all available years, are only marginally stronger: the Pearson correlation is 0.59 and the reduction of error is 0.29. These results suggest that the model is not being overfit, and that the reconstruction contains useful information (Figure 2).

Residuals Analysis

An examination of the regression residuals revealed two factors that complicate simple interpretation of the results. First, the model underestimates the magnitude of extreme events. This result is typical of regression analyses in general (Meko and Graybill, 1995), and tree-ring based reconstructions in particular (Fritts, 1976; Fritts *et al.*, 1990; Peterson *et al.*, 1999). However this bias is not symmetric, with the magnitude of low-flow events more poorly captured by the reconstruction. Indeed, a scatter plot of the regression residuals against the predicted flow record suggests that underestimates of severe low-flow events account for a substantial fraction of the error in the regression model (Figure 3). One interpretation of this finding is that the reconstructed record is probably performing better than the verification statistics suggest – at least with respect to the occurrence of low flow events if not the absolute magnitude of those events.

Figure 1. Map of the Columbia River Basin Showing the Location of The Dalles, Oregon and Tree-Ring Sites Used in the Analysis.

Secondly, the residuals exhibit an increasing trend over time. This trend is evident in a plot of the residuals as a function of time (Figure 4), though is significant only at the 90 percent confidence level (p = 0.08). This finding can be explained as a consequence of increases in the gauged flow at The Dalles that are not matched by increases in radial growth at the sites considered in this study. The most likely explanation for this trend is that changes in land cover within the Columbia River basin are contributing to increased runoff relative to total precipitation or drought severity. Hessburg *et al.* (2000) document large changes in forest composition and structure within the Columbia River basin over the 20th Century, which they attribute to forest management practices including timber harvest, fire exclusion, cropland expansion, and introduced species. These changes have almost certainly had a measurable impact on the hydrology of the basin. Using the variable infiltration capacity (VIC) model Matheussen *et al.* (2000) estimated changes in runoff production that could be attributed to land cover changes between 1900 and 1990. They determined that runoff has increased within all but one of the subbasins of the Columbia River system, typically by 2 to 7 percent. Because they used the same climatic parameters to force the model under both land cover scenarios this change in runoff can be attributed to changes in surface characteristics. Losses of mature forest stands to logging and agriculture have resulted in increased snow accumulation and reduced evapotranspiration, which in turn have increased runoff. This trend has been partially offset by fire suppression efforts, which have increased the area of mature forest types in some regions, thereby

TABLE 1. Characteristics of the Sites Used in this Analysis.

Site Name	Source[1]	Contributor[2]	Species[3]	Lat. (N)	Long. (W)	Elevation (m)	Start Year	End Year	R (PDSI)[4]	R (Flow)[5]
Sicamous Creek	ITRDB	Parish	PCEN	50.49	-119.54	1550	1665	1994	N/A	-0.536
Big White	ITRDB	Parish	PCEN	49.52	-118.51	1700	1669	1998	-0.248	-0.226
Big White	ITRDB	Parish	ABLA	49.52	-118.51	1700	1712	1998	-0.256	-0.306
Adams Lake	ITRDB	Parish	PCEN	51.02	-119.03	1900	1710	1996	N/A	-0.422
Adams Lake	ITRDB	Parish	ABLA	51.02	-119.03	1900	1710	1996	N/A	-0.422
Fredrick Butte	PPDO	Meko	JUOC	43.58	-120.45	1494	936	1996	0.683	0.345
Gray Creek Pass	PPDO	Colenutt	LALY	49.62	-116.67	2275	1216	1993	-0.323	-0.365
Larch Valley	PPDO	Colenutt	LALY	51.35	-116.22	2250	1347	1994	-0.256	0.040
North Fork Ridge	ITRDB	King	PSME	45.18	-111.20	2500	819	2000	0.416	-0.097
North Fork Ridge	ITRDB	King	PIFL	45.18	-111.20	2500	500	2000	0.211	-0.043
Cross Canyon	ITRDB	Swetnam	PIPO	45.58	-117.41	1317	1485	1991	0.399	0.366
Grizzly Bear	ITRDB	Swetnam	PIPO	45.58	-117.43	1231	1502	1991	0.458	0.329
Drumhill Ridge	ITRDB	Wickman	PIPO	45.28	-118.12	N/A	1672	1990	0.202	-0.009
Indian Crossing	ITRDB	Wickman	PIPO	45.07	-117.01	N/A	1550	1990	0.316	0.010
Bally Mountain	ITRDB	Wickman	PIPO	45.17	-118.34	N/A	1469	1990	0.436	0.230
Big Sink	ITRDB	Wickman	PIPO	45.47	-117.55	1203	1665	1990	0.377	0.204
Fish Lake	ITRDB	Wickman	PIPO	45.00	-117.04	1600	1585	1991	0.238	-0.004
Lugar Springs	ITRDB	Wickman	PIPO	45.46	-117.58	1200	1675	1991	0.251	0.037
Pringle Falls RNA	ITRDB	Speer	PIPO	43.42	-121.37	1460	1476	1993	0.350	0.226
Experimental Forest	ITRDB	Speer	PIPO	43.43	-121.36	1530	1334	1993	0.243	0.255
Deschutes	ITRDB	Speer	PIPO	43.28	-121.24	1420	1574	1995	0.377	0.303
Junction Hwys. 51 and 97	ITRDB	Speer	PIPO	43.19	-121.45	1420	1419	1995	-0.229	-0.023
Diamond Lake	ITRDB	Speer	PIPO	43.05	-121.57	1510	1513	1995	-0.263	-0.012
Blue Jay Spring	ITRDB	Speer	PIPO	42.55	-121.32	1490	1423	1995	0.259	0.203
Telephone Draw South	ITRDB	Speer	PIPO	42.45	-121.31	1550	1442	1995	0.335	0.008
Crater Lake	ITRDB	Speer	PIPO	42.47	-122.04	1370	1572	1990	0.224	0.080
Hart's Pass N1	ITRDB	Peterson	LALY	48.00	-120.00	N/A	1685	1991	-0.203	-0.317
Annette Lake Trail	ITRDB	Earle	PSME	47.22	-121.20	798	1515	1987	0.421	0.085
Big Quilcene	ITRDB	Earle	PSME	47.50	-123.02	867	1288	1987	0.265	0.145
Olympic Road 3116	ITRDB	Earle	PSME	48.00	-124.00	267	1394	1987	0.203	0.082
Silver Creek	ITRDB	Earle	PSME	46.38	-121.50	900	1539	1987	0.244	-0.012
Sheep Mountain, Wyoming	PPDO	Earle	PSME	41.08	-106.03	2375	1412	1990	0.526	0.115

[1] TRDB = International Tree-Ring Data Bank; PPDO = PastPDO Working Group.

[2] Indicates original contributor to data bank.

[3] ABLA = *Abies lasiocarpa*, JUOC = *Juniperus occidentalis*, LALY = *Larix Lyallii*, PCEN = *Picea engelmannii*, PIFL = *Pinus flexilis*, PIPO = *Pinus ponderosa*, and PSME = *Pseudotsuga menziesii.*

[4] Maximum correlation between monthly PDSI and annual radial growth, calculated for the months December (of the preceeding year) to August (of the year of growth) over the interval 1896 to 1987. The PDSI is not calculated for Canada, so correlations are not shown for Canadian sites that are distant from the U.S. border.

[5] Correlation between annual radial growth and mean water year flow at The Dalles, Oregon.

increasing evapotranspirative losses. Although they do not report the total change in naturalized flow at The Dalles, summer high flows are approximately 10 percent higher and winter low flows are 2 to 3 percent lower under modern land cover than under 1900 conditions (see Figure 5 in Matheussen *et al.,* 2000).

Because the tree-ring sites considered in this study have not been subjected to these land use changes, they should not exhibit this trend. As a consequence of this disparity, the trend in the regression residuals can be interpreted as supporting evidence for the modeled results. The magnitude of this trend amounts to 3.7 percent of the mean flow over the period of record, or about 5.7 percent extrapolating to the same interval used by Matheussen *et al.* (2000). Given that this trend is a consequence of two opposing processes operating within the basin, it seems likely that changes in runoff relative to precipitation have probably occurred in other basins as well. In particular, basins that are more homogenous with respect to the historical dominant forest type may exhibit more pronounced changes than were found here.

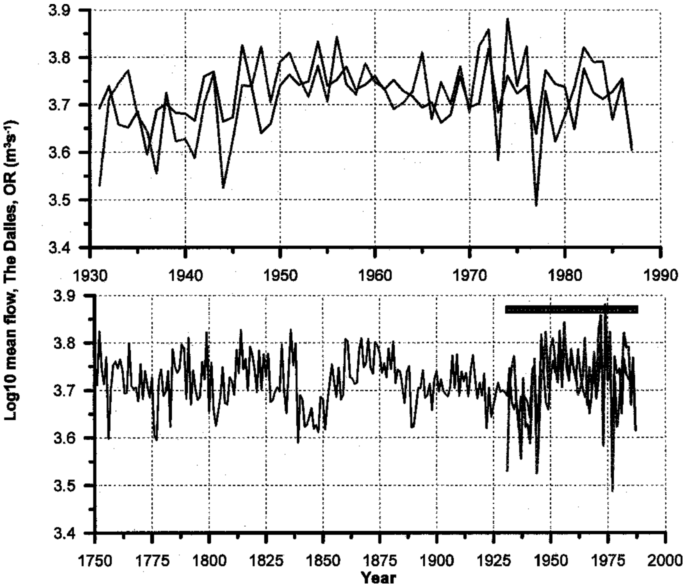

Figure 2. (top panel) Observed (gray) and Cross-Validated Reconstructed (black) Flow at The Dalles, Oregon, for the Calibration Interval 1931 to 1987; (bottom panel) Flow at The Dalles, Oregon, since 1750 Reconstructed Using Tree Rings (black line). The gray overbar indicates the calibration interval.

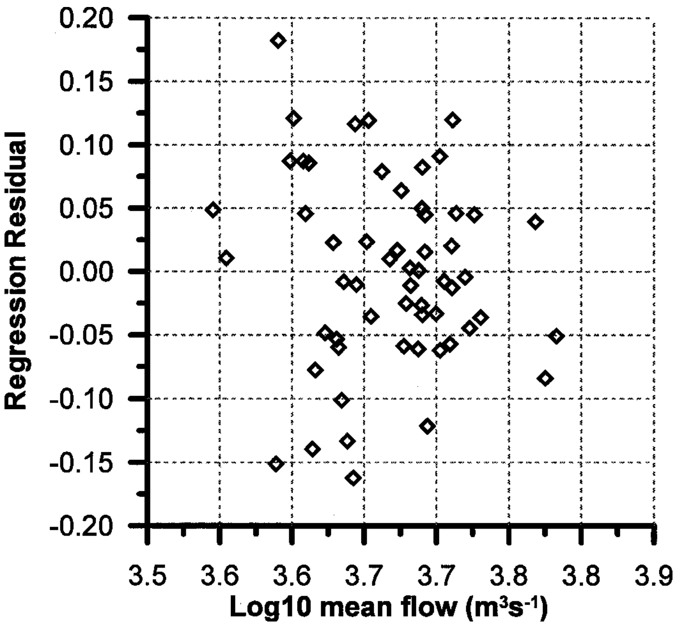

Figure 3. Scatter Plot of the Regression Residuals Against the Cross-Validated Reconstructed Flow Record.

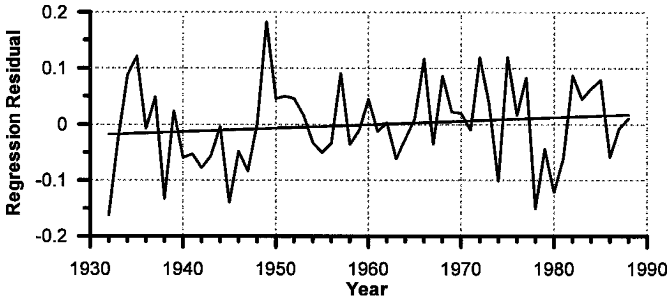

Figure 4. Regression Residuals Plotted as a Function of Time.

Multiyear Drought Events

In order to assess the persistence of drought over the period of the record the reconstruction was filtered using a range of multiyear center moving averages. Window lengths of 5, 11, and 25 years were chosen to characterize interannual, decadal, and interdecadal flow regimes. Years that fell into the lowest 15 percent (i.e., the 35 lowest flow years) were then ranked and plotted as a function of time (see Woodhouse, 2001) (Figure 5). Using this criterion the distribution of single-year low flow events is fairly constant over time, although there is a conspicuous cluster of low flow years during the 1840s. Intervals of persistent drought become more evident as longer window lengths are considered. In particular, the interval from circa 1840 to 1855 appears to be the most severe and most persistent drought on record. The 1930s and 1890s also emerge as periods of sustained low flows. Notable shorter intervals of low flow occurred at circa 1775, 1805, 1925. The period from 1950 to 1987 is notable for having no multiyear droughts in the bottom 15th percentile. These results are generally consistent with a regional precipitation reconstruction developed by Graumlich (1987) using a network of tree-ring data independent of the network used here. In her reconstruction, prolonged dry intervals occurred in the 1790s, 1840s, around 1870, around 1890, and the 1930s (see Graumlich, 1987; Figure 4). The Columbia River reconstruction described here places the drought of the 1790s closer to 1800, but otherwise there is good consistency between the two records.

The period of low flows during the 1840s coincides with drought on the Great Plains as reconstructed from tree rings and historical reports of sand dune activity (Muhs and Holliday, 1995; Woodhouse and Overpeck, 1998; Woodhouse, 2001). Similarly, streamflow in California as reconstructed by tree rings was also substantially below normal (Earle, 1991; Meko *et al.*, 2001). In contrast, lake levels at Crater Lake were likely among the highest they have been in the

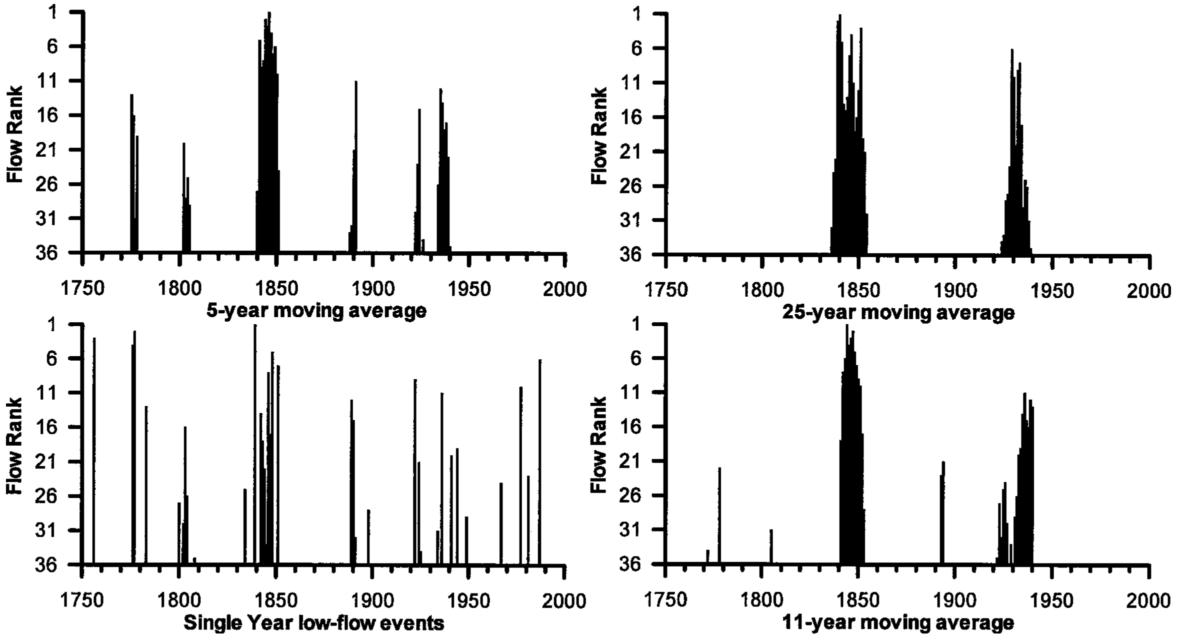

Figure 5. The Distribution of n-Year Moving Average Mean Flow for the Lowest 15th Percentile Over the Period of Reconstruction. Low rankings are indicated by longer bars, and represent lower flow events.

last 200 years (Peterson *et al.,* 1999), and streamflow in the US Southwest was close to normal (Meko and Graybill, 1995). Cook *et al.* (1999) describe a pattern in drought that is fairly persistent throughout the 1840s east of the Cascade Mountains, but sporadic in coastal areas, possibly accounting for these discrepancies in the paleorecords. In contrast to these findings, the drought of the 1890s is absent from the records of California streamflow (Earle, 1991; Meko *et al.,* 2001) and Crater Lake level (Peterson *et al.,* 1999), but is present in the Colorado Front Range (Woodhouse, 2001), the Great Plains, and the US Southwest (see Figure 3 in Woodhouse and Overpeck, 1998).

The drought of the 1930s is well recognized and corresponds to a period of widespread crop failures and mass migrations out of the Great Plains region. Analyses of tree-ring reconstructions suggest that in some regions this drought may have been the most severe of the last 300 years (Earle, 1991; Cook *et al.,* 1999; Meko *et al.,* 2001). In northwestern New Mexico and parts of the Great Plains, however, the 1930s drought is relatively minor in the longer context (D'Arrigo and Jacoby, 1991; Woodhouse and Overpeck, 1998). The results presented here suggest that in the interior Columbia River Basin the 1930s drought was probably matched only once for length in the last 250 years; although the drought of the 1840s was probably more severe in terms of sustained low flows.

Comparison to the Instrumental Record

The strength of this reconstruction, as measured by the correlation coefficient and RE, is comparable to other dendrohydrologic reconstructions from temperate regions (e.g., Cook and Jacoby, 1983; Jones *et al.,* 1984), but is weaker than reconstructions from arid and semi-arid regions (e.g., Meko and Graybill, 1995; Meko *et al.,* 2001; Woodhouse, 2001). In order to assess whether this difference can be attributed to limitations in the tree-ring record or to a low signal-to-noise ratio in the streamflow data, an identically specified reconstruction of streamflow was attempted using the divisional PDSI data in lieu of the tree-ring record. Four scenarios were considered: (1) mean water year PDSI at all climate divisions within the Columbia River basin; (2) mean winter and mean summer PDSI at all climate divisions; (3) mean water year PDSI for only those climate divisions represented by tree-ring chronologies; and (4) mean winter and mean summer PDSI for the same climate divisions. These data were treated in the same manner as the ring width chronologies – that is, they were combined using PCA, autoregressive modeled, bootstrapped, and independently cross-validated (Table 2).

The instrumental record captures between 65 and 78 percent of the variability in the flow record. Additionally, the quality of the reconstruction increases when only those climate divisions from which this study uses tree-ring data are used. Using these

TABLE 2. Cross-Validated Summary Statistics for the Instrumental PDSI and Tree-Ring Based Reconstructions of Streamflow at The Dalles, Oregon.

Subset*	PCs in Model	Reduction of Error	Pearson R	R^2
1	1, 2	0.650	0.81	0.65
2	1,2,5	0.719	0.85	0.72
3	1, 2	0.716	0.85	0.72
4	1, 2, 5	0.779	0.88	0.78
Cross-Validated Reconstruction	1, 2, 4	0.241	0.50	0.25
Full Model Reconstruction	1, 2, 4	0.290	0.59	0.35

*See text for subset descriptions.

results as a benchmark, the tree-ring chronologies used in this study are capturing between one-third and one-half of the recoverable signal in streamflow variability. There are several potential causes for this disparity: (1) the tree-ring chronologies are imperfect recorders of drought; (2) drought is spatially heterogeneous within a given climate division, and the tree-ring network is not extensive enough to capture this variability; and (3) trees may not be sensitive to drought at the time of year relevant to runoff production. Of these factors, the first seems the most likely, and the results presented here are probably not limited by the relatively sparse network of tree-ring sites. While it is possible that a more restrictive screening process could produce a stronger reconstruction, even modest increases in the minimum correlation to PDSI resulted in very small data matrices. For example, increasing the correlation threshold to $|r| > 0.35$ excluded all but eight of the potential chronologies, including all of the sites in Canada and Washington. Bootstrapping the resulting PC regression coefficients did not yield any significant predictors of streamflow. An alternative interpretation of this result is that whereas the climate division records represent composites of dozens of measuring stations throughout the region, each tree-ring site represents a single point. The spatial heterogeneity of precipitation (in particular) may contribute to local noise being incorporated into the streamflow reconstruction because of the sparseness of the sampling network compared to the instrumental record. Similar to the analysis of the tree-ring data, the regression residuals from the instrumental record showed an increasing trend in streamflow relative to drought. The magnitude of this trend corresponds to an increase in flow of 5.8 percent over the interval 1900 to 1990.

Comparison to Proxy Records of Large-Scale Climatic Variability

Streamflow on the Columbia River responds strongly to climatic forcing from ENSO, the PDO, and interactions between the two (Hamlet and Lettenmaier, 1999a). Warm ENSO events (i.e., El Niños) are characterized by positive sea surface temperature (SST) anomalies in the far eastern tropical Pacific, coupled with weakened or reversed trade winds (Enfield, 1989). The typical response in the North Pacific sector to ENSO forcing is a deepened wintertime Aleutian Low, cold SST anomalies in the Gulf of Alaska, warm SST anomalies in coastal regions, and associated downstream teleconnections (Ropelewski and Halpert, 1986; Yarnal and Diaz, 1986). ENSO events typically recur every three to seven years, although strong events are more rare (Enfield, 1989). The PDO is similar to ENSO in terms of its effects on the North Pacific ocean/atmosphere system, except that it is expressed primarily in the extratropics, and individual events typically persist for two or more decades (Mantua *et al.*, 1997; Zhang *et al.*, 1997). Interannual variability within individual phases of the PDO is substantial, and shifts between states may be abrupt (Mantua *et al.*, 1997; Gedalof and Smith, 2001b), making it difficult to identify the state of the system except in hindsight. Constructive (destructive) interference typically causes the effects of ENSO and the PDO to be additive (confounded) when the modes are acting in (out of) phase (Gershunov and Barnett, 1998).

Hamlet and Lettenmaier (1999a) developed composite hydrographs for various combinations of warm, cool, and neutral PDO and ENSO events and showed that forecasting skill could be improved significantly by incorporating information on the state of these systems. Streamflow during El Niño events is on average 12 percent below normal, and during La Niña events it is on average 8 percent higher. The response to PDO is comparable, with flow typically 9 percent below normal during warm regimes and about 6 percent above normal during cool regimes. When ENSO and the PDO are in phase, flow is on average 17 percent below normal (El Niño coeval with warm phase PDO) and 14 percent above normal (La Niña coeval with cool phase PDO). When the two systems are in opposing states their effect on flow may be diminished due to interference in the teleconnections.

Several long records of PDO/ENSO activity offer the possibility of evaluating these relationships prior to the initiation of instrumental records (e.g., Quinn *et al.*, 1987; Stahle *et al.*, 2000; Biondi *et al.*, 2001; D'Arrigo *et al.*, 2001; Gedalof and Smith, 2001b). Two such indices of ocean/atmosphere variability provide a context for the reconstructed flow record. Gedalof and Smith (2001b) developed a proxy record of the PDO index since 1600 using chronologies of mountain hemlock (*Tsuga mertensiana*) from the Pacific Northwest. Stahle *et al.* (1998) developed a record of the Southern Oscillation Index (SOI) from ENSO sensitive regions of subtropical North America and Indonesia. The correlation between flow at The Dalles and these indices was calculated over selected time intervals in order to characterize the time stability of the associations (Table 3). This analysis shows that over the 20th Century the correlation between streamflow and ENSO, and between streamflow and the PDO, is significant whether instrumental or proxy records are considered. In contrast when the preinstrumental interval is considered separately the correlations are substantially weaker: the correlation to the Gedalof and Smith (2001) PDO index is not significantly different from zero, and correlation to the Stahle *et al.* (1998) SOI reconstruction indicates that approximately half the variance is explained over the preinstrumental portion as over the 20th Century.

These results imply that the relationship between PDO, ENSO, and flow on the Columbia River has not been consistent over time. Gedalof *et al.* (2002) found evidence that a number of proxy records of Pacific Basin variability exhibited poor intercorrelations over much of the 19th Century. Prior to circa 1825, however, the intercorrelations are comparable to those seen in the 20th Century. They concluded that the PDO might have been a less important organizing structure of the North Pacific ocean/atmosphere system over this interval. The tree-ring chronologies used to develop this reconstruction are independent of those reconstructions and support these inferences regarding the North Pacific ocean/atmosphere system during the 19th Century.

One other relevant paleoproxy reconstruction is the gridded PDSI reconstruction of Cook *et al.* (1999). This reconstruction was developed using tree-ring chronologies largely independent to those used in this analysis, and therefore represents a reasonably independent verification of the reconstruction presented here. From the network of reconstructed PDSI grid points, the points needed to represent variability within the Columbia River drainage basin were extracted (GPs 1-4, 8-11, and 16-18). Because these grid points are highly spatially autocorrelated, a PCA was applied to reduce the dimensionality of the dataset and derive orthogonal predictors. Two PCs were retained, explaining 65 and 16 percent of the variance, respectively. The leading PC is well correlated with the reconstructed flow record (r = 0.502), as well as the gauged flow records (r = 0.479). The intervals of persistent low flows identified in the streamflow reconstruction generally correspond to periods of prolonged drought (Figure 6). In particular, low flows during the 1770s, 1840s, 1890s, and 1930s all correspond to periods of reconstructed drought.

TABLE 3. Cross Correlations for the Gauged and Reconstructed Flow at The Dalles, Oregon, With Proxy Records of PDO and ENSO Variability for Selected Time Intervals.

	Gauged Flow Record	**Reconstructed Flow Record**		
Proxy Record	**1931 to 1987**	**1750 to 1987**	**1900 to 1987**	**1750 to 1899**
Instrumental PDO Index*	**-0.435**	–	**-0.334**	–
Instrumental SOI**	**0.377**	–	**0.202**	–
Gedalof and Smith, 2001b (PDO)	**-0.246**	-0.101	**-0.241**	-0.044
Stahle *et al.*, 1998 (SOI)	**0.518**	**0.195**	**0.240**	**0.177**

Note: Correlations that are significant at 90 percent confidence are indicated by bold script.
*PDO index averaged over October of the preceeding year to March of the current year.
**SOI averaged over June to November of the preceeding year.

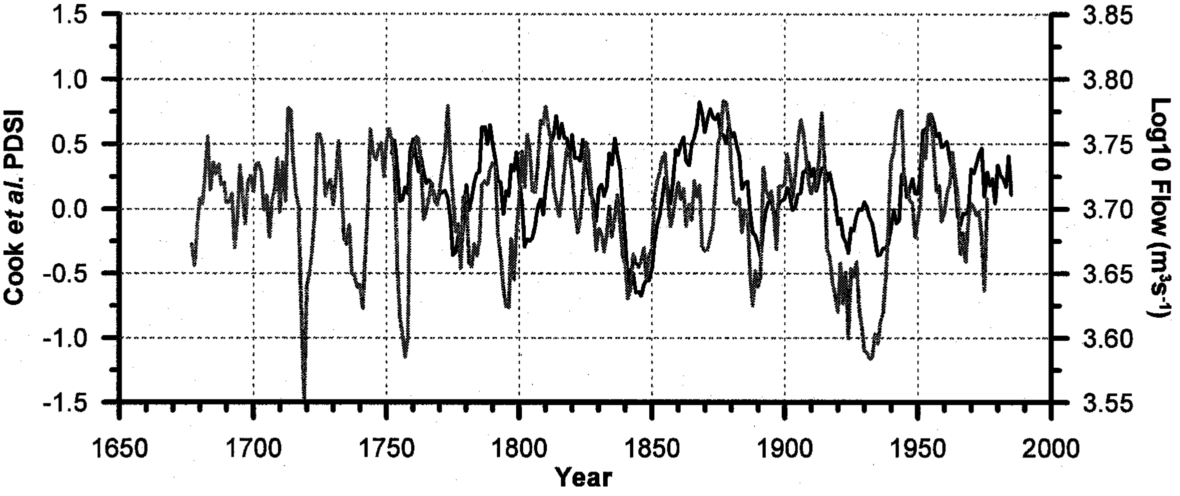

Figure 6. The Leading Principal Component of Reconstructed PDSI (Cook *et al.*, 1999) for Grid Points Representing the Columbia River Basin (gray), and the Reconstructed Columbia River Flow for The Dalles, Oregon (black). The low frequency variability has been emphasized in both records using a five-year running average filter.

CONCLUDING REMARKS

Tree-ring chronologies offer the opportunity to extend instrumental records into the past for the purpose of assessing the representativeness of recent observations, especially with respect to low frequency changes and extreme events. This reconstruction of flow on the Columbia River has revealed four key findings.

1. Severe droughts have occurred in the past, probably more severe than what has been experienced in the 20th Century. An interval of persistently lower flows than has occurred during the gauged record occurred around the 1840s. However, the drought of the 1930s is probably the second most severe of the last 250 years. This drought should not be regarded as an anomalous event, but is likely a typical fluctuation of the Columbia River system.

2. Land use changes in the Columbia River Basin have probably contributed to increases in runoff relative to drought severity or precipitation. This trend is evident in the residual statistics of both instrumental and tree-ring based reconstructed flow, and corresponds to an increase in flow of about 3.7 percent over the interval 1931 to 1987. Both the magnitude and phase of the increase are consistent with results from numerical models.

3. The tree-ring chronologies used in this study do not adequately capture the magnitude of severe low flow events. This limitation is probably not caused by the sparse distribution of tree-ring sample sites within the basin, because a comparable network of climate divisions was able to reconstruct flow records more accurately. The model performance may be limited by the imperfect correspondence between PDSI and radial growth increment, or it may be a consequence of sparse within division distribution of tree-ring sites failing to capture the spatial heterogeneity of precipitation that is reflected in divisional means.

4. The relationship between reconstructed flow and long records of ocean/atmosphere variability has not been constant over time. In particular, the correlation between the PDO and reconstructed flow is conspicuously stronger during the 20th Century than during earlier centuries. This result is coeval with a period of poor correspondence between independent proxy records distributed throughout the Pacific Basin. Severe low flow events occurred under 20th Century and pre-20th Century circulation regimes, suggesting that disparate forcing mechanisms can lead to comparable low flow events.

The Columbia River Basin supports diverse natural resources, economic investment, and social values. With a rapidly growing population this region is increasingly vulnerable to drought events (Miles *et al.*, 2000). Recent droughts have led to conflicts among uses (e.g., hydroelcetric production versus protecting salmon runs), increased costs to end users (notably municipal power users), and in some cases the total loss of access to water (in particular junior water rights holders in the agricultural sector). These recent droughts were not exceptional in the context of the last 250 years and were of shorter duration than many past events. Furthermore, water management strategies have been developed over the last half century, a period characterized by a unique lack of multiyear droughts. Additionally, impending climate change could cause the frequency of severe low flow years in the Columbia River system to at least double by 2045 and possibly quadruple (Hamlet and Lettenmaier, 1999b). Interpreted together these findings pose substantial challenges to water managers in the Pacific Northwest: the basin has been fully exploited in terms of storage capacity, the demands posed on the system continue to increase, availability is likely to diminish, and the potential for multiyear droughts has probably been underestimated.

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