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RECONSTRUCTION OF PAST RIVER FLOW AND PRECIPITATION IN CANTERBURY, NEW ZEALAND FROM ANALYSIS OF TREE-RINGS

D. A. Norton

School of Forestry, University of Canterbury, Private Bag, Christchurch, New Zealand

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ABSTRACT

Nothofagus solandri tree-ring chronologies developed from four mid-altitude sites in Canterbury, New Zealand are statistically similar but distinct from subalpine *N. solandri* chronologies in the same area. Ring-width is strongly influenced by summer precipitation, with less growth in summers of below average precipitation. Reconstructions from 1879 A.D. of Lake Coleridge summer precipitation and Hurunui River summer flow records from tree-rings are presented. The flow reconstruction suggests that the frequency of low river flow summers between 1879 and 1977 was three times greater than over the period of measured river flow (1956–1977). These reconstructions illustrate the potential of dendroclimatology to provide long-term proxy hydrological data for the management of water.

INTRODUCTION

In some areas of New Zealand variable precipitation and river flow seriously limit agriculture, and affect other water-dependent activities, such as forestry, fisheries, engineering, and hydro-electric power generation. Long-term plans for water resources are based on often short instrumental records, as few New Zealand precipitation records extend prior to 1900 A.D. and many are no longer than 30 to 40 years. Records of river flow cover largely the last 20 to 30 years only. Evaluation of long-term variations in precipitation and river flow are based on these data, but it is not known if these records are representative of longer-term conditions. Proxy sources of information on past precipitation and river flow could overcome this uncertainty.

Dendroclimatology is a technique that takes advantage of the influence of the limiting climatic conditions on tree growth. This technique was developed for dry areas of western North America where tree growth at sites near the lower forest border was found to be very dependent on available soil moisture and hence precipitation (Douglass 1914). During dry years, little growth occurred and narrow growth rings were formed, while in years with adequate precipitation, wide growth rings were formed. The correlation between ring-width and precipitation suggested that past precipitation could be estimated using annual growth rings, and past droughts were reconstructed using tree-ring sequences (e.g. Schulman 1956).

More recently, tree-ring reconstructions of past precipitation and other meteorological variables have been statistically analysed (Fritts 1976), and several reconstructions of past precipitation (e.g. Blasing and Duvick 1984, Stockton and Meko 1983) and river flow (e.g. Cook and Jacoby 1983, Jones et al. 1984) developed. In these studies, instrumental records of precipitation and river flow have been calibrated against ring-width times-series, and the relationship verified with independent data to produce statistically-significant reconstructions of conditions prior to instrumental records. Most studies have reconstructed growing season (i.e. summer) precipitation and river flow.

Over the last decade, dendroclimatological techniques have been successfully applied to New Zealand trees (Dunwiddie 1979, Norton 1983a,b, 1984,1985, Ahmed and Ogden 1985; Norton and Ogden 1987). In the present paper I evaluate the potential of using *Nothofagus solandri* tree-ring chronologies for reconstructing past precipitation and river flow in Canterbury, New Zealand.

Three of the tree-ring chronologies used here (GHC, LKP, RTA) were first presented in unpublished dissertations (Norton 1979; Aston 1982), and the fourth (LGH) was presented by Norton (1985). The original ring-width data are re-analysed in the present study.

STUDY AREA

Trees were sampled at three sites in Castle Hill and Flock Hill basins, 30 to 40 km east of the main divide of the Southern Alps, and at a fourth site

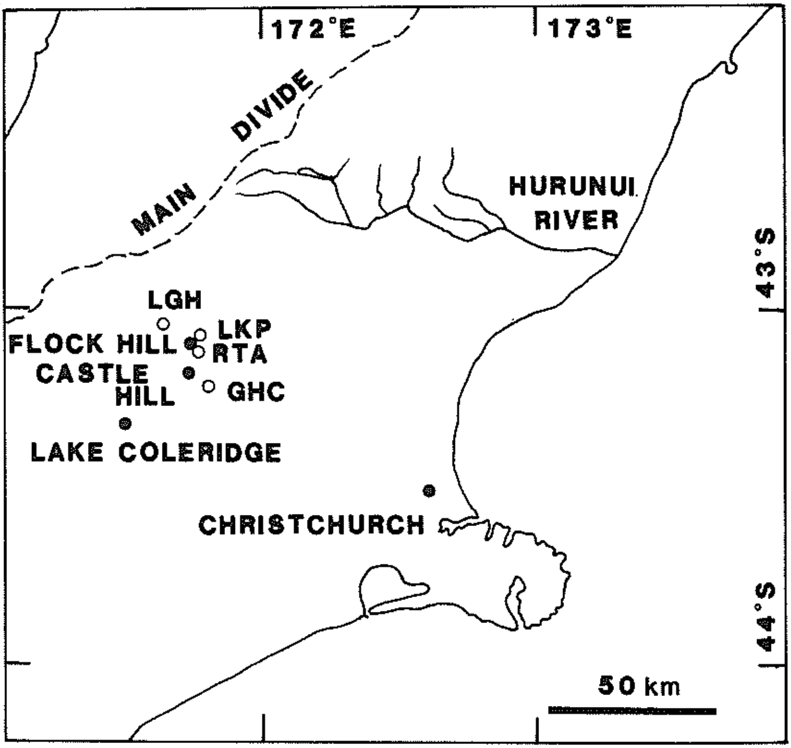

FIG. 1. Central South Island, New Zealand. o, tree-ring sampling sites ●, climate stations.

TABLE 1: Sampling site details for the four chronologies.

CODE	ALTITUDE (m)	ASPECT	SLOPE (°)	SAMPLING DATE	GRID REF. (NZMSI S66)
GHC[1]	870	NW	30	July 1981	222917
LGH[2]	900	N	30	January 1981	185118
LKP[3]	970	NW	25	April 1979	266078
RTA[1]	950	N	25	July 1981	265027

(Source of chronologies: 1, Aston 1982. 2, Norton 1979. 3, Norton 1985).

in Cass Valley (Fig. 1). The Castle Hill and Flock Hill basins, adjacent to the Craigieburn Range, are inter-montane depressions surrounded by mountain ranges rising to about 2000m. These mountains are composed of Mesozoic sandstones and are characterized by long, steep talus slopes and areas of outcropping bedrock forming steep bluffs.

Small forest remnants are present on bluffs, on talus slopes and in stream gullies in this area. These are relics of previously more extensive forests that were largely removed by fire (Molloy 1977). Today the deforested areas support modified grassland and shrubland communities, and are used extensively at lower altitudes for pastoral farming. The forest remnants on the bluffs and talus slopes are dominated almost solely by *Nothofagus solandri* and have a very sparse and open understorey with little ground vegetation (cf. association D1, Wardle 1970).

The climate of these inland basins has not been described in detail. 1951–1980 annual precipitation normals at Flock Hill and Castle Hill stations (Fig. 1) were 1258mm and 932mm respectively (New Zealand Meteorological Service 1980), with a winter precipitation maximum. No temperature records exist for the basins. Winter-time minimum temperatures are certainly below −10° C and summer-time maximum temperatures are above 25° C (pers. obs.). Heavy snowfalls occur to low levels in winter and spring (Burrows 1976).

The Cass Valley site, located on a ridge crest at the northern end of the Craigieburn Range, is fully described by Norton (1985; LGH622 site). Although precipitation is probably higher than at the other sites, the steep slopes (30°) undoubtably reduce soil water availability. Forest cover is more extensive in Cass Valley but the forest at the study site location is similar to the other sites.

METHODS

Chronology development

Field sampling was undertaken between 1979 and 1981. Two cores were extracted from 10 to 15 trees at each site with a 7mm Swedish increment borer, and some trees were also felled to obtain cross-section samples. Site details are summarized in Table 1. Preparation of the cores followed standard procedures (Stokes and Smiley 1968, Norton and Ogden 1987).

The patterns of narrow and wide growth rings were matched (crossdated) between the individual ring-width series at each site to identify absent or false growth rings (Fritts 1976), thus ensuring the absolute dating of the ring-widths. After crossdating, ring-widths were measured to the nearest 0.01mm using an Addo-x tree-ring measuring machine.

Low-frequency 'growth trends' related to biological growth and aging processes are commonly present in ring-width time-series from individual trees. For dendroclimatological purposes this biological growth trend is removed by some curve-fitting or related technique, a process termed 'standardization' (Fritts 1976). Standardization involves dividing the measured ring-widths for each ring-width time-series by some value representing this non-climatic growth trend. The measured ring-width series were standardized here by dividing the measured data by equivalent yearly values derived by smoothing these data with a Gaussian filter which passes 25% (or less) of the variance at periods of 30 years (or greater) (Briffa 1984, Norton and Ogden 1987). Little of the variance above 30 years is preserved in the standardized series, and climate fluctuations on these time-scales cannot be reconstructed using this technique.

The climate signal, assumed common to all trees at a site, was then enhanced by averaging all the cores for each site to produce a site tree-ring chronology. Various statistics characterizing these chronologies were then calculated (see Fritts 1976, and Wigley et al. 1984, for further details.)

Climate analysis

The climate analysis falls into two parts: response-function analysis, identifying the main climatic factors influencing tree growth, and transfer-function analysis, using the tree-ring chronologies to reconstruct past climate.

The response-function analysis compared monthly mean daily temperature and total precipitation with the tree-ring chronologies. Although these are not necessarily the most biologically significant climatic variables, the lack of long homogeneous records makes the use of other data (e.g. radiation intensity) impractical. Based on 'response areas' with similar climate identified by Salinger (1979), temperature data from Christchurch and precipitation data from Lake Coleridge (Fig. 1) were used. These were the longest homogeneous records within the temperature and precipitation response areas of the tree-ring sampling sites.

The number of months of climate data used in such analyses can be varied, but to reduce statistical interference between climate in the previous and current years only 12 months each of temperature and precipitation data were used, starting in June before the growing season. The significance of previous climate was assessed by including the three preceding growth years in the regression.

The principal-components multiple-regression technique described by Briffa et al. (1983) and Norton (1984) was used to relate the climate variables to the tree-ring chronologies. The climate data are first subjected to principal components analysis to remove inter-correlations within these data. The resultant orthogonal variables are then regressed against each tree-ring chronology separately. The significance of the regression equation was determined using the multiple correlation coefficient (R) which indicates how similar are the values estimated from the regression to the observed values.

The second part of the climate analysis uses tree-ring chronologies to reconstruct past climate through transfer-function analysis. The rationale for using transfer-function techniques has been discussed by Fritts (1976) and Webb and Clarke (1977), while Fritts et al. (1971, 1979), Lofgren and Hunt (1982) and Briffa et al. (1983) discuss aspects of its use. The four tree-ring chronologies were regressed against recent climate data to calibrate a transfer-function using the principal-components multiple-regression technique. The transfer-function was then tested on independent data, and finally applied to the period prior to instrumental records to estimate past climate.

The calibration was verified by splitting the instrumental data into two subsets: the first and larger subset for calibration and the second, smaller subset for verification. The estimated and observed values over the verification period were compared using the Pearson product — moment correlation coefficient (r) and the reduction-of-error statistic (Fritts 1976). The latter is a more rigorous statistic than r because it accounts for the position of the calibration mean relative to the observed and estimated means. Positive reduction-of-error values are considered encouraging.

Tree growth in any one year (i) is influenced by both climate in that year and by growth in the previous year (i-1). Climate in any one year also affects growth in the subsequent year (i+1). To reconstruct climate, both prior growth and lag effects (Fritts 1976) must be taken into account. For each chronology, values for years i-1, i, and i+1 were used as predictors in the regression analysis, giving a total of 12 predictors.

Choice of suitable hydrological data to reconstruct was constrained by the record length and quality, and proximity to the tree-ring sampling sites. As no reliable precipitation records are available from the study area, that for Lake Coleridge was chosen as it lies within the same climate-response area (Salinger 1979).

To reconstruct river flow it is necessary that precipitation in the river's main catchment area is influenced by the same synoptic situations that affect the tree-ring sampling sites. In Canterbury, catchments of the main rivers (Rangitata, Rakaia, Waimakariri) extend back to the main divide of the Southern Alps and are located at high altitude (e.g. 28% of the Rakaia catchment is above 1500m, Bowden 1977). The flow of these rivers is therefore strongly correlated with westerly airflow (Ibbitt 1979). It was thus necessary to select a river whose catchment lies mainly in the eastern ranges where the tree-rings were sampled. The Hurunui River (Fig. 1) had the longest record and drains only a short section of the main divide; only 8% of its catchment is above 1500m (Bowden 1977). The Hurunui was therefore chosen for this study.

RESULTS AND DISCUSSION

Chronology development

The four chronologies and statistics describing them are presented in Fig. 2 and Table 2. These chronologies readily crossdate with each other (mean inter-chronology r = 0.45±0.16) and appear distinct from other *Nothofagus solandri* chronologies. Few growth ring sequences could be reliably crossdated with those from adjacent subalpine *N. solandri* trees. Tree growth rates are on average fast compared with trees sampled for other New Zealand chronologies (LaMarche et al. 1979, Norton 1983a,b, Ahmed and Ogden 1985). However, tree ages are young: the oldest tree measured was only 200 years. This is considerably less than obtained for *N. solandri* trees growing near the alpine

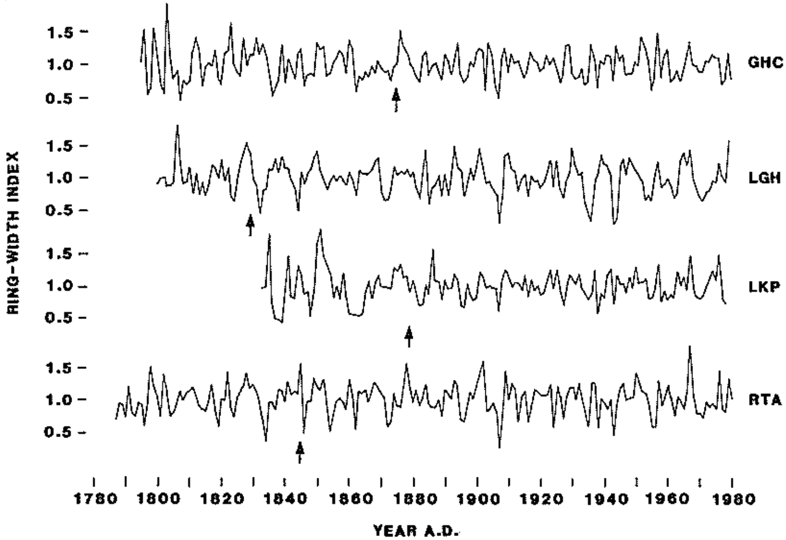

FIG. 2. Plots of the four *Nothofagus solandri* chronologies. The arrows indicate the first year in which the chronologies become reliable.

timberline (Norton 1983a). The nature of the sites, with the possibility of frequent rockfall, probably limits tree life in many cases.

Autocorrelation values are low to moderate and mean sensitivities moderate. Autocorrelation (lag-one correlation) is a measure of the average dependence of the ring-width value for a given year on the value for the previous year. Low autocorrelation may reflect a short leaf-retention period in these trees (c.f. LaMarche and Stockton 1974). Mean sensitivity is the average absolute difference between two successive ring-width values divided by their mean value; the moderate values observed here indicate considerable variation in ring-width from year to year. For the period common to all trees in each chronology, correlation values between trees within chronologies range from 0.40–0.53. These are comparable to values calculated for subalpine *N. solandri* chronologies (Norton 1983a) and suggest that the same factor influences growth in most of the trees within each site. The percentage of absent rings is lower than in the subalpine chronologies (0.10% c.f. 1.35% in Norton 1983a), confirming that fewer rings tend to be absent at lower altitudes, as noted by Norton (1985).

The number of individual ring-width time-series making up each chronology decreases further back in time. The minimum number of time-series needed for a reliable statistical estimate of the chronology can be estimated (Wigley et al. 1984). The first reliable year in each chronology and the number of cores required are indicated in Table 2 and Fig. 2; portions of the chronologies prior to this date cannot be considered reliable and are not used in the climate analysis.

TABLE 2: Chronology statistics (see Fritts 1976 and Wigley et al. 1984 for full descriptions).

	GHC	LGH	LKP	RTA
PERIOD	1795-1980	1800-1979	1833-1978	1787-1980
RADII	20(12)	21(11)	11(6)	21(12)
AC	0.09	0.35	0.28	0.13
MS	0.20	0.18	0.18	0.21
SE	0.15	0.15	0.17	0.14
r	0.45	0.53	0.40	0.46
%ABS	0.23	0.04	0.00	0.12
SERIES	5	4	4	4
YEAR	1875	1830	1879	1845
MRW	1.41	0.90	1.00	1.27

PERIOD	total period covered by chronology
RADII	total number of radii in chronology (number of trees from which these were collected in brackets)
AC	autocorrelation (lag-one correlation)
MS	mean sensitivity
SE	Standard error of chronology (mean=1.0)
r	correlation between all series in chronology
%ABS	percentage absent rings
SERIES	minimum number of ring-width series required for a reliable estimate of the chronology
YEAR	year in which the required number of series first present
MRW	mean ring width for all cores (mm)

Response-function analysis

Regression coefficients for the four regression analyses are presented in Fig. 3 and the regression statistics tabulated in Table 3. Multiple correlation coefficients are similar, ranging from 0.76 to 0.81. However, variance explained by climate ranges from 43.6 to 63.5%, and is substantially greater than that found for other *Nothofagus* chronologies (Norton 1984). Only in the LGH regression is important variance explained by prior growth. Clearly climate explains much more of the variability of ring-width than does prior growth.

Interpretation of the response-functions is usually based on the individual regression coefficients. However although regression coefficients may be statistically significant ($p<0.05$), this does not necessarily imply a direct cause-and-effect relationship between ring-width and climate. Gray et al. (1981) showed that, for a response-function with 28 elements (27 in the present study), three could be expected to be significant by chance. The number of significant

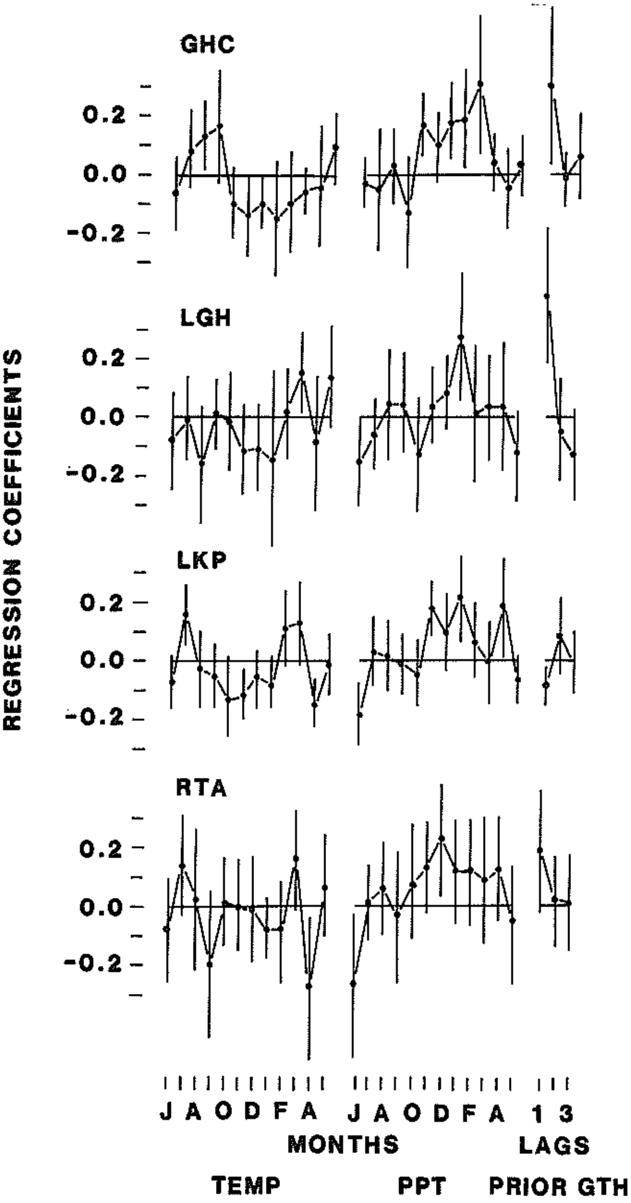

FIG. 3. Regression coefficients plotted for the four chronologies. 95% confidence limits are plotted for each coefficient; significant coefficients are those where the confidence limits are either both above or below the zero line. The analyses ran from June before growth to May at the end of the growing season.

TABLE 3: Performance of regression equations in response function analysis.

	GHC	LGH	LKP	RTA
K	6	9	7	10
R	0.76	0.81	0.76	0.80
F	8.93	7.74	7.52	6.39
p	$0.46x10^{-5}$	$0.37x10^{-5}$	$0.13x10^{-4}$	$0.19x10^{-4}$
r^2_{total}	0.58	0.66	0.58	0.64
$r^2_{climate}$	0.54	0.44	0.57	0.63
$r^2_{prior\ growth}$	0.04	0.22	0.01	0.01

K	number of predictors entering the regression using a t-value cut-off of 1.0
R	multiple correlation coefficient
F	F-value and probability (p) of obtaining such a value by chance
r^2_{total}	total variance explained in regression
$r^2_{climate}$,	variance explained by climate in regression
$r^2_{prior\ growth}$,	variance explained by prior growth in regression

TABLE 4: Performance of regression equations over the calibration and verification periods. Calibration 1913-1962 and verification 1963-1977 for Lake Coleridge. Calibration 1956-1977 for Hurunui (no verification).

	COLERIDGE	HURUNUI
K	2	2
R	0.68	0.72
F	19.7	10.4
p	$0.12x10^{-5}$	$0.94x10^{-3}$
r_v	0.76	—
RE	0.56	—

K	number of predictors retained in regression equation
R	multiple correlation coefficient
F	F-value and probability (p) of obtaining such a value by chance
r_v	simple correlation coefficient obtained over vertification period
RE	reduction-of-error statistic (see Fritts 1976)

regression coefficients here ranged from three to eight per response-function (Fig. 3). The similarity in the sign of the regression coefficients of the four response-functions, especially the positive association with spring-summer precipitation, increases confidence in their interpretation. Of the 20 significant climate regression coefficients eight are with precipitation between October and February, and are positive. Most of the temperature coefficients at this time are negative (17 out of 20), three significantly so. This relationship suggests a strong dependence of growth on summer precipitation. The reasons for the strong negative association with June precipitation are unclear.

The strong association between ring-width and summer precipitation is similar to that described for arid-site conifers in western North America (Fritts 1976). This probably reflects the influence of soil-moisture deficits on growth, with stomata closing as soil-moisture levels decrease, resulting in reduced CO_2 absorption and photosynthesis. The net result of such water deficits is a reduction in the amount of dry-matter accumulation and hence ring-width. Soil-moisture deficits appear to affect *Nothofagus solandri* growth most in early to mid summer (November, December, January). These results suggest that the four chronologies developed here are potentially useful for reconstructing past hydrological conditions, especially for November-January.

Transfer-function analysis

The summer component (November to January) of the precipitation and river flow series were used in the transfer-functions. The precipitation data set was divided into two for calibration (1913-1962) and verification (1963-1977). The calibration data set is necessarily longer to allow adequate data for the regression analysis. The short length of the river flow record (n=22) precluded verification. The last year included in the analysis (1977) was set

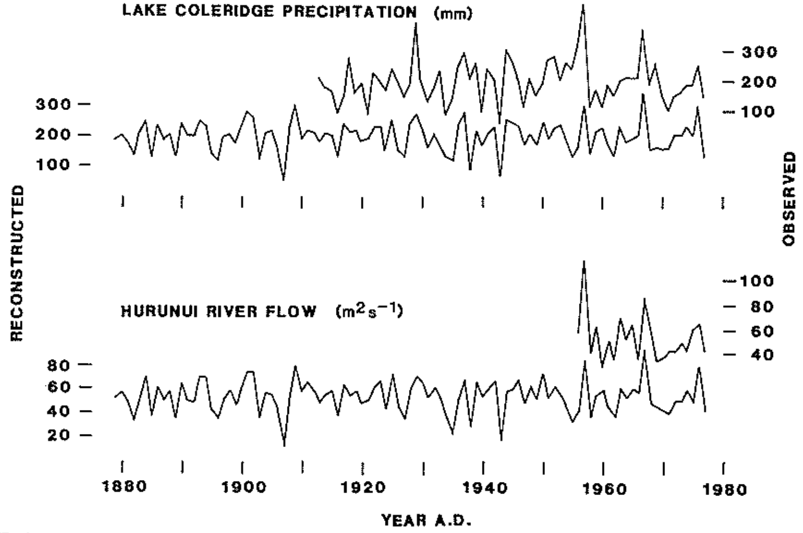

FIG. 4. Observed (upper) and reconstructed (lower) summer values of Lake Coleridge precipitation and Hurunui River flow to 1879 A.D.

by the earliest developed tree-ring chronology (LKP; 1979), allowing for lag years in the analysis.

Statistics describing the two regressions are presented in Table 4. The regression between Lake Coleridge precipitation and the tree-ring chronologies explains 46% of the variance over the calibration period, while 52% of the variance is explained in calibrating the Hurunui River flow regression. 58% of the variance is explained in verifying the Lake Coleridge regression and the reduction-of-error value is positive. As the Hurunui River flow regression could not be directly verified, an indirect test was used. A correlation coefficient of 0.85 was calculated between observed summer river flow and observed Lake Coleridge summer precipitation for the period 1956-1977 (n=22) compared with a value of 0.64 between estimated river flow and observed Lake Coleridge precipitation for the period 1933-1955 (n=22). The significant correlation coefficient for the earlier period ($p<0.002$) suggests that the Hurunui regression equation is valid.

The regression equations were then applied to the same tree-ring data set for the period prior to instrumental measurements back to 1879, the first year in which one of the chronologies was statistically unreliable (Table 2, see above). The observed and estimated values for the two regressions and the estimated values prior to instrumental records are presented in Fig. 4. The regression weights in the Lake Coleridge and Hurunui regressions show an even spread across all four chronologies, suggesting that no one chronology dominated the reconstructions.

Mean values for both the observed and estimated series are almost identical (Table 5) but the standard deviations of the estimated series are less than for the observed series. The skewnesses of the reconstructed series are also less than in the observed data. This suggests that the tree-ring variations do not reflect the full range of hydrological conditions occurring. Summers with high

TABLE 5: Properties of observed and reconstructed (estimated) precipitation and river-flow data sets.

	mean	standard deviation	skewness	frequency
Lake Coleridge precipitation (mm)				
1913-1977 (obs)	197.6	75.2	0.99	0.18
1913-1977 (est)	197.6	50.8	-0.28	0.20
1879-1977 (est)	198.4	51.3	-0.10	0.17
Hurunui River flow (m^3s^{-1})				
1956-1977 (obs)	54.4	21.2	1.50	0.05
1956-1977 (est)	54.4	15.3	1.20	0.09
1879-1977 (est)	53.9	13.6	-0.13	0.15

river flows and precipitation are not being reconstructed as well as those with low river flows and precipitation (Fig. 4). This is not surprising as tree growth is limited by low soil-moisture levels, but once soils are at field capacity, additional precipitation will not further increase growth. The inability to reconstruct high precipitation/flow events has also been commented on for other tree-ring hydrological reconstructions (e.g. Jones et al. 1984).

Adequate calibration and verification of data sets is limited by the short lengths of the available records. Historical records can, however, be used to further verify the reconstructions. Records of floods and droughts in Canterbury since the 1840's have been compiled by Burrows and Greenland (1979) but they do not document the month in which the event occurred. Kidson (1931) and Bondy (1950) have discussed the occurrence of droughts during the period 1900 to 1950. One prominent drought in Canterbury occurred over the 1907-1908 summer (only 20mm rain fell over 81 days in Christchurch; Bondy 1950). Although Christchurch is not in the same precipitation response area as the study site, it is likely that precipitation was also low at the study site at this time. This low precipitation event has been reconstructed well (Fig. 4) and it is also apparent as a low-flow summer. This historical verification adds further confidence to the reconstructions.

Comparison of the observed and estimated frequency of low-flow and precipitation summers (Table 5) highlights the potential of these reconstructions. Summer precipitation and river flow are defined as low if they are more than one standard deviation below the mean. For Lake Coleridge, the frequencies of low-precipitation summers are similar between the observed and reconstructed data, both for the period over which observations were made (1913-1977) and for the total reconstruction period (1879-1977). However, the frequencies for Hurunui River flow would indicate that, for the period 1879-1977, summers characterized by low flows were three times more common than for the observed period 1956-1977 (f=0.15 c.f. 0.05).

CONCLUSIONS

This paper has presented preliminary reconstructions of river flow and precipitation for Canterbury, New Zealand, based on dendroclimatological techniques. The reconstructions extend existing instrumental records back to 1879, permitting analysis of hydrological events over a much longer period than previously possible. The detection of a higher proportion of summers characterized by low river flows for the Hurunui River highlights the potential usefulness of such reconstructions. The development of better replicated and longer tree-ring chronologies for a wide range of sites through the eastern South Island will permit improved reconstruction of both river flow and precipitation back to at least 1800 A.D. The potential value of such reconstructions in managing water resources is considerable.

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