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Paleohydrological context for recent floods and droughts
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E-mail: rbrice@usgs.gov**Keywords:** Fraser River Basin, paleohydrology, dendroclimatology, water resources, streamflow extremesSupplementary material for this article is available [online](#)

Abstract

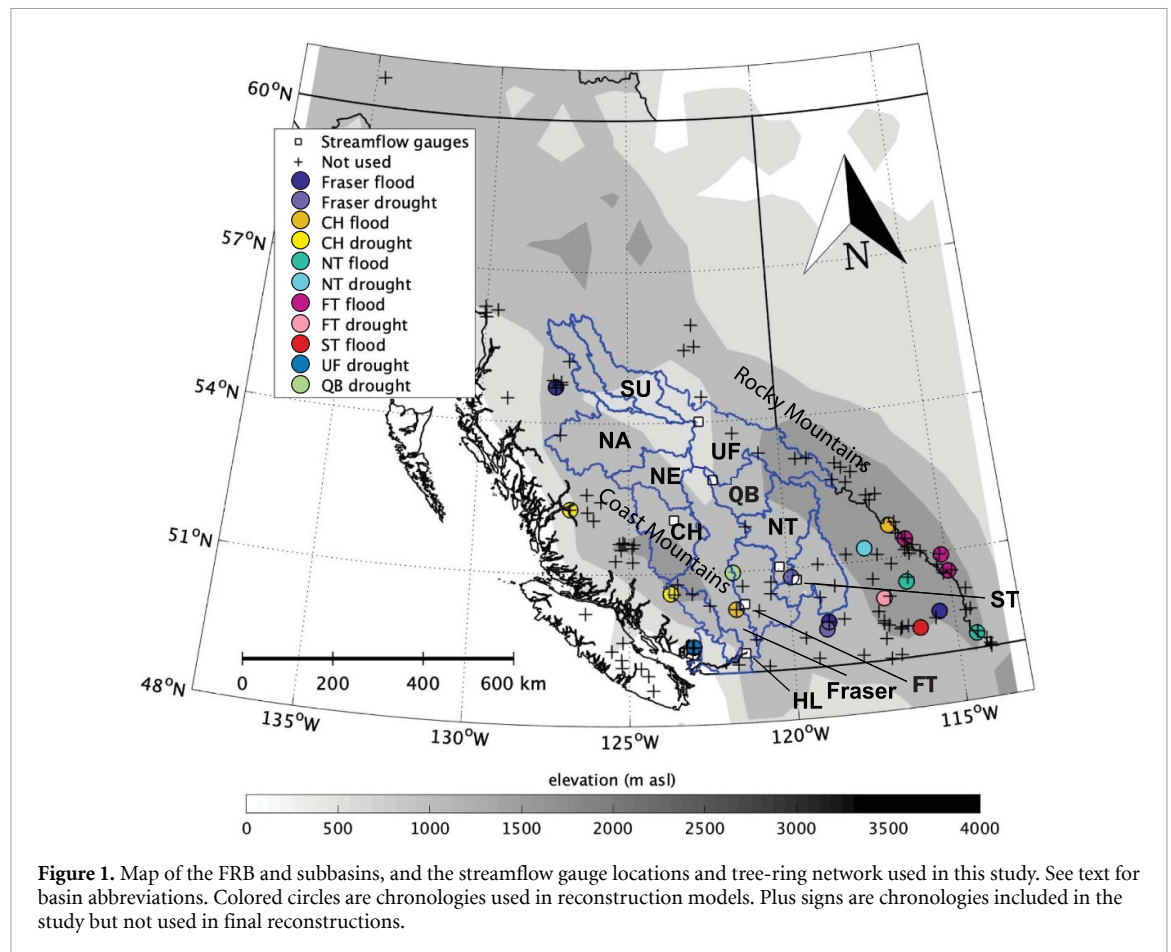
The recent intensification of floods and droughts in the Fraser River Basin (FRB) of British Columbia has had profound cultural, ecological, and economic impacts that are expected to be exacerbated further by anthropogenic climate change. In part due to short instrumental runoff records, the long-term stationarity of hydroclimatic extremes in this major North American watershed remains poorly understood, highlighting the need to use high-resolution paleoenvironmental proxies to inform on past streamflow. Here we use a network of tree-ring proxy records to develop 11 subbasin-scale, complementary flood- and drought-season reconstructions, the first of their kind. The reconstructions explicitly target management-relevant flood and drought seasons within each basin, and are examined in tandem to provide an expanded assessment of extreme events across the FRB with immediate implications for water management. We find that past high flood-season flows have been of greater magnitude and occurred in more consecutive years than during the observational record alone. Early 20th century low flows in the drought season were especially severe in both duration and magnitude in some subbasins relative to recent dry periods. Our Fraser subbasin-scale reconstructions provide long-term benchmarks for the natural flood and drought variability prior to anthropogenic forcing. These reconstructions demonstrate that the instrumental streamflow records upon which current management is based likely underestimate the full natural magnitude, duration, and frequency of extreme seasonal flows in the FRB, as well as the potential severity of future anthropogenically forced events.

1. Introduction

The Fraser River Basin (FRB) in British Columbia (BC), Canada, has the seventh largest annual discharge in North America, sustains some of Earth's most biodiverse wildlands and productive salmon fisheries in the world, contributes to food and economic sovereignty for over 80 First Nations, flows into the third largest metropolitan city in Canada, and is a cornerstone of the western Canadian economy (Fraser Basin Council 2006, 2009, Kang *et al* 2014). The FRB's largely nival (snowmelt-derived) runoff regime is dominated by spring floods and summer droughts, with virtually no significant diversions or impoundment buffering these extreme events. Recent

periods in the FRB historical data indicate significant changes in seasonal streamflow variability (1980–005, $p < 0.10$; Déry *et al* 2012), earlier peak streamflow (1912–2001, $p < 0.05$; Foreman *et al* 2001), and decline in the snow water equivalent (SWE) to runoff ratio (1949–2006, $p < 0.05$; Kang *et al* 2014). Pacific salmon populations, fisheries, industry, and agriculture are all potentially threatened by these emerging shifts in timing and severity of seasonal extremes that are expected to intensify under anthropogenic climate change (Rand *et al* 2006, Kang *et al* 2014).

The FRB comprises the main stem Fraser River (Fraser) and six major subbasins, the Upper Fraser (UF), Thompson (FT), North Thompson (NT), South Thompson (ST), Chilcotin (CH), and Quesnel

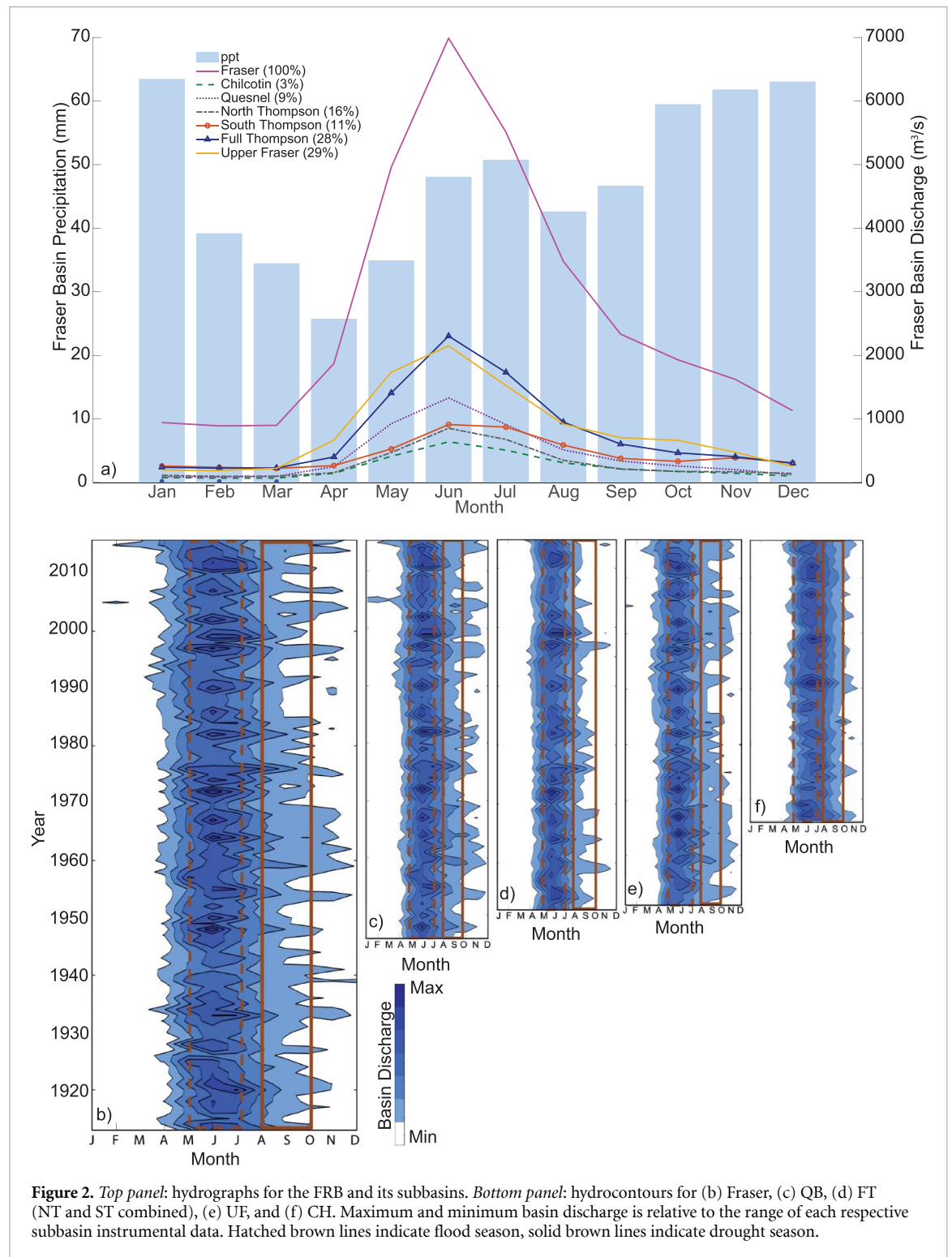


(QB), which together contribute $\sim 76\%$ of annual flow in the Fraser River, as well as the Stuart (SU), Nautley (NA), Nechako (NE), and Harrison-Lillooet (HL, figure 1) (Kang *et al* 2014, 2016). Worsening seasonal high and low streamflow extremes across the FRB are linked to rising air temperatures and attendant widespread alterations to the form, quantity, and timing of cool-season precipitation and snowmelt (Morrison *et al* 2002, Ferrari *et al* 2007, Déry *et al* 2012, Kang *et al* 2016). The resulting broad-scale shift from nival- to more pluvial (rainfall)-dominated runoff regimes (Shrestha *et al* 2012, Kang *et al* 2014) has driven runoff quantity and timing changes (Shrestha *et al* 2012, Kang *et al* 2014) with serious socioecological and economic consequences (Council 2016) that are projected to intensify (Morrison *et al* 2002, Ferrari *et al* 2007, Déry *et al* 2012, Kang *et al* 2016). At seasonal timescales high and low streamflow in the FRB preconditions streams for flood and drought events. For example, when flows are high during the rising limb of the hydrograph, an extreme precipitation event is likely to lead to a flood. *Spring-season high flows* that increase the risk of a flood are hereafter referred to as ‘flood.’ *Summer season low flows* that increase the risk of hydrologic drought are hereafter referred to as ‘drought.’

Snow meltwater delivered in late spring and early summer represents the dominant historical

contribution to annual FRB streamflow (Curry and Zwiers 2018). This pulse of increased and rapid runoff is evident as the rising limb of FRB water year (WY) hydrographs (figure 2), typically drives highest annual flows from May–July and peaking in June, and often leads to recurrent flooding in April, May, or June (Curry and Zwiers 2018). Past flooding has caused large-scale disruptions to human and natural systems (Morrison *et al* 2002). Since the 1940s, peak flows have occurred earlier, suggesting climate change is already impacting the timing of snowmelt and seasonal FRB flows (Morrison *et al* 2002, Stewart *et al* 2005, Shrestha *et al* 2012).

Lowest annual flows and occasional hydrologic drought typically occur in July–August (Kang *et al* 2016), during which time runoff is still derived mainly from slow-melting high-elevation snowpack, such that streamflow dynamics remain tightly coupled with cool-season precipitation (Leith and Whitfield 1998). Due to a lack of impoundments, little FRB flood-season runoff is stored and flooding may be followed by substantially lower flows during late-summer (Kang *et al* 2014). In 2015, the Lower Fraser region was classified at Level 4 drought conditions (requiring implementation of water use restrictions) from June to September and municipalities faced dangerously low reservoir levels, prompting scrutiny of the BC Drought and Water Scarcity Response



Plan (Econics 2010). Model projections and water balance modeling suggest less future precipitation stored as snowpack will further reduce warm season streamflow volumes and cause earlier and longer drought in the FRB (Morrison *et al* 2002, Lutz *et al* 2012, Islam *et al* 2017). Spring and summer evapotranspiration rates have already increased significantly across the basin, reducing warm-season runoff despite concurrent increases in rainfall (Kang *et al* 2016).

Responses to climate change across this topographically, biogeographically, and hydroclimatically-complex basin are heterogeneous, for example shifting from snow-dominant to hybrid regimes in the eastern and coastal mountains, and from hybrid to rain-dominant regimes in the central plateau (Shrestha *et al* 2012). Taken together, a nearly 50% decrease in the fraction of precipitation falling as snow by the 2050s (Kang *et al* 2014, Islam *et al* 2017) will result in more rapid, frequent, and earlier spring

floods preceding longer and more severe summer droughts, sometimes in the same year, and with immediate and intensifying impacts to human water use, as well as terrestrial and aquatic species and their habitats (Morrison *et al* 2002, Ferrari *et al* 2007, Shrestha *et al* 2012, Kang *et al* 2014, Padilla *et al* 2015). In particular, increased seasonal and inter-annual runoff variability and extremes may be life threatening for Pacific salmon populations whose survival is highly sensitive to discharge volume and water temperature (Ferrari *et al* 2007, Kang *et al* 2014, Padilla *et al* 2015).

Because the FRB encompasses a highly diverse topographic and biogeographic region with short streamflow records (Watson and Luckman 2006), quantifying flood (Hart *et al* 2010, Curry and Zwiers 2018) and drought variability (Ferrari *et al* 2007) at water management-relevant spatiotemporal scales is an ongoing challenge (Déry *et al* 2012). Long-term and high-resolution (sub-annual) runoff reconstructions based on tree-ring archives have been used worldwide to extend instrumental records, provide more complete characterizations of runoff variability, and benchmark ‘natural’ hydrologic extremes (Meko and Woodhouse 2011). These records have the potential to make significant contributions to hydrologic model inputs and improve predictions for water management (Morrison *et al* 2002, Ferrari *et al* 2007, Déry *et al* 2012, Shrestha *et al* 2012, Kang *et al* 2014, 2016, Curry and Zwiers 2018, Huning and AghaKouchak 2020). Huning and AghaKouchak (2020) demonstrate that even ~50 additional years of hydrological data significantly change hydrological statistics. While dendrohydrological reconstructions have been primarily accomplished in semi-arid regions where annual runoff quantities and tree-ring widths are both controlled by total integrated winter moisture supplies (Stockton and Jacoby 1976, Woodhouse *et al* 2006, Meko and Woodhouse 2011), dendrohydrology in non-arid basins with complex seasonal flow contributions remains a frontier of the discipline (Biondi and Strachan 2012).

Given the hydroclimatic complexity of the FRB, traditional dendrohydrological methods focusing on main-stem and water-year streamflow reconstructions are not appropriate since they cannot capture the contributions of each subbasin, reveal hydroclimatic shifts occurring in individual subbasins, or provide seasonal-scale local extremes information critical for management and adaptation. This complexity has precluded developing reconstructions of FRB runoff using traditional methods in the past (Luckman and Wilson 2005, Hart *et al* 2010). Here, we developed a set of complementary subbasin and main-stem streamflow tree-ring reconstructions for the FRB with sub-seasonal resolution. The first of their kind, each targets a locally-defined (by watershed) flood season and drought season based on the local hydrograph. Flows during these seasons

precondition overall flood and drought risk. We used a novel study design based on isolating tree-ring chronology sensitivity to the same hydroclimate variables that drive seasonal (flood, drought) streamflow in each subbasin (see table 1; figure 1). We then use our reconstruction to quantify the magnitude, duration, and frequency of flood and drought extremes across the FRB over the last several centuries.

2. Methods and materials

2.1. Streamflow and climate data

We obtained monthly volumetric discharge ($\text{m}^3 \text{s}^{-1}$) records for the main stem and six major, unpounded subbasins (Déry *et al* 2012, Kang *et al* 2014) from the BC Water Office (website: https://wateroffice.ec.gc.ca/index_e.html) (table 1). Hydro-metric data gaps were filled with the daily mean flow value over the period of record for QB and ST (0.002% and 0.006% missing data, respectively). This gap filling has little effect on trend with attenuation effects when <10% of the data are missing (Déry *et al* 2012). Flood and drought seasons were defined for each basin based upon timing, duration, and statistical significance (table 1). We evaluated the climate signals in our tree-ring chronologies using gridded (0.5×0.5 degree) monthly precipitation data from the Global Precipitation Climatology Centre (Schneider *et al* 2011, GPCC v2018) and gridded high-resolution (0.5×0.5 degree) monthly mean temperature data from by the Climate Research Unit (CRU, TS v4.04, Harris *et al* 2020). We explored the modern seasonal climate drivers of streamflow using the Hope (Fraser) gauge records and the gridded climate data across all basins for winter (October–April) and summer (July–September) precipitation, as well as WY (October–September) temperature and WY flow at Hope, for the common period of 1914–2016.

2.2. Tree-ring data

Nine new tree-ring chronologies were developed for this study based on gaps in existing tree-ring data coverage. These sites all demonstrated statistically significant relationships to SWE, summer temperature, cool-season precipitation, and/or warm-season precipitation. Two cores per tree were collected using a 5 mm diameter increment borer (minimum of 20 trees per site) and processed following standard methods (Speer 2010). Visual crossdating was verified statistically using the program COFECHA v.6.06P (Holmes 1983). Total ring, earlywood-, and latewood-widths were measured using a Velmex stage and Tellervo measuring software (Brewer 2014). We obtained the raw ring-width data from an additional 143 existing tree-ring sites that demonstrated statistically significant Pearson correlation ($p < 0.05$) to at least one of the same previously mentioned climate variables from the International Tree-Ring

Table 1. FRB gauges, streamflow extremes seasons, and bounding boxes for gridded climate variables (* data period used 1971–2017). See text for basin abbreviations.

Sub basin	Gauge name	Gauge ID	Gauge Lat (°N)	Gauge Lon (°W)	Gauge period	Seasons (Flood/Drought)	Climate variable box coordinates
Fraser	Hope	08MF005	49.39	−121.45	1913–2016	May–Jun/Sep	54.75 N, −127.25 W; 54.75 N, −118.25 W; 49.25 N, −118.25 W; 49.25 N, −127.25 W
UF	FraserR, Shelley	08KB001	54.00	−122.62	1951–2017	May/Aug–Sep	53.25 N, −120.25 W; 54.25 N, −127.25 W; 54.25 N, −120.25 W; 53.25 N, −127.25 W
FT	Thomson R, Spences Bridge	08LF051	50.35	−121.39	1951–2015	May/Sep	53.00 N, −121.75 W; 53.00 N, −118.75 W; 50.25 N, −118.75 W; 50.25 N, −121.75 W
NT	NThompson R, McLure	08LB064	50.04	−120.24	1958–2018	May–Jun/Aug–Sep	52.68 N, −120.34 W; 52.68 N, −119.67 W; 50.68 N, −120.34 W; 50.68 N, −119.67 W
ST	SThompson R, Chase	08LE031	50.76	−119.74	1914–2017*	May–Jun/Sep	50.83 N, −119.69 W; 50.83 N, −120.34 W; 50.68 N, −119.69 W; 50.68 N, −120.34 W
CH	ChilkoR, Redstone	08MA001	52.07	−123.54	1966–2017	May–Jun/Aug–Sep	52.25 N, −123.25 W; 52.25 N, −124.25 W; 50.75 N, −123.25 W; 50.75 N, −124.25 W
QB	QuesnelR, Quesnel	08KH006	52.84	−122.23	1946–2016	May–Jun/Sep	52.62 N, −121.57 W; 52.62 N, −122.50 W; 52.97 N, −121.57 W; 50.97 N, −122.50 W

Data Bank (ITRDB, www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring). We evaluated two detrending and standardization methods to remove age-related growth trends in tree-ring series while maximizing the climate signal of interest (Melvin and Briffa 2008). No particular added benefit of using the signal-free (Melvin and Briffa 2008) method was observed (figure S2 available online at stacks.iop.org/ERL/16/124074/mmedia), so we used the modified negative exponential curve to develop the chronologies using dplR (Bunn 2008, R Core Team 2019). Chronologies were truncated where the expressed population signal reached 0.80 (see Wigley *et al* 1984, Briffa and Jones 1990). Our made-for-purpose FRB tree-ring network consists of *Pinus ponderosa*, *Tsuga mertensiana*, *Larix lyallii*, *Pinus albicaulis*, *Pseudotsuga menziesii*, *Picea engelmannii*, *Abies lasiocarpa*, *Thula plicata*, *Pinus contorta*, and *Abies amabilis* chronologies (Brice *et al* 2021).

Climate-growth relationships were explored using the seasonal correlation (SEASCORR) procedure developed by Meko *et al* (2011). We tested individual monthly and seasonal SWE, precipitation,

and temperature records integrating 2, 3, or 4 months, within a 14-month window starting in the August prior to the growing year and ending in the following September. Significance was estimated using exact simulation (Percival and Constantine 2006).

2.3. Streamflow reconstructions

Based on instrumental hydroclimate patterns, we identified distinct flood and drought seasons for each basin based on a compromise between (1) the seasonal hydroclimate information recorded by the tree-ring proxies, (2) the timing of extreme events based on the rising and falling limbs on each hydrograph, and (3) water management relevance. We calculated Pearson's pairwise correlations between monthly and seasonal runoff data and the tree-ring proxies using SEASCORR (Meko *et al* 2011). Chronologies with similar monthly or seasonal hydroclimate sensitivities were then grouped using k-means cluster analysis on the 112 monthly SEASCORR and partial correlation coefficients for each chronology (Touchan *et al* 2014). The optimal number of clusters was

determined by iterative testing of the gap statistic and silhouette plots (Rousseeuw and Kaufman 1990, Tibshirani *et al* 2001). This resulted in the identification of reconstruction ‘seasons’ (flood or drought) and the associated candidate tree-ring chronology model predictor pools (cluster members) for each season and basin. Where chronologies were duplicated in both seasonal reconstructions for a single basin, the chronology was only retained in the predictor pool with the strongest correlation with the predictand flow data. Chronologies that did not have a minimum of 30 years of overlap with the streamflow series or that were too short to develop reconstructions of adequate length over the 20th century were removed.

We used stepwise multiple linear least-squares regression to calibrate each reconstruction model on seasonal flow data (criteria: probability-of-F-to-enter ≤ 0.05 , probability-of-F-to-remove ≥ 0.10). Model cross-validation was accomplished using a leave-one-out process (Michaelsen 1987). The validation statistics reduction of error (RE) and root mean square error (RMSEv) describe the skill of the model, and the explained variance statistic (R^2) in the calibration process is similar to the RE used during validation, which provides an average estimation to be compared to the regression estimate (Fritts 1976, Cook *et al* 1999). We used the sign test (Dixon and Mood 1946) to test the frequency of agreement between the sign of the departures from the sample mean in the instrumental and reconstruction data ($p < 0.01$, determined following the cumulative distribution tables for the binomial distribution) (Beyer *et al* 1971).

2.4. Analysis of extreme events

We identified extreme seasonal flows in both the instrumental and reconstructed datasets using percentile thresholds representing the driest and wettest years in the low and high flow seasons, respectively (Hirschboeck and Meko 2005, Austin and Nelms 2017, Fernández *et al* 2018, He *et al* 2020, Muñoz *et al* 2020). Years in the bottom quintile (20th percentile) and the top quintile of flow (80th percentile) were categorized as drought and flood extremes, respectively, for each basin. For each season and basin, we then used runs analysis on the quintile subsets (González and Valdés 2011, Meko and Woodhouse 2011) to evaluate flood and drought magnitudes and duration (consecutive years). Flow values in the top and bottom quintiles were divided by the long-term mean of each respective reconstruction to determine the magnitude (%) of the anomaly. Runs ‘interruptions’ (one or more years without a same-sign anomaly) ended the run, such that this analysis provides the most conservative possible perspective on both event magnitudes and number of consecutive event years. We also examined a 30-year running empirical cumulative distribution function (ECDF) of flood-drought

frequency in each subbasin to determine the probability of flood or drought occurrence, the number of flood-drought events within each 30-year period, and potential recent changes in the frequency of extreme events in each basin.

3. Results

3.1. Reconstructions

Instrumental flood season and drought season timing varies across basins (figure 2), so the months and/or seasons selected for the flood and drought reconstructions for each basin varied as well. Reconstructed seasons, predictor chronologies, and model statistics are listed in table 2. Given the lack of old, sensitive chronologies in BC some strong predictors may not be co-located in the associated subbasin, but may still enter the reconstruction model due to synoptic scale climate patterns that link across large spatial scales. Only models that explain more than 30% of the variance and with robust RE and RMSEv statistics were retained for further analysis (minimum $R^2 = 0.342$, maximum $R^2 = 0.684$, figure 3). Flood reconstructions generally show larger variance at multidecadal to centennial scales than the drought reconstructions, especially in FT, NT, CH and QB. Flood reconstructions in every subbasin do not follow the centennial-scale patterns in the flood reconstruction of the mainstem of the Fraser. There is an upward trend in flood discharge in the latter decades of the 20th century in both the CH and ST basins. Each drought reconstruction shows a decline in the running mean flow between 1900 and 1940. High frequency similarities are also present across each drought reconstruction with mild drought years in 1801, 1876, 1880, and 1899 and with severe droughts in 1878, 1940, 1946, and 1992 across multiple basins.

3.2. Runs analysis

Runs analysis on the reconstructed streamflow years in common with the instrumental record demonstrate flood (seasonal high flow) magnitude between 105% and 146% of the reconstructed mean (figure 4, light blue circles). The highest magnitude flood run lasted two years in the FT basin in 1957–1958. In 1951–1957, the longest duration run of flood in the record lasted seven years on the Fraser River with a magnitude of 110% (not shown). Instances of two-year flood runs are present in every basin, though the most frequent run duration is a single year. Drought (seasonal low flow) magnitude in reconstructed common years ranges between 64% and 90% (figure 4, light orange circles). The lowest magnitude drought (64%; most severe) occurred in the QB basin in 1946, and the second lowest (65%) in 1992 in UF. The longest drought run lasted three years on the Fraser in 1940–1942 (76%). Droughts of two years occurred

Table 2. FRB and subbasin flood and drought reconstruction model statistics, model predictors, season of reconstruction, and reconstruction period.

Basin	std/res	R^2	R^2_a	RE	SEE	RMSEv	Predictors	Recon season(s)	Recon period
Fraser	std	0.344	0.309	0.24	1546.98	1612.35	cana152 cana353 cana386 cana422	Flood (MJ)	1803–1993
Fraser	std	0.45	0.428	0.38	410.911	423.884	cana147 cana234x cana237x	Drought (S)	1754–1993
NT	std	0.493	0.458	0.36	215.63	230.739	cana398 cana528	Flood (MJ)	1691–1997
NT	res	0.432	0.397	0.32	175.438	183.522	cana223 cana237x	Drought (AS)	1848–1997
CH	std	0.544	0.507	0.39	48.895	53.39	cana09 cana396	Flood (MJ)	1760–1995
CH	res	0.342	0.297	.0.14	42.641	46.485	cana469 cana495	Drought (AS)	1808–2005
FT	std	0.684	0.65	0.56	218.038	241.763	cana414 cana355 cana438	Flood (M)	1668–1987
FT	std	0.515	0.498	0.43	139.039	146.474	cana225b	Drought (S)	1757–1996
ST	std	0.381	0.352	0.23	167.41	178.89	cana408	Flood (MJ)	1560–1999
QB	std	0.474	0.463	0.43	49.094	50.09	cana237x	Drought (S)	1694–1997
UF	std	0.557	0.527	0.45	284.847	302.341	cana237x cana110	Drought (AS)	1754–1993

on three occasions in Fraser in 1930–1931 and 1945–1946, and in FT 1970–1971. All other drought runs lasted a single year.

Runs analysis on the pre-instrumental stream-flow records demonstrates flood magnitudes in all basins range between ~106% and 158% (figure 4, dark blue circles). The highest magnitude flood in all records (158%) was in CH from 1774–1775. Flood runs lasting longer than five years occur at least once in every basin with the exception of the Fraser (not shown). The longest duration flood was during the nine-year period 1701–1709 in FT and had a magnitude of 135%. Most flood runs are 1–3 years in duration. Reconstructed summer drought magnitude ranged between 56% and 93% of the long-term mean. The most severe drought (lowest % of mean) occurred in the QB in 1936, and the longest drought duration is five years. Droughts of this length occurred in UF (1938–1942) and QB (1928–1932). Droughts lasting 1–2 years are most common in all reconstructions.

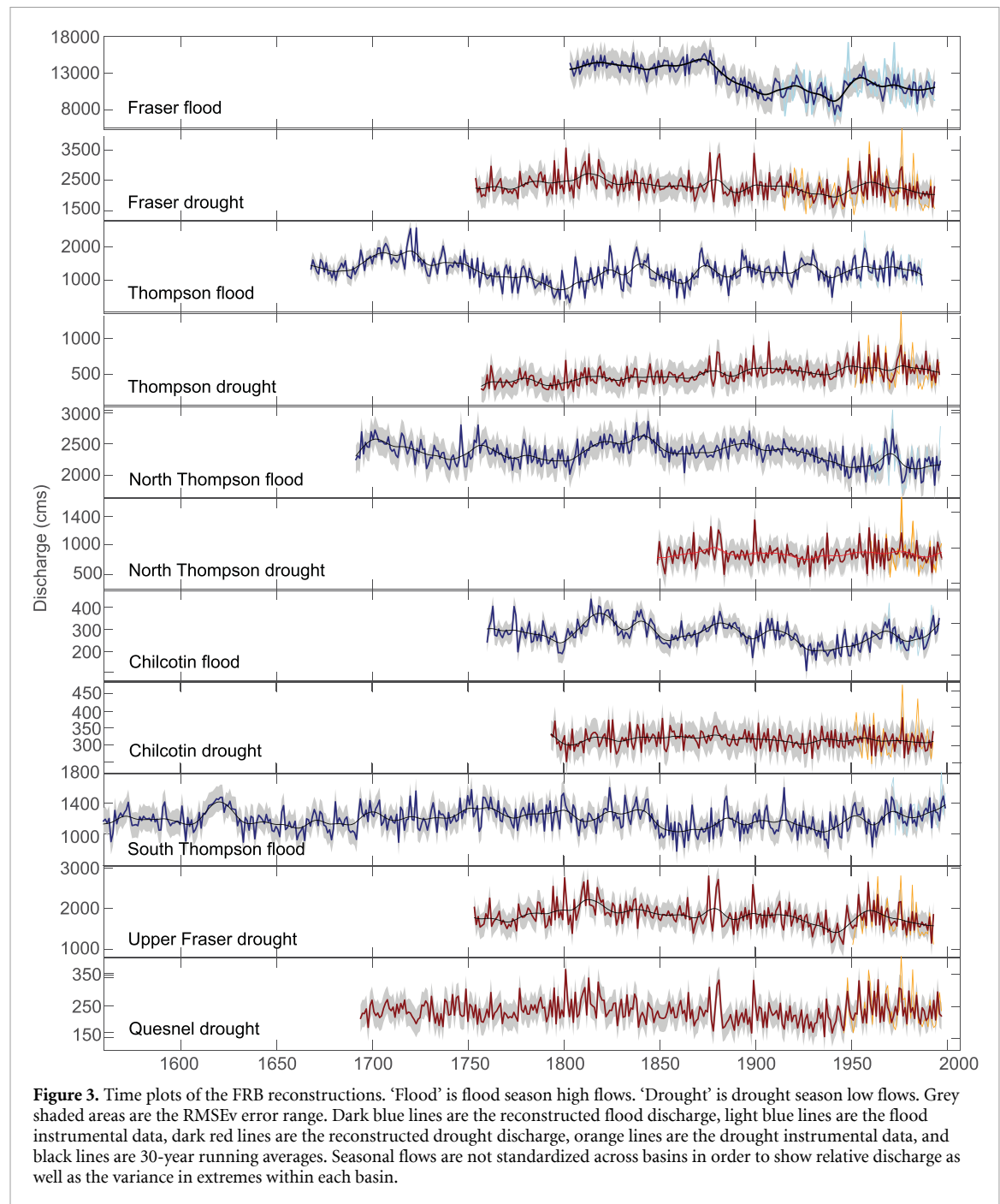
3.3. Empirical cumulative distribution functions

The frequency of flood (drought) occurring within 30-year windows in the FRB instrumental record is heterogeneous across subbasins (figures 5(a) and (b), dashed lines) and has shifted over the past 7–10 decades. The Fraser main stem experienced a maximum of ten flood seasons in any given 30-year period, with 8 of those in the most recent 30 years (figure 5(a)). The probability of the number of floods in any basin exceeding those experienced in the last 30 years is between 30% (Fraser) and 100% (FT,

NT, CH) (figure 5(a)). With respect to droughts, no other 30-year period in the instrumental record has experienced as many droughts in the Fraser, QB, FT, NT, and UF than in the last 30 years (6–7 events, figure 5(b)). By contrast, the probability of drought frequency exceeding that of the last 30 years in CH is 100% (figure 5(b)).

For every basin, substantially more floods occurred within pre-instrumental 30-year periods than occurred within either the last 30 years or within the instrumental record (figure 5(a)). The flood reconstruction ECDF suggests the probability of the number of floods in any basin exceeding those experienced in the last 30 years is between 13% (ST) and 100% (Fraser), which differs substantially from probabilities calculated from the instrumental record (figure 5(a), dashed lines). The FT, for example, shows the highest number of floods in any given 30-year period is 25 based on the reconstruction and only 5 based on instrumental observations. Maximum frequency probabilities in NT, CH and Fraser converge at 20 floods in a given 30-year window.

For all basins, more droughts also occurred within the reconstructed period (maximum of 18) than within the instrumental record (maximum of 7, dots on figure 5(b)). In addition, more droughts occurred prior to the last 30 years for every basin except Fraser. Thirteen reconstructed droughts are classified as extreme on the Fraser main stem in the last 30 years, compared with only 7 where the instrumental record is used (figure 5(b), red dashed line). Over the 239 reconstructed years, only one other 30-year



period in the Fraser has had more droughts. Correspondingly, within each basin’s most recent period, 12 years are classified as droughts in UF, 8 years in CH, and 4 or fewer years in FT, QB, and NT basins, with a 9%, 11%, and 45% (or greater) chance of more droughts occurring in a reconstructed 30-year period, respectively.

4. Discussion

4.1. A seasonal extremes, subbasin approach to tree-ring streamflow reconstructions

Instrumental hydroclimate datasets indicate FRB sub-basins have distinct flood- and drought-season runoff

regimes, each with associated precipitation and temperature drivers, that non-uniformly interact with full Fraser basin hydroclimatic dynamics (figures 2 and S1, table S1). Subbasin contributions to main stem flows also vary in timing and quantity (figure 2, table S1). This heterogeneity underscores the importance of evaluating the paleohydroclimatology of the FRB as the sum of many parts rather than a synchronous whole, especially with respect to seasonal hydrologic extremes, and in contrast with other high-resolution reconstructions of other major basins (Stockton and Jacoby 1976, MacDonald *et al* 2007, Abatzoglou 2011, Gallant and Gergis 2011, Devineni *et al* 2013, Ferrero *et al* 2015, Agafonov *et al* 2016,

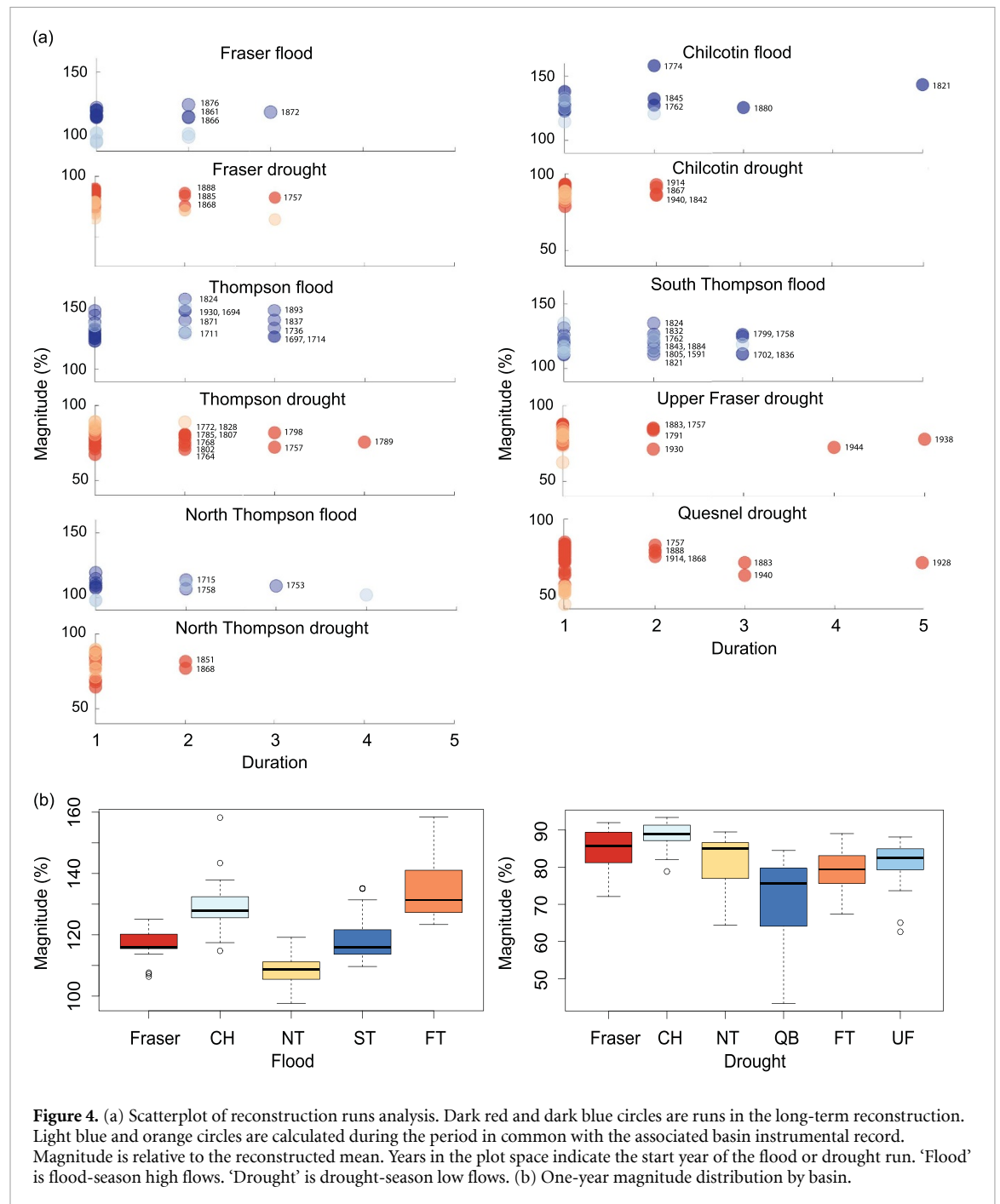
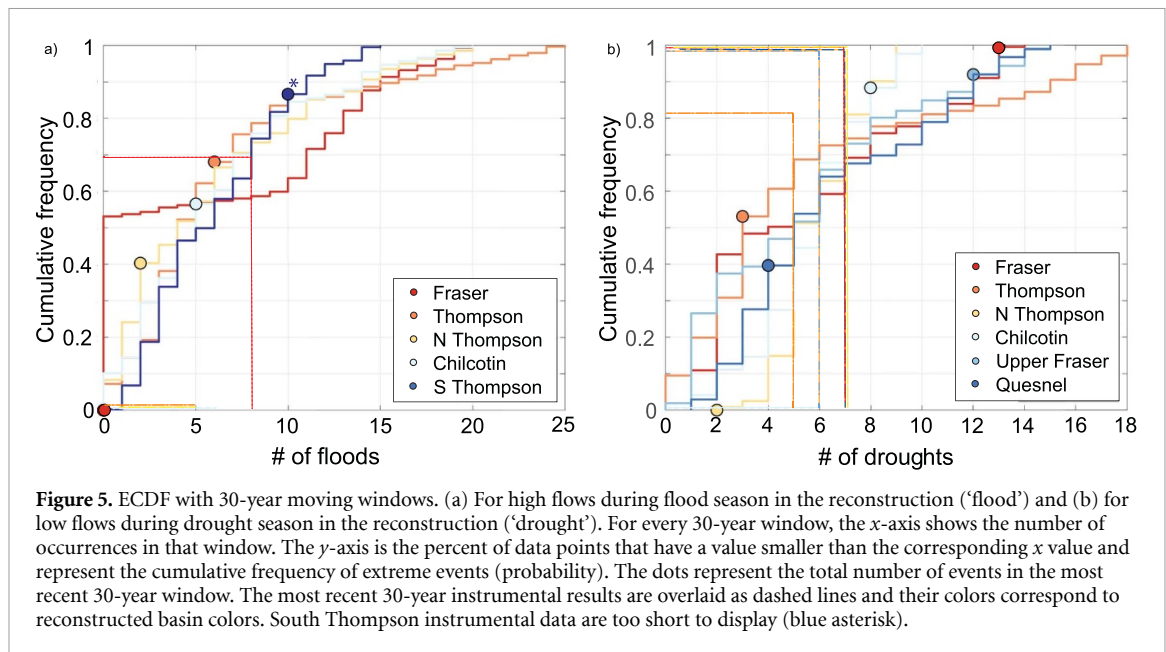


Figure 4. (a) Scatterplot of reconstruction runs analysis. Dark red and dark blue circles are runs in the long-term reconstruction. Light blue and orange circles are calculated during the period in common with the associated basin instrumental record. Magnitude is relative to the reconstructed mean. Years in the plot space indicate the start year of the flood or drought run. 'Flood' is flood-season high flows. 'Drought' is drought-season low flows. (b) One-year magnitude distribution by basin.

Littell *et al* 2016, Sidibe *et al* 2018, Chen *et al* 2019, Ravindranath *et al* 2019, Rao *et al* 2020).

Our subbasin-based approach allowed for the development and interpretation of the first complementary and management-relevant flood-season high flow and drought-season low flow reconstructions for the FRB. Of 14 possible reconstructions (two seasons for each of seven subbasins), we successfully developed 11 skillful reconstruction models that extend streamflow records between 110 and 354 years. Given the size and complexity of the FRB, some reconstruction models explain nearly one-third of the variance in seasonal streamflow (e.g. CH

drought) versus others (e.g. FT flood) that explain more than two-thirds of variance. All models are skillful and supply information not available in the instrumental record. All reconstructions are statistically independent within and across watersheds, with the exception of four drought reconstructions: QB, UF, Fraser, and NT (table 2). Our primary aim was to develop the most robust reconstruction for each subbasin, regardless of shared predictors. The reconstructions provide long-term benchmarks for FRB flood and drought variability and demonstrate that instrumental FRB streamflow records cannot fully characterize the range of natural magnitudes,



durations, frequencies, or probabilities of extreme flood and drought events in these watersheds (figures 4 and 5).

Tree-ring based reconstructions are known to frequently underestimate extreme wet conditions (Fritts 1976, Meko and Woodhouse 2011) and statistical models used to generate reconstructions will compress variance compared to their respective calibration datasets (Hughes 2011). Our results above suggest that while the reconstructions are skillful, FRB trees may still underestimate flood magnitudes and drought durations in some basins.

4.2. Reconstructed floods

Across all basins, floods that occurred during the pre-instrumental period were of both greater magnitude (~30% magnitude difference) and occurred in more consecutive years (~1 year longer) than any in the common period (figure 4). Reconstructed flood frequencies (the number of events count within a 30-year period) in every subbasin also substantially exceeded those experienced in the last 30 years (figure 5). Flood reconstructions also reveal decadal to centennial scale variability and trends distinctive to individual subbasins but not evident in short instrumental records. These results suggest that despite warming air temperatures driving an intensification of FRB floods over the past several decades (Kang *et al* 2016), more severe and frequent floods occurred in the past as well. As floods are projected to intensify further due to anthropogenic climate change (Shrestha *et al* 2012, Islam *et al* 2017), if events of past magnitude were to occur in the future they would likely exceed the severity of any in the past ~200–350 years. This has direct implications for statistical hydrological analysis and modeling such

as the calculation of return periods and associated uncertainty quantification, design floods, and overall FRB flood risk and water resources planning (Huning and AghaKouchak 2020).

Flood extremes impact subbasins differently. Pre-instrumental flood magnitudes (158%) in FT and CH were considerably higher than in other subbasins, yet rarely propagated to the Fraser main stem (figure 4). These two basins, along with NT and Fraser, also experience the highest 30-year flood frequencies (figure 5). The large eastern subbasins (FT and NT) have the highest probability of frequent floods over the ~400 year reconstruction period and make by far the highest contributions to total Fraser main stem flows during the flood season other than UF, which has no flood reconstruction (table S1). The lack of historical flood propagation from these basins to the Fraser main stem (figure 4) suggests future impacts of flood intensification in these basins may primarily be local (Morrison *et al* 2002, Shrestha *et al* 2012, Kang *et al* 2016).

4.3. Reconstructed droughts

Although the results are spatially heterogeneous, 20th century drought magnitudes and/or durations (consecutive years) exceed those in the full reconstructed record in some subbasins (figure 4). These include the northern UF, QB, and CH basins, the first of which represents the headwaters of the FRB. UF and QB exhibit the most consecutive summers of extremely low flow (5 years), although these events were relatively recent (mid-20th century; figure 5). In contrast, the most severe and longest duration droughts occurred prior to the 20th century in the FT, NT, and Fraser (figure 4). For all basins, droughts during the last few decades do not

stand out as particularly extreme in magnitude or duration.

The *frequency* of past droughts (the number of events counted within all earlier 30-year periods) exceeded that of the most recent period in each reconstruction, with the notable exception of Fraser main stem (figure 5). Even with the several hundred additional years provided by the tree-ring reconstruction, the Fraser still experienced more frequent droughts in the most recent 30 years than at any other period since 1754. In contrast to FT, QB, and NT, the reconstruction of UF and CH shows more drought years in their most recent period than is evident in the most recent period of the instrumental record. Our long-term reconstructed record provides an improved estimate on what qualifies as a drought in these systems in a multi-century context. Given distinct differences between drought in the instrumental data alone and in the longer reconstructions (figures 4, 5 and S3), probabilistic analysis and water management strategies based only on the recent gauge data would underestimate future drought risk in the FRB in a similar manner to floods (Coulthard *et al* 2016, Coulthard and Smith 2016, Huning and AghaKouchak 2020).

By all metrics our reconstructions suggest Fraser, UF, CH, and QB are the most drought-vulnerable basins examined in this study, although comparisons among our drought reconstructions are conservative given four of the six drought-season models are not statistically independent. Droughts originating in CH and QB have primarily local impacts since they contribute least to main stem Fraser flows (table S1) and rarely propagate downstream (figure 4). Though significant summer-season flow contributions in the main stem Fraser come from UF, drought timing in the Fraser and UF rarely coincides. Fraser, FT, UF and QB did experience a multi-year joint-basin drought beginning in 1757 and persisting until 1758–1759. While joint-basin droughts would represent a significant water management challenge as low flows continue to intensify in future, more work is needed to determine the extent to which these events are a product of partially shared chronology membership among the reconstructions.

5. Conclusions

Floods and droughts present a fundamental water management challenge and risk to the western Canadian economy, ecosystems, and culture that is expected to intensify under a warmer climate. Our Fraser subbasin-scale reconstructions provide critical pre-instrumental benchmarks for natural FRB flood-season high flow and drought-season low flow variability that occurred in the absence of strong anthropogenic forcing. They suggest gauged streamflow records upon which current management is

based likely underestimate both the full natural magnitude, duration, or frequency of extreme flood- and drought- season flows in the FRB, as well as the risk of future anthropogenically-forced flood and drought events. Specifically, both the magnitude and duration of spring high flows were larger and longer in the pre-instrumental past, while recent summer low flows exceed those of the past in both occurrence and duration. Furthermore, our models underestimate hydrologic extremes both due to properties of least squares regression and the design of the runs analyses wherein only consecutive extreme events years are considered, with no interruptions. They therefore still provide only a conservative estimate of natural extreme magnitudes and durations.

In both the instrumental and pre-instrumental period, the subbasins of the Fraser River have distinct hydrologic characteristics that nonuniformly influence overall FRB flows, making some subbasins more vulnerable to extreme events (e.g. drought in Fraser, UF, CH, and QB), and others more likely to experience or to be linked with downstream events. This hydroclimate heterogeneity is reflected in both the gauged streamflow data and tree-ring based reconstructions. Joint-basin droughts (e.g. 1757) may have occurred prior to the installation of streamflow gauges, representing a particular water management challenge as low flows intensify in the future.

In addition to the reconstructions and hydrological insights, this study provides a research design model that uses tree-ring proxies that capture the spatial and temporal heterogeneity inherent in large, hydroclimatically complex watersheds like the FRB. We suggest that selecting reconstruction proxies and target seasons using a data-driven approach based on local hydrographs is an effective approach for developing statistically independent, management-relevant paleohydrological reconstructions in these systems, and extend caution against generalizing seasonal hydrologic extremes in watersheds like the FRB as a synchronous whole.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://www.ncdc.noaa.gov/paleo/study/34332>.

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