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Is worst-case scenario streamflow drought underestimated in British Columbia? A multi-century perspective for the south coast, derived from tree-rings

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SUMMARY

Recent streamflow droughts in south coastal British Columbia have had major socioeconomic and ecological impacts. Increasing drought severity under projected climate change poses serious water management challenges, particularly in the small coastal watersheds that serve as primary water sources for most communities in the region. A 332-year dendrohydrological record of regionalized mean summer streamflow for four watersheds is analyzed to place recent drought magnitudes in a long-term perspective. We present a novel approach for optimizing tree-ring based reconstructions in small watersheds in temperate environments, combining winter snow depth and summer drought sensitive proxies as model predictors. The reconstruction model, estimated by regression of observed flows on *Tsuga mertensiana* ring-width variables and a tree-ring derived paleorecord of the Palmer Drought Severity Index, explains 64% of the regionalized streamflow variance. The model is particularly accurate at estimating lowest flow events, and provides the strongest annually resolved paleohydrological record in British Columbia. The extended record suggests that since 1658 sixteen natural droughts have occurred that were more extreme than any within the instrumental period. Flow-duration curves show more severe worst-case scenario droughts and a higher probability of those droughts in the long-term reconstruction than in the hydrometric data. Such curves also highlight the value of dendrohydrology for probabilistic drought assessment. Our results suggest current water management strategies based on worst-case scenarios from historical gauge data likely underestimate the potential magnitudes of natural droughts. If the low-flow magnitudes anticipated under climate change co-occur with lowest possible natural flows, streamflow drought severities in small watersheds in south coastal British Columbia could exceed any of those experienced in the past ~350 years.

1. Introduction

In 2014 and 2015 many British Columbia (B.C.) watersheds experienced streamflow droughts that were likely the most severe since streamflow monitoring began in the mid-20th century. Record-breaking low snowpacks and historic high summer temperatures took a particular toll on south coastal basins (Agriculture and Agri-Food Canada, 2014; B.C. River Forecast Centre, 2015). Despite very wet winters, these small watersheds can experience streamflow drought during late summer when snow has melted and weather is warm and dry.

Though they have relatively low storage capacity, small coastal watersheds serve as the primary water source for most communities in south coastal B.C. Many of the streams and rivers in these catchments are also used for hydroelectric power generation, support industry and agriculture, and are critical to the survival of local Pacific Salmon populations. Drought presents a major water management challenge, especially where there is high uncertainty around potential low flow severities (B.C. Ministry of Environment, 2013; Lill, 2002; Mishra and Coulibaly, 2009).

In western Canada, few hydrometric records extend beyond the 1970s. These short instrumental records translate to less accurate estimates of potential low flow severities in a river, and less sound water management strategies (Rodenhuis et al., 2007). Short hydrometric records also make it difficult to determine if recent

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droughts are extreme relative to those that occurred in the past. Longer term proxy records of streamflow variability can be estimated from climate-sensitive tree-ring (TR) records by capitalizing upon the influence of climate on both annual radial growth and seasonal runoff (Loaiciga et al., 1993). Dendrohydrological reconstructions can contextualize hydrological changes and inform on connections between modes of regional climatic variability and runoff that are not captured in the instrumental record (e.g., Earle, 1993). The tree-ring based approach is particularly valuable since trees are often distributed over a large hydrological 'sample landscape' and, unlike many other paleoenvironmental proxies (i.e. lake cores, ice cores), information derived from them is annually to sub-annually resolved.

Dendrohydrological modeling has largely been accomplished in dry continental settings, where annual radial tree growth is limited by available soil moisture derived from the same rain and snow meltwater that supports streamflow (Meko and Woodhouse, 2011). The approach is typically applied in large watersheds where errors related to evaporation and 'flashy' rainfall do not contribute to model error (Margolis et al., 2011). Long-term perspectives on hydrological phenomena such as low flows, drought, and long-term runoff declines, have been incorporated into multi-scale and multi-agency watershed management strategies in the southwestern United States (Meko et al., 2001; Woodhouse and Lukas, 2006), western interior Canada (Sauchyn et al., 2015), and internationally (Gou et al., 2010; Norton and Palmer, 1992; Pederson et al., 2001).

Small, temperate watersheds represent a frontier in dendrohydrology due to small basin concentration times, flashy runoff, and an absence of moisture-sensitive tree species (Biondi and Strachan, 2012). In coastal B.C. the approach is hindered further by complex hydroclimatology resulting from mountainous terrain and streamflow contributions from rainfall–runoff, snowmelt–runoff and glacier icemelt runoff. This heterogeneity can lead to differences in seasonal streamflow behavior even in spatially adjacent watersheds (Eaton and Moore, 2010). Previous efforts to establish dendrohydrological records in B.C. have focused on snow- and glacier-melt dominated runoff regimes in continental settings, using moisture-limited TRs (Gedalof et al., 2004; Hart et al., 2010; Starheim et al., 2013; Watson and Luckman, 2005).

In this paper we develop a novel approach for dendrohydrological modeling in small, temperate watersheds in coastal B.C. Despite a lack of moisture-limited trees in this area, the radial growth of some high-elevation conifers is sensitive to annual maximum snow depth as a result of its influence on the length of the growing (energy) season (Peterson and Peterson, 1994). This type of TR data has rarely been used for dendrohydrology. We combine TR width records from a snow depth-sensitive tree species (Mountain hemlock; *Tsuga mertensiana* (Bong.) Carrière; Laroque and Smith, 1999; Gedalof and Smith, 2001; Peterson and Peterson, 2001; Marcinkowski et al., 2015) with a paleoenvironmental record of seasonal drought as predictors in a dendrohydrological model. Our reconstruction targets regionalized summer streamflow in small, hybrid (rain- and snowmelt-driven) watersheds, where summer runoff is driven by a combination of snow meltwater from the previous winter, and summer air temperature and summer precipitation variations. We hypothesized that TR variability and summer discharge in these watersheds are determined by regional-scale climate fluctuations to the extent that TR records can be used as proxies for climate in a model of historical streamflow. We apply the reconstruction to place droughts in long-term perspective, and relate streamflow anomalies to El Niño Southern Oscillation (ENSO; Holton and Dmowska, 1989) events and variations in the Pacific Decadal Oscillation (PDO; Mantua, 2002). Our approach presents an opportunity to develop paleohydrological records for watersheds both smaller in scale and of a different hydrological regime type than those typically conducive to dendrohydrology.

2. Hydroclimatic setting

The regional hydroclimatology of south coastal B.C. is affected by interannual and decadal climate variability driven by ocean–atmosphere interactions in the Pacific Basin, including synoptic-scale modes described by the PDO and ENSO, and to a lesser extent by the Pacific North America (PNA) pattern (Kiffney et al., 2002). Winter storms originating in the North Pacific Ocean deliver moisture to the B.C. coast where it is orographically released upon encountering the Vancouver Island Insular and Coast Mountain ranges, resulting in large quantities of snow and rain. Persistent high-pressure systems typically bring stable warm and dry conditions during the summer months (Stahl et al., 2006).

Atmospheric warming and changing rainfall, snowpack and snowmelt dynamics increasingly moderate these hydroclimate patterns (Barnett et al., 2004; Bonfils et al., 2008). Characteristically mild and wet winters have become milder and wetter over the past 100 years, while summers have become warmer and drier (Pike et al., 2010). Coast and Coast Mountain areas experienced a 1.4 °C rise in mean winter temperature from 1895 to 1995 and winter precipitation (rain and snow) totals are expected to increase by 6% by 2050 (December–February; B.C. Ministry of Water, Land and Air Protection, 2002; Pike et al., 2010). Milder winters and a larger proportion of cool-season precipitation falling as rain have caused widespread snowpack declines; snow water equivalent (SWE) totals diminished by 6% per decade from 1953 to 2000 (B.C. Ministry of Water, Land and Air Protection, 2002; Rodenhuis et al., 2007).

Regional climate trends have altered the seasonal timing and magnitude of peak and low flows, and these changes are expected to intensify in all streamflow regime types (Schnorbus et al., 2014; Stewart et al., 2005). However, hybrid streams are probably most susceptible to earlier, lower, longer, and more frequent low flows over the short term since they are strongly influenced by both warmer and drier summers, and shifting snowpack depth and snowmelt dynamics (Déry et al., 2009; Eaton and Moore, 2010; Loukas et al., 2002; Whitfield and Cannon, 2000). Our use of the term "drought" refers to streamflow drought, a sustained period of below-average stream discharge (Van Loon and Laaha, 2015). Given the low storage capacity of the study catchments, and in keeping with B.C. government environmental management practices, below-average runoff over a period of >1 month is considered streamflow drought (B.C. Ministry of Environment, 2013; Van Lanen et al., 2013).

2.1. Hybrid streams

Hybrid hydrological regimes predominate in south coastal B.C. and are typically found in mid- to low elevation coastal and near-coastal areas. Runoff in these streams is generally highest during winter (November, December, January) as a result of heavy rainfall. A secondary peak occurs in spring (April or May) as a result of snowmelt. Lowest flows occur during summer when inputs from snowmelt are exhausted and regional warm and dry high-pressure systems persist (Eaton and Moore, 2010). Snowmelt can significantly recharge deep flow paths and contribute to summer baseflow, even where a basin contains only a small snow-fed headwater (Beaulieu et al., 2012; Wade et al., 2001). The quantity of discharge in the low-flow season is, therefore, determined by a combination of previous winter snowpack and snowmelt dynamics, summer season precipitation, and summer air temperature.