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Multi-millennial streamflow dynamics in two forested watersheds on Vancouver Island, Canada

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ABSTRACT

Holocene streamflow was reconstructed for two rivers on Vancouver Island, British Columbia, Canada in 500-yr intervals. The San Juan River watershed is located on the wetter western side of the island, whereas the Koksilah River watershed is positioned on the drier eastern side. Both watersheds are forested. To reconstruct streamflow, temporal changes in precipitation (estimated using a pollen-based transfer function) and evapotranspiration were established for each watershed and integrated into a water balance model, calibrated using modern data. While seasonal streamflow variability was maintained throughout the Holocene, with greater flow in the winter relative to the summer, the amount of discharge has changed markedly through time. Lowest simulated flow occurred in the earliest Holocene, with low-flow conditions beginning earlier in the year and extending later into the fall. Such conditions may have inhibited salmon from using many of the smaller rivers in the region. Streamflow steadily increased throughout the early Holocene so that by ca. 6500 cal yr before present near-modern flow regimes were established. As climate changes in the future, the San Juan and Koksilah watersheds are expected to remain as pluvial hydroclimatic regimes, though with an extended season of low flow similar to conditions during the early Holocene.

Introduction

Rivers and other waterways have many important natural functions. They transport water, nutrients and sediment, maintain floodplains, build deltas and provide habitat for many plant and animal species (Milliman and Meade, 1983; Maddock, 1999; Smith et al., 2003; Brown and Pasternack, 2004, 2005; Pasternack and Brown, 2006). From an economic perspective, rivers are likewise critically important, supporting industries such as fishing, hunting, manufacturing and agriculture (Pasternack, 2013). They are also used in transportation, the production of hydroelectric power and for recreation (Loomis, 2002; Mallik and Richardson, 2009). Given these various ecological, economic and social aspects, it is important to understand how streamflow varies over different time scales and in response to different forcing mechanisms. This is especially important when considering that future anticipated changes in climate (IPCC, 2013), specifically to the hydrologic cycle (Wentz et al., 2007), will variously impact waterways over both the short- and long-term.

Gauging stations are widely used to record variations in river flow over short time scales (Dettinger and Diaz, 2000). To extend beyond the comparatively short instrumental record, calibrated tree-ring chronologies are often used to reconstruct annual river flow over centuries (Cook and Jacoby, 1983; Cleaveland, 2000; Case and MacDonald, 2003; Woodhouse and Lukas, 2006; Meko et al., 2007; Lara et al., 2008). Consequently, such reconstructions provide insight into temporal patterns of streamflow that otherwise would have likely been unattainable. Moreover, because tree-rings are annually resolved, they are well-suited to reconstruct year-to-year variations in streamflow, with multi-annual to decadal patterns discerned by combining successive years. Subsequently, the corresponding mechanism(s) responsible for any variations may be identified. For example, Lara et al. (2008) were able to reconstruct streamflow in the Puelo River (South America) over a 400-yr period and show that temporal variations in flow are related to *El Niño* and *La Niña* events. Likewise, Meko et al. (2007) show that overall low-flow conditions characterized the Colorado River Basin (USA) during the Medieval Climatic Anomaly, with lowest flow coinciding with a decadal drought around 1150 AD.

Gaining perspectives beyond multi-centennial time scales, however, is both a challenge and necessity, especially since future changes in climate may be of similar or greater amplitude relative to those observed during the Holocene (COHMAP, 1988; Bartlein et al., 1998; Kutzbach

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et al., 1998; IPCC, 2013). For example, the early- to mid-Holocene intervals represent a time when, in many northern high-latitude regions, temperatures were warmer and growing seasons longer relative to present (Heusser et al., 1985; Hebda, 1995; Bartlein et al., 1998, 2011; Viau et al., 2006; Wanner et al., 2008). Such uniquely different climate conditions would have affected the flow regime, potentially altering the seasonality of flow as well as total discharge. While intervals such as the early and mid-Holocene do not provide exact analogies for the future (Hebda, 1998; Bartlein et al., 2011), they can be targeted for study to examine how streamflow changed in response to large-scale changes in climate.

Streamflow variability can be related to a number of factors, including human activities as well as changes in climate, snowmelt, vegetation, geomorphology and fire disturbance (Dettinger and Diaz, 2000; Jefferson et al., 2008; Zhou et al., 2013). Critically, many of these parameters are linked and in (quasi-) equilibrium on long time scales. Thus, this investigation seeks to estimate streamflow variability throughout the Holocene using a water balance model that incorporates temporal changes in precipitation and evapotranspiration. The former will be reconstructed using a pollen-precipitation transfer function applied to pollen records from lake sediment sequences. In contrast to high-resolution centennial-scale tree-ring based reconstructions, the reconstruction presented here will be of lower temporal resolution, though spanning millennia.

Setting

The coastal temperate rainforest complex of western North America represents the largest remaining intact tract of temperate rainforest in the world, stretching from Alaska to California (Fig. 1). A steep coastal–inland precipitation gradient characterizes the rainforest complex, with moist maritime conditions prevailing on the outer western coast and drier conditions inland (Fig. 2). Vancouver Island (British Columbia, Canada) is located centrally in the complex and is characterized by a central mountain range. Consequently, watersheds on western Vancouver Island drain towards the Pacific Ocean, whereas those in eastern regions drain eastwards into the Strait of Georgia. In this study, two juxtaposed watersheds (San Juan and Koksilah) from Vancouver Island were targeted for study (Fig. 1).

The San Juan watershed is located on western Vancouver Island and has a surface area of 578 km^2 (Figs. 1 and 2). The San Juan watershed is characterized by a pluvial hydroclimatic regime since it is dominated by rainfall (Schnorbus et al., 2014). Average annual precipitation is 3519 mm. The primary river in the watershed is the San Juan River, flowing westward and draining into the Pacific Ocean. Regarding vegetation, plant communities in British Columbia are divided into zones according to the Biogeoclimatic Ecological Classification system of Meidinger and Pojar (1991), and further divided into subzones according to the level of precipitation (xeric, moist, and very wet) and degree of continentality (maritime to hypermaritime; Fig. 1). The Coastal Western Hemlock (CWH) zone prevails in the San Juan watershed, divided further into very wet (CWHvm), moist (CWHmm) and xeric (CWHxm) subzones. Of these, the latter subzone is least prevalent in the watershed. The only other zone in the watershed is the Mountain

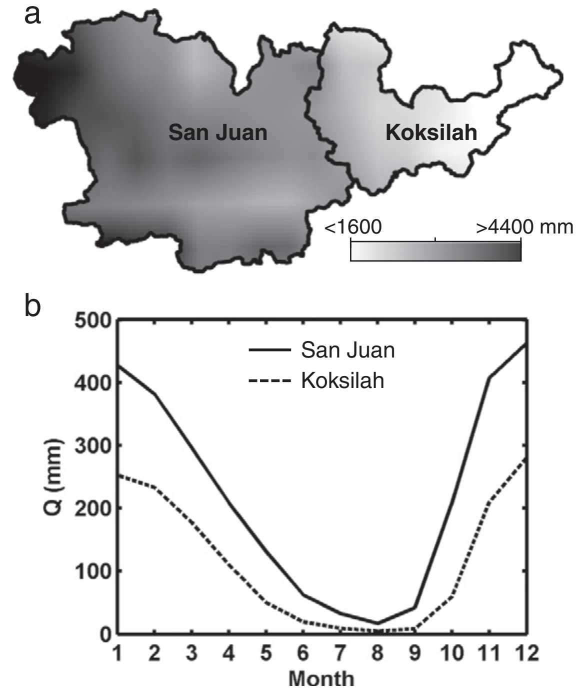

Figure 2. Map shows distribution of precipitation across the watersheds, whereas the graph shows annual discharge data for the San Juan (solid) and Koksilah (dashed) rivers. Months numbered 1–12 on the x-axis correspond to January–December, respectively.

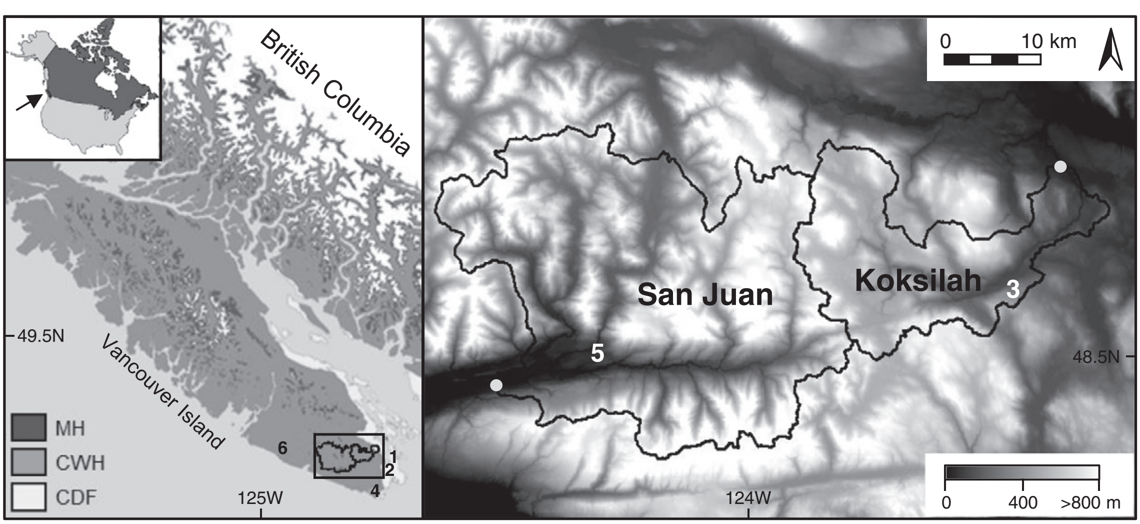

Figure 1. Study location map (inset) and distribution of biogeoclimatic (vegetation) zones along the coast of British Columbia, where MH = Mountain Hemlock, CWH = Coastal Western Hemlock and CDF = Coastal Douglas-fir. The San Juan and Koksilah watersheds are located within the black box on southern Vancouver Island. The right-side map delineates the San Juan and Koksilah watersheds on a digital elevation model, with the locations of stream gauging stations shown by solid circles. Coring locations are shown as 1. Heal Lake, 2. Langford Lake, 3. Rhamnus Lake, 4. East Sooke Fen, 5. Pixie Lake and 6. Whyac Lake.