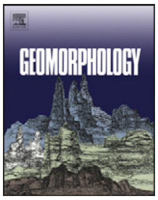
Geomorphology 276 (2017) 164–179

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph



Wood export varies among decadal, annual, seasonal, and daily scale hydrologic regimes in a large, Mediterranean climate, mountain river watershed

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ARTICLE INFO

Article history:
Received 17 May 2016
Received in revised form 29 September 2016
Accepted 29 September 2016
Available online 1 October 2016

Keywords:
Wood export
Mountain watershed
Large river
Mediterranean climate

ABSTRACT

The dynamics that move wood through and out of watersheds are complex and not yet fully understood. In this study, climatic conditions, hydrologic responses, and watershed processes were explored to better understand variations in wood export using aerial imagery, event-based video monitoring, and field measurements from the 1097 km^2 mountainous Mediterranean climate North Yuba River, California, watershed and its reservoir near the downstream outlet. Over a 30-year study period, 198\5–2014, volumetric estimates of annual wood export into the reservoir, available for a subset of years, were used to investigate watershed-scale wood export dynamics. Variations in annual peak discharge explained 79% of the variance in interannual wood export, with 84% of total observed wood export (ca. >10,000 m^3 of wood per event) delivered by three discharge events of 19-year, 21.5-year, and 60-year flood recurrence intervals. Continuous video monitoring conducted during snowmelt season periods in 2010 and 2011 yielded wood discharge observations at minima 15% of statistical bankfull flow, while maximum daily discharge explained 55% of observed daily wood piece variation. No statistically significant wood discharge differences were found in snowmelt season observations, likely because of domination of the hydrograph by diurnal pulses within the seasonal cycle. A conceptual model and functional framework are introduced in support of a watershed-scale explanation of wood export, transport, and storage processes applicable to large, Mediterranean-climate, mountain watershed settings.

1. Introduction

Scientific understanding of wood as a mechanistic agent in riverine environments has expanded since reports from the Pacific Northwest United States detailed adverse effects brought about by forestry extraction practices. Logging to stream edge and clearing wood out of streams alters channel morphology, increases sediment transport, and leads to declines in aquatic productivity (Swanson et al., 1976; Anderson et al., 1978; Bilby and Likens, 1980; Bilby, 1985; Harmon et al., 1986; Bisson et al., 1987). An early and enduring conceptual framework of wood dynamics described important physical and biological drivers and processes that deliver, store, break down, and move wood through stream channels (Keller and Swanson, 1979).

The introduction of a wood budget equation provided a quantitative framework of known first-order constraints on wood dynamics in streams (Benda and Sias, 2003; Benda et al., 2003). Wood budgets use conservation of mass principals to enumerate wood inputs, outputs, and the processes in between in a manner analogous to hydrologic and sediment mass balance budgets (e.g., Curtis et al., 2005; Merz et al., 2006). Construction of complete wood budgets remains infrequent (but see Martin and Benda, 2001; MacVicar and Piégay, 2012; Schenk et al., 2014) because of the breadth of necessary wood data collection elements, which can be summarized into recruitment, storage, decay, transport, and export categories (Benda and Sias, 2003; Swanson, 2003; Hassan et al., 2005), and the complexity of additional mechanisms in the surrounding environment that contribute to the stochastic regulation of these wood variables (Gregory et al., 2003; Wohl et al., 2010; Wohl, 2016).

Efforts to understand, describe, and quantify wood processes have advanced substantially (e.g., Gurnell et al., 2002; Gregory et al., 2003; Wohl et al., 2010; Merten et al., 2010; Ruiz-Villanueva et al., 2016; Wohl, 2016), yet research activities are still emerging in efforts to identify and quantify stochastic complexities between wood processes and hydrologic variations, climatic forcings, and watershed processes. The purpose of this study was to explore how watershed-scale wood processes vary under multiscalar hydrologic regimes and associated climate forcings.

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http://dx.doi.org/10.1016/j.geomorph.2016.09.039
0169-555X/

1.1. Wood dynamics

Investigations that have focused on linkages between stream discharge (Q, volume/time), wood discharge (Q_w, volume/time) or wood piece discharge (Q_{wp}, piece count/time), and climate forcings have taken advantage of reservoirs as depositional zones where cumulative wood export quantities (W_{exp}, volume or piece count on an event to multiyear basis) can be surveyed within the context of other watershed characteristics. A reservoir study in France revealed that large Q peaks delivered large quantities of W_{exp} but antecedent conditions had a dampening effect during subsequent Q peaks (Moulin and Piégay, 2004; Veronique et al., 2016). Across a wide range of reservoirs in Japan, peak annual Q (Seo et al., 2008) and latitudinal variations in precipitation were significant factors in explaining differences in W_{exp} quantities (Seo et al., 2012), with typhoon-generated flooding delivering more W_{exp} into reservoirs even though less stored wood was available for transport in watersheds with higher precipitation totals (Seo et al., 2015).

Technological advances in remote sensing capabilities have opened access to wood dynamics at wider spatial and temporal scales than a field campaign alone can attain (MacVicar et al., 2009). A combination of satellite imagery analyses, reservoir surveys, and channel surveys was effective in assessing total W_{exp} after Typhoon Morakot in Taiwan, where landsliding was the dominant delivery mechanism (West et al., 2011). Video imagery collected from channels and a reservoir shoreline during helicopter flights was used to estimate total W_{exp} after an extreme rain event caused landsliding in tropical Costa Rica (Wohl and Ogden, 2013). Satellite and aerial imagery was effective at capturing temporal variations in wood accumulations in a complex delta in eastern Quebec, Canada (Boivin et al., 2015). A cost- and effort-effective method to estimate Q_w when wood velocity is sufficiently low may include the use of time-lapse photography and probabilistic sampling of images, as demonstrated by a wood study in Canada (Kramer and Wohl, 2014).

Direct methods of monitoring wood in transport have recently been developed and have the potential to reveal processes as they occur. MacVicar et al. (2009) identified the difficulty of obtaining field data to validate theoretical concepts about Q_w as a technical problem primarily limited by available methods. To solve this, they reported on a proof-of-concept, at-a-station, continuous video monitoring technique that successfully collected Q_w footage on the lowland Ain River, France. MacVicar and Piégay (2012) used that empirical data to refine the theoretical relationship, first presented by Benda and Sias (2003), between Q and Q_w, as written here:

$$Q_w = b(Q - Q_{min}) \text{ and } b = \left[\frac{Q_{wref}}{Q_{ref} - Q_{min}}\right] \tag{1}$$

where Q_{min} is defined as threshold Q at which wood begins to transport, and Q_{wref} is defined as Q_w at a Q_{ref} of bankfull discharge. Assuming linearity, b is defined as a slope coefficient found via regression. The simplification of b is useful, as individual parameters are difficult to determine when no data yet exist to establish Q_{wref} values. Analyses revealed higher rates of Q_w on rising limbs of flood hydrographs than on falling limbs, which resulted in development of a two-step linear model that reflected the observed clockwise hysteresis behavior (MacVicar and Piégay, 2012).

Use of a stilling basin and bedload traps allowed Turowski et al. (2013) to collect wood data across three orders of magnitude in mass, 1 g to 3 kg (i.e., particulate to large wood sizes), exporting from a small headwater catchment in the Swiss Alps. They developed a power relation between decreasing number of wood pieces and increasing particle mass, reported in the form of:

$$C = kM^{-\alpha} \tag{2}$$

where C is the relative fraction of wood with a particle mass M, k is a constant, and $-\alpha$ is a scaling exponent independent of Q. The $-\alpha$ scaling exponent mean was 1.84, with a range 1.41–2.26, using 28 samples. Wood data from the Ain River (MacVicar and Piégay, 2012) yielded a similar $-\alpha$ value of 1.8, which may help to independently support the use of a scaling exponent to predict Q_w frequency (Turowski et al., 2013). Data also revealed a power relation across seven orders of Q_w mass (kg/s) and four orders of Q in the form of:

$$Q_w\ (mass) = aQ^b \tag{3}$$

Two large discharge events not used in the Turowski et al. (2013) development of this rating curve aligned with the upper reaches of the regression line, suggesting continued strength of the relation during higher flood flows.

The use of remotely sensed data collection techniques and the recognition of reservoirs as depositional zones in which to enumerate wood export have thus proven quite valuable in advancing scientific understanding of the interactions between wood, hydrologic regimes, and a suite of watershed-scale environmental factors.

1.2. Study objectives

Within the scope of decadal, annual, seasonal, and daily scale hydrologic regimes and by using field and remotely sensed data collected from the North Yuba River watershed in California, USA, specific study objectives were to (i) use imagery analyses and field data collected from New Bullards Bar Reservoir to investigate decadal, interannual, and winter season patterns of W_{exp}; (ii) analyze at-a-station continuous video monitoring data collected during snowmelt season Q periods in two consecutive years to understand seasonal, event-based, and daily patterns of Q_w and Q_{wp}; and (iii) test for geometric similarities and differences in wood metrics collected in different locations within the watershed. These analyses form the basis for the introduction of a conceptual model that illustrates, and a functional framework that details, watershed-scale wood processes applicable to large, Mediterranean climate, mountain river watersheds.

2. Study site

2.1. General setting

The North Yuba River watershed is located in the forested Sierra Nevada Mountain Range of northern California, USA. The watershed originates at an elevation of 2139 m at Yuba Pass and contains 1097 km^2 in area and 1074 river-km of channels to the confluence of Deadwood Creek at the upstream extent of New Bullards Bar Reservoir (hereafter, NBB; Fig. 1). The watershed is unregulated until its termination into NBB and is considered an important test basin for climate change scenarios related to precipitation variation and salmonid refugia (YSPI, 2015). The NBB dam face is 193 m tall with a crest elevation of 599 m (39°23′36.18″ N, 121°08′34.78″ W) and reservoir storage capacity of 1.2 km^3.

The heavily forested watershed has a disturbance legacy as one of the epicenters of the California gold mining era in the mid- to late 1800s when hydraulic mining operations and other extraction methods dramatically altered stream corridor morphology, riparian continuity, and aquatic ecology (Gilbert, 1917; James, 2005). This economy was supported by intense logging of hillsides that continued to be profitable for decades, so forests are now mostly even-aged stands <100 years old (Hitchcock et al., 2011). Woody vegetation that enters the channel network and that could transport into NBB includes, in approximate order of increasing elevational bands, foothill California black oak and canyon oak; ponderosa pine, white fir, and Douglas fir in a mixed conifer belt; red fir, Lodgepole pine, and Jeffrey pine; and subalpine tree species including western white pine (Fites-Kaufmann et al., 2007). Riparian