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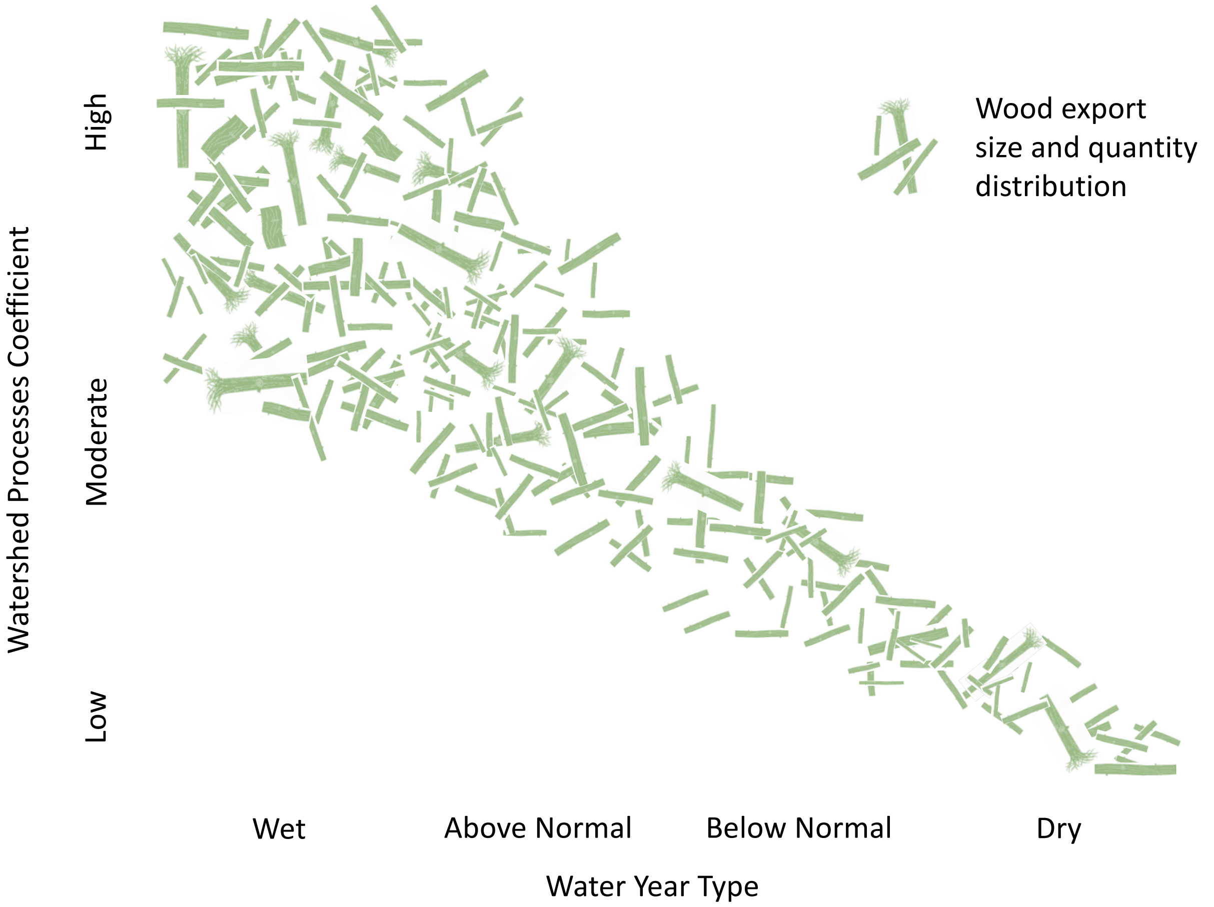
Short Abstract

Theory of wood export quantification is extended by generalizing complex watershed processes into a water year type multiplicative coefficient. The coefficient is tested and validated in a new DVWP (‘discharge variations modified by watershed processes’) equation that provides a modifier to discharge-only relations. Results show that predictions for dry WYs improve dramatically, while predictions for wet WYs, when most wood moves, remain variable, likely as a function of antecedent conditions.



Synthesis Figure. Watershed processes coefficients can be calculated using generalization techniques by grouping wood export quantities by water year types. The contribution of watershed processes to wood export are high in wet water years and diminish as water years become drier.

Abstract

Wood export from a watershed is a function of peak annual discharge, but one hydrologic relationship alone does not fully explain observed variability. Consideration of physical processes that influence the amount of wood available for transport is needed. However, wood recruitment, storage, mobilization, breakage, and transport rates and processes remain difficult to quantify. A theoretical wood transport equation focused on variations in discharge was the motivation for investigation into watershed-specific wood export rates. Herein, multiplicative coefficients categorized by water year type are developed, paired with the equation, and validated to provide a new method for prediction of wood export at the watershed scale. The coefficients are defined as representing a broad suite of watershed processes that encompass spatio-temporally variable scales. Two complementary data sets from the 1,097 km^2 mountainous North Yuba River, California watershed were used. Wood surveys above New Bullards Bar Reservoir yielded a wood availability estimate of 250,000–300,000 m^3 along the channel network. Annual wood export into the reservoir was field-surveyed in 2010, 2012, and 2013, and estimated in seven years via remotely sensed images over the 30-year study period of water years 1985–2014. Empirical, watershed-scale wood export rates ranged from 0.3-5.6%. Comparison of predicted quantities using the new DVWP (discharge variations modified by watershed processes) wood export equation to observed wood export quantities resulted in an aggregate error rate of $\pm$ 10%. When individual wood export quantities were compared, predicted to observed varied by 0.5–3.0 times. Total wood export of 59,000–71,000 m^3 was estimated over the 30-year period, yielding a rate of 1.8 to 2.2 m^3/year/km^2. Wood export predictive capabilities at the watershed scale may help water resource and regulatory agencies plan for wood transfers to augment downstream ecosystems.

Key words: Wood export, wood transport, wood storage, wood availability, watershed processes, reservoir management, Sierra Nevada

Introduction

Forested watersheds provide opportunities to study wood budgeting components (Benda and Sias, 2003) in locations around the world (e.g., Moulin and Piégay, 2004; Comiti et al., 2006; Andreoli et al., 2007; Latterell and Naiman, 2007; Warren and Kraft, 2008; Seo et al., 2008; Wohl and Goode, 2008; Benda and Bigelow, 2014; Schenk et al., 2014; Jochner et al., 2015; Lucia et al., 2015; Ruiz-Villanueva et al., 2016b; Steeb et al., 2017). Wood recruitment and related processes that store, transport, break down, and ultimately export wood pieces through watershed networks are key elements of stream complexity and ecosystem health (Keller and Swanson, 1979; Harmon et al., 1986; Gregory et al., 2003).

Wood dynamics fluctuate broadly depending on landscape, watershed, and local controls (Benda and Sias, 2003; Hassan et al., 2005; Benda and Bigelow, 2014), but are known to vary as a function of hydrologic processes (Moulin and Piégay, 2004; Marcus et al., 2011; MacVicar and Piégay, 2012; Seo et al., 2012; Boivin et al., 2017; Senter et al., 2017), hydraulic processes (Braudrick and Grant, 2000; Bocchiola et al., 2008; Ruiz-Villanueva et al., 2014), forest and riparian corridor dynamics (Latterell and Naiman, 2007; Gurnell, 2014), mass movement associated with episodic precipitation events (West et al., 2011; Wohl and Ogden, 2013; Steeb et al., 2017), and geomorphic and morphologic interactions between channel corridor elements and wood architecture (Gurnell et al., 2002; Abbe and Montgomery, 2003; Pettit et al., 2006; Wohl and Goode, 2008; Merten et al., 2010).

These processes and others constitute what are defined herein as a broad suite of "watershed processes" that promote or impede wood transport and export, are spatio-temporally variable across hierarchical scales, may include a response to discharge but does not explicitly represent the peak annual event, and remain difficult to quantify. The initial motivation for this paper was an existing conceptual equation from Marcus et al. (2011) that was developed using discharge variations but not watershed processes. The purpose of this paper is to describe development of a parsimonious set of watershed processes coefficients that support wood export prediction, given a relatively small set of known quantities.

Watershed processes

From a watershed-process basis, the volumetric quantity of wood fluctuates about a mean as a function of wood recruitment rates, wood storage capabilities of the channel corridor, wood transport rates, hydrographic variability, decomposition and fragmentation rates, and other natural processes (Benda and Sias, 2003; Moulin and Piégay, 2004; Marcus et al., 2011). Wood storage locations are more stable and prevalent in reaches where wood piece length or jam size is large relative to channel width (Lienkaemper and Swanson, 1987; Gurnell et al., 2002). Interactions between piece architecture, such as length and diameter dimensions, and channel features tend to increase the geomorphic function and stability of wood (Merten et al., 2010), while pieces that are not geomorphically active may transport more readily. Wood pieces will break apart and disintegrate as wood density decreases (Latterell and Naiman, 2007; MacVicar et al., 2009), although physical breakage rates of wood in transport remain mostly unknown (Hassan et al., 2005).

Once a wood piece is recruited into a channel it can spiral downstream (Latterell and Naiman, 2007) over a series of discharge events that vary in magnitude and duration. Storage scenarios include short durations in-channel, on a gravel bar, or along the channel bank; potentially longer durations in jams or on the floodplain; and decadal-scale burial and subsequent exhumation. These internal watershed processes induce a lag between the wood budget variables of input (recruitment) and output (export), mainly through a storage function that fluctuates depending on current and antecedent conditions (Berg et al., 1998; Benda and Sias, 2003; Moulin and Piégay, 2004; Marcus et al., 2011). Quantification of wood storage is relatively simple, whereas wood transport dynamics are less so, as highlighted by predictive wood mobility analyses that yielded models explaining 47% (Wohl and Goode, 2008) and 39% (Merten et al., 2010) of data variability.

Wood export quantities have been correlated with peak annual discharge (Moulin and Piégay, 2004; Boivin et al., 2015; Senter et al., 2017) and watershed area (Seo et al., 2008; Ruiz-Villanueva et al., 2016b). The depositional nature of reservoirs provides ideal locations in which to study wood export patterns and characteristics (Moulin and Piégay, 2004; Seo et al., 2008; Senter et al., 2017) in a manner analogous to sediment budget studies (Dendy and Bolton, 1976). Reservoir studies have shown that large flood events will produce large wood export events but also that antecedent floods can depress subsequent quantities at seasonal scales (Moulin and Piégay, 2004) and at yearly to decadal scales (Senter et al., 2017). Modeling of linked stream discharge-wood discharge behavior suggests that wood recruitment will accumulate faster than wood export rates under typical hydrologic conditions and then periodic large flood events will yield large wood export events (Marcus et al., 2011).

The concept of discharge as a primary driver of wood export led to the development of a theoretical wood transport equation (Marcus et al., 2011) to estimate the ratio of wood that moves between minimum and maximum discharge thresholds. This conceptual wood transport rule rests on the principle that the fraction of available wood that moves in a given water year depends proportionally on the relative amount of flow in transport during the annual peak flow event compared to a maximum flow needed to move all available wood, adapted here as:

$$f_W = \frac{Q_{peak} - Q_{crit}}{Q_{max} - Q_{crit}} \tag{1a}$$

where f_w represents the frequency at which wood may export from a catchment or reach as a function of variations in stream discharge, Q_{peak} is peak annual discharge, Q_{crit} represents a theoretical critical discharge where wood transport begins, and Q_{max} represents a theoretical flood discharge where all available wood transports (Table I).

Table I. Wood export parameters and definitions

Equation		Parameter	Definition
1a	$f_W = \frac{Q_{peak} - Q_{crit}}{Q_{max} - Q_{crit}}$	f_W	Theoretical wood export rate as a function of discharge variations (Marcus et al., 2011)
		Q_{peak}	Peak annual discharge, m^3/s
		Q_{crit}	Minimum discharge at which wood will mobilize; defined in this study as minimum discharge at which wood was observed in transport (Senter et al., 2017), m^3/s
		Q_{max}	Maximum discharge at which all wood may mobilize; defined in this study as a calculated 100-year flood event, m^3/s
1b	$W_Q = f_W \times W_{av}$	W_Q	Theoretical volumetric wood export, given a known wood volume available for transport, m^3
		W_{av}	Empirically derived wood volume available for transport, m^3
2	$c_W = W_{exp} \div W_{av}$	c_W	Empirical wood export rate
		W_{exp}	Empirical volume of wood export as measured at a station or outlet, m^3
3	$W_{max} = 905 \times {A_c}^{0.49}$	W_{max}	Predicted maximum wood export volume, m^3 (Ruiz-Villanueva et al., 2016b)
		A_c	Contributing watershed area, km^2
4	$W_\theta = f_W \times W_{max}$	W_θ	Potential maximum wood export, m^3, as a function of theoretical wood export rate and watershed area
5	$W_\% = (W_{exp} \div W_\theta) \times 100$	$W_\%$	Potential maximum wood export percentage as a function of discharge and watershed area, given a known wood volume available for transport
6	$\delta = c_w \div f_w$	δ	"Watershed processes" coefficient representing wood export variability within a watershed that remain difficult to quantify
7	$\delta_{max} = W_\theta \div W_Q$	δ_{max}	Maximum value of the watershed process coefficient
8	$W_{DVWP} = \delta \times W_Q$	W_{DVWP}	DVWP: "discharge variations modified by watershed processes" wood export, m^3, given an estimated wood volume available for transport

Study Objectives

The primary purpose of this study is to introduce a practical approach to wood export predictions in watersheds where wood export and wood storage data are available. Complementary wood datasets were collected from the North Yuba River, Sierra Nevada, California, in the form of field efforts to characterize upper watershed wood storage and reservoir surveys that measured annual wood export quantities either through field efforts or from remotely sensed imagery. These datasets were analyzed in conjunction with a 30-year discharge record from water years (WY) 1985–2014. The first study objective was to (i) explore the capability of the existing theoretical wood transport equation to adequately represent wood export quantities measured at the downstream reservoir of a forested mountain watershed, which led to subsequent (ii) development of theory, validation exercises, and refinement through introduction of multiplicative watershed processes coefficients that improved the prediction of wood export quantities. Theoretical development of a generalized, parsimonious approach, using water year type categories, may be beneficial for systems that lack sufficient capabilities to undertake a comprehensive mechanistic framework approach.

Study Site

The North Yuba River watershed originates along the western slope of the northern Sierra Nevada Mountain Range in California, USA at an elevation of 2,139 m at Yuba Pass. The watershed is unregulated until its termination into New Bullards Bar reservoir (NBB). The NBB dam face is 193 m tall with a crest elevation of 599 m and reservoir storage capacity of 1.2 km^3 (39°23’36.18” N, 121°08’34.78” W). The watershed is considered an important test basin for climate change scenarios related to precipitation variation and salmonid refugia (YSPI, 2015). The upper watershed, defined as the catchment area above the confluence of Deadwood Creek into the upper extent of NBB, contains 1,097 km^2 in area and 1,074 river-km of headwaters to Strahler 5th order channels (Fig. 1).

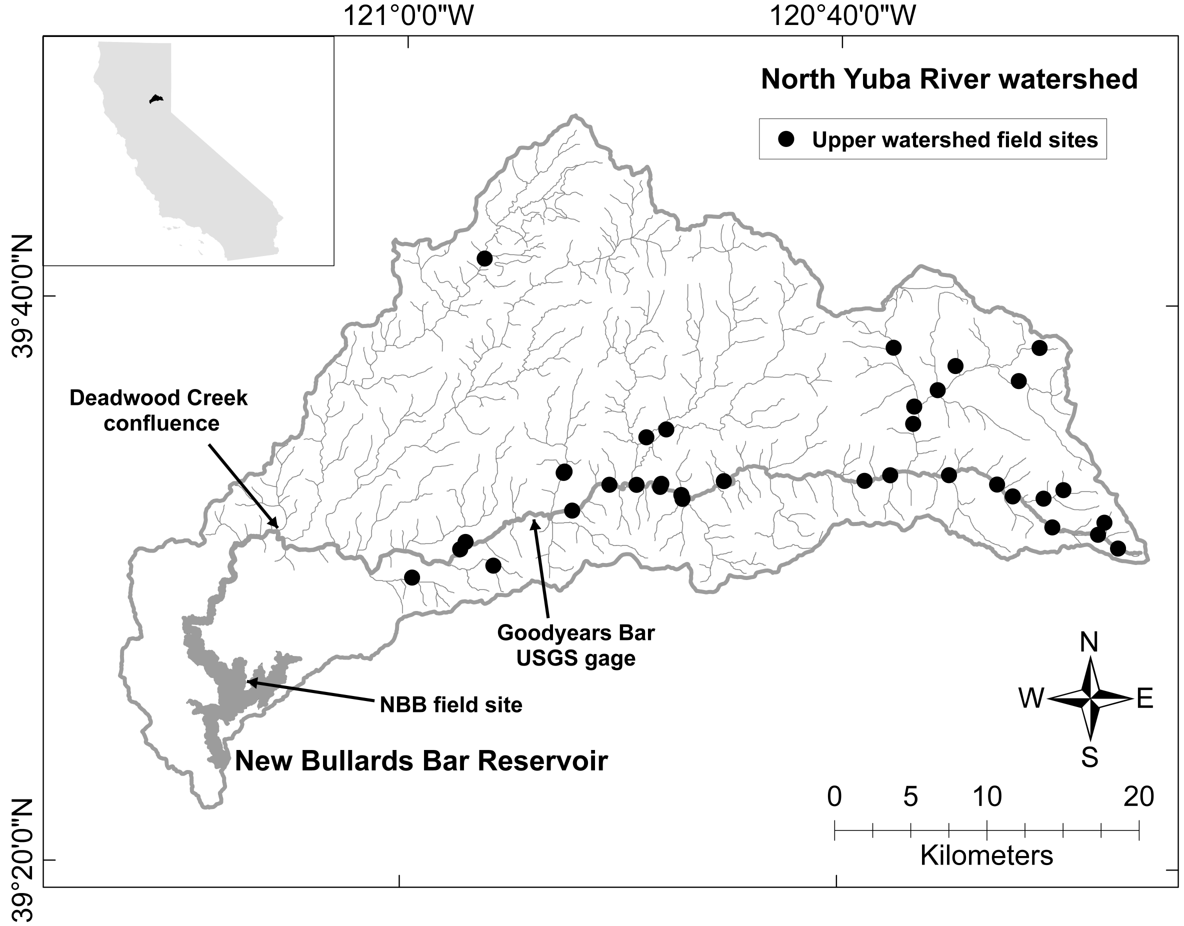


Figure 1. Geographic setting of the North Yuba River watershed, New Bullards Bar Reservoir, and Goodyears Bar USGS gage 1141300 in the northern Sierra Nevada Mountain Range, California, USA. Wood volumes and characteristics in the upper watershed were collected at field sites in 2012.

The greater Yuba River watershed, of which the North Yuba is the largest of three mountain sub-basins, has a disturbance legacy as one of the epicenters of California gold mining in the mid-1800's (Gilbert, 1917; James, 2005). Coniferous forests are mostly even-aged stands less than 100 years old given regeneration and replanting after decades of extensive logging (Hitchcock et al., 2011). Woody vegetation 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 corridor species include cottonwood, willow, and alder. Bedrock geology consists primarily of granitic batholith which dominates much of the channel corridor, with lesser amounts of metamorphosed sedimentary and volcanic rock, and glacial till (Curtis et al., 2005).

The Sierra Nevada climate is characterized as Mediterranean-montane, with cool, wet winters and warm, dry summers. In California, the WY is defined as October of a previous year through September of the designation year, and can be simplified into a wet winter season from October through March, a snowmelt season from April through July with progressively diminishing precipitation, and an overlapping drought condition summer season from June through September. Annual precipitation ranges from 500–2000 mm dependent on elevation and aspect, with a rain-snow mix between 500–1800 m in elevation dependent on temperature at the time of precipitation. Snowfall predominates above 1800 m from November through March (Mount, 1995).

Flood pulses during the wet winter rain-snow season are generated by narrow-banded atmospheric river events that can deliver localized, intense, high-magnitude precipitation (Ralph et al., 2006; Dettinger, 2011), as well as by low-pressure systems that can deliver moderate to heavy precipitation over extended periods of time. The largest flood pulses occur when warm rain falls on snow, leading to rapid melting of snowpack and quick release of stored water via episodic flood events (McCabe et al., 2007; Garvelmann et al., 2015). Within the 30-year study period (Fig. 2), the return intervals for the three largest wet winter flood magnitudes into NBB were 21.5, 60, and 19 years in WY1986 (warm rain-on-snow event), WY1997 (atmospheric river event), and WY2006 (atmospheric river event), respectively, with each flood exporting a large quantity of wood from the upper watershed into NBB.

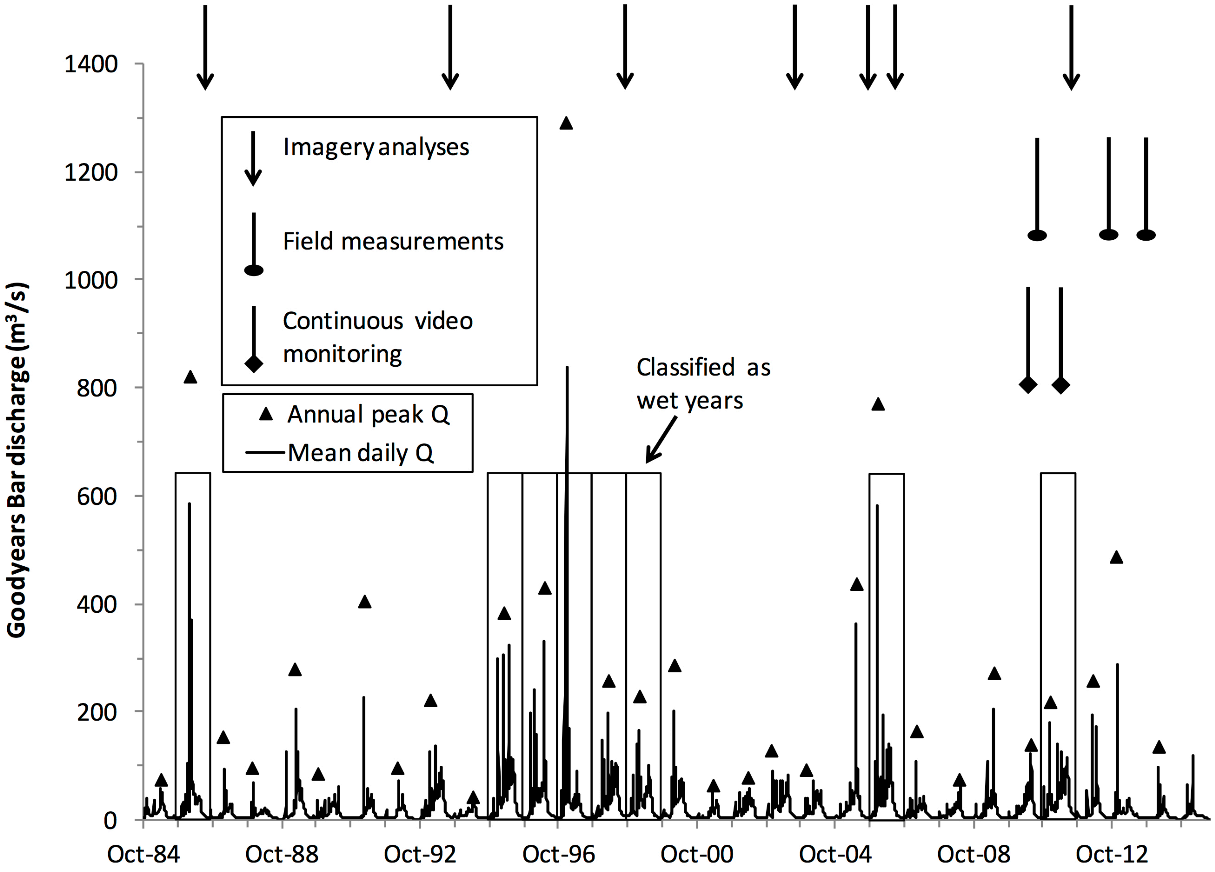


Figure 2. Goodyears Bar discharge hydrograph and the time periods in which data were available or collected in the watershed over the 30-year study period. Boxed hydrographs signify years designated as wet WY types.

Theory Development

Wood Transport Theory

A theoretical wood transport rule (Eq. 1a) was introduced as one facet of exploration into observed wood distributions following wildfire in Yellowstone National Park, USA (Marcus et al., 2011). Marcus et al. (2011) defined Q_{peak} as annual peak flood discharge in a given year and it is applied likewise in this study; however, the form of the equation could be used to assess wood transport on an event basis when sufficient data are available, as most years have multiple wood-mobilizing flows. The ratio f_W from Eq. 1a converts to a volumetric quantity when an estimate of wood available for transport in the upper watershed is known:

$$W_Q = f_W \times W_{av} \tag{1b}$$

where W_Q (m^3) is the theoretical volumetric estimate of wood that transports as a function of Q_{peak}, and W_{av} (m^3) is an empirically derived estimate of the volumetric quantity of wood available for transport in a watershed, inclusive of wood storage and wood recruitment inputs (Table I). The value of W_{av} will vary with fluctuating rates of other wood budget variables such as recruitment, transport and export (Benda and Sias, 2003; Marcus et al., 2011).

Marcus et al. (2011) stated that Eq. 1a was "not intended to be an accurate predictive tool but, rather, a conceptual device for exploring possible reasons for variations in the empirical data". As a conceptual devise, the Marcus et al. (2011) equation considers theoretical variations within a discharge envelop from initiation of mobility through complete mobilization of all available wood pieces; important parameters that poise this equation for use across multiple flows within a given timeframe. Furthermore, development of the equation was grounded in the physical behavior of wood transport as a function of variations in stream discharge, and conclusions were drawn regarding the stream segments to which it was applied. Other studies have reported on peak discharge relationships (Moulin and Piégay, 2004; Boivin et al., 2015; Senter et al., 2017). Annual peak discharge may be the value specified in those regression equations, but watershed processes are included by inference. We therefore considered it fundamentally sound and most practical to use Eq. 1a,b as the initial basis for exploration of wood export dynamics using the North Yuba River, California as a test watershed and NBB reservoir as a depositional basin where wood export could be quantified.

Testing the efficacy of Eq. 1a,b was predicated on the ability to evaluate wood export volume from other perspectives. MacVicar and Piégay (2012) redefined f_W to reflect physical processes of observed wood discharge as a function of a wood discharge rate at bankfull stream discharge, but their relation remains focused on wood response to discharge only and necessitates knowledge of wood transport rates. The theoretical construct of how wood exports from a catchment is extended here by generalizing the complex set of watershed processes that interact both with and against discharge. To do so, a physical definition of wood response to watershed behavior is advanced by using empirically derived wood export and W_{av} data, written here as:

$$c_W = W_{exp} \div W_{av} \tag{2}$$

where c_W defines a wood export rate that is assumed equal to the ratio of volumetric wood export to wood available for transport within a watershed and W_{exp} (m^3)

represents the wood export volume that exits from a watershed (or reach) via transport processes.

Wood pieces that fall in low-order upper watershed channels where wood length to channel width is greater than unity are unlikely to reach the watershed outlet; however, predictions of wood export as a function of watershed area are not uncommon (e.g., Seo et al., 2008). A probabilistic examination of wood transport distances as a function of wood length to channel width ratios may yield additional insights into watershed area analyses, but that was beyond the scope of this study. Prediction of an upper limit of volumetric wood export as a function of watershed area has recently emerged using empirically derived wood export quantities aggregated from locations around the world (Ruiz-Villanueva et al., 2016b), adapted here as:

$$W_{max} = 905 \times {A_c}^{0.49}, r^2 = 0.89 \tag{3}$$

where W_{max} represents the largest volumetric quantity of wood that may export from a watershed given a statistically exceptional flood, and A_c represents upstream watershed contributing area. Pairing W_{max} with Eq. 1a yields a theoretical upper limit to wood export quantities in a watershed, written as:

$$W_{\theta} = f_W \times W_{max} \tag{4}$$

where W_{θ} represents a maximum potential wood export as a function of discharge variations (Eq. 1a) and watershed area (Eq. 3), where watershed area serves as another form of the broadly defined suite of watershed processes that may promote or impeded wood export dynamics.

A relation can also be developed between observed wood export and maximum potential wood export:

$$W_{\%} = (W_{exp} \div W_{\theta}) \times 100 \tag{5}$$

where $W_{\%}$ represents the percentage of known wood export to maximum potential wood export, encapsulating the relationship into one metric supported by wood export data and using North Yuba River watershed area to solve for Eq. 4.

Exploratory analyses of the above equations revealed clear differences between results of theoretical f_W and W_Q as a function of discharge variations (Eq. 1a,b), observed wood export (Eq. 2), and maximum potential wood export as a function of watershed area (Eq. 3). The degree of variability supported development of an approach that could represent temporal and spatial lags in wood dynamics that are known to exist but remain difficult to quantify. The most parsimonious approach was to identify these controls as quotients of the empirical wood export rates (Eq. 2) divided by the theoretical wood export rates for each WY (Eq. 1a), which yields:

$$\delta = c_w \div f_w \tag{6}$$

where the watershed processes coefficients δ are defined as the natural spatio-temporal variability that promotes or impedes wood transport and export, may include a response to discharge but does not explicitly represent the peak annual event, and are relatively difficult to describe in detail because the set of environmental drivers is diverse, hierarchical, and not yet fully understood.

The quotient of Eq. 4 divided by Eq. 1b adds an important insight into the control of watershed processes on wood export by defining a watershed-scale upper limit to coefficient values, which can be written as:

$$\delta_{max} = W_\theta \div W_Q \tag{7}$$

where the coefficient δ_{max} represents the ratio of maximum potential wood export to theoretical wood export.

Individual watershed processes coefficients (Eq. 6) derived from known wood export quantities can be multiplied by theoretical wood export quantities (Eq. 1b), to yield a volumetric wood export value that conforms to those known quantities:

$$W_{DVWP} = \delta \times W_Q \tag{8}$$

where W_{DVWP} (m^3) export is defined as a wood export quantity that takes into consideration “discharge variations modified by watershed processes” (DVWP). When wood export quantities are known and a specific coefficient for that WY has been calculated, DVWP wood export would be equivalent to W_{exp} in Eq. 2. More notably, DVWP wood export can be predicted in years when wood export quantities are not known by applying an appropriate generalized watershed processes coefficient based on WY type, as discussed shortly.

Application to the North Yuba River watershed

Hydrologic data

Continuous hourly inflow data into NBB were available over a nine-year period, WY2007-WY2015 (CDWR, 2015). Nine consecutive years of annual peak discharge data were not sufficient for a statistical analysis, so data from the USGS gage 11413000, North Yuba River below Goodyears Bar, California (GYB) was calibrated and used to extend the data set to 30 years. The GYB gage is located 24.9 river-km upstream of the Deadwood Creek confluence along the mainstem and provides discharge data for 648 km^2 (59%) of the watershed. First, annual peak discharge data was obtained from GYB for the same timeframe as NBB inflow. Next, a regression analysis between the set of coincident NBB and GYB annual peak discharges resulted in a linear relation:

$$NBB\ Q_{peak} = 2.04 * GYB_{peak} + 92.43, r^2 = 0.70, p = 0.036 \tag{9}$$

Third, the relation was used to construct missing annual peak discharge values for NBB over the 30-year study period WY1985-WY2014.

A Log-Pearson III analysis of the resultant NBB Q_{peak} data yielded a 100-year recurrence interval estimate of 3,470 m^3/s that was used for Q_{max} in Eq. 1a, the discharge at which all wood may be expected to mobilize. Although larger floods are possible and may yield more wood as the likelihood of bank erosion and hillslope failure increases, a statistically exceptional 100-year flood event was considered as a realistic theoretical discharge that could mobilize all wood available for export from the watershed. A larger Q_{max} would have the effect of reducing Eq. 1a,b estimates. The critical minimum discharge Q_{crit} at which wood may mobilize was set at 60 m^3/s, the lowest discharge that wood was observed in transport during a continuous video monitoring field effort at the upstream end of NBB during spring snowmelt periods in 2010 and 2011 (Senter et al., 2017). A larger Q_{crit} would have the effect of increasing Eq. 1a,b estimates.

Water year types

Classification of a watershed's hydrologic behavior over the period of a WY is used by water resource agencies throughout California as a proven yet simple means by which to manage water supplies for environmental and consumptive uses at the watershed to state-wide scale (CDWR, 2016). The Yuba County Water Agency (YCWA) issues yearly Yuba River Index (YRI) hydrologic classifications to fulfill regulatory requirements related to dam operations and instream flow requirements (YCWA, 2012). The YRI uses cumulative discharge data from the North Yuba River, Middle Yuba River, South Yuba River, and Deer Creek subbasins, as recorded at the USGS gage 11418000 Yuba River below Englebright Dam near Smartville, California. Official classifications for YRI WY types include wet, above normal, below normal, dry, critical, and critically dry. Each WY is assigned according to a weighted equation that factors in antecedent conditions from the previous WY as well as proportions of discharge totals from the October-March wet season and April-July snowmelt season. A YRI index number is calculated at the end of each WY:

$$YRI = 0.2 \times YRI_{previous} + 0.3_{wet\ season\ runoff} + 0.5_{snowmelt\ season\ runoff} \qquad (10)$$

where $YRI_{previous}$ represents the previous WY's index number. A WY type is assigned based on where each YRI index value falls within a set of predetermined ranges that define each WY type (YCWA, 2012); thus, WY types represent relatively narrow ranges in hydrologic responses to precipitation and snowmelt magnitudes, which can nevertheless manifest as considerably variable within any individual WY. For instance, a large flood event can play a role in a wet WY type designation, but so can cumulative discharge over a series of smaller flood magnitudes that results in the same wet year type classification even though the WY hydrographs would be markedly different.

Designations of WY types are a key component of the generalization technique used in this study, providing a straightforward method for classifying temporally variable watershed-scale hydrographic responses into watershed processes coefficients. California's climate is semi-arid, and low flows initiate less wood mobility, so the three driest WY types were lumped into one dry group. This yielded four WY classes for further analyses: wet, above normal, below normal, and dry WY types (Table II).

Table II. Wood export and WY type characteristics, ordered by WY type then WY

WY type	Water Year (WY)	W_{exp}, m^3	W_{exp} data source	NBB Q peak, m^3/s	NBB Q peak return interval, years
wet	1986	11925	Landsat	1765	21.5
wet	1997	10800	Landsat	3028	60.0
wet	2006	14125	YWCA	1661	19.0
wet	2011	1113	Google Earth	626	3.0
above normal	1993	1976	Google Earth	546	2.3
above normal	2005	1897	Google Earth	981	7.0
below normal	2012	1680	field measure	726	4.0
dry	2013	83	field measure	1132	9.2

Wood export into New Bullards Bar Reservoir

Each year prior to summertime recreational water activities, all wood pieces found in NBB floating on the water surface or lodged along the shoreline are collected and moved to one location for safety purposes. The same methods of entrapment are used each year. A line of buoys that holds floating wood along the shoreline is systematically tightened with each addition of wood pieces, presumably resulting in consistent wood piece compaction across the corralled area, which differs from assumptions used when wood rafts are free-floating (Benacchio et al., 2017). Reservoir levels decrease over the summer months as water is withdrawn and wood eventually deposits onto the sloped reservoir shoreline. Disposal via burning may occur at the start of a new WY when enough wood has accumulated to warrant costs and enough rain has fallen to minimize fire risks. If both conditions are not met then the wood is not burned, which can delay disposal for multiple years, and over these years wood gets added annually to the sequestered accumulation. In years with episodic flooding and consequently large pulses of wood, pieces are stored in a larger cove and depending on condition get chipped or set aside for milling.

Field measurements were collected from wood export accumulations at the end of summer seasons in WY2010, WY2012, and WY2013 on dry land after reservoir levels receded. A minimum of 100 wood piece dimensions were recorded each year using the large wood criteria of $\geq$ 1 m length and $\geq$ 10 cm diameter (Macka et al., 2011). These three field efforts yielded mean and standard deviation wood piece length of 2.8 ± 2.1 m, median 2.0 m, and diameter of 25 ± 18 cm, median 19 cm.

Wood density was found by extracting three samples each from 19 dry wood pieces and performing water displacement analyses that resulted in mean wood density estimate of 480 ± 120 kg/m^3. Wood piece decay condition varied, which may explain the density range of 260-770 kg/m^3. Wood species were not recorded, but presumed to be predominately coniferous. Mean density conforms to a typical estimate in the literature of 500 kg/m^3 (e.g., Seo et al., 2008) but not to the reported instream wood value of 660 ± 220 kg/m^3 in Ruiz-Villanueva et al. (2016a). The wood species examined in their study were deciduous hardwoods rather than coniferous softwoods, which may be the reason for this inconsistency and emphasizes the need for additional instream wood density data across a broad spectrum of wood species and decay conditions (e.g., Harmon et al., 1986).

Each year, a survey starting location was randomly selected along the edge of the accumulation, and then sampling was conducted toward the interior to accommodate potential compaction variations. A GPS unit was used to delineate sampled and total wood accumulation areas. Wood piece volume was calculated under the assumption that each piece could be approximated as a cylinder, and then total wood export was calculated (Table II) using a linear assumption that the sampled area adequately represented the large wood size distribution of the entire accumulation. These assumptions were used in each field campaign, so any biases in volumetric calculations remained constant. In years when remotely sensed imagery was available, area delineations were assumed to contain equivalent wood size distributions as those from the field estimates under the presumption that wood transport size classes may fluctuate but remain relatively equivalent over time. In larger floods, larger wood pieces may transport with increased discharge (Merten et al., 2010), so averaged metrics from more typical years may result in an underestimation of wood export quantities in episodic years; however, no adjustments were made to accommodate this potential.

Field data and aerial image analyses yielded a total of eight years where wood export quantities were known to represent one year of accumulation (Table II). These data were used to derive the empirical wood export rate (c_w), and to derive the set of watershed processes coefficients. In two additional years, wood export quantities were known, but reservoir personnel reported that these quantities were the result of multiple years of wood accumulation (S. Craig, YCWA staff, pers. comm.). The WY2003 aerial image was therefore assumed to represent five years of cumulative wood export from WY1999 through WY2003, and the WY2010 field campaign data was assumed to represent four years of wood export from WY2007 through WY2010. Cumulative values were initially apportioned into theoretical annual wood export quantities using Eq. 1b and then predicted using the DVWP wood export equation (Eq. 8).

Landsat images provided documentation of episodic wood export quantities resulting from episodic flooding in WY1986 and WY1997. A comparative analysis was performed to explore uncertainties using a 1-m resolution USGS image taken two days earlier than the 30-m resolution 1986 Landsat image (Gonzalez et al., 2011), which constrained identification errors using a set of spatial coherence tests such as dispersion, compactness, and angularity. An error rate of ±15% was found to contain two end members: a 30-m pixel could be falsely identified as containing wood or falsely identified as not containing wood. Once pixels were identified through this analysis and expert judgement, volumetric wood estimates used the same assumptions as detailed above.

Wood availability in the channel network

Volumetric wood availability, a key variable required for the extension of theory, was the focus of a field effort to measure wood storage within the mountainous Yuba River watershed (three sub-basins totaling 2874 km^2) in the summer of WY2012 (Vaughan, 2013). A stratified random sampling scheme was used to collect data from 114 reaches 50- or 100-m in length that spanned Strahler stream orders 1–5. Measurements were recorded for wood pieces that fit the large wood criteria, and geomorphic attributes of each wood piece and jam (defined as two or more large wood pieces touching) were collected along with morphologic reach characteristics. Total wood volume (wood pieces plus jams) was found to be highly variable between sample sites, yet two basic metrics, total wood volume per channel length and overbank wood volume per channel length, showed few statistically significant differences between stream orders using Mann-Whitney *U* tests that tested for differences greater than zero between mean rank scores of the raw data values at a significance level of $p_{(1)} < 0.05$. Only in-channel wood distribution, about 14% of total wood volume, exhibited statistically significant systematic decreases in wood volume in the downstream direction at the greater Yuba River watershed scale.

In the North Yuba River watershed, the Vaughan (2013) field effort collected data from 34 study reaches (Fig. 1). An average of 15.5 individual large wood pieces per 100 m were identified for a total of 384 pieces. Piece length was 3.8 ± 3.7 m, median 2.6 m; diameter was 23.7 ± 12.3 cm, median 20 cm; and volume was 0.31 ± 1.0 m^3, median 0.08 m^3. About 12% of individual wood pieces were located in the wetted channel, 15% on bars, 32% on floodplains, and 42% along the lateral extent of the active channel margins (Table III). Three jam measurements were recorded: the longest dimension, the axis perpendicular to the longest dimension, and representative jam thickness. Each jam was classified into a density category as high, medium or low, and then jam porosities of 10%, 40% and 70% (Manners and Doyle, 2008), respectively, were applied to estimate jam volume. The field effort located an average of 4.4 jams per 100 m for a total of 110 jams, with number of pieces per jam of 12.6 ± 25.0, median 6.0; and volume of 4.4 ± 10.2 m^3, median 1.0 m^3. Jam volume was 75% of total surveyed wood volume. About 15% of wood jams were located in the wetted channel, 39% on bars, and equal distributions of 23% each on floodplains and along active channel margins (Table III).

Table II. Wood export and WY type characteristics, ordered by WY type then WY

WY type	Water Year (WY)	W_{exp}, m^3	W_{exp} data source	NBB Q peak, m^3/s	NBB Q peak return interval, years
wet	1986	11925	Landsat	1765	21.5
wet	1997	10800	Landsat	3028	60.0
wet	2006	14125	YWCA	1661	19.0
wet	2011	1113	Google Earth	626	3.0
above normal	1993	1976	Google Earth	546	2.3
above normal	2005	1897	Google Earth	981	7.0
below normal	2012	1680	field measure	726	4.0
dry	2013	83	field measure	1132	9.2

Wood piece and jam volumetric data stratified by Strahler stream order were visualized using box plots (Fig. 3). Mann-Whitney *U* tests found that three of ten wood piece volume combinations yielded statistically significant differences whereas there were no significant differences between wood jam volumes. The relative lack of statistical differences between piece volume, and no statistical differences between wood jam volume, led to a broad assumption that volumes of both individual pieces and jams were approximately equally distributed throughout the channel network at a scale of 10^1 m. Consequently, a simple extrapolation calculation was performed to estimate the number of wood pieces in the channel network, yielding 0.155 pieces per meter of channel, or approximately 180,000 individual pieces. An equivalent calculation for wood jams yielded 0.044 wood jams per meter, or approximately 51,000 jams.

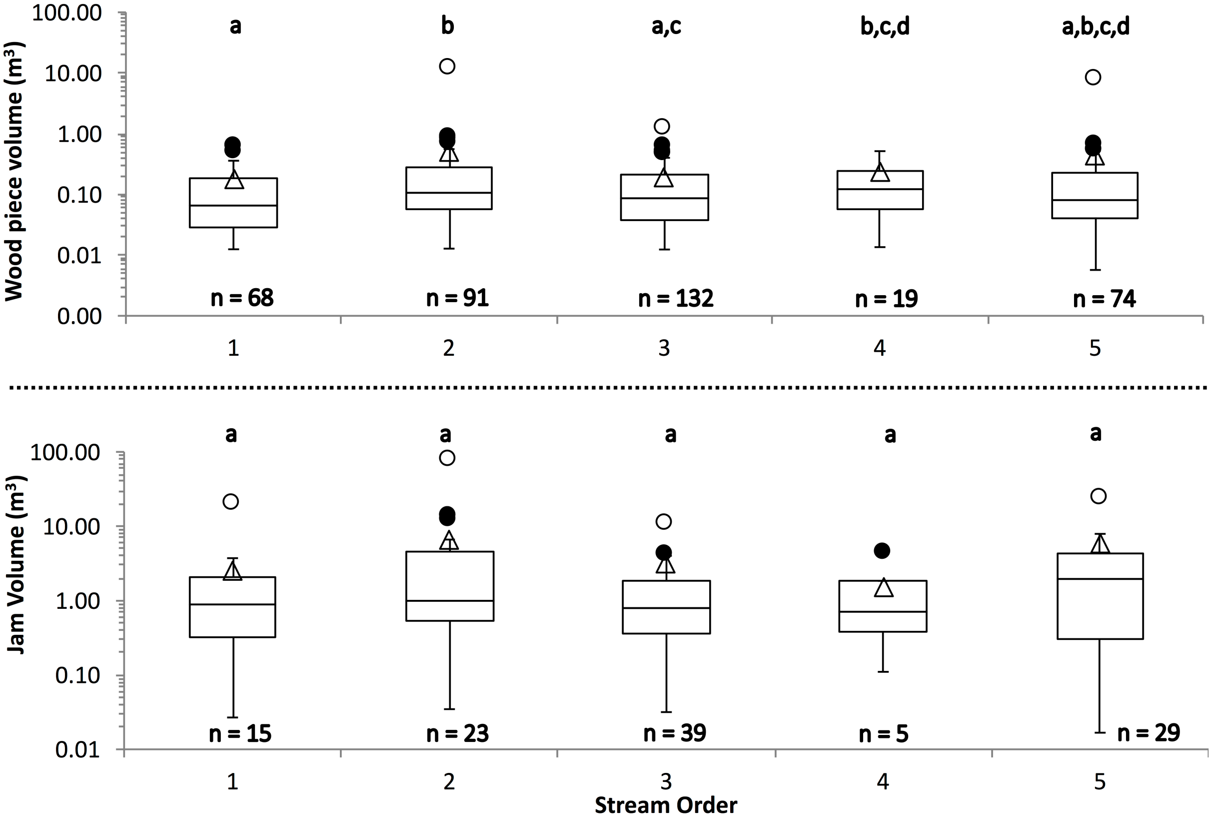


Figure 3. Box plots of individual wood piece volume (top) and jam volume (bottom) from the upper watershed, delineated by stream order. Matched letters indicate MW-U test results of no significant differences between mean ranked values, where $p_{(1)} < 0.05$. Box plot horizontal lines indicate 25th, 50th, and 75th percentiles; triangles represent the mean; whiskers represent minimum and maximum values minus the nearest quartile. Open circles and closed circles represent outliers above whisker values that are greater than and less than 1.5 times the interquartile range, respectively.

The use of an assumption of approximately equivalent wood distribution throughout the watershed channel network is unusual compared to other studies (Wohl, 2017). However, the data and statistical analyses (Fig. 3), and those in Vaughan (2013) using different techniques, yielded the same conclusions and thus are considered verified and valid. It may be that our data collection method, which included all wood within the active channel width defined as any area showing evidence of inundation, and which differs from most studies that tend to collect data from the bankfull channel extent (e.g., Benda and Bigelow, 2014), is driving this apparent disparity. This is supported by the result that in-channel wood distribution did decrease in the downstream direction, and also reveals the relative lack of in-stream wood (i.e., 14% of all identified wood). We suggest that data collection of wood and channel morphology metrics that include the active channel width would provide a more complete understanding of the quantities of wood available for transport under high flow conditions (Ruiz-Villanueva et al., 2016b) and of the broad suite of watershed processes that this study has generalized into a set of coefficients.

Benda and Bigelow (2014) reported values for a number of wood budget variables across a wide physiographic range of forested, mountainous, California watersheds. The grouped sub-basins most like the North Yuba River in their study were observations from 17 Sierra Nevada 3rd order watersheds (< 30 km^2) that were characterized as managed, and which included data from Haypress Creek, the eastern- and upper-most sub-basin along the mainstem in the North Yuba River watershed (Fig. 1). Data from this group are utilized herein to estimate and validate procedures used to develop a range in wood availability storage quantities within the North Yuba River watershed.

Wood recruitment rates were reported as ~10 ± 20 m^3 per year per bankfull channel hectare in this category (Benda and Bigelow, 2014). Recruitment origins were identified for about 50% of wood pieces at an approximate 40%-60% ratio between tree mortality and bank erosion processes, with negligible contributions from landslides, and about 90% of pieces were identified as coniferous species. Channel widths were reported as 4.4 ± 3.0 m and riparian biomass densities as 106 ± 95 m^3, and a 20-year residence time was estimated by dividing wood storage quantities by recruitment rates.

In our sampled reaches, average active channel width generally increased as stream order increased, ranging from 0.9–39.5 m, median 10.3 m. We used a median 10 m channel width by 1 km channel length throughout the watershed as an approximation of 1 channel hectare, and assumed that Benda and Bigelow's (2014) recruitment rates are approximately equivalent to those across the North Yuba watershed in most years. Multiplying their recruitment rate by our approximation of 1,000 channel-ha in the watershed yielded an estimated range in annual wood recruitment of 10,000–30,000 m^3 at the watershed scale, or 10–30 m^3 per river-km per year.

Extrapolation of wood storage to the watershed scale using WY2012 mean wood piece and jam volumetric measurements yielded an estimated 280,000 m^3 of wood available for transport. In keeping with temporally variable wood quantities available for transport, lower and upper bound values of 250,000 m^3 and 300,000 m^3 were used to explore the study objectives under the assumptions that (a) wood available for transport varies about a mean depending on antecedent conditions (Moulin and Piégay, 2004), (b) recruitment outpaces export in years between large flood events (Marcus et al., 2011), and (c) episodic flood events occur at approximate 10 year intervals regardless of magnitude (Fig. 2) and mobilize wood throughout the watershed network, which results in commensurately episodic wood export quantities at the watershed outlet (Senter et al., 2017). Wood storage of 250–300 m^3 per river-km at a median channel width of 10 m falls at the mid-range of the wood storage loads of 226 ± 289 m^3 per bankfull channel hectare reported by Benda and Bigelow (2014), which supports the assumptions involved in calculating the wood available for transport in this study.

Generalizing δ coefficient values

Watershed processes coefficients were calculated for each of the eight years in which wood export quantities were known to represent one WY using the upper and lower bound values of wood available for transport. This provided a dataset of 16 coefficient values (δ) across four WY categories. The wet year category contained eight calculated coefficients, the above normal category four, the below normal category two, and the dry category two. Each set was averaged to yield a generalized coefficient to be used to predict wood export in years categorized by WY type.

The effectiveness of using generalized coefficients was tested using the two wood export datasets from WY2003 and WY2010 where accumulation periods encompassed multiple years rather than one year, such that cumulative volumetric quantities were known but discrete annual wood export quantities were unknown. To separate these datasets into theoretical wood export quantities using discharge variables only, Eq. 1b was solved using the appropriate annual Q_{peak} value (Eq. 9). To separate these datasets into annual wood export quantities that also consider watershed processes, Eq. 8 was solved by multiplying theoretical wood export (Eq. 1b) by the generalized coefficient depending on WY type, and then the two prediction techniques were compared. Finally, volumetric estimations of wood export in WYs where no records exist were calculated by solving Eq. 8 using Q_{peak} and the appropriate generalized coefficient depending on WY type, and then comparisons were made between these results and those reported in Senter et al. (2017), where a regression analysis of wood export yielded a predictive equation focused exclusively on annual peak discharge.

Results

Theoretical wood export, Eq. 1a,b

Solving Eq. 1a was accomplished using a Q_{crit} of 60 m^3/s, a Q_{max} of 3,470 m^3/s, and the appropriate annual Q_{peak} for the years where wood export was known. These calculations resulted in theoretical export frequency percentages of 14–87% of the volumetric wood available for transport into NBB in a given year (Table IV). The smallest percentage of theoretical f_w was associated with a Q_{peak} of 546 m^3/s in WY1993, a statistical 2.3-year flood event in an above normal WY (Table II). The largest percentage was associated with a Q_{peak} of 3,028 m^3/s in WY1997, a 60-year flood event in a wet WY.

Table IV. Theoretical and observed wood export calculations, ordered by WY type, then WY

	Eq. 1a	Eq. 1b^{a,b}		Eq. 2^{a,b}		Eq. 2, Observed	Eq. 4^c	Eq. 5
	fw	*Theoretical wood export, W_Q*		*Empirical wood export rate, c_W*		W_{exp}	W_{Θ}	$W_{\%}$
Water Year	%	m^3		%		m^3	m^3	
1986	50	125000	150000	4.8	4.0	11925	15000	80
1997	87	217595	261114	4.3	3.6	10800	26100	41
2006	47	117375	140850	5.6	4.7	14125	14100	100
2011	17	41496	49795	0.4	0.4	1113	5100	22
1993	14	35608	42730	0.79	0.66	1976	4200	47
2005	27	67486	80983	0.76	0.63	1897	8100	23
2012	20	48827	58592	0.67	0.56	1680	6000	28
2013	31	78592	94311	0.03	0.03	83	9300	1

a left column results when W_{av} equals 250,000 m^3

b right column results when W_{av} equals 300,000 m^3

c when Eq. 3 equals 30,000 m^3 as calculated for the North Yuba River watershed

When Eq. 1b was solved using lower and upper volumetric bounds of available wood for transport, theoretical wood export ranged from 35,608 m^3 in WY1993 to 261,114 m^3 in WY1997 (Table IV). To support these theoretical export quantities, minimum wood export rates in WY1993 of 30 m^3 per river-km would have been generated across the entire watershed, whereas a maximum rate of 225 m^3 per river-km would be required in WY1997. In a year with a statistically typical return interval of 2.3 years, theoretical wood export of 35,000 m^3 exceeds the upper bound of the estimated annual wood recruitment rate for the entire watershed. In a year with a statistically unusual return interval of 60 years, theoretical wood export of 260,000 m^3 is equivalent to transport of all available wood into NBB if the lower bound of 250,000 m^3 is used. Neither of these scenarios was observed in aerial image estimations of wood export quantities in those two years (Table II). Furthermore, theoretical wood export in both years exceeded the empirically derived maximum wood export calculated as a function of watershed area (Eq. 3), so the export of these theoretical values is extremely unlikely.

Empirical wood export, Eq. 2

Based on empirically derived field measures and image analyses, the wood export rate ranged from 0.03–5.6% of wood available for transport delivered into NBB, averaging 1.8-2.3% across years and depending on the W_{av} end member (Table IV). The smallest percentage was associated with a Q_{peak} of 1,132 m^3/s in WY2013, a statistical 9.2-year flood event in a dry WY (Table II). The largest percentage was associated with a Q_{peak} of 1,661 m^3/s in WY2006, a 19-year flood event in a wet WY. These results notably indicate that small proportions of the volumetric wood available for transport actually export into NBB in any given year, even with statistically unusual flood magnitudes.

Comparisons between empirically derived wood export quantities and theoretical values reveal obvious numerical differences. Observed wood export quantities were 8–1,136 times smaller (median 25–30 times) than theoretical values, with WY2006 the only WY in which the smallest difference was less than one order of magnitude (Table IV). These disparate results support (i) the conclusion that an equation such as Eq. 1a,b, which is focused on discharge variations, does not adequately represent watershed processes that exert substantial internal controls on wood dynamics in the North Yuba River watershed and (ii) the development of parsimonious coefficients to represent these differences.

Maximum potential wood export, Eq. 3,4,5

Maximum potential wood export as a function of watershed area (W_{max}, Eq. 3) for the 1,073 km^2 North Yuba River watershed yields an empirically derived maximum wood export quantity of 30,000 m^3 that could potentially transport into NBB. The constraint of W_{max} was applied to Eq. 1a to solve for W_θ (Table IV, Eq. 4) and $W_\%$ (Table IV, Eq. 5) to explore how known export quantities in the North Yuba watershed may compare to the calculated potential maximum, and whether a potential maximum is produced in any WY. This set of calculations using known export values, *n* = 8, yielded a maximum potential wood export average of 43% with a range 1-100%. Maximum potential wood export was 80% in WY1986 (Fig. 4), followed by a gradual decrease in response rate until another peak in WY2006 when the watershed produced 100% of maximum potential wood export followed again by a relatively steady decrease.

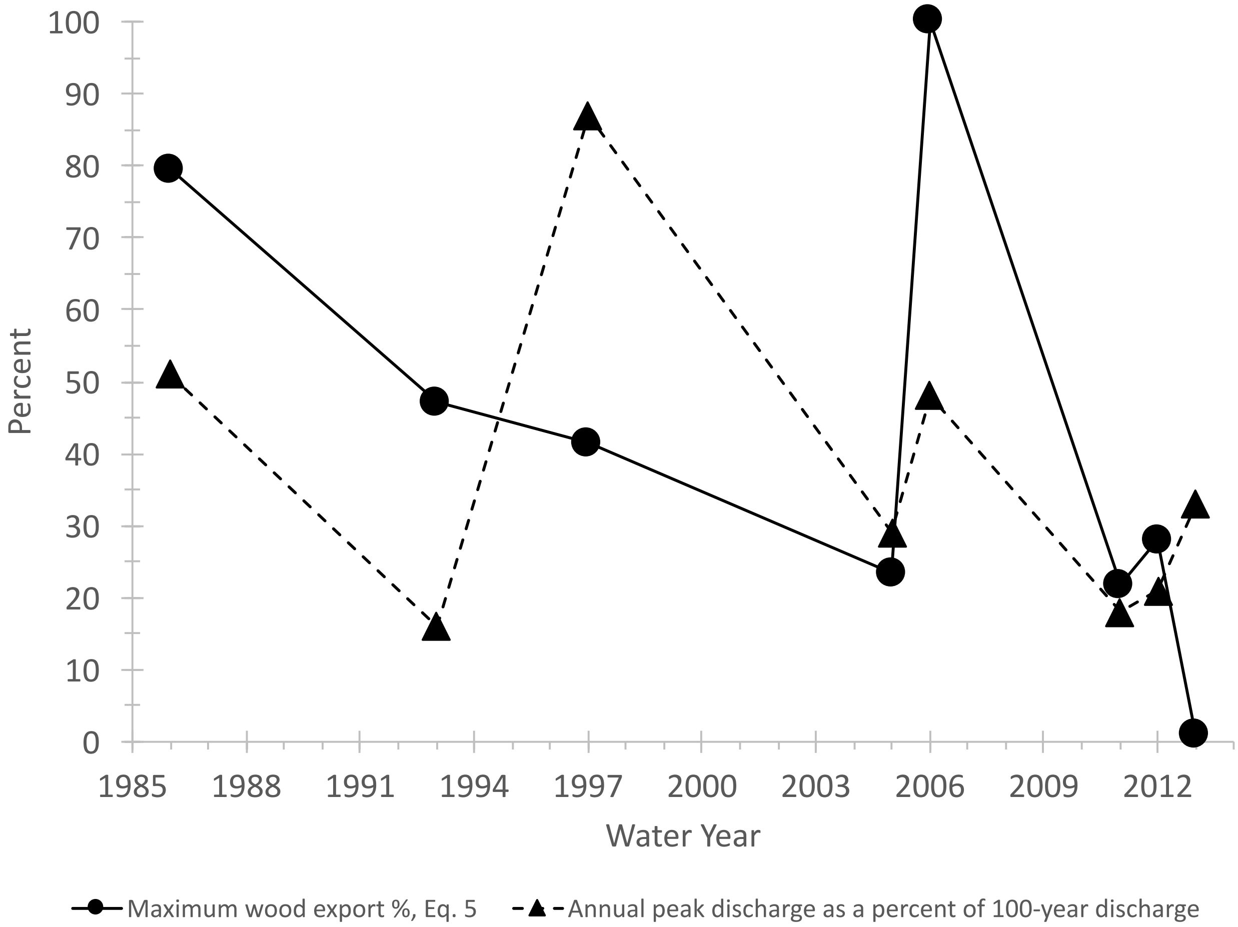


Figure 4. Comparison of the variability between potential maximum wood export percent and annual peak discharge magnitude.

The $W_{\%}$ calculated for WY2006 indicates that the North Yuba River watershed may be capable of delivering maximum wood quantities to the reservoir under optimal conditions. However, in wet WY1997, a statistical 60-year Q_{peak} flood event, an expectation of a larger wood export quantity was not realized. Instead, a $W_{\%}$ of 41% was calculated while the Q_{peak} was 87% of Q_{max} (Fig. 4). Conversely, dry WY2013 yielded $W_{\%}$ of 1% while the Q_{peak} was 33% of Q_{max}. These results suggest that an equation that considers discharge variations and watershed area may provide reasonable predictions of wood export in some cases, and the use of a maximum wood export equation (Ruiz-Villanueva et al., 2016b) is promising, but the broad suite of watershed processes as defined in this study do not appear to be fully represented given the observed range in variability of wood export quantities into NBB.

Watershed processes coefficients, Eq. 6,7

Theoretical Eq. 1a,b results were appreciably larger than observed wood export, given the caveat that the original equation was not meant to be predictive. However, the disparity motivated this effort to understand the differences, which led to a back-calculation of a simple proxy to represent the defined broad suite of watershed processes. The watershed processes coefficient (Eq. 6) was solved for using each observed wood export quantity (Table II) and at both defined W_{av} endmembers (Table V, Eq. 6). The lowest coefficient value of 0.0009 was calculated for WY2013 as a result of the smallest observed wood export quantity of the study. The theoretical δ_{max} result (Eq. 7) was 0.12 when using the lower limit of wood available for transport of 250,000 m^3, associated with the largest observed wood export quantity of the study in WY2006, and this relation is reflected in the $W_{\%}$ of 100% (Eq. 5).

Table V. Watershed processes δ coefficient results

		Eq. 6 Watershed processes coefficient, δ		Generalized Eq. 6,	Eq. 7
Water Year	WY type	250,000 m^3	300,000 m^3	Averaged δ	δ_{max}
1986	wet	0.095	0.080	0.0670	0.12
1997		0.050	0.041		0.12
2006		0.120	0.100		0.12
2011		0.027	0.022		0.12
1993	above normal	0.055	0.046	0.0383	0.12
2005		0.028	0.023		0.12
2012	below normal	0.034	0.029	0.0315	0.12
2013	dry	0.0011	0.0009	0.00097	0.12

Examination of the efficacy of generalizing by WY type sought to determine whether coefficients derived from one set of data could be used to predict other years in which data were not available. This generalization technique resulted in a mean coefficient value for wet WYs of 0.0670, above normal WYs of 0.0383, below normal WYs of 0.0315, and dry WYs of 0.00097 (Table V, generalized Eq. 6). It is particularly notable that during dry years the coefficient dropped by two orders of magnitude compared to the other WY categories, which are otherwise within the same order of magnitude. The substantially lower value of the dry WY coefficient suggests that a disproportionate drop in wood export per unit discharge in dry WYs is controlled by an equivalent drop in mountain watershed precipitation runoff when compared to wetter years.

DVWP wood export predictions, Eq. 8

Equation 8 was solved by multiplying the appropriate generalized watershed processes coefficient (Table V, generalized Eq. 6) by the appropriate theoretical wood export quantity (Table IV, Eq. 1b). The key test calculations were those involved in the validation process for the multi-year wood export quantities that were estimated from a WY2003 aerial image and a WY2010 field survey (Table VI). Calculations for these sets of years resulted in DVWP wood export quantities that ranged from a high of almost 2,500 m^3 in wet WY1999 to essentially zero in dry WY2001, WY2002, and WY2007. The sum of results from WY1999–WY2003 overestimated the observed cumulative wood export quantity in WY2003 by 2.2 times, and results from WY2007–WY2010 overestimated the observed cumulative wood export quantity in WY2010 by 1.3 times.

Table VI. Comparison of theoretical Eq. 1b and DVWP wood export Eq. 8 in predicting annual wood export from known cumulative volumetric quantities

Water Year	WY Type	Observed wood export, m^3	Eq. 8, DVWP wood export, m^3	Overprediction Eq. 8 summed values to observed, ratio	Eq. 1b, Theoretical wood export, m^3	Overprediction Eq. 1b/Eq. 8 ratio
2003	--	2256^a	--	2.2	--	--
1999	Wet	--	2461	--	36750	15
2000	Above Normal	--	1727	--	45078	26
2001	Dry	--	11	--	11848	1033
2002	Dry	--	14	--	13962	1033
2003	Above Normal		814	--	21234	26
2010	--	1230^b	--	1.3	--	--
2007	Dry	--	4	--	4179	1033
2008	Dry	--	31	--	31525	1033
2009	Below Normal	--	1121	--	35557	32
2010	Below Normal	--	504	--	15982	32

a observed in 2003 via Google Earth, representing 5 years of wood accumulation in NBB
b observed in 2010 via field measures, representing 4 years of wood accumuation in NBB

Conversely, theoretical wood export quantities overestimated DVWP wood export quantities by 15 to 1033 times, depending on WY type. Moreover, the sums of theoretical wood export quantities overestimated observed wood export in WY2003 by 57 times and in WY2010 by 71 times. Individual annual wood export values remain unknown; however, using generalized coefficients averaged by WY type provided a rational modifier to the use of discharge variations only and substantially narrowed the degree of uncertainty between DVWP wood export quantities and observed cumulative wood export quantities.

The use of the DVWP wood export equation was extended to all study years (Table VII), resulting in an estimated volumetric range of 59,000–71,000 m^3 transporting into NBB over the 30-year study period, yielding a rate of 1.8 to 2.2 m^3/year/km^2. Another validation exercise was conducted by summing and comparing observed wood export quantities and the equivalent eight years of predicted DVWP wood export quantities. Observed wood export totaled 43,598 m^3 and the equivalent eight years of predicted W_{DVWP} was 39,000–47,000 m^3 as a function of the lower and upper bounds of W_{av}, yielding remarkably comparable aggregate results. Differences between aggregate observed wood export and equivalent-WY predicted W_{DVWP} values resulted in a net positive error estimate of +10.2% with W_{av} of 250,000 m^3 and a net negative error estimate of –7.7% with W_{av} of 300,000 m^3; modest error estimates given the generalities involved. When individual WY values were compared, W_{DVWP} varied by 0.5–3.0 times that of observed wood export (Table VII), thus exhibiting nominally greater degrees of variability on an individual basis than on an averaged or summed basis.

Table VII. Water year characteristics, and comparisons of the results of the DVWP wood export equation, the peak annual discharge regression equation of Senter et al. (2017) and observed wood export

Water Year	WY type	NBB Qpeak, m^3/s	Return Interval, yrs	Predicted Eq. 8 DVWP wood export m^3		Predicted W$_{exp}$	Observed wood export, m^3	Predicted/Observed ratio			Senter et al. (2017)/Eq. 8 W$_{av}$ low bound, ratio
				Wav = 250,000 m^3	Wav = 300,000 m^3	Senter et al. (2017)		Wav = 250,000 m^3	Wav = 300,000 m^3	Senter et al. (2017)	
1986	Wet	1765	21.5	8369	10043	7803	11925	0.7	0.8	0.7	0.9
1987	Dry	403	1.3	24	29	807					33.1
1988	Dry	289	0.7	16	20	484					29.7
1989	Below Normal	663	3.3	1395	1674	1734					1.2
1990	Dry	262	0.6	14	17	416					29.0
1991	Dry	917	6.1	61	73	2853					46.9
1992	Dry	288	0.7	16	19	481					29.7
1993	Above Normal	546	2.3	1364	1637	1284	1976	0.7	0.8	0.6	0.9
1994	Dry	179	0.3	8	10	231					27.4
1995	Wet	871	5.5	3981	4777	2635					0.7
1996	Wet	963	6.7	4434	5321	3076					0.7
1997	Wet	3028	60.0	14571	17485	17893	10800	1.3	1.6	1.7	1.2
1998	Wet	620	3.0	2747	3296	1561					0.6
1999	Wet	561	2.5	2461	2953	1341					0.5
2000	Above Normal	675	3.5	1727	2073	1780					1.0
2001	Dry	222	0.4	11	14	321					28.0
2002	Dry	250	0.5	14	16	388					28.7
2003	Above Normal	350	1.0	814	976	648					0.8
2004	Below Normal	280	0.6	508	610	460					0.9
2005	Above Normal	981	7.0	2586	3103	3162	1897	1.4	1.6	1.7	1.2
2006	Wet	1661	19.0	7860	9432	7109	14125	0.6	0.7	0.5	0.9
2007	Dry	117	0.1	4	5	120					29.8
2008	Dry	490	1.9	31	37	1088					35.7
2009	Below Normal	545	2.3	1121	1346	1282					1.1
2010	Below Normal	278	0.6	504	605	455					0.9
2011	Wet	626	3.0	2779	3334	1586	1113	2.5	3.0	1.4	0.6
2012	Below Normal	726	4.0	1540	1848	1992	1680	0.9	1.1	1.2	1.3
2013	Dry	1132	9.2	76	91	3943	83	0.9	1.1	47.5	51.8
2014	Dry	382	1.2	23	27	742					32.5
2015	Dry	346	0.9	20	24	638					31.4

The largest overestimation in predicted W_{DVWP} versus observed wood export was associated with WY2011, classified as a wet WY (Table VII). There were two notable differences between WY2011 and the other wet WYs that may provide an explanation. First, the hydrograph for WY2011 reached about one-third of the Q_{peak} that other wet WYs exhibited (Fig. 2). Second, WY2011 had substantially longer elevated discharge associated with the snowmelt season than other wet WYs, while remaining below the winter Q_{peak}. The wet winter and spring snowmelt seasons of WY2011 were unusually cold, resulting in a snowpack that melted slowly and sustained a long hydrograph through the snowmelt season. Consequently, on an annual basis the longer periodicity of elevated discharge in WY2011 resulted in enough cumulative discharge to be classified as a wet WY according to the YRI index (Eq. 10) even though Q_{peak} was small relative to the other wet WYs, thus yielding lower observed wood export than predicted with Eq. 8.

The largest underestimation in predicted W_{DVWP} versus observed wood export was associated with WY2006, also classified as a wet WY. Analyses showed that $W_{\%}$ for this year was 100% (Table IV), suggesting that maximum W_{exp} was generated to the outlet of the watershed. A review of WYs between WY1997 and WY2006 showed that annual Q_{peak} were relatively low, as seen in the GYB discharge record (Fig. 2) as well as in the constructed NBB Q_{peak} record (Table VII). Relatively low Q_{peak}, combined with the broad suite of watershed processes that may promote or inhibit wood transport dynamics, may provide the necessary time for wood replenishment through recruitment and limited wood mobility, which primed the watershed for maximum wood export in WY2006. The examination of year to year hydrologic variations suggest that antecedent WY behaviors may be used to explain inter-annual variations revealed by use of watershed processes coefficients and the DVWP wood export equation.

Discussion

The broadly defined term of watershed processes used in this study includes hydrologic, geomorphic, hydraulic, ecological, and climatic processes that are known to be present, active, and responsible for variations in wood budgeting components at local and watershed scales (e.g., Benda and Sias, 2003; Gregory et al., 2003) and at landscape scales (Seo et al., 2015). A companion paper, Senter et al. (2017), detailed additional aspects of the work done in the North Yuba River watershed, and introduced a conceptual illustration and functional framework of watershed process wood responses to hydrologic and climatic conditions. Here we extend that work by introduction of watershed processes coefficients (Eq. 6) and a predictive DVWP wood export equation (Eq. 8), which helps to close the gap between hydrologic variations and other watershed processes known to exist but that remain difficult to quantify as a function of the hierarchical nature of watersheds and the challenge of integration across multiple spatio-temporal scales.

Linking wood availability with wood export quantities and then finding a method of simplification using WY types provided a set of generalized, watershed-specific coefficients that resulted in first-order approximations of wood export for every year within the 30-year study period. We propose that this paper provides early validation of the theory and equations (Table I), which may be improved upon with additional data and testing from the North Yuba River and other watersheds. If WY typing is not available elsewhere, classifications of WYs into generalized groups could be achieved by establishing parameters related to hydrographic variations between years such as methods used in California watersheds by resource agencies (YCWA, 2012; CDWR, 2016).

Wood export prediction

Theoretical Eq. 1a,b performed poorly in predicting wood export when compared to the eight years of observed wood export. However, discharge remains a primary variable in predicting W_{exp}, as shown in analyses that reveal significant correlation between wood export quantities and Q_{peak}, albeit with inherent variability and subject to hysteresis (MacVicar and Piégay, 2012). Peak annual discharge regression analyses have reported coefficients of determination of 0.58 (Moulin and Piégay, 2004), 0.41 (Boivin et al., 2015), 0.66 in a meta-analysis (Ruiz-Villanueva et al., 2016b), and 0.79 (Senter et al., 2017). Comparison between DVWP wood export (Eq. 8) and Senter et al. (2017) predictions revealed mostly similar results for observed W_{exp} quantities (Table VII). However, the W_{exp} quantity from WY2013 was excluded in the previous study as anomalously low; inclusion would have reduced the coefficient of determination to 0.60, which is more in line with the other studies.

The correlation coefficients suggest that perhaps one-half to two-thirds of the variations observed in W_{exp} quantities might be explained by Q_{peak} alone, although this broad statement does not take into account the magnitude, duration or intensity of rising and falling limbs of a peak annual event, smaller yet significant discharge events, or cumulative annual discharge from a wood export perspective, nor antecedent watershed conditions (e.g., Moulin and Piégay, 2004). Continuous video monitoring (MacVicar et al, 2009) is a promising technological advance that has the potential to record entire WY hydrographs. To date, video monitoring of individual storm events (MacVicar and Piegay, 2012), two snowmelt season periods (Senter et al., 2017), and multiple flood flows including an ice break-up event (Boivin et al., 2017), have reported linkages between wood export and discharge. In each of these studies, the authors discussed the effects of watershed processes, including upstream bank erosion, diurnal snowmelt cycle, and ice flows, respectively, on wood export variations.

Wood export predictions using the peak discharge regression equation from Senter et al. (2017) yielded a 30-year estimate of ~68,000 m^3, which falls at the high end of the DVWP wood export equation prediction range of 59,000-71,000 m^3 (Table VII). Individual years except for dry WYs were similar to those of Eq. 8 predictions. The DVWP wood export equation was far superior in predicting observed wood export in dry WYs, whereas the Senter et al. (2017) equation overestimated Eq. 8 dry WY predictions 23-43 times (Table VII). There were multiple dry WYs in the validation exercise (Table

VI) but no annual observations, so additional data are needed to validate the conclusion that dry WY years have low wood export quantities as a function of commensurately low watershed precipitation runoff.

Senter et al. (2017) investigated the efficiency of their peak discharge regression equation to predict wood export using daily mean discharge values greater than the observed Q_{crit} of 60 m^3/s as a delimiter for number of days where wood was mobile. This approach resulted in a count of days for each investigated time period (two snowmelt periods and two full WYs) for which potential wood volumes were calculated given a range in observed wood size metrics. Results overestimated wood export during video monitoring time periods and underestimated wood export during almost all of the WY time periods, except at the WY scale using the global standard deviation for volume per piece (see Table 5 last row, Senter et al., 2017), which was the largest possible volumetric quantity. Thus, wood piece measurements collected during video monitoring were not fully representative of piece sizes that export into NBB during winter flood conditions, which underscores the need to monitor entire WY hydrographs, including nighttime hours. Other techniques may be useful in developing models of wood piece spiraling downstream (Latterell and Naiman, 2007; Schenk et al., 2014), such as those used to examine how excess flow energy expenditures driving sediment dispersion patterns are linked to flow durations above a Q_{crit} (Haschenburger, 2013).

Ruiz-Villanueva et al. (2016b) predicts that there is an upper volumetric limit to wood export as a function of watershed area. Their meta-analysis reveals an important insight that supports our conclusion that wood export is small relative to the quantity of wood available for transport in the North Yuba River watershed. Their upper boundary at a global scale suggests limits to the ability of a watershed to export wood quantities. Export as predicted by theoretical Eq. 1a,b alone may be achievable only in the most extreme circumstances, such when Typhoon Morakot made landfall in Taiwan in 2009 and caused massive landsliding in steep, forested mountain watersheds (West et al., 2011).

What is in evidence for the North Yuba River is that the largest floods mobilized small fractions of W_{av} from the upper watershed into NBB, as highlighted by WY1997 data where a statistical 60-year flood generated a wood export quantity equivalent to a c_w rate of 5.6% (Table IV). Even if W_{av} was considerably smaller than the lower bound estimate, for instance 150,000 m^3 in the entire watershed (i.e. 50% of the upper bound estimate), solving Eq. 2 would result in a wood export rate of 10% instead of 5.6%, which is not appreciably larger given the still considerable volume of wood available for transport. Conversely, if W_{av} was larger than our upper estimate, then wood export rates would decrease.

Watershed processes and wood budget variables

Wood dynamics in the mountainous, forested North Yuba River align with watershed processes and interactions between wood, floods, channels, floodplains, and hillslopes. The degree of floodplain area that was scoured (wood recruitment) versus floodplains where standing vegetation remained (wood storage potential) were important controls on natural wood trapping during a flash flood in a small catchment in Italy (Lucia et al., 2015). Floodplains and active channel margins in the North Yuba watershed held ~75% and ~50% of individual wood pieces and jams, respectively (Table III). Thus, morphologic locations and geomorphic functions of wood pieces and jams surveyed in WY2012 may indicate that large proportions of wood available for transport may not mobilize except in larger floods, which supports some of the observed variance in wood export quantities and rates between WY types.

Merten et al. (2010) found that burial, bracing, rootwad presence, length ratio, effective depth, downstream force ratio, and draft ratio were significant factors in the likelihood of wood mobility in Minnesota streams, while the explanatory power of 39% across those seven variables demonstrates the difficulty in unraveling complex watershed mechanisms associated with wood transport and export. Almost all wood jams surveyed in North Yuba River were geomorphically active as were many wood pieces, but 46% of individual wood pieces did not warrant a geomorphic classification (Table III). Wood piece length to channel width ratio was 0.7 ± 1.2, median 0.3, so most wood pieces were shorter than channel width. About 25% of wood pieces were located within the wetted channel, on bars, or not associated with sediment deposition, and therefore were less likely to be actively engaged in the type of functionality that would promote stability. Shorter, less geomorphically active wood pieces would be first to mobilize once flows are fast enough or deep enough to initiate motion (Braudrick and Grant, 2000; Merten et al., 2010).

Jams held 75% of surveyed wood volume (Fig. 3) with length to channel width ratios of 1.3 ± 4.7, median 0.4, so jams were on average longer than channel width, but the median indicates that most were not. Larger jams are more likely to remain stable depending on positioning relative to flow direction and magnitude. Mobilized wood pieces in years with typical flows have a lower chance of transporting long distances and are more likely to spiral to a new location (Latterell and Naiman, 2007) including onto existing jams (Gurnell et al., 2002; Manners et al., 2008).

On the North Yuba, WYs with the largest Q_{peak} yielded the largest volumetric quantities of wood export (Table II). In a headwater catchment in Switzerland, the stability of log jams was found to control wood export until floods with > 20-year recurrence intervals contributed to two dynamic processes: jam breakup resulting in large quantities of wood export leaving the catchment, while simultaneously activating channel margin-hillslope coupling that recruited wood needed to form new jams

(Jochner et al., 2015). These coupled processes may explain why North Yuba River discharge recurrence intervals in WY1986, WY1997 and WY2006 (Table VII) yielded the largest W_{exp} quantities into NBB. Floods of this magnitude increase the rate of jam disintegration and consequently promote wood mobility within the active channel during the flood hydrograph (e.g., Ruiz-Villanueva et al., 2016b). Newly recruited wood meanwhile promotes jam formation, and may provide optimal depositional environments for spiraling wood pieces in lower recurrence interval floods, such that subsequent wood recruitment rates outpace wood export until the next large flood (Marcus et al., 2011; Kramer and Wohl, 2017).

Observed wood export rates ranged from 0.3–5.6% and averaged 1.8-2.3% depending on which W_{av} endmember was used (Table IV). These rates represent annual wood export at the watershed scale in a steep, forested mountain river watershed. Mobility rates in other studies have been reported in the range of 0–50% (Berg et al., 1998; Jacobson et al., 1999; Moulin and Piégay, 2004; Latterell and Naiman, 2007; Wohl and Goode, 2008 and see their Table 1; Merten et al., 2010; Benda and Bigelow, 2014; Schenk et al., 2014; Kramer and Wohl, 2017), which implies that watershed dynamics are highly variable, and supports development of watershed processes coefficients by binning highly variable wood export quantities as a function of WY type.

Wood transport rates ranging from 0.6-8% of total wood volume were reported from six Sierra Nevada headwater streams, including two sub-watersheds in the North Yuba River (Lavezzola and Pauley Creeks; Berg et al., 1998); remarkably similar values to the wood export rates reported in this study. Contributing area of their study sites ranged from 8-25 km^2, bankfull channel widths from 2.1-12.8 m, and mean wood transport distances of 70-361 m. Berg et al. (1998) reported very low rates of mobility in WY1994, the first year of their study, and then many wood pieces moved or were not found and presumed to have transported out of the study reaches over WY1995, with high gaged discharges. Their interpretation was that low flows in the first year did not trigger transport, while the 31% transport rate in the second year may have been near the maximum limit of a high discharge event to influence wood mobility. Their observations provide an independent validation of our supposition that dry WYs have very low wood export capacities (see Table VII for WY types).

A similar wood export rate to our rates was reported from the Lower Roanoke River, Virginia, USA, a wide, low slope, sand bedded, piedmont river with a mature bottomland forest (Schenk et al., 2014), a distinctly different physiographic environment than the Sierra Nevada. They found that 2% of wood was exported from the watershed during their three-year study period, 3% were buried or fragmented, 16% transported internally (i.e., spiraled) within the 210 river-km study segment, and the remaining 79% of wood located on channel banks and available for transport did not move, a potential validation of our conjecture that most wood pieces available for transport in the North

Yuba River may not move except in large flood events. Mobilized wood piece residence time for their study was calculated as < 10 years, while pieces that stayed in place had a 20-year residence time, similar to the Sierra Nevada rate reported by Benda and Bigelow (2014). Wood mobility rates in the North Yuba River channel network have not been quantified, so a fruitful area of future inquiry would be to quantify how much wood available for transport is subject to internal spiraling.

Wood storage quantities in the North Yuba River watershed range from 200-300 m^3/channel-ha and m^3/km^2. This value is similar to Sierra Nevada storage quantities of 226 ± 289 m^3/channel ha (Benda and Bigelow, 2014). Values from the two North Yuba River sub-watersheds in Berg et al. (1998) were lower at 20-180 m^3/km channel length with narrower channels widths, an indication of inherent variability in the system at local scales also seen in this study (Fig. 3). Estimated North Yuba River wood storage (Vaughan, 2013) was at least 10 times the estimated annual wood recruitment rate (Benda and Bigelow, 2014). Berg et al. (1998) noted that wood recruitment followed the same pattern as wood transport. The first year of their study resulted in few additional wood pieces whereas many pieces were added to the study sites after the high flows of year two; an observation supported by the work of Jochner et al. (2015) at the episodic hydrologic event scale.

Review of the 30-year hydrograph and individual WY designations (Table VII, Fig. 2) suggest a watershed-scale climatic explanation to the pattern that emerges in the negative trend in maximum potential wood export percent (Eq. 5) from 80% in WY1986 to 23% in WY2005, followed by an increase to 100% in WY2006 and then another decreasing trend (Fig. 4). A Q_{peak} of 3,028 m^3/s in WY1997 should have produced the largest wood export quantity of the 30-year study period at almost twice the peak discharge of WY1986 and WY2006, yet the observed wood export of 10,800 m^3 was instead the third largest W_{exp} quantity, and produced just 41% of predicted maximum potential wood export. This disparity between expected and observed may be explained by the two wet WYs in WY1995 and WY1996, prior to the third wet WY in WY1997 that experienced the statistically rare 60-year flood recurrence interval (Fig. 2). Although there were no substantial Q_{peak} events in the previous two years, there were multiple smaller flood peaks with enough cumulative discharge to classify each as a wet WY type; Berg et al. (1998) reported WY1995 flows as in the 71st percentile. Multiple flood peaks mobilized individual wood pieces that could disintegrate, spirale and lodge onto a jam, or transport into NBB in the two WYs prior to WY1997, resulting in less wood available for transport during the 60-year event. Other dynamic fluctuation scenarios can be inferred in a review of the 30-year discharge record along with observed and predicted wood export patterns (Table VII, Fig. 2).

Moulin and Piégay (2004) reported an analogous antecedent condition phenomenon within WYs, where an initial flood event yielded high W_{exp} followed by a similar flood magnitude that yielded a smaller quantity. They conjectured that most W_{av}

was exported to the downstream reservoir in the first flood event, and that the recruitment rate between events did not produce enough additional W_{av} to produce a similar volumetric export quantity during the next flood. In the North Yuba River watershed, an annual wood recruitment rate of 10,000–30,000 m^3 combined with low export rates and potentially low mobility rates might not provide enough W_{av} in optimal locations to generate large W_{exp} quantities in consecutive wet WYs. These observations provide evidence that watershed processes act to increase wood available for transport in years with lower flood peaks leading to an increase in wood export in years with higher flood peaks (Moulin and Piégay, 2004; Marcus et al., 2011).

Research directions

High-resolution remotely sensed imagery at yearly to sub-yearly time steps is now commonly available from Google Earth and other resources, so barriers to historic estimates and wood export monitoring on an annual to sub-annual basis are rapidly declining. However, observations of wood export are needed over multiple peak discharge events (Moulin and Piégay, 2004; Benacchio et al., 2017) to compliment those collected at annual time scales (Seo et al., 2008). Hydrographic peaks smaller than annual Q_{peak} events will mobilize and export wood at lower rates than flood events (Moulin and Piégay, 2004; Senter et al., 2017). Wood discharge monitoring has been achieved using still image analysis (Moulin and Piégay, 2004; Kramer and Wohl, 2014; Boivin et al., 2015; Benacchio et al., 2017) and video monitoring at-a-station (MacVicar et al., 2009; MacVicar and Piégay, 2012; Boivin et al., 2017; Senter et al., 2017). These studies reveal semi-continuous to continuous real-time transport processes; data which are necessary to obtain further insights into associations between wood discharge, water discharge, and watershed processes. Establishing permanent wood discharge monitoring stations at select long-term gaging stations could support such studies in conjunction with repetitive field efforts to collect data on wood budget components. Bracketing multiple individual storm events over a period of years would greatly enhance our abilities to understand how mechanistic watershed processes operate across multiple watersheds, at varying spatial and temporal scales, and between climate zones (e.g., Comiti et al., 2016, Ruiz-Villanueva et al., 2016b; Kramer and Wohl, 2017; Wohl, 2017).

Conclusion

Watershed-specific coefficients generalized by WY type are introduced as multipliers into an existing theoretical wood transport equation, such that the dynamics involved in watershed processes as well as peak annual discharge can be used to explain and predict wood export quantities. The refined equation predicted wood export quantities over a 30-year timeframe that resulted in acceptable error ranges within the context of observed data, and was superior to an existing annual peak discharge equation in predicting dry WY wood export. Initial validation of the concept suggests that the DVWP wood export equation may be testable in other watersheds where wood export, availability, and WY type data can be collected.

Regulated river managers tasked with resource allocation may use these procedures to understand wood dynamics and variability and to plan for a range of climate scenarios related to flooding and drought conditions. Understanding that the vast majority of wood remains stable within a watershed even at the highest flows may help shift public and agency perceptions toward less wood removal from channels. Water resource agencies tasked with environmental health and welfare of aquatic resources could use these new predictive capabilities to plan for wood transfers from reservoirs to enhance below-dam stream channel ecosystems in years where large wood export quantities are generated.

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