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Wood export prediction at the watershed scale

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The data associated with this publication are available upon request.

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1 Wood export prediction at the watershed scale

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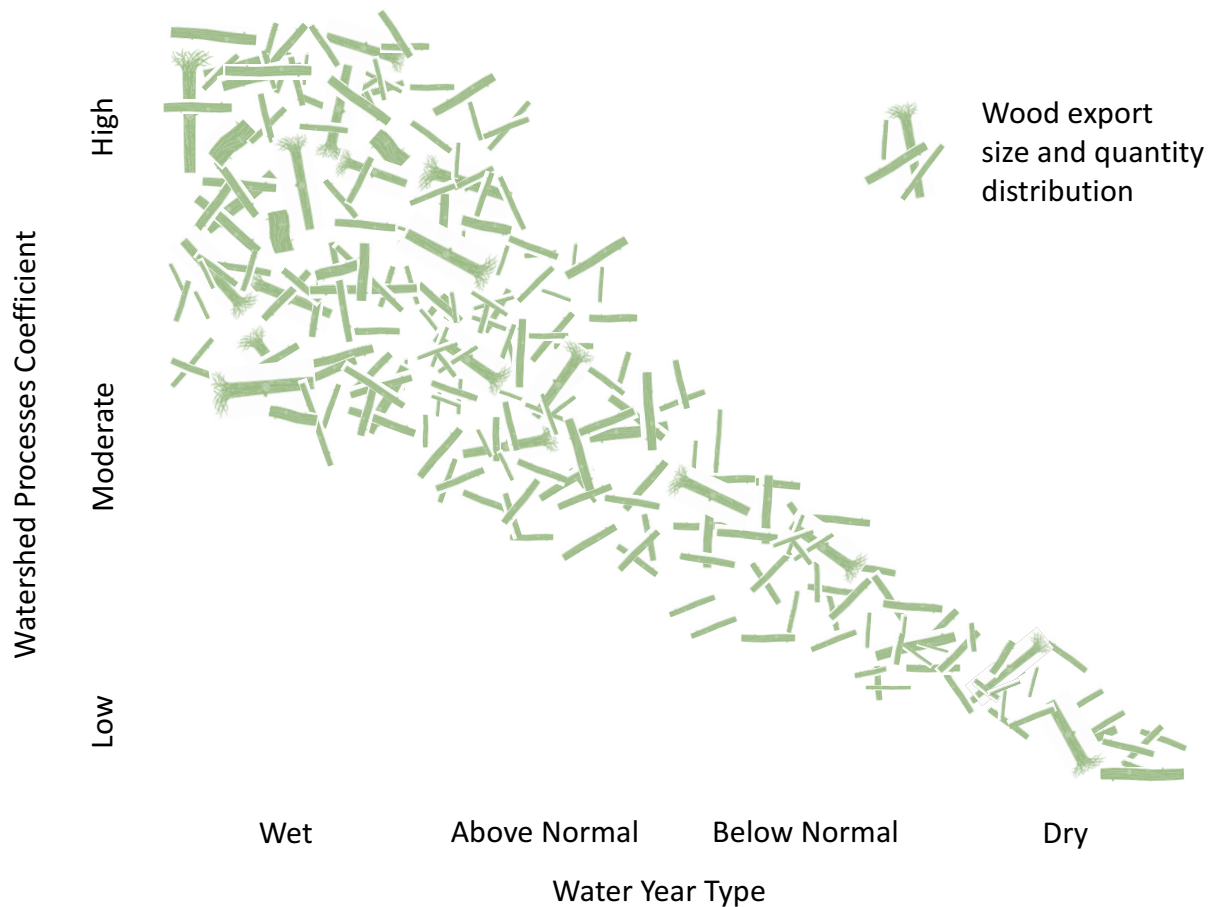
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33 Short Abstract

34 Theory of wood export quantification is extended by generalizing complex
35 watershed processes into a water year type multiplicative coefficient. The coefficient is
36 tested and validated in a new DVWP ('discharge variations modified by watershed
37 processes') equation that provides a modifier to discharge-only relations. Results show
38 that predictions for dry WYs improve dramatically, while predictions for wet WYs, when
39 most wood moves, remain variable, likely as a function of antecedent conditions.
40



41
42 **Synthesis Figure.** Watershed processes coefficients can be calculated using
43 generalization techniques by grouping wood export quantities by water year types. The
44 contribution of watershed processes to wood export are high in wet water years and
45 diminish as water years become drier.
46

47 **Abstract**

48 Wood export from a watershed is a function of peak annual discharge, but one
49 hydrologic relationship alone does not fully explain observed variability. Consideration of
50 physical processes that influence the amount of wood available for transport is needed.
51 However, wood recruitment, storage, mobilization, breakage, and transport rates and
52 processes remain difficult to quantify. A theoretical wood transport equation focused on
53 variations in discharge was the motivation for investigation into watershed-specific wood
54 export rates. Herein, multiplicative coefficients categorized by water year type are
55 developed, paired with the equation, and validated to provide a new method for
56 prediction of wood export at the watershed scale. The coefficients are defined as
57 representing a broad suite of watershed processes that encompass spatio-temporally
58 variable scales. Two complementary data sets from the 1,097 km² mountainous North
59 Yuba River, California watershed were used. Wood surveys above New Bullards Bar
60 Reservoir yielded a wood availability estimate of 250,000–300,000 m³ along the
61 channel network. Annual wood export into the reservoir was field-surveyed in 2010,
62 2012, and 2013, and estimated in seven years via remotely sensed images over the 30-
63 year study period of water years 1985–2014. Empirical, watershed-scale wood export
64 rates ranged from 0.3-5.6%. Comparison of predicted quantities using the new DVWP
65 (discharge variations modified by watershed processes) wood export equation to
66 observed wood export quantities resulted in an aggregate error rate of $\pm 10\%$. When
67 individual wood export quantities were compared, predicted to observed varied by 0.5–
68 3.0 times. Total wood export of 59,000–71,000 m³ was estimated over the 30-year
69 period, yielding a rate of 1.8 to 2.2 m³/year/km². Wood export predictive capabilities at
70 the watershed scale may help water resource and regulatory agencies plan for wood
71 transfers to augment downstream ecosystems.

72

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

75 **Introduction**

76 Forested watersheds provide opportunities to study wood budgeting components
77 (Benda and Sias, 2003) in locations around the world (e.g., Moulin and Piégay, 2004;
78 Comiti et al., 2006; Andreoli et al., 2007; Latterell and Naiman, 2007; Warren and Kraft,
79 2008; Seo et al., 2008; Wohl and Goode, 2008; Benda and Bigelow, 2014; Schenk et
80 al., 2014; Jochner et al., 2015; Lucia et al., 2015; Ruiz-Villanueva et al., 2016b; Steeb et
81 al., 2017). Wood recruitment and related processes that store, transport, break down,
82 and ultimately export wood pieces through watershed networks are key elements of
83 stream complexity and ecosystem health (Keller and Swanson, 1979; Harmon et al.,
84 1986; Gregory et al., 2003).

85 Wood dynamics fluctuate broadly depending on landscape, watershed, and local
86 controls (Benda and Sias, 2003; Hassan et al., 2005; Benda and Bigelow, 2014), but
87 are known to vary as a function of hydrologic processes (Moulin and Piégay, 2004;
88 Marcus et al., 2011; MacVicar and Piégay, 2012; Seo et al., 2012; Boivin et al., 2017;
89 Senter et al., 2017), hydraulic processes (Braudrick and Grant, 2000; Bocchiola et al.,
90 2008; Ruiz-Villanueva et al., 2014), forest and riparian corridor dynamics (Latterell and
91 Naiman, 2007; Gurnell, 2014), mass movement associated with episodic precipitation
92 events (West et al., 2011; Wohl and Ogden, 2013; Steeb et al., 2017), and geomorphic
93 and morphologic interactions between channel corridor elements and wood architecture
94 (Gurnell et al., 2002; Abbe and Montgomery, 2003; Pettit et al., 2006; Wohl and Goode,
95 2008; Merten et al., 2010).

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

105

106 *Watershed processes*

107 From a watershed-process basis, the volumetric quantity of wood fluctuates
108 about a mean as a function of wood recruitment rates, wood storage capabilities of the
109 channel corridor, wood transport rates, hydrographic variability, decomposition and
110 fragmentation rates, and other natural processes (Benda and Sias, 2003; Moulin and
111 Piégay, 2004; Marcus et al., 2011). Wood storage locations are more stable and
112 prevalent in reaches where wood piece length or jam size is large relative to channel

113 width (Lienkaemper and Swanson, 1987; Gurnell et al., 2002). Interactions between
114 piece architecture, such as length and diameter dimensions, and channel features tend
115 to increase the geomorphic function and stability of wood (Merten et al., 2010), while
116 pieces that are not geomorphically active may transport more readily. Wood pieces will
117 break apart and disintegrate as wood density decreases (Latterell and Naiman, 2007;
118 MacVicar et al., 2009), although physical breakage rates of wood in transport remain
119 mostly unknown (Hassan et al., 2005).

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

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

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

151

$$152 \quad f_W = \frac{Q_{peak} - Q_{crit}}{Q_{max} - Q_{crit}} \quad (1a)$$

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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

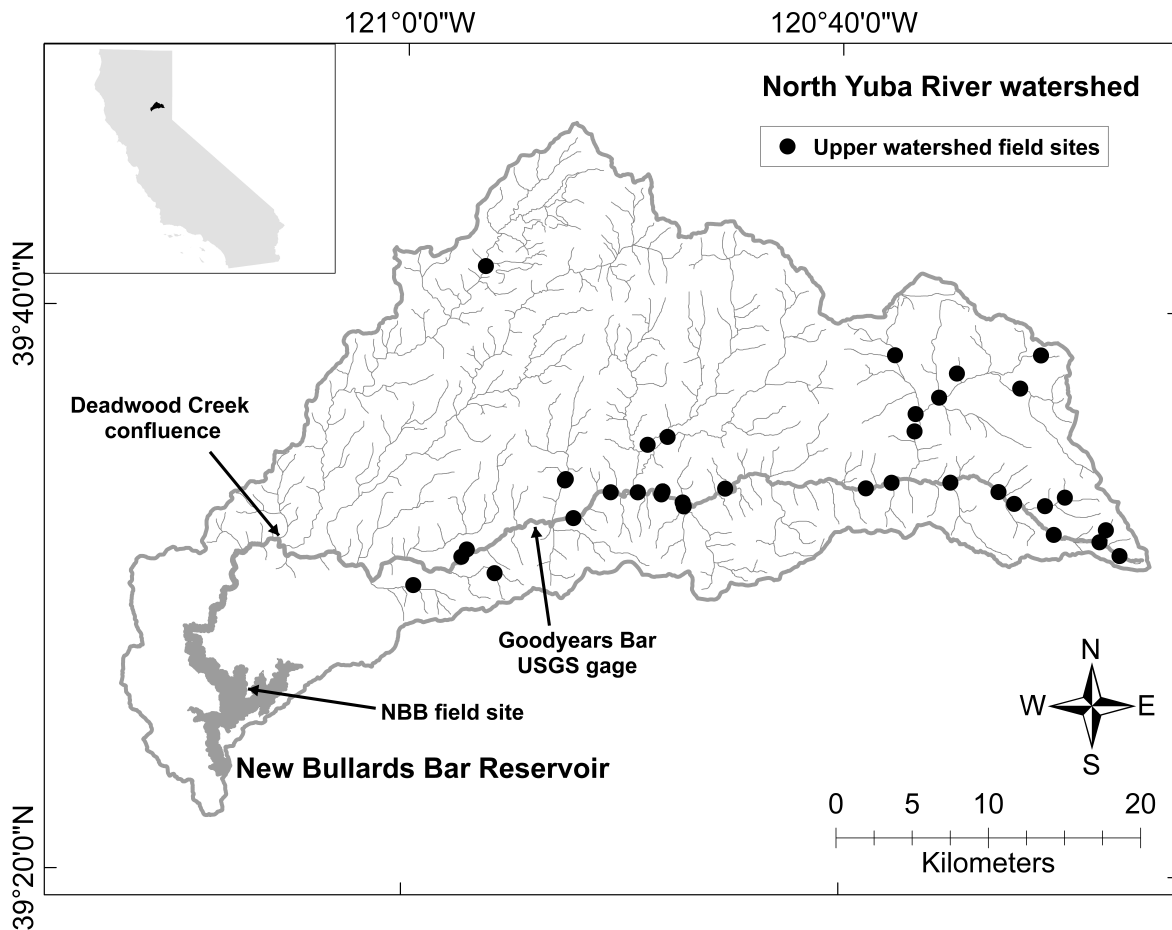
159

160 *Study Objectives*

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

176 177 **Study Site**

178 The North Yuba River watershed originates along the western slope of the
179 northern Sierra Nevada Mountain Range in California, USA at an elevation of 2,139 m
180 at Yuba Pass. The watershed is unregulated until its termination into New Bullards Bar
181 reservoir (NBB). The NBB dam face is 193 m tall with a crest elevation of 599 m and
182 reservoir storage capacity of 1.2 km³ (39°23'36.18" N, 121°08'34.78" W). The
183 watershed is considered an important test basin for climate change scenarios related to
184 precipitation variation and salmonid refugia (YSPI, 2015). The upper watershed, defined
185 as the catchment area above the confluence of Deadwood Creek into the upper extent
186 of NBB, contains 1,097 km² in area and 1,074 river-km of headwaters to Strahler 5th
187 order channels (Fig. 1).



188

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

193

194 The greater Yuba River watershed, of which the North Yuba is the largest of
 195 three mountain sub-basins, has a disturbance legacy as one of the epicenters of
 196 California gold mining in the mid-1800's (Gilbert, 1917; James, 2005). Coniferous
 197 forests are mostly even-aged stands less than 100 years old given regeneration and
 198 replanting after decades of extensive logging (Hitchcock et al., 2011). Woody vegetation
 199 that could transport into NBB includes, in approximate order of increasing elevational
 200 bands, foothill California black oak and canyon oak; ponderosa pine, white fir, and
 201 Douglas fir in a mixed conifer belt; red fir, Lodgepole pine, and Jeffrey pine; and
 202 subalpine tree species including western white pine (Fites-Kaufmann et al., 2007).
 203 Riparian corridor species include cottonwood, willow, and alder. Bedrock geology
 204 consists primarily of granitic batholith which dominates much of the channel corridor,

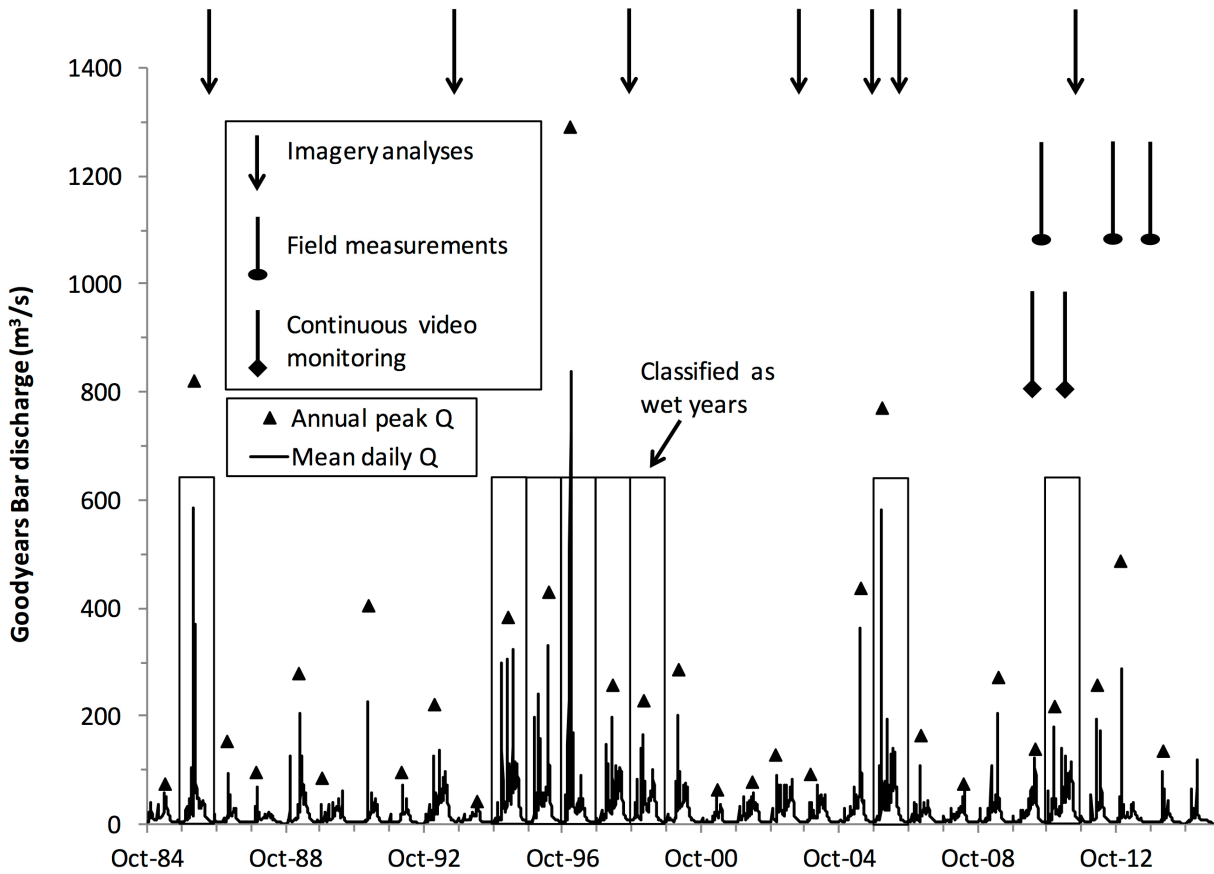
205 with lesser amounts of metamorphosed sedimentary and volcanic rock, and glacial till
206 (Curtis et al., 2005).

207 The Sierra Nevada climate is characterized as Mediterranean-montane, with
208 cool, wet winters and warm, dry summers. In California, the WY is defined as October of
209 a previous year through September of the designation year, and can be simplified into a
210 wet winter season from October through March, a snowmelt season from April through
211 July with progressively diminishing precipitation, and an overlapping drought condition
212 summer season from June through September. Annual precipitation ranges from 500–
213 2000 mm dependent on elevation and aspect, with a rain-snow mix between 500–1800
214 m in elevation dependent on temperature at the time of precipitation. Snowfall
215 predominates above 1800 m from November through March (Mount, 1995).

216 Flood pulses during the wet winter rain-snow season are generated by narrow-
217 banded atmospheric river events that can deliver localized, intense, high-magnitude
218 precipitation (Ralph et al., 2006; Dettinger, 2011), as well as by low-pressure systems
219 that can deliver moderate to heavy precipitation over extended periods of time. The
220 largest flood pulses occur when warm rain falls on snow, leading to rapid melting of
221 snowpack and quick release of stored water via episodic flood events (McCabe et al.,
222 2007; Garvelmann et al., 2015). Within the 30-year study period (Fig. 2), the return
223 intervals for the three largest wet winter flood magnitudes into NBB were 21.5, 60, and
224 19 years in WY1986 (warm rain-on-snow event), WY1997 (atmospheric river event),
225 and WY2006 (atmospheric river event), respectively, with each flood exporting a large
226 quantity of wood from the upper watershed into NBB.

227

CORRECTED FINAL MANUSCRIPT



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229

230 **Figure 2.** Goodyears Bar discharge hydrograph and the time periods in which data
231 were available or collected in the watershed over the 30-year study period. Boxed
232 hydrographs signify years designated as wet WY types.
233

234 Theory Development

235 Wood Transport Theory

236 A theoretical wood transport rule (Eq. 1a) was introduced as one facet of
237 exploration into observed wood distributions following wildfire in Yellowstone National
238 Park, USA (Marcus et al., 2011). Marcus et al. (2011) defined Q_{peak} as annual peak
239 flood discharge in a given year and it is applied likewise in this study; however, the form
240 of the equation could be used to assess wood transport on an event basis when
241 sufficient data are available, as most years have multiple wood-mobilizing flows. The
242 ratio f_W from Eq. 1a converts to a volumetric quantity when an estimate of wood
243 available for transport in the upper watershed is known:
244

$$245 \quad W_Q = f_W \times W_{av} \quad (1b)$$

246

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

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

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

278

$$279 \quad c_w = W_{exp} \div W_{av} \quad (2)$$

280

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

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

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

$$294 \quad W_{max} = 905 \times A_c^{0.49}, r^2 = 0.89 \quad (3)$$

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

$$301 \quad W_\theta = f_w \times W_{max} \quad (4)$$

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

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

$$310 \quad W_\% = (W_{exp} \div W_\theta) \times 100 \quad (5)$$

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

316 Exploratory analyses of the above equations revealed clear differences between
317 results of theoretical f_w and W_Q as a function of discharge variations (Eq. 1a,b),
318 observed wood export (Eq. 2), and maximum potential wood export as a function of
319 watershed area (Eq. 3). The degree of variability supported development of an
320 approach that could represent temporal and spatial lags in wood dynamics that are

321 known to exist but remain difficult to quantify. The most parsimonious approach was to
322 identify these controls as quotients of the empirical wood export rates (Eq. 2) divided by
323 the theoretical wood export rates for each WY (Eq. 1a), which yields:

$$324 \delta = c_w \div f_w \quad (6)$$

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

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

$$334 \delta_{max} = W_{\theta} \div W_Q \quad (7)$$

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

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

$$342 W_{DVWP} = \delta \times W_Q \quad (8)$$

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

353

354 Application to the North Yuba River watershed

355 Hydrologic data

356 Continuous hourly inflow data into NBB were available over a nine-year period,
357 WY2007-WY2015 (CDWR, 2015). Nine consecutive years of annual peak discharge
358 data were not sufficient for a statistical analysis, so data from the USGS gage
359 11413000, North Yuba River below Goodyears Bar, California (GYB) was calibrated
360 and used to extend the data set to 30 years. The GYB gage is located 24.9 river-km
361 upstream of the Deadwood Creek confluence along the mainstem and provides
362 discharge data for 648 km² (59%) of the watershed. First, annual peak discharge data
363 was obtained from GYB for the same timeframe as NBB inflow. Next, a regression
364 analysis between the set of coincident NBB and GYB annual peak discharges resulted
365 in a linear relation:

$$366 \quad \quad \quad 367 \quad \quad \quad NBB Q_{peak} = 2.04 * GYB_{peak} + 92.43, r^2 = 0.70, p = 0.036 \quad (9)$$

368
369 Third, the relation was used to construct missing annual peak discharge values for NBB
370 over the 30-year study period WY1985-WY2014.

371 A Log-Pearson III analysis of the resultant NBB Q_{peak} data yielded a 100-year
372 recurrence interval estimate of 3,470 m³/s that was used for Q_{max} in Eq. 1a, the
373 discharge at which all wood may be expected to mobilize. Although larger floods are
374 possible and may yield more wood as the likelihood of bank erosion and hillslope failure
375 increases, a statistically exceptional 100-year flood event was considered as a realistic
376 theoretical discharge that could mobilize all wood available for export from the
377 watershed. A larger Q_{max} would have the effect of reducing Eq. 1a,b estimates. The
378 critical minimum discharge Q_{crit} at which wood may mobilize was set at 60 m³/s, the
379 lowest discharge that wood was observed in transport during a continuous video
380 monitoring field effort at the upstream end of NBB during spring snowmelt periods in
381 2010 and 2011 (Senter et al., 2017). A larger Q_{crit} would have the effect of increasing
382 Eq. 1a,b estimates.

383

384 Water year types

385 Classification of a watershed's hydrologic behavior over the period of a WY is
386 used by water resource agencies throughout California as a proven yet simple means
387 by which to manage water supplies for environmental and consumptive uses at the
388 watershed to state-wide scale (CDWR, 2016). The Yuba County Water Agency (YCWA)
389 issues yearly Yuba River Index (YRI) hydrologic classifications to fulfill regulatory

390 requirements related to dam operations and instream flow requirements (YCWA, 2012).
 391 The YRI uses cumulative discharge data from the North Yuba River, Middle Yuba River,
 392 South Yuba River, and Deer Creek subbasins, as recorded at the USGS gage
 393 11418000 Yuba River below Englebright Dam near Smartville, California. Official
 394 classifications for YRI WY types include wet, above normal, below normal, dry, critical,
 395 and critically dry. Each WY is assigned according to a weighted equation that factors in
 396 antecedent conditions from the previous WY as well as proportions of discharge totals
 397 from the October-March wet season and April-July snowmelt season. A YRI index
 398 number is calculated at the end of each WY:

$$400 \quad YRI = 0.2 \times YRI_{previous} + 0.3_{wet\ season\ runoff} + 0.5_{snowmelt\ season\ runoff} \quad (10)$$

401
 402 where $YRI_{previous}$ represents the previous WY's index number. A WY type is assigned
 403 based on where each YRI index value falls within a set of predetermined ranges that
 404 define each WY type (YCWA, 2012); thus, WY types represent relatively narrow ranges
 405 in hydrologic responses to precipitation and snowmelt magnitudes, which can
 406 nevertheless manifest as considerably variable within any individual WY. For instance, a
 407 large flood event can play a role in a wet WY type designation, but so can cumulative
 408 discharge over a series of smaller flood magnitudes that results in the same wet year
 409 type classification even though the WY hydrographs would be markedly different.

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

416

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

417

418

419 *Wood export into New Bullards Bar Reservoir*

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

435 Field measurements were collected from wood export accumulations at the end
436 of summer seasons in WY2010, WY2012, and WY2013 on dry land after reservoir
437 levels receded. A minimum of 100 wood piece dimensions were recorded each year
438 using the large wood criteria of ≥ 1 m length and ≥ 10 cm diameter (Macka et al.,
439 2011). These three field efforts yielded mean and standard deviation wood piece length
440 of 2.8 ± 2.1 m, median 2.0 m, and diameter of 25 ± 18 cm, median 19 cm.

441 Wood density was found by extracting three samples each from 19 dry wood
442 pieces and performing water displacement analyses that resulted in mean wood density
443 estimate of 480 ± 120 kg/m³. Wood piece decay condition varied, which may explain the
444 density range of 260-770 kg/m³. Wood species were not recorded, but presumed to be
445 predominately coniferous. Mean density conforms to a typical estimate in the literature
446 of 500 kg/m³ (e.g., Seo et al., 2008) but not to the reported instream wood value of 660
447 ± 220 kg/m³ in Ruiz-Villanueva et al. (2016a). The wood species examined in their study
448 were deciduous hardwoods rather than coniferous softwoods, which may be the reason
449 for this inconsistency and emphasizes the need for additional instream wood density
450 data across a broad spectrum of wood species and decay conditions (e.g., Harmon et
451 al., 1986).

452 Each year, a survey starting location was randomly selected along the edge of
453 the accumulation, and then sampling was conducted toward the interior to
454 accommodate potential compaction variations. A GPS unit was used to delineate
455 sampled and total wood accumulation areas. Wood piece volume was calculated under
456 the assumption that each piece could be approximated as a cylinder, and then total
457 wood export was calculated (Table II) using a linear assumption that the sampled area

458 adequately represented the large wood size distribution of the entire accumulation.
459 These assumptions were used in each field campaign, so any biases in volumetric
460 calculations remained constant. In years when remotely sensed imagery was available,
461 area delineations were assumed to contain equivalent wood size distributions as those
462 from the field estimates under the presumption that wood transport size classes may
463 fluctuate but remain relatively equivalent over time. In larger floods, larger wood pieces
464 may transport with increased discharge (Merten et al., 2010), so averaged metrics from
465 more typical years may result in an underestimation of wood export quantities in
466 episodic years; however, no adjustments were made to accommodate this potential.

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

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

488

489 *Wood availability in the channel network*

490 Volumetric wood availability, a key variable required for the extension of theory,
491 was the focus of a field effort to measure wood storage within the mountainous Yuba
492 River watershed (three sub-basins totaling 2874 km²) in the summer of WY2012
493 (Vaughan, 2013). A stratified random sampling scheme was used to collect data from
494 114 reaches 50- or 100-m in length that spanned Strahler stream orders 1–5.
495 Measurements were recorded for wood pieces that fit the large wood criteria, and
496 geomorphic attributes of each wood piece and jam (defined as two or more large wood

497 pieces touching) were collected along with morphologic reach characteristics. Total
 498 wood volume (wood pieces plus jams) was found to be highly variable between sample
 499 sites, yet two basic metrics, total wood volume per channel length and overbank wood
 500 volume per channel length, showed few statistically significant differences between
 501 stream orders using Mann-Whitney U tests that tested for differences greater than zero
 502 between mean rank scores of the raw data values at a significance level of $p_{(1)} < 0.05$.
 503 Only in-channel wood distribution, about 14% of total wood volume, exhibited
 504 statistically significant systematic decreases in wood volume in the downstream
 505 direction at the greater Yuba River watershed scale.

506 In the North Yuba River watershed, the Vaughan (2013) field effort collected data
 507 from 34 study reaches (Fig. 1). An average of 15.5 individual large wood pieces per 100
 508 m were identified for a total of 384 pieces. Piece length was 3.8 ± 3.7 m, median 2.6 m;
 509 diameter was 23.7 ± 12.3 cm, median 20 cm; and volume was 0.31 ± 1.0 m³, median
 510 0.08 m³. About 12% of individual wood pieces were located in the wetted channel, 15%
 511 on bars, 32% on floodplains, and 42% along the lateral extent of the active channel
 512 margins (Table III). Three jam measurements were recorded: the longest dimension, the
 513 axis perpendicular to the longest dimension, and representative jam thickness. Each
 514 jam was classified into a density category as high, medium or low, and then jam
 515 porosities of 10%, 40% and 70% (Manners and Doyle, 2008), respectively, were applied
 516 to estimate jam volume. The field effort located an average of 4.4 jams per 100 m for a
 517 total of 110 jams, with number of pieces per jam of 12.6 ± 25.0 , median 6.0; and volume
 518 of 4.4 ± 10.2 m³, median 1.0 m³. Jam volume was 75% of total surveyed wood volume.
 519 About 15% of wood jams were located in the wetted channel, 39% on bars, and equal
 520 distributions of 23% each on floodplains and along active channel margins (Table III).
 521

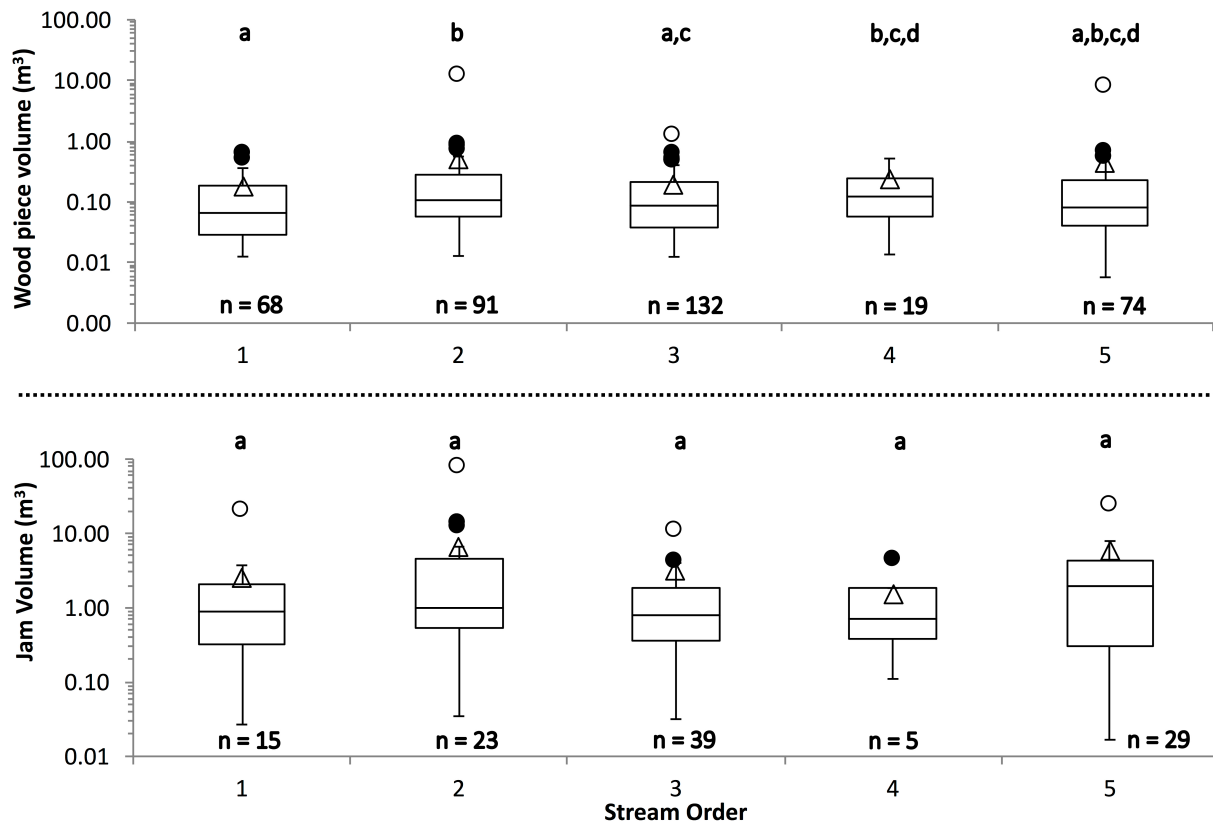
Table II. Wood export and WY type characteristics, ordered by WY type then WY

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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

522
 523

524 Wood piece and jam volumetric data stratified by Strahler stream order were
 525 visualized using box plots (Fig. 3). Mann-Whitney U tests found that three of ten wood

526 piece volume combinations yielded statistically significant differences whereas there
 527 were no significant differences between wood jam volumes. The relative lack of
 528 statistical differences between piece volume, and no statistical differences between
 529 wood jam volume, led to a broad assumption that volumes of both individual pieces and
 530 jams were approximately equally distributed throughout the channel network at a scale
 531 of 10^1 m. Consequently, a simple extrapolation calculation was performed to estimate
 532 the number of wood pieces in the channel network, yielding 0.155 pieces per meter of
 533 channel, or approximately 180,000 individual pieces. An equivalent calculation for wood
 534 jams yielded 0.044 wood jams per meter, or approximately 51,000 jams.
 535



536
 537 **Figure 3.** Box plots of individual wood piece volume (top) and jam volume (bottom) from
 538 the upper watershed, delineated by stream order. Matched letters indicate MW-U test
 539 results of no significant differences between mean ranked values, where $p_{(1)} < 0.05$. Box
 540 plot horizontal lines indicate 25th, 50th, and 75th percentiles; triangles represent the
 541 mean; whiskers represent minimum and maximum values minus the nearest quartile.
 542 Open circles and closed circles represent outliers above whisker values that are greater
 543 than and less than 1.5 times the interquartile range, respectively.
 544

545
 546 The use of an assumption of approximately equivalent wood distribution
 547 throughout the watershed channel network is unusual compared to other studies (Wohl,

548 2017). However, the data and statistical analyses (Fig. 3), and those in Vaughan (2013)
549 using different techniques, yielded the same conclusions and thus are considered
550 verified and valid. It may be that our data collection method, which included all wood
551 within the active channel width defined as any area showing evidence of inundation,
552 and which differs from most studies that tend to collect data from the bankfull channel
553 extent (e.g., Benda and Bigelow, 2014), is driving this apparent disparity. This is
554 supported by the result that in-channel wood distribution did decrease in the
555 downstream direction, and also reveals the relative lack of in-stream wood (i.e., 14% of
556 all identified wood). We suggest that data collection of wood and channel morphology
557 metrics that include the active channel width would provide a more complete
558 understanding of the quantities of wood available for transport under high flow
559 conditions (Ruiz-Villanueva et al., 2016b) and of the broad suite of watershed processes
560 that this study has generalized into a set of coefficients.

561 Benda and Bigelow (2014) reported values for a number of wood budget
562 variables across a wide physiographic range of forested, mountainous, California
563 watersheds. The grouped sub-basins most like the North Yuba River in their study were
564 observations from 17 Sierra Nevada 3rd order watersheds (< 30 km²) that were
565 characterized as managed, and which included data from Haypress Creek, the eastern-
566 and upper-most sub-basin along the mainstem in the North Yuba River watershed (Fig.
567 1). Data from this group are utilized herein to estimate and validate procedures used to
568 develop a range in wood availability storage quantities within the North Yuba River
569 watershed.

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

577 In our sampled reaches, average active channel width generally increased as
578 stream order increased, ranging from 0.9–39.5 m, median 10.3 m. We used a median
579 10 m channel width by 1 km channel length throughout the watershed as an
580 approximation of 1 channel hectare, and assumed that Benda and Bigelow's (2014)
581 recruitment rates are approximately equivalent to those across the North Yuba
582 watershed in most years. Multiplying their recruitment rate by our approximation of
583 1,000 channel-ha in the watershed yielded an estimated range in annual wood
584 recruitment of 10,000–30,000 m³ at the watershed scale, or 10–30 m³ per river-km per
585 year.

586 Extrapolation of wood storage to the watershed scale using WY2012 mean wood
587 piece and jam volumetric measurements yielded an estimated 280,000 m³ of wood

588 available for transport. In keeping with temporally variable wood quantities available for
589 transport, lower and upper bound values of 250,000 m³ and 300,000 m³ were used to
590 explore the study objectives under the assumptions that (a) wood available for transport
591 varies about a mean depending on antecedent conditions (Moulin and Piégay, 2004),
592 (b) recruitment outpaces export in years between large flood events (Marcus et al.,
593 2011), and (c) episodic flood events occur at approximate 10 year intervals regardless
594 of magnitude (Fig. 2) and mobilize wood throughout the watershed network, which
595 results in commensurately episodic wood export quantities at the watershed outlet
596 (Senter et al., 2017). Wood storage of 250–300 m³ per river-km at a median channel
597 width of 10 m falls at the mid-range of the wood storage loads of 226 ± 289 m³ per
598 bankfull channel hectare reported by Benda and Bigelow (2014), which supports the
599 assumptions involved in calculating the wood available for transport in this study.
600

601 *Generalizing δ coefficient values*

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

609 The effectiveness of using generalized coefficients was tested using the two
610 wood export datasets from WY2003 and WY2010 where accumulation periods
611 encompassed multiple years rather than one year, such that cumulative volumetric
612 quantities were known but discrete annual wood export quantities were unknown. To
613 separate these datasets into theoretical wood export quantities using discharge
614 variables only, Eq. 1b was solved using the appropriate annual Q_{peak} value (Eq. 9). To
615 separate these datasets into annual wood export quantities that also consider
616 watershed processes, Eq. 8 was solved by multiplying theoretical wood export (Eq. 1b)
617 by the generalized coefficient depending on WY type, and then the two prediction
618 techniques were compared. Finally, volumetric estimations of wood export in WYs
619 where no records exist were calculated by solving Eq. 8 using Q_{peak} and the appropriate
620 generalized coefficient depending on WY type, and then comparisons were made
621 between these results and those reported in Senter et al. (2017), where a regression
622 analysis of wood export yielded a predictive equation focused exclusively on annual
623 peak discharge.
624

625 **Results**

626 *Theoretical wood export, Eq. 1a,b*

627 Solving Eq. 1a was accomplished using a Q_{crit} of 60 m³/s, a Q_{max} of 3,470 m³/s,
 628 and the appropriate annual Q_{peak} for the years where wood export was known. These
 629 calculations resulted in theoretical export frequency percentages of 14–87% of the
 630 volumetric wood available for transport into NBB in a given year (Table IV). The
 631 smallest percentage of theoretical f_w was associated with a Q_{peak} of 546 m³/s in
 632 WY1993, a statistical 2.3-year flood event in an above normal WY (Table II). The largest
 633 percentage was associated with a Q_{peak} of 3,028 m³/s in WY1997, a 60-year flood event
 634 in a wet WY.
 635

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

Water Year	Eq. 1a	Eq. 1b ^{a,b}		Eq. 2 ^{a,b}		Eq. 2, Observed	Eq. 4 ^c	Eq. 5
	f_w	Theoretical wood export, W_Q		Empirical wood export rate, c_w		W_{exp}	W_θ	$W_\%$
	%	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 m³

b right column results when W_{av} equals 300,000 m³

c when Eq. 3 equals 30,000 m³ as calculated for the North Yuba River watershed

636
637

638 When Eq. 1b was solved using lower and upper volumetric bounds of available
 639 wood for transport, theoretical wood export ranged from 35,608 m³ in WY1993 to
 640 261,114 m³ in WY1997 (Table IV). To support these theoretical export quantities,
 641 minimum wood export rates in WY1993 of 30 m³ per river-km would have been
 642 generated across the entire watershed, whereas a maximum rate of 225 m³ per river-km
 643 would be required in WY1997. In a year with a statistically typical return interval of 2.3
 644 years, theoretical wood export of 35,000 m³ exceeds the upper bound of the estimated
 645 annual wood recruitment rate for the entire watershed. In a year with a statistically
 646 unusual return interval of 60 years, theoretical wood export of 260,000 m³ is equivalent
 647 to transport of all available wood into NBB if the lower bound of 250,000 m³ is used.
 648 Neither of these scenarios was observed in aerial image estimations of wood export
 649 quantities in those two years (Table II). Furthermore, theoretical wood export in both
 650 years exceeded the empirically derived maximum wood export calculated as a function
 651 of watershed area (Eq. 3), so the export of these theoretical values is extremely
 652 unlikely.

653

654 *Empirical wood export, Eq. 2*

655 Based on empirically derived field measures and image analyses, the wood
656 export rate ranged from 0.03–5.6% of wood available for transport delivered into NBB,
657 averaging 1.8-2.3% across years and depending on the W_{av} end member (Table IV).
658 The smallest percentage was associated with a Q_{peak} of 1,132 m³/s in WY2013, a
659 statistical 9.2-year flood event in a dry WY (Table II). The largest percentage was
660 associated with a Q_{peak} of 1,661 m³/s in WY2006, a 19-year flood event in a wet WY.
661 These results notably indicate that small proportions of the volumetric wood available
662 for transport actually export into NBB in any given year, even with statistically unusual
663 flood magnitudes.

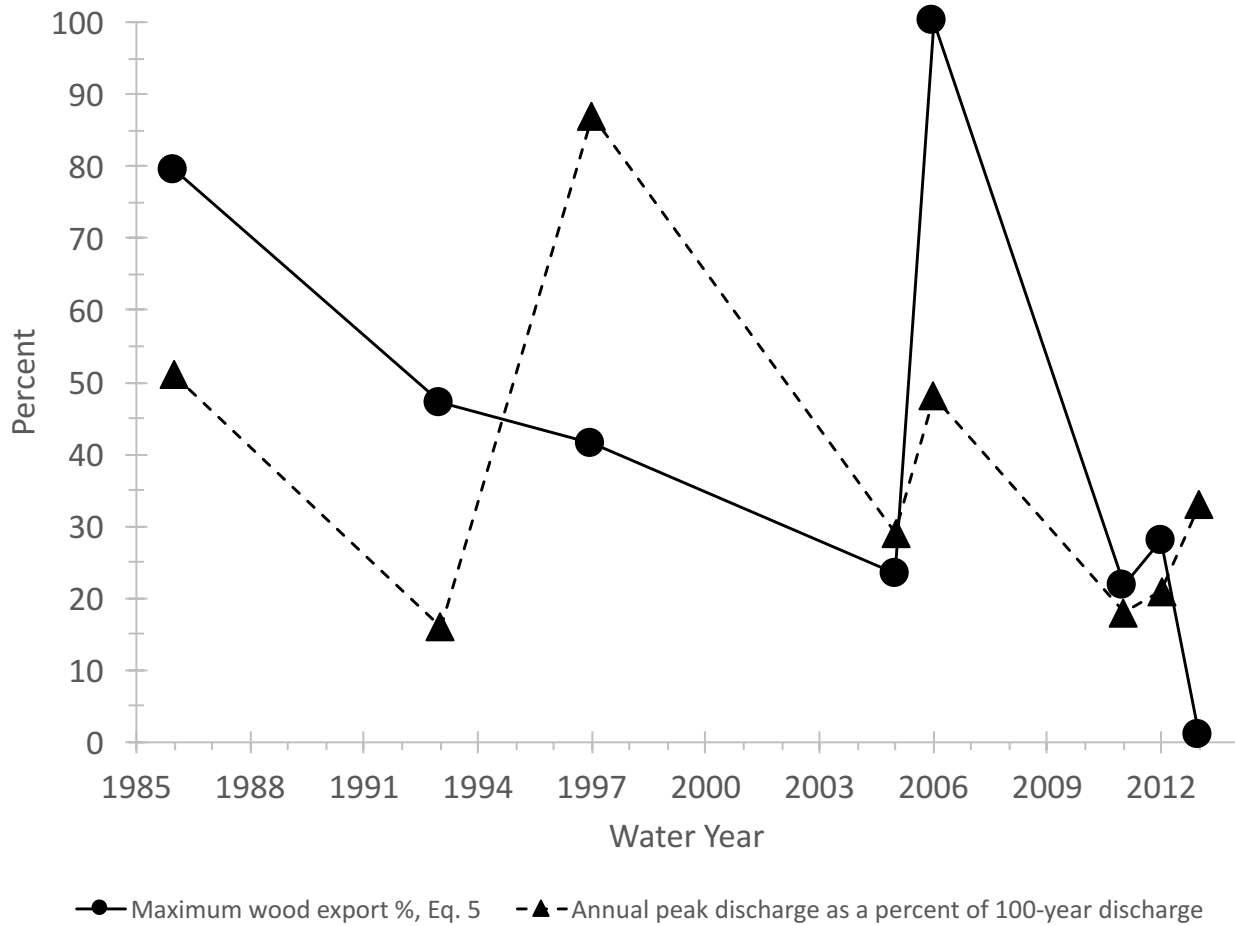
664 Comparisons between empirically derived wood export quantities and theoretical
665 values reveal obvious numerical differences. Observed wood export quantities were 8–
666 1,136 times smaller (median 25–30 times) than theoretical values, with WY2006 the
667 only WY in which the smallest difference was less than one order of magnitude (Table
668 IV). These disparate results support (i) the conclusion that an equation such as Eq.
669 1a,b, which is focused on discharge variations, does not adequately represent
670 watershed processes that exert substantial internal controls on wood dynamics in the
671 North Yuba River watershed and (ii) the development of parsimonious coefficients to
672 represent these differences.

673

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

675 Maximum potential wood export as a function of watershed area (W_{max} , Eq. 3) for
676 the 1,073 km² North Yuba River watershed yields an empirically derived maximum
677 wood export quantity of 30,000 m³ that could potentially transport into NBB. The
678 constraint of W_{max} was applied to Eq. 1a to solve for W_{θ} (Table IV, Eq. 4) and $W_{\%}$
679 (Table IV, Eq. 5) to explore how known export quantities in the North Yuba watershed
680 may compare to the calculated potential maximum, and whether a potential maximum is
681 produced in any WY. This set of calculations using known export values, $n = 8$, yielded
682 a maximum potential wood export average of 43% with a range 1-100%. Maximum
683 potential wood export was 80% in WY1986 (Fig. 4), followed by a gradual decrease in
684 response rate until another peak in WY2006 when the watershed produced 100% of
685 maximum potential wood export followed again by a relatively steady decrease.

686



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690
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Figure 4. Comparison of the variability between potential maximum wood export percent and annual peak discharge magnitude.

692 The $W_{\%}$ calculated for WY2006 indicates that the North Yuba River watershed
693 may be capable of delivering maximum wood quantities to the reservoir under optimal
694 conditions. However, in wet WY1997, a statistical 60-year Q_{peak} flood event, an
695 expectation of a larger wood export quantity was not realized. Instead, a $W_{\%}$ of 41%
696 was calculated while the Q_{peak} was 87% of Q_{max} (Fig. 4). Conversely, dry WY2013
697 yielded $W_{\%}$ of 1% while the Q_{peak} was 33% of Q_{max} . These results suggest that an
698 equation that considers discharge variations and watershed area may provide
699 reasonable predictions of wood export in some cases, and the use of a maximum wood
700 export equation (Ruiz-Villanueva et al., 2016b) is promising, but the broad suite of
701 watershed processes as defined in this study do not appear to be fully represented
702 given the observed range in variability of wood export quantities into NBB.
703

704 *Watershed processes coefficients, Eq. 6,7*

705 Theoretical Eq. 1a,b results were appreciably larger than observed wood export,
 706 given the caveat that the original equation was not meant to be predictive. However, the
 707 disparity motivated this effort to understand the differences, which led to a back-
 708 calculation of a simple proxy to represent the defined broad suite of watershed
 709 processes. The watershed processes coefficient (Eq. 6) was solved for using each
 710 observed wood export quantity (Table II) and at both defined W_{av} endmembers (Table
 711 V, Eq. 6). The lowest coefficient value of 0.0009 was calculated for WY2013 as a result
 712 of the smallest observed wood export quantity of the study. The theoretical δ_{max} result
 713 (Eq. 7) was 0.12 when using the lower limit of wood available for transport of 250,000
 714 m³, associated with the largest observed wood export quantity of the study in WY2006,
 715 and this relation is reflected in the $W_{\%}$ of 100% (Eq. 5).
 716

Table V. Watershed processes δ coefficient results

Water Year	WY type	Eq. 6 Watershed processes coefficient, δ		Generalized Eq. 6, Averaged δ	Eq. 7 δ_{max}
		250,000 m ³	300,000 m ³		
1986		0.095	0.080		0.12
1997	wet	0.050	0.041	0.0670	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

717
 718
 719 Examination of the efficacy of generalizing by WY type sought to determine
 720 whether coefficients derived from one set of data could be used to predict other years in
 721 which data were not available. This generalization technique resulted in a mean
 722 coefficient value for wet WYs of 0.0670, above normal WYs of 0.0383, below normal
 723 WYs of 0.0315, and dry WYs of 0.00097 (Table V, generalized Eq. 6). It is particularly
 724 notable that during dry years the coefficient dropped by two orders of magnitude
 725 compared to the other WY categories, which are otherwise within the same order of
 726 magnitude. The substantially lower value of the dry WY coefficient suggests that a
 727 disproportionate drop in wood export per unit discharge in dry WYs is controlled by an
 728 equivalent drop in mountain watershed precipitation runoff when compared to wetter
 729 years.
 730

731 *DVWP wood export predictions, Eq. 8*

732 Equation 8 was solved by multiplying the appropriate generalized watershed
 733 processes coefficient (Table V, generalized Eq. 6) by the appropriate theoretical wood
 734 export quantity (Table IV, Eq. 1b). The key test calculations were those involved in the
 735 validation process for the multi-year wood export quantities that were estimated from a
 736 WY2003 aerial image and a WY2010 field survey (Table VI). Calculations for these sets
 737 of years resulted in DVWP wood export quantities that ranged from a high of almost
 738 2,500 m³ in wet WY1999 to essentially zero in dry WY2001, WY2002, and WY2007.
 739 The sum of results from WY1999–WY2003 overestimated the observed cumulative
 740 wood export quantity in WY2003 by 2.2 times, and results from WY2007–WY2010
 741 overestimated the observed cumulative wood export quantity in WY2010 by 1.3 times.
 742

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 accumulation in NBB

743
 744
 745 Conversely, theoretical wood export quantities overestimated DVWP wood
 746 export quantities by 15 to 1033 times, depending on WY type. Moreover, the sums of
 747 theoretical wood export quantities overestimated observed wood export in WY2003 by
 748 57 times and in WY2010 by 71 times. Individual annual wood export values remain
 749 unknown; however, using generalized coefficients averaged by WY type provided a
 750 rational modifier to the use of discharge variations only and substantially narrowed the
 751 degree of uncertainty between DVWP wood export quantities and observed cumulative
 752 wood export quantities.

753 The use of the DVWP wood export equation was extended to all study years
 754 (Table VII), resulting in an estimated volumetric range of 59,000–71,000 m³ transporting
 755 into NBB over the 30-year study period, yielding a rate of 1.8 to 2.2 m³/year/km².
 756 Another validation exercise was conducted by summing and comparing observed wood
 757 export quantities and the equivalent eight years of predicted DVWP wood export

758 quantities. Observed wood export totaled 43,598 m³ and the equivalent eight years of
 759 predicted W_{DVWP} was 39,000–47,000 m³ as a function of the lower and upper bounds of
 760 W_{av} , yielding remarkably comparable aggregate results. Differences between aggregate
 761 observed wood export and equivalent-WY predicted W_{DVWP} values resulted in a net
 762 positive error estimate of +10.2% with W_{av} of 250,000 m³ and a net negative error
 763 estimate of –7.7% with W_{av} of 300,000 m³; modest error estimates given the generalities
 764 involved. When individual WY values were compared, W_{DVWP} varied by 0.5–3.0 times
 765 that of observed wood export (Table VII), thus exhibiting nominally greater degrees of
 766 variability on an individual basis than on an averaged or summed basis.
 767

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} Senter et al. (2017)	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			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

768 The largest overestimation in predicted W_{DVWP} versus observed wood export was
 769 associated with WY2011, classified as a wet WY (Table VII). There were two notable
 770 differences between WY2011 and the other wet WYs that may provide an explanation.
 771 First, the hydrograph for WY2011 reached about one-third of the Q_{peak} that other wet
 772 WYs exhibited (Fig. 2). Second, WY2011 had substantially longer elevated discharge
 773 associated with the snowmelt season than other wet WYs, while remaining below the
 774 winter Q_{peak} . The wet winter and spring snowmelt seasons of WY2011 were unusually
 775
 776

777 cold, resulting in a snowpack that melted slowly and sustained a long hydrograph
778 through the snowmelt season. Consequently, on an annual basis the longer periodicity
779 of elevated discharge in WY2011 resulted in enough cumulative discharge to be
780 classified as a wet WY according to the YRI index (Eq. 10) even though Q_{peak} was small
781 relative to the other wet WYs, thus yielding lower observed wood export than predicted
782 with Eq. 8.

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

795 796 **Discussion**

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

810 Linking wood availability with wood export quantities and then finding a method
811 of simplification using WY types provided a set of generalized, watershed-specific
812 coefficients that resulted in first-order approximations of wood export for every year
813 within the 30-year study period. We propose that this paper provides early validation of
814 the theory and equations (Table I), which may be improved upon with additional data
815 and testing from the North Yuba River and other watersheds. If WY typing is not

816 available elsewhere, classifications of WYs into generalized groups could be achieved
817 by establishing parameters related to hydrographic variations between years such as
818 methods used in California watersheds by resource agencies (YCWA, 2012; CDWR,
819 2016).

820

821 *Wood export prediction*

822 Theoretical Eq. 1a,b performed poorly in predicting wood export when compared
823 to the eight years of observed wood export. However, discharge remains a primary
824 variable in predicting W_{exp} , as shown in analyses that reveal significant correlation
825 between wood export quantities and Q_{peak} , albeit with inherent variability and subject to
826 hysteresis (MacVicar and Piégay, 2012). Peak annual discharge regression analyses
827 have reported coefficients of determination of 0.58 (Moulin and Piégay, 2004), 0.41
828 (Boivin et al., 2015), 0.66 in a meta-analysis (Ruiz-Villanueva et al., 2016b), and 0.79
829 (Senter et al., 2017). Comparison between DVWP wood export (Eq. 8) and Senter et al.
830 (2017) predictions revealed mostly similar results for observed W_{exp} quantities (Table
831 VII). However, the W_{exp} quantity from WY2013 was excluded in the previous study as
832 anomalously low; inclusion would have reduced the coefficient of determination to 0.60,
833 which is more in line with the other studies.

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

847 Wood export predictions using the peak discharge regression equation from
848 Senter et al. (2017) yielded a 30-year estimate of $\sim 68,000 \text{ m}^3$, which falls at the high
849 end of the DVWP wood export equation prediction range of 59,000-71,000 m^3 (Table
850 VII). Individual years except for dry WYs were similar to those of Eq. 8 predictions. The
851 DVWP wood export equation was far superior in predicting observed wood export in dry
852 WYs, whereas the Senter et al. (2017) equation overestimated Eq. 8 dry WY predictions
853 23-43 times (Table VII). There were multiple dry WYs in the validation exercise (Table

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

857 Senter et al. (2017) investigated the efficiency of their peak discharge regression
858 equation to predict wood export using daily mean discharge values greater than the
859 observed Q_{crit} of 60 m³/s as a delimiter for number of days where wood was mobile.
860 This approach resulted in a count of days for each investigated time period (two
861 snowmelt periods and two full WYs) for which potential wood volumes were calculated
862 given a range in observed wood size metrics. Results overestimated wood export during
863 video monitoring time periods and underestimated wood export during almost all of the
864 WY time periods, except at the WY scale using the global standard deviation for volume
865 per piece (see Table 5 last row, Senter et al., 2017), which was the largest possible
866 volumetric quantity. Thus, wood piece measurements collected during video monitoring
867 were not fully representative of piece sizes that export into NBB during winter flood
868 conditions, which underscores the need to monitor entire WY hydrographs, including
869 nighttime hours. Other techniques may be useful in developing models of wood piece
870 spiraling downstream (Latterell and Naiman, 2007; Schenk et al., 2014), such as those
871 used to examine how excess flow energy expenditures driving sediment dispersion
872 patterns are linked to flow durations above a Q_{crit} (Haschenburger, 2013).

873 Ruiz-Villanueva et al. (2016b) predicts that there is an upper volumetric limit to
874 wood export as a function of watershed area. Their meta-analysis reveals an important
875 insight that supports our conclusion that wood export is small relative to the quantity of
876 wood available for transport in the North Yuba River watershed. Their upper boundary
877 at a global scale suggests limits to the ability of a watershed to export wood quantities.
878 Export as predicted by theoretical Eq. 1a,b alone may be achievable only in the most
879 extreme circumstances, such as when Typhoon Morakot made landfall in Taiwan in 2009
880 and caused massive landsliding in steep, forested mountain watersheds (West et al.,
881 2011).

882 What is in evidence for the North Yuba River is that the largest floods mobilized
883 small fractions of W_{av} from the upper watershed into NBB, as highlighted by WY1997
884 data where a statistical 60-year flood generated a wood export quantity equivalent to a
885 c_w rate of 5.6% (Table IV). Even if W_{av} was considerably smaller than the lower bound
886 estimate, for instance 150,000 m³ in the entire watershed (i.e. 50% of the upper bound
887 estimate), solving Eq. 2 would result in a wood export rate of 10% instead of 5.6%,
888 which is not appreciably larger given the still considerable volume of wood available for
889 transport. Conversely, if W_{av} was larger than our upper estimate, then wood export rates
890 would decrease.

891

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

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

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

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

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

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

950 Wood transport rates ranging from 0.6–8% of total wood volume were reported
951 from six Sierra Nevada headwater streams, including two sub-watersheds in the North
952 Yuba River (Lavezzola and Pauley Creeks; Berg et al., 1998); remarkably similar values
953 to the wood export rates reported in this study. Contributing area of their study sites
954 ranged from 8–25 km², bankfull channel widths from 2.1–12.8 m, and mean wood
955 transport distances of 70–361 m. Berg et al. (1998) reported very low rates of mobility in
956 WY1994, the first year of their study, and then many wood pieces moved or were not
957 found and presumed to have transported out of the study reaches over WY1995, with
958 high gaged discharges. Their interpretation was that low flows in the first year did not
959 trigger transport, while the 31% transport rate in the second year may have been near
960 the maximum limit of a high discharge event to influence wood mobility. Their
961 observations provide an independent validation of our supposition that dry WYs have
962 very low wood export capacities (see Table VII for WY types).

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

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

977 Wood storage quantities in the North Yuba River watershed range from 200-300
978 $\text{m}^3/\text{channel-ha}$ and m^3/km^2 . This value is similar to Sierra Nevada storage quantities of
979 $226 \pm 289 \text{ m}^3/\text{channel ha}$ (Benda and Bigelow, 2014). Values from the two North Yuba
980 River sub-watersheds in Berg et al. (1998) were lower at 20-180 m^3/km channel length
981 with narrower channels widths, an indication of inherent variability in the system at local
982 scales also seen in this study (Fig. 3). Estimated North Yuba River wood storage
983 (Vaughan, 2013) was at least 10 times the estimated annual wood recruitment rate
984 (Benda and Bigelow, 2014). Berg et al. (1998) noted that wood recruitment followed the
985 same pattern as wood transport. The first year of their study resulted in few additional
986 wood pieces whereas many pieces were added to the study sites after the high flows of
987 year two; an observation supported by the work of Jochner et al. (2015) at the episodic
988 hydrologic event scale.

989 Review of the 30-year hydrograph and individual WY designations (Table VII,
990 Fig. 2) suggest a watershed-scale climatic explanation to the pattern that emerges in
991 the negative trend in maximum potential wood export percent (Eq. 5) from 80% in
992 WY1986 to 23% in WY2005, followed by an increase to 100% in WY2006 and then
993 another decreasing trend (Fig. 4). A Q_{peak} of 3,028 m^3/s in WY1997 should have
994 produced the largest wood export quantity of the 30-year study period at almost twice
995 the peak discharge of WY1986 and WY2006, yet the observed wood export of 10,800
996 m^3 was instead the third largest W_{exp} quantity, and produced just 41% of predicted
997 maximum potential wood export. This disparity between expected and observed may be
998 explained by the two wet WYs in WY1995 and WY1996, prior to the third wet WY in
999 WY1997 that experienced the statistically rare 60-year flood recurrence interval (Fig. 2).
1000 Although there were no substantial Q_{peak} events in the previous two years, there were
1001 multiple smaller flood peaks with enough cumulative discharge to classify each as a wet
1002 WY type; Berg et al. (1998) reported WY1995 flows as in the 71st percentile. Multiple
1003 flood peaks mobilized individual wood pieces that could disintegrate, spirale and lodge
1004 onto a jam, or transport into NBB in the two WYs prior to WY1997, resulting in less
1005 wood available for transport during the 60-year event. Other dynamic fluctuation
1006 scenarios can be inferred in a review of the 30-year discharge record along with
1007 observed and predicted wood export patterns (Table VII, Fig. 2).

1008 Moulin and Piégay (2004) reported an analogous antecedent condition
1009 phenomenon within WYs, where an initial flood event yielded high W_{exp} followed by a
1010 similar flood magnitude that yielded a smaller quantity. They conjectured that most W_{av}

1011 was exported to the downstream reservoir in the first flood event, and that the
1012 recruitment rate between events did not produce enough additional W_{av} to produce a
1013 similar volumetric export quantity during the next flood. In the North Yuba River
1014 watershed, an annual wood recruitment rate of 10,000–30,000 m³ combined with low
1015 export rates and potentially low mobility rates might not provide enough W_{av} in optimal
1016 locations to generate large W_{exp} quantities in consecutive wet WYs. These observations
1017 provide evidence that watershed processes act to increase wood available for transport
1018 in years with lower flood peaks leading to an increase in wood export in years with
1019 higher flood peaks (Moulin and Piégay, 2004; Marcus et al., 2011).

1020

1021 *Research directions*

1022 High-resolution remotely sensed imagery at yearly to sub-yearly time steps is
1023 now commonly available from Google Earth and other resources, so barriers to historic
1024 estimates and wood export monitoring on an annual to sub-annual basis are rapidly
1025 declining. However, observations of wood export are needed over multiple peak
1026 discharge events (Moulin and Piégay, 2004; Benacchio et al., 2017) to compliment
1027 those collected at annual time scales (Seo et al., 2008). Hydrographic peaks smaller
1028 than annual Q_{peak} events will mobilize and export wood at lower rates than flood events
1029 (Moulin and Piégay, 2004; Senter et al., 2017). Wood discharge monitoring has been
1030 achieved using still image analysis (Moulin and Piégay, 2004; Kramer and Wohl, 2014;
1031 Boivin et al., 2015; Benacchio et al., 2017) and video monitoring at-a-station (MacVicar
1032 et al., 2009; MacVicar and Piégay, 2012; Boivin et al., 2017; Senter et al., 2017). These
1033 studies reveal semi-continuous to continuous real-time transport processes; data which
1034 are necessary to obtain further insights into associations between wood discharge,
1035 water discharge, and watershed processes. Establishing permanent wood discharge
1036 monitoring stations at select long-term gaging stations could support such studies in
1037 conjunction with repetitive field efforts to collect data on wood budget components.
1038 Bracketing multiple individual storm events over a period of years would greatly
1039 enhance our abilities to understand how mechanistic watershed processes operate
1040 across multiple watersheds, at varying spatial and temporal scales, and between
1041 climate zones (e.g., Comiti et al., 2016, Ruiz-Villanueva et al., 2016b; Kramer and Wohl,
1042 2017; Wohl, 2017).

1043

1044 **Conclusion**

1045 Watershed-specific coefficients generalized by WY type are introduced as
1046 multipliers into an existing theoretical wood transport equation, such that the dynamics
1047 involved in watershed processes as well as peak annual discharge can be used to
1048 explain and predict wood export quantities. The refined equation predicted wood export

1049 quantities over a 30-year timeframe that resulted in acceptable error ranges within the
1050 context of observed data, and was superior to an existing annual peak discharge
1051 equation in predicting dry WY wood export. Initial validation of the concept suggests that
1052 the DVWP wood export equation may be testable in other watersheds where wood
1053 export, availability, and WY type data can be collected.

1054 Regulated river managers tasked with resource allocation may use these
1055 procedures to understand wood dynamics and variability and to plan for a range of
1056 climate scenarios related to flooding and drought conditions. Understanding that the
1057 vast majority of wood remains stable within a watershed even at the highest flows may
1058 help shift public and agency perceptions toward less wood removal from channels.
1059 Water resource agencies tasked with environmental health and welfare of aquatic
1060 resources could use these new predictive capabilities to plan for wood transfers from
1061 reservoirs to enhance below-dam stream channel ecosystems in years where large
1062 wood export quantities are generated.

1063

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1077

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