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1 [FULL TITLE] PRECIPITATION PATTERNS CONTROL THE DISTRIBUTION AND
2 EXPORT OF LARGE WOOD AT THE CATCHMENT SCALE

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4 [RUNNING HEAD] PRECIPITATION PATTERNS CONTROL THE DISTRIBUTION
5 AND EXPORT OF LARGE WOOD

6

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25

26 **Abstract**

27 Large wood (LW) plays an important role in river ecosystems, but LW-laden floods
28 may cause serious damage to human lives and property. The relationship between
29 precipitation patterns and variations in LW distribution and export at the watershed scale is
30 poorly understood. To explore these linkages, we examined differences in LW distribution as
31 a function of channel morphologies in six watersheds located in southern and northern Japan,
32 and analyzed the impacts of different precipitation patterns on the fluvial export of LW from
33 river catchments. In southern Japan, intense rainfalls caused by typhoons or localized
34 torrential downpours initiate landslides and debris flows that introduce massive amounts of
35 LW into channels. Gravel bars formed by frequent flood events are widely prevalent, and the
36 LW temporarily stored on these bars is frequently moved and/or broken into smaller pieces
37 by floods. In these systems fluvial export of LW is supply-limited, with smaller
38 accumulations and shorter residence times than in northern Japan. Conversely, in northern
39 Japan, where typhoons and torrential downpours rarely occur, LW is mostly recruited by
40 bank erosion, tree mortality and windthrow into channels, rather than by landslides and debris
41 flows. Recruited pieces accumulate in log jams on valley floors, particularly on floodplains
42 supporting mature forests, resulting in larger accumulations and longer residence times. In
43 these watersheds fluvial export of LW is transport-limited, and the pieces gradually
44 decompose during long-term storage as log jams.

45

46 **Keywords** large wood distribution; disturbance regime; channel morphology; supply-
47 limited; transport-limited; Japanese archipelago

48

49 **1. Introduction**

50 The dynamics of in-stream large wood (LW) are influenced directly and indirectly by
51 precipitation patterns, particularly rainfall (e.g., Lienkaemper and Swanson, 1987; Nakamura
52 and Swanson, 1993; Moulin and Piégay, 2004; Seo and Nakamura, 2009) and snowmelt (e.g.,
53 Robison and Beschta, 1990; Richmond and Fausch, 1995; Thevenet *et al.*, 1998; Marcus *et*
54 *al.*, 2002). Furthermore, precipitation regulates species, size and productivity of riparian
55 forests (Naiman *et al.*, 2000) which, in turn, may influence the size and amount of in-stream
56 LW. Heavy rainfall caused by typhoons and/or seasonal rain fronts in East Asia can lead to
57 an elevated groundwater table and increased stream discharge. These processes can result in
58 landslides and debris flows on hillslopes or at the heads of steep tributaries, and bank erosion
59 in larger channels (Swanson *et al.*, 1982; Nakamura *et al.*, 2000), delivering large volumes of
60 LW into channels where it is transported downstream (Keller and Swanson, 1979; Seo *et al.*,
61 2008). Increased stream discharges caused by snowmelt alone can also undercut channel
62 banks, recruiting standing trees in riparian zones into channels where they are fluvially
63 transported downstream (Harmon *et al.*, 1986; Johnson *et al.*, 2000).

64 Many studies have documented the dynamics of in-stream LW in response to major
65 runoff events caused by certain precipitation patterns (i.e., rainfall and/or snowmelt) in
66 temperate zones. Nakamura and Swanson (1993) and Seo and Nakamura (2009) investigated
67 the size, distribution, and breakage/decay status of LW pieces introduced by landslides and/or
68 debris flows during intense rainfall in mountain catchments, and LW dynamics in relation to
69 geomorphic and hydrologic parameters. Marcus *et al.* (2002) and Moulin and Piégay (2004)
70 quantified spatial and temporal variations in LW export associated with flood events
71 generated by heavy rainfall and snowmelt, and discussed LW dynamics controlling fluvial

72 export at the watershed scale. By contrast, Cadol and Wohl (2010) and Wohl *et al.* (2012)
73 documented LW distributions in tropical streams, and observed a higher transport capacity
74 and decay rate of LW pieces in comparison with temperate streams. However, no study has
75 specifically documented how varying precipitation regimes control the distribution and
76 export pattern of LW in temperate zones.

77 Precipitation patterns in Japan vary along a latitudinal gradient, and flood frequency,
78 magnitude, and driving processes differ between southern and northern Japan. The most
79 influential events in southern and central Japan are typhoons and seasonal rain storms, which
80 produce heavy rainfall. In northern Japan, however, much precipitation occurs as heavy
81 snowfall, and typhoon-related heavy rainfall rarely occurs. We hypothesize that these
82 differences in precipitation patterns in Japan lead to differences in the magnitude and
83 frequency of hydrogeomorphic disturbances, thereby regulating the dynamics of in-stream
84 LW in mountain landscapes.

85 In Japan, agencies responsible for local reservoir management remove LW pieces
86 trapped by reservoirs, and typically estimate total annual volumes delivered to the reservoirs
87 (see Seo *et al.*, 2008, 2012; Fremier *et al.*, 2010). From these databases, Seo *et al.* (2012)
88 examined variations in LW export as a function of precipitation pattern in watersheds >20
89 km² (see Figures 3c and 3d in Seo *et al.* (2012)). They argued that LW pieces in southern and
90 central Japan are constantly removed from channels due to repeated typhoons and heavy
91 rainfall, resulting in supply-limited LW export. Conversely, in northern Japan, LW pieces
92 accumulate on valley floors because opportunities to remove LW from the main channel are
93 limited by less rainfall and corresponding floods; thus LW export is transport-limited. These
94 findings were derived from statistical models using a large database of LW export from

95 across the Japanese archipelago and further examination through field surveys is required to
96 test this hypothesis. The specific objectives of this paper are to: (i) investigate differences in
97 the physical characteristics of stream and river channels as a function of precipitation pattern
98 in watersheds located in southern and northern Japan; and (ii) examine differences in LW
99 distribution and relevant export as a function of precipitation pattern and channel
100 characteristics.

101

102 **2. Study site description**

103 Our study was conducted in six watersheds with reservoirs where annual export
104 volumes of LW have been collected: the Yanase, Hatsuse and Nagase watersheds in Shikoku,
105 southern Japan and the Jouzankei, Katsurazawa and Taisetsu watersheds in Hokkaido,
106 northern Japan (Figure 1, Table I). While the Yanase, Hatsuse and Nagase watersheds in
107 southern Japan are primarily underlain by sedimentary and metamorphic rocks of Jurassic
108 and Cretaceous ages, the Jouzankei and Katsurazawa watersheds in northern Japan are
109 underlain by volcanic and sedimentary rocks of Cretaceous to Tertiary ages and the Taisetsu
110 watershed is underlain by Pliocene pyroxene andesite (Geological Survey of Japan, 2005).

111 Channel morphology in the headwaters of the six watersheds is dominated by step-
112 pool sequences constrained by boulders, bedrock outcrops and valley walls, while braided
113 patterns with pool-riffle sequences occur further downstream. Most of these catchments are
114 covered by forest (91–97%) composed of mixed stands of deciduous broad-leaved trees and
115 evergreen conifers, with partial coverage by plantation stands. The riparian zones in all
116 watersheds are dominated by *Salix* spp., *Betula* spp., *Fraxinus mandshurica* var. *japonica*,
117 and *Alnus hirsuta*, and the maximum heights and diameters at breast height of these tree

118 species are approximately 30 m and 50 cm, respectively.

119 Although the climate zone for all study watersheds is classified as temperate, with
120 four seasons, the meteorological characteristics in southern and northern Japan differ.
121 According to the observation data collected by the Japan Meteorological Agency closest to
122 each study watershed, the mean annual temperature over the past 20 years (1991–2010) in
123 southern Japan was 12.6–16.2°C, whereas in northern Japan it was 4.7–8.6°C. These
124 temperature differences underscore fundamental differences in hydrologic regime.
125 Precipitation data from the observed reservoirs over the period monitored for LW export
126 (Table I) showed that the annual precipitation of 1988–5800 mm in southern Japan
127 corresponded with a peak streamflows produced by rainfall during storms. Conversely, the
128 annual precipitation of 465–1560 mm in northern Japan corresponded with peak discharges
129 due to a mixture of both rain- and snowmelt-driven discharges.

130 Based on relative differences in drainage area as well as total channel length, all
131 watersheds in this study were categorized into three groups: small (Yanase and Jozankei
132 watersheds); intermediate (Hatsuse and Katsurazawa watersheds); and large (Nagase and
133 Taisetsu watersheds) (Table I).

134

135 **3. Methods**

136 ***3.1. Estimation of LW export from study watersheds***

137 We used the annual volume of LW pieces exported from the study watershed (V_{LW}
138 $_{export}$, $m^3 yr^{-1}$), which was monitored by local reservoir management offices in reservoirs
139 (Table I). All $V_{LW export}$ data were divided by total channel lengths within study watersheds to
140 express the $V_{LW export}$ per unit channel length (*unit* $V_{LW export}$, $m^3 km^{-1} yr^{-1}$), making it possible

141 to compare long-term continuous movement of LW pieces along the stream network for
142 watershed of different sizes. Total channel lengths were estimated using channel network
143 data (1:25000) derived from a digital elevation model (50×50 m resolution) in a geographic
144 information system (GIS) (Environmental Systems Research Institute, 2007). To explore
145 discharge-dependency of $V_{LW\ export}$, we established the correspondence between precipitation
146 and peak discharge by calculating cumulative daily precipitation greater than or equal to 60
147 mm ($cP_{\geq 60}$, mm) and cumulative water discharge per unit drainage area associated with that
148 precipitation ($cD_{P_{\geq 60}}$, $\text{m}^3 \text{sec}^{-1}$), based on the results of Seo *et al.* (2012).

149

150 ***3.2. Selection of channel segments within the study watersheds***

151 Drainage area is a proxy for a variety of both geomorphic and hydrologic processes
152 that control LW dynamics; specifically watershed size is associated with large variations in
153 longitudinal patterns of channel morphology and hydrology (Nakamura and Swanson, 1993;
154 Gurnell *et al.*, 2002; Wohl and Jaeger, 2009). To explore these controls we analyzed multiple
155 channel segments (400 m in length) in each watershed that varied in upstream drainage areas:
156 10 segments in the Yanase and Jouzankei watersheds; 15 segments in the Hatsuse and
157 Katsurazawa watersheds; and 25 segments in the Nagase and Taisetsu watersheds. We
158 carefully selected the segments to include all representative variations in lateral and
159 longitudinal profiles (e.g., channel width, planform of floodplains, bed gradient, and bed
160 materials). Channel morphology in these segments has not been affected by artificial
161 structures, although there are several small check dams in these catchments.

162

163 ***3.3. Investigation of channel segment geomorphology***

164 We conducted fieldwork during base flow conditions in autumn after the summer
165 monsoon season in 2009. The dynamics of LW pieces can be affected by channel
166 geomorphology (e.g., width, gradient, surface form and obstruction) (Nakamura and Swanson,
167 1994; Gurnell *et al.*, 2002; Wohl and Jaeger, 2009). Thus, in each segment, we established 4–
168 8 transect lines and measured bankfull channel width. We also measured the widths of
169 channel adjacent surfaces, which consist of the bankfull channel widths and include the: (i)
170 low-flow channels (LFC), (ii) gravel bars (GB), (iii) young-forested floodplains (YFF), and
171 (iv) mature-forested floodplains (MFF). From this data we then estimated surface areas (i.e.,
172 A_{LFC} ; A_{GB} ; A_{YFF} ; and A_{MFF} , ha). To quantify degree of channel obstruction to LW transport,
173 we measured the intermediate-axes of boulders distributed within channel segments and
174 counted the number of boulders (N_B) with a minimum diameter of 1.0 m, whose threshold of
175 mobility often exceeds the tractive force of contemporary fluvial events. The data were
176 transformed to express the N_B per unit channel length (*unit* N_B , EA km⁻¹). Finally, we
177 sketched the plan view of the channel to record the relation between geomorphic features and
178 the spatial distribution of LW.

179

180 **3.4. LW sampling and measurement**

181 LW pieces are directly recruited into the channels from hillslopes or channel banks by
182 forest dynamics, hillslope processes and bank erosion, and are then redistributed by fluvial or
183 non-fluvial processes (Nakamura and Swanson, 1994; Seo and Nakamura, 2009). The form
184 of storage of LW pieces recruited into and redistributed within the channel can be classified
185 into two categories: (i) single pieces and (ii) log jams. In this study, a single piece was
186 defined as in-stream wood that is lodged within the bankfull width, and has a minimum

187 diameter of 0.1 m and a minimum length of 1.0 m (Nakamura and Swanson, 1994). We
188 defined a log jam as an in-stream wood accumulation composed of two or more pieces.

189 We first estimated the total volume of LW ($V_{LW\ accum}$, m³) accumulated within the
190 bankfull channel width as either single pieces or log jams. We measured the diameters at both
191 ends for single pieces. The volume of a single-piece ($V_{LW\ piece}$, m³) was calculated as:

$$192 \quad V_{LW\ piece} = \pi \cdot (d1^2 + d2^2) \cdot (l / 8)$$

193 where $d1$ and $d2$ are the diameters at each end and l is the length. The root-wad volume was
194 measured separately. We only measured the visible, aboveground portion of LW pieces
195 buried in either the bank or streambed. To measure log jam volume ($V_{LW\ jam}$, m³), we divided
196 jam piles into multiple hexahedral shapes and then recorded their widths, lengths, and heights.
197 Importantly, we considered void spaces to constitute 30% of the measured volume (Seo and
198 Nakamura, 2009) based on Ohuchi (1987), whose measurements ranged from 20% to 40% of
199 the pile volume. Therefore, $V_{LW\ jam}$ was calculated as:

$$200 \quad V_{LW\ jam} = \sum w \cdot l \cdot h \cdot 0.7$$

201 where w , l , and h are the width, length, and height respectively of a component part
202 (hexahedral shape) of a log jam. The volumes of the components were summed to calculate
203 the entire volume of jam. The total $V_{LW\ accum}$ comprising $V_{LW\ piece}$ and $V_{LW\ jam}$ was
204 transformed to express the $V_{LW\ accum}$ per unit channel length (*unit* $V_{LW\ accum}$, m³ km⁻¹).

205 Second, all single pieces and log jams were classified into four fragmentation and
206 decomposition categories: (i) pieces with entire twigs, branches, stem and root wad; (ii)
207 pieces with twigs, branches and stem or branches, stem and root wad; (iii) pieces with stem
208 and root wad; and (iv) pieces with only stem or root wad. The decomposition classification
209 consisted of: (i) pieces with fresh bark; (ii) pieces with loose bark; (iii) pieces with hard wood

210 trunks; and (iv) pieces with only soft wood.

211

212 **3.5. Estimation of LW residence time**

213 The accumulation form (i.e., single piece or log jam) and condition (i.e.,
214 fragmentation and decomposition) of LW are closely related to residence time (Hyatt and
215 Naiman, 2001; Piégay, 2003), which refers to the length of time that a single piece or log jam
216 remains within a channel network (Swanson and Lienkaemper, 1978; Wohl and Goode,
217 2008). Assuming a steady-state distribution of LW within bankfull channel widths, we used
218 the relationship between $V_{LW\ export}$ ($\text{m}^3 \text{ yr}^{-1}$) and *unit* $V_{LW\ accum}$ ($\text{m}^3 \text{ km}^{-1}$) to estimate the LW
219 residence time per unit channel length (*unit* $T_{LW\ resid}$, yr km^{-1}):

$$220 \quad \textit{unit } T_{LW\ resid} = \textit{unit } V_{LW\ accum} / V_{LW\ export}$$

221 In order to provide context for our precipitation and flow measurements and
222 corresponding interpretations of wood stability, we collected the: (i) annual precipitation
223 records during the study periods, as monitored by the local reservoir management office, as
224 well as (ii) annual precipitation records for the 5 years before and after our study periods, as
225 monitored by the Japan Meteorological Agency closest to each study watershed. We
226 confirmed that mean annual precipitation for all watersheds during the study periods was
227 approximately average with respect to the longer-term records (16–23 years), and there were
228 no exceptional annual precipitation records in all the watersheds, which might cause
229 exceptional runoff events.

230

231 **3.6. Statistical analyses**

232 A generalized linear model (GLM) with a Gaussian error distribution and identity link

233 function was used in three ways in this study. The first objective of GLM was to compare
234 geomorphic conditions and LW accumulations between southern and northern Japan. The
235 response variables were the: (i) ratio of LW piece length to bankfull channel width ($R_{length-}$
236 $width$); (ii) *unit* N_B ; (iii) A_{LFC} ; (iv) A_{GB} ; (v) A_{YFF} ; (vi) A_{MFF} ; and (vii) *unit* $V_{LW\ accum}$ in each
237 watershed group (i.e., small, intermediate or large). The explanatory variables were the: (i)
238 drainage area ($A_{drainage}$); (ii) latitudinal location of watersheds ($LAT_{watershed}$), classified as
239 either southern or northern Japan; and (iii) interaction between $A_{drainage}$ and $LAT_{watershed}$. The
240 second objective was to detect the differences between the *unit* $T_{LW\ resid}$ in each watershed
241 group. The $LAT_{watershed}$ category was selected as the only explanatory variable to explain the
242 *unit* $T_{LW\ resid}$. The third objective was to identify the best predictor(s) for explaining the
243 variation in *unit* $V_{LW\ accum}$ in each watershed, and to assess the relative strength of each
244 predictor in the best-fit model. The explanatory variables chosen were the: (i) $R_{length-width}$; (ii)
245 *unit* N_B ; (iii) A_{LFC} ; (iv) A_{GB} ; (v) A_{YFF} ; and (vi) A_{MFF} .

246 Model selection was performed by the best-subset procedure based on the Akaike
247 Information Criterion (AIC), which is a standard value of the relative quality of a given data
248 set. The regression model(s) with the lowest AIC value was considered the best-fit model for
249 the measured variation in the data, and the regression model(s) with $\Delta AIC < 2$ was considered
250 equally influential as the best-fit model (Burnham and Anderson, 2002). However, in the
251 third GLM analysis, we selected the model with the lowest AIC value, and then examined the
252 relative magnitude of the factors' strengths based on changing ΔAIC by including or
253 excluding each variable from the best-fit model. Here, ΔAIC refers to the difference between
254 AIC values for the best-fit model and each of the other models in the set.

255 Prior to the analyses, the normality of the distributions was tested using the

256 Kolmogorov–Smirnov test. We used $P < 0.05$ to indicate statistical significance for all tests.
257 All statistical analyses were performed using the statistical language R version 2.15.2
258 (<http://www.r-project.org>).

259

260 **4. Results**

261 ***4.1. Differences in LW export patterns between southern and northern Japan***

262 The differences in precipitation pattern and resultant flood events between southern
263 and northern Japan should influence LW export (Seo *et al.*, 2012). We examined the effects
264 of precipitation intensity and water discharge on *unit* $V_{LW\ export}$ (Figure 2). Although *unit* $V_{LW\ export}$
265 increased with $cP_{\geq 60}$ and the associated water discharge (i.e., $cD_{P_{\geq 60}}$), the
266 corresponding slopes of the regression models differed between southern and northern Japan
267 (Figures 2a and 2b). In addition, in the range of comparable precipitation and runoff
268 intensities shaded in Figures 2a and 2b, *unit* $V_{LW\ export}$ was greater in northern than in southern
269 Japan, meaning that more LW pieces can be exported by the same level of precipitation and
270 flood events in northern Japan.

271

272 ***4.2. Longitudinal changes in factors limiting LW transport in southern and northern***

273 ***Japan***

274 $R_{length-width}$ and *unit* N_B are influential parameters that limit LW transport (Table II).
275 To explain $R_{length-width}$, the model consisting of only $A_{drainage}$ was preferentially selected as the
276 best predictor in all watershed groups, although several models that were wholly or partially
277 combined with $A_{drainage}$, $LAT_{watershed}$ and their interaction were equally influential in the
278 intermediate and large watershed groups. Conversely, to explain *unit* N_B , the model

279 consisting of $A_{drainage}$, $LAT_{watershed}$, and their interaction was the best predictor in all
280 watershed groups, although the model of only $A_{drainage}$ was equally influential in the small
281 watershed group ($\Delta AIC=0.75$) (Table II).

282 Scatter diagrams displaying the relationship between $unit N_B$ and $A_{drainage}$ as a
283 function of location ($LAT_{watershed}$, i.e., southern and northern Japan) revealed that $unit N_B$
284 decreased with increasing $A_{drainage}$ in both locations. However, the corresponding slopes of
285 the regression models differed between $LAT_{watershed}$ categories: that is, in upstream channels
286 with smaller $A_{drainage}$, $unit N_B$ was greater in northern than in southern Japan watersheds,
287 while in downstream channels with larger $A_{drainage}$, $unit N_B$ was greater in southern than in
288 northern Japan watersheds.

289

290 ***4.3. Longitudinal changes in factors regulating LW storage in southern and northern*** 291 ***Japan***

292 The channel surface planforms (i.e., A_{LFC} , A_{GB} , A_{YFF} , and A_{MFF}) are dominant
293 parameters that regulate LW storage, and their extents vary with $A_{drainage}$ and $LAT_{watershed}$
294 categories (Table III). In almost all watershed groups, the model consisting of $A_{drainage}$,
295 $LAT_{watershed}$, and their interaction was the best predictor explaining A_{LFC} , A_{GB} , A_{YFF} , and A_{MFF} ,
296 although the model consisting of only $A_{drainage}$ or the model consisting of $A_{drainage}$ and
297 $LAT_{watershed}$ without interaction was an equally influential predictor explaining A_{LFC} in the
298 small watershed group as well as A_{YFF} in all watershed groups. The only exception was A_{LFC}
299 in the large watershed group, for which the model consisting of only $A_{drainage}$ and the model
300 consisting of $A_{drainage}$ and $LAT_{watershed}$ without interaction were selected as the best predictors.

301 Among the channel surface planforms, A_{GB} and A_{MFF} in particular differed

302 significantly by $LAT_{watershed}$ (Figure 3). In all watershed groups, A_{GB} was greater in southern
303 than in northern Japan watersheds, whereas A_{MFF} was greater in northern than in southern
304 Japan watersheds, although both A_{GB} and A_{MFF} increased with $A_{drainage}$.

305

306 **4.4. Differences in LW accumulation between southern and northern Japan**

307 We examined standing stocks of in-stream LW and potential controls between
308 southern and northern Japan. In the small watershed group, the null model, together with
309 all conceivable combinations of $A_{drainage}$ and $LAT_{watershed}$, was selected as the best-fit model
310 explaining $unit V_{LW accum}$ (Table IV), reflecting a lack of influential parameters explaining $unit$
311 $V_{LW accum}$. However, to explain $unit V_{LW accum}$ in all watershed groups, the model consisting of
312 only $LAT_{watershed}$ was commonly selected as the best predictor, particularly in the intermediate
313 and large watershed groups, although several models that were wholly or partially combined
314 with $A_{drainage}$, $LAT_{watershed}$ and their interaction were equally influential. Based on this result, a
315 box-and-whisker plot displaying the difference in $unit V_{LW accum}$ and a related bar percentage
316 chart displaying the log-jam contribution to $unit V_{LW accum}$ in southern and northern Japan
317 revealed that both values were higher in northern than in southern Japan watersheds (Figures
318 4a and 4b). Assuming that the $unit V_{LW accum}$ is under a steady-state condition, in all watershed
319 groups, $unit T_{LW resid}$ was significantly higher in northern compared to southern Japan
320 watersheds (Figure 4c).

321 To confirm the relative magnitude of LW fragmentation and decomposition, we
322 calculated the proportions of $V_{LW accum}$ by fragmentation and decomposition class in each
323 watershed. The proportions of $V_{LW accum}$ classified as the most fragmented, i.e., 3rd and 4th
324 fragmentation classes, to total $V_{LW accum}$ were higher in southern compared to northern Japan

325 watersheds (Figure 5a). By contrast, the proportions of $V_{LW\text{accum}}$ classified as the 3rd and 4th
326 decomposition classes to total $V_{LW\text{accum}}$ were higher in northern compared to southern Japan
327 watersheds (Figure 5b).

328

329 **4.5. Factors controlling LW accumulation in southern and northern Japan**

330 To understand the relative importance of geomorphic factors (i.e., number of boulders,
331 LW length-channel width ratio and areas of channel surface planforms) controlling LW
332 transport and storage processes, models built by various combinations of parameters were
333 compared to explain *unit* $V_{LW\text{accum}}$ in all watersheds (Table V). Combinations of all factors
334 (i.e., $R_{\text{length-width}}$, *unit* N_B , A_{LFC} , A_{GB} , A_{YFF} , and A_{MFF}) were influential in explaining *unit* V_{LW}
335 *accum* in southern Japan watersheds, and combinations of $R_{\text{length-width}}$, A_{LFC} , A_{GB} , A_{YFF} and
336 A_{MFF} were selected in northern Japan watersheds. Thus, the predictors selected in southern
337 and northern Japan were identical, with the exception of *unit* N_B .

338 We found that the AIC was greatly enhanced by excluding N_B or A_{GB} in southern
339 Japan watersheds, whereas in northern Japan watersheds, the AIC was enhanced by excluding
340 A_{MFF} , although its strength in the small and intermediate watershed groups was not
341 remarkable compared to the large watershed group.

342

343 **5. Discussion**

344 Based on the reservoir database, Seo *et al.* (2012) hypothesized that LW export is
345 supply-limited in southern Japan and transport-limited in northern Japan. The LW distribution
346 and export volumes examined in the present study at the contrasting districts (Shikoku vs.
347 Hokkaido islands) support this hypothesis. The streams in southern Japan were characterized

348 by a lower standing stock of LW pieces with a short residence time due to frequent removal
349 by repeated floods (supply-limited). By contrast, streams in northern Japan featured a greater
350 stock of LW pieces on the wide valley floors with forested floodplains, and a longer residence
351 time because of infrequent, low-magnitude floods (transport-limited).

352

353 *5.1. Differences in channel physical characteristics in relation to different precipitation*
354 *patterns*

355 Numerous studies worldwide have documented that LW dynamics are regulated by
356 channel hydrogeomorphic characteristics, such as water discharge, LW piece length relative
357 to channel width, and LW buoyant depth relative to channel depth. All of these factors are
358 strongly influenced by relative channel size and position within channel networks (Seo *et al.*,
359 2010). In small channels, the distribution of LW pieces is spatially and temporally regulated
360 by local channel hydrogeomorphic conditions (i.e., narrow channel width and shallow flow
361 depth), as well as by the physical characteristics of the wood itself (i.e., size and specific
362 gravity) (Braudrick and Grant, 2000; Faustini and Jones, 2003; Seo and Nakamura, 2009).
363 Consequently, in the absence of major floods and related disturbances, many LW pieces are
364 retained in channels and on valley floors for years or decades (Nakamura and Swanson, 1993;
365 Seo and Nakamura, 2009). Episodic debris flows can transport LW pieces to larger channels
366 with lower bed gradients (Benda and Cundy, 1990; Nakamura *et al.*, 2000); debris flows are
367 common in small steep channels in Japan such as our study watersheds. In larger channels,
368 which are characterized by a wider valley floor and deeper flow depth, LW pieces introduced
369 by debris flows are easily transported downstream by fluvial processes, and are stored at
370 various depositional sites (e.g., bars or floodplains), particularly where geomorphic or

371 hydraulic complexity is high. Overarching control on LW transport and storage by channel
372 size is supported by our results, since all factors regulating LW transport and storage
373 processes (i.e., $R_{length-width}$, $unit N_B$, A_{LFC} , A_{GB} , A_{YFF} , and A_{MFF}) were controlled by $A_{drainage}$
374 (Tables II and III).

375 Longitudinal trends of these factors are likely to vary with runoff processes, however,
376 particularly the type, intensity, and frequency of precipitation. Wohl *et al.* (2012)
377 demonstrated that, because tropical streams with relatively more intense and frequent rainfall
378 have higher channel transport capacity than temperate streams, the amount of LW
379 accumulated in tropical streams is lower than in temperate streams. The results in this study
380 demonstrated that most of the influential factors, particularly $unit N_B$, A_{GB} , A_{YFF} , and A_{MFF} ,
381 were controlled by the interaction between $LAT_{watershed}$ and $A_{drainage}$. Large boulders delivered
382 from hillslopes by mass movements such as landslides and debris flows (Anderson and Burt,
383 1990; Grant and Swanson, 1995) may be immovable due to the limited stream power,
384 resulting in channel storage for long periods of time at locations where they were initially
385 introduced, thereby affecting channel morphology over long time scales. However, in
386 channels where debris flows occur relatively frequently, the delivered boulders together with
387 LW pieces can be further transported downstream by subsequent debris flows and stored
388 at/around lower-gradient channels (Grant *et al.*, 1990; Lancaster *et al.*, 2003; Rigon *et al.*,
389 2008). We therefore interpret the greater number of large boulders in downstream relative to
390 upstream locations in southern Japan as evidence of a greater frequency of rainfall-driven
391 debris flows. In contrast, northern Japan watersheds tend to have boulders concentrated in
392 smaller watersheds (i.e., no transport) (Figure 3). High-magnitude floods also frequently
393 disturb geomorphic surfaces (Swanson *et al.*, 1998; Montgomery *et al.*, 2003), resulting in

394 widely developed gravel bars and a limited extent of forested floodplains in southern Japan
395 (Figure 3). Conversely, the extent of forested floodplains in northern Japan is greater than
396 that of gravel bars, most likely because heavy rainfalls and floods are limited and the
397 residence time of sediment in northern Japan is longer than that in southern Japan (Figure 4c).

398

399 ***5.2. Differences in LW distribution and relevant export as a function of channel physical***
400 ***characteristics in southern and northern Japan***

401 The present study demonstrated that *unit* $V_{LW\ accum}$ was commonly influenced by
402 $LAT_{watershed}$ in all watershed groups (Table IV): that is, *unit* $V_{LW\ accum}$ was substantially higher
403 in northern Japan than in southern Japan, although there were no significant differences
404 between the two watersheds in the small watershed group (Figure 4a). This difference is most
405 likely due to different combinations of factors influencing *unit* $V_{LW\ accum}$ in each study
406 watershed. The results of this study indicate that *unit* N_B and A_{GB} are the most influential
407 factors regulating *unit* $V_{LW\ accum}$ in southern Japan (Table V). Braudrick *et al.* (1997)
408 suggested that large boulders scattered within active channels in headwater streams could trap
409 LW pieces as flow obstructions by reducing the channel width available for the LW pieces to
410 pass through. In addition, Faustini and Jones (2003) addressed the relationship between LW
411 inventory and channel morphology in boulder-rich mountain streams, and observed that large
412 boulders provide more potentially stable depositional sites for LW pieces in transport; thus, a
413 positive interaction exists between boulders and LW transport. In southern Japan, large
414 boulders delivered by upstream debris flows act as roughness elements that trap LW pieces.
415 With increasing downstream distance, these LW pieces should be stored on fluvial
416 depositional sites in downstream channels, particularly gravel bars, which were more

417 prevalent in southern Japan (Figure 3). These low elevation sites are particularly vulnerable
418 to attack and inundation by rising water levels during subsequent flood events, and LW is
419 easily refloated from these locations, resulting in relatively less LW accumulation on the
420 valley floor (Figure 4a). During transport, LW pieces are broken into smaller pieces due to
421 impact with the channel bed and banks, resulting in higher fragmentation rates and shorter
422 residence times of LW in southern Japan (Figures 4c and 5a). As a consequence, in southern
423 Japan watersheds, the fluvial export of LW is expected to be supply-limited, explaining why
424 $unit V_{LW\ export}$ was lower in this area than in northern Japan for the same range of $cP_{\geq 60}$ and
425 $cD_{P_{\geq 60}}$ intensities (Figure 2).

426 In contrast to southern Japan, forested floodplains (particularly A_{MFF}) broadly cover
427 the valley floors in northern Japan (Figure 3). Those geomorphic surfaces provide storage
428 sites and thereby increase $unit V_{LW\ accum}$; these higher elevation and vegetated sites are less
429 subject to attack and inundation by the less frequent high-magnitude flood events (Table V).
430 LW depositional sites with high geomorphic complexity (e.g., lateral eddies, concave banks,
431 and woodlands and associated sheltered areas parallel to channel margins) are common in
432 these lower-gradient channels (Hickin, 1984; Abbe and Montgomery, 1996; Piégay and
433 Marston, 1998; Piégay, 2003; Latterell and Naiman, 2007). Because of the greater
434 opportunity for LW lodging in these complex environments, many LW pieces form debris
435 jams (Piégay *et al.*, 1999; Gurnell *et al.*, 2002). In their review of the spatial and temporal
436 variability of LW dynamics worldwide, Seo *et al.* (2010) indicated that while LW pieces
437 stored as debris jams can be refloated and transported by large-magnitude floods, those pieces
438 are often retrapped by larger log jams and/or standing trees on mature stands in floodplains,
439 resulting in long-term storage, and decomposition rather than fragmentation. Although we

440 could not evaluate contributions of air temperature, humidity, and tree species to
441 decomposition processes, which might differently influence decomposition of LW pieces
442 between southern and northern Japan, the decomposition rate and the relevant residence time
443 of LW pieces in the study watersheds were higher and longer in northern Japan than in
444 southern Japan (Figures 4c and 5b). Consequently, in northern Japan watersheds, the fluvial
445 export of LW pieces is expected to be transport-limited, and those pieces might be easily
446 transported if infrequent floods occur. We believe that this transport-limited situation
447 explains why $unit V_{LW\ export}$ was greater in this area than in southern Japan for the same range
448 of the $cP_{\geq 60}$ and $cD_{P_{\geq 60}}$ intensities (Figure 2).

449

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459

460 **Nomenclature**

461

$V_{LW\ export}$	–	annual volume of LW exported from the upstream watershed, $m^3\ yr^{-1}$
$unit\ V_{LW\ export}$	–	$V_{LW\ export}$ per unit channel length, $m^3\ km^{-1}\ yr^{-1}$
$cP_{\geq 60}$	–	cumulative daily precipitation greater than or equal to 60 mm, mm
$cD_{P_{\geq 60}}$	–	cumulative water discharge per unit drainage area caused by daily precipitation greater than or equal to 60 mm, $m^3\ sec^{-1}$
A_{LFC}	–	area of low-flow channel within channel segment, ha
A_{GB}	–	area of gravel bar within channel segment, ha
A_{YFF}	–	area of young-forested floodplain within channel segment, ha
A_{MFF}	–	area of mature-forested floodplain within channel segment, ha
N_B	–	number of boulder within channel segment, EA
$unit\ N_B$	–	N_B per unit channel length, $EA\ km^{-1}$
$V_{LW\ accum}$	–	volume of LW accumulated within channel segment, m^3
$V_{LW\ piece}$	–	volume of LW comprised of only single-piece, m^3
$V_{LW\ jam}$	–	volume of LW comprised of only log-jam, m^3
$unit\ V_{LW\ accum}$	–	$V_{LW\ accum}$ per unit channel length, $m^3\ km^{-1}$
$unit\ T_{LW\ resid}$	–	LW residence time per unit channel length, $yr\ km^{-1}$
$R_{length-width}$	–	ratio of LW piece length to bankfull channel width
$A_{drainage}$	–	drainage area, km^2
$LAT_{watershed}$	–	latitudinal category of watersheds

462

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598 wood dynamics in headwater neotropical rivers. *Journal of Hydrology* **462–463**: 67–
599 76. DOI: 10.1016/j.jhydrol.2011.01.061.

600 Table I. General characteristics of the six study watersheds in southern and northern Japan^{a,b,c,d}

Watershed name	Latitude (° ' ")	Drainage area (km ²)	Total channel length (km)	Elevation range (m)	Ratio of forest area to total riparian area (%)	LW annual export volume (m ³ yr ⁻¹)	Study period (yr)	Annual precipitation for study period (mm yr ⁻¹)	Annual precipitation for long-term period (mm yr ⁻¹)	Water discharge for study period (m ³ sec ⁻¹)
<i>[Southern Japan]</i>										
Yanase	33° 35' 34"	101.7	97.9	436–1423	91.7	394.1 ± 81.5	13	3,462.1 ± 284.7	3,489.6 ± 182.6	12.2 ± 0.4
Hatsuse	33° 20' 59"	172.0	184.4	313–1456	87.9	66.8 ± 11.0	9	2,773.0 ± 235.4	2,709.0 ± 161.7	10.5 ± 0.4
Nagase	33° 42' 21"	298.8	283.4	191–1893	87.9	446.1 ± 145.4	9	2,640.6 ± 234.4	2,735.0 ± 154.2	21.9 ± 0.7
<i>[Northern Japan]</i>										
Jozankei	42° 58' 57"	103.3	101.9	383–1302	94.4	196.8 ± 13.2	9	1,390.4 ± 38.5	1,340.2 ± 25.9	5.1 ± 0.1
Katsurazawa	43° 14' 14"	150.6	144.5	185–1068	92.1	104.2 ± 21.2	6	1,451.5 ± 64.0	1,417.6 ± 39.9	10.8 ± 0.3
Taisetsu	43° 40' 25"	288.0	283.8	805–2230	86.7	184.2 ± 31.5	9	720.8 ± 49.2	716.1 ± 29.7	14.0 ± 0.2

601 ^a Annual precipitation, water discharge, and LW annual export volume were expressed as the mean ± standard error.

602 ^b Total channel length was estimated using channel network data (1:25000) derived from a digital elevation model (50 × 50 m resolution). In
603 calculation of ratio of forest area to total riparian area, the riparian zone was treated as polygons with a 200 m radius from channel network
604 data (1:25000) derived from a digital elevation model (50 × 50 m resolution).

605 ^c All numerical values, except for those in the latitude, elevation range and study period columns, were rounded to the nearest 10th.

606 ^d Annual precipitation for long-term period includes records for the study periods and 5 years record before and after the study periods.

607 Table II. Changes in factors limiting LW transport along the drainage area and latitudinal
 608 gradients in the three watershed groups^{a,b}

Construction of parameters in the model	AIC	ΔAIC
<i>[Ratio of LW piece length to bankfull channel width]</i>		
Small watersheds		
$R_{length-width} \sim A_{drainage}$	-26.392	-
Intermediate watersheds		
$R_{length-width} \sim A_{drainage}$	-32.055	-
$R_{length-width} \sim A_{drainage} + LAT_{watershed}$	-30.279	1.776
Large watersheds		
$R_{length-width} \sim A_{drainage}$	-18.448	-
$R_{length-width} \sim A_{drainage} + LAT_{watershed}$	-17.929	0.519
$R_{length-width} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-17.284	1.164
<i>[Boulder number per unit channel length]</i>		
Small watersheds		
$unit N_B \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	154.77	-
$unit N_B \sim A_{drainage}$	155.52	0.75
Intermediate watersheds		
$unit N_B \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	258.42	-
Large watersheds		
$unit N_B \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	421.61	-

609 ^a GLM, generalized linear model; AIC, Akaike Information Criterion; $A_{drainage}:LAT_{watershed}$,
 610 interaction between $A_{drainage}$ and $LAT_{watershed}$.

611 ^b ΔAIC refers to the difference between the AIC values for the best-fit model and each of the
 612 other models in the set. The regression model(s) with ΔAIC<2 was considered equally
 613 influential as the best-fit model.

614

615 Table III. Changes in factors regulating LW storage along the drainage area and latitudinal
 616 gradients in the three watershed groups^{a,b}

Construction of parameters in the model	AIC	ΔAIC
<i>[Area of low-flow channels]</i>		
Small watersheds		
$A_{LFC} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-54.792	-
$A_{LFC} \sim A_{drainage}$	-52.856	1.936
Intermediate watersheds		
$A_{LFC} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-61.357	-
Large watersheds		
$A_{LFC} \sim A_{drainage}$	-87.702	-
$A_{LFC} \sim A_{drainage} + LAT_{watershed}$	-87.581	0.121
<i>[Area of gravel bars]</i>		
Small watersheds		
$A_{GB} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-27.930	-
Intermediate watersheds		
$A_{GB} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-50.422	-
Large watersheds		
$A_{GB} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-63.117	-
<i>[Area of young-forested floodplains]</i>		
Small watersheds		
$A_{YFF} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-32.926	-
$A_{YFF} \sim A_{drainage}$	-31.469	1.457
Intermediate watersheds		
$A_{YFF} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-52.192	-
$A_{YFF} \sim A_{drainage} + LAT_{watershed}$	-51.829	0.363
Large watersheds		
$A_{YFF} \sim A_{drainage}$	-82.162	-
$A_{YFF} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-80.253	1.909
<i>[Area of mature-forested floodplains]</i>		
Small watersheds		
$A_{MFF} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-17.870	-
Intermediate watersheds		
$A_{MFF} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-30.617	-
Large watersheds		
$A_{MFF} \sim A_{drainage} + LAT_{watershed} + A_{drainage}:LAT_{watershed}$	-31.315	-

617 ^a GLM, generalized linear model; AIC, Akaike Information Criterion; $A_{drainage}:LAT_{watershed}$,
 618 interaction between $A_{drainage}$ and $LAT_{watershed}$.

619 ^b ΔAIC refers to the difference between the AIC values for the best-fit model and each of the
 620 other models in the set. The regression model(s) with ΔAIC<2 was considered equally
 621 influential as the best-fit model.

622

623 Table IV. Changes in *unit V_{LW accum}* along the drainage area and latitudinal gradients in the
 624 three watershed groups^{a,b}

Construction of parameters in the model	AIC	ΔAIC
Small watersheds		
<i>unit V_{LW accum}</i> ~ Null	124.88	–
<i>unit V_{LW accum}</i> ~ <i>A_{drainage}</i>	125.07	0.19
<i>unit V_{LW accum}</i> ~ <i>LAT_{watershed}</i>	126.27	1.39
<i>unit V_{LW accum}</i> ~ <i>A_{drainage}</i> + <i>LAT_{watershed}</i>	126.46	1.58
Intermediate watersheds		
<i>unit V_{LW accum}</i> ~ <i>LAT_{watershed}</i>	217.45	–
<i>unit V_{LW accum}</i> ~ <i>A_{drainage}</i> + <i>LAT_{watershed}</i>	217.99	0.54
<i>unit V_{LW accum}</i> ~ <i>A_{drainage}</i> + <i>LAT_{watershed}</i> + <i>A_{drainage}:LAT_{watershed}</i>	218.04	0.59
Large watersheds		
<i>unit V_{LW accum}</i> ~ <i>LAT_{watershed}</i>	396.80	–
<i>unit V_{LW accum}</i> ~ <i>A_{drainage}</i> + <i>LAT_{watershed}</i>	398.78	1.98

625 ^a GLM, generalized linear model; AIC, Akaike Information Criterion; *A_{drainage}:LAT_{watershed}*,
 626 interaction between *A_{drainage}* and *LAT_{watershed}*.

627 ^b ΔAIC refers to the difference between the AIC values for the best-fit model and each of the
 628 other models in the set. The regression model(s) with ΔAIC<2 was considered equally
 629 influential as the best-fit model.

630

631 Table V. The influential factors in the models selected to explain *unit V_{LW accum}* and their
 632 strengths in each study watershed^{a,b}

Construction of parameters in the model	AIC	ΔAIC
[Small watersheds]		
<i>Southern Japan – Yanase</i>		
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{LFC}</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	58.694	–
<i>unit V_{LW accum}</i> ~ <i>A_{LFC}</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	67.530	8.836
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	61.231	2.537
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{LFC}</i> + <i>A_{MFF}</i>	65.341	6.647
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{LFC}</i> + <i>A_{GB}</i>	64.000	5.306
<i>Northern Japan – Jouzankei</i>		
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	63.105	–
<i>unit V_{LW accum}</i> ~ <i>A_{GB}</i> + <i>A_{MFF}</i>	65.226	2.121
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{MFF}</i>	66.331	3.226
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{GB}</i>	66.390	3.285
[Intermediate watersheds]		
<i>Southern Japan – Hatsuse</i>		
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{GB}</i> + <i>A_{YFF}</i>	79.668	–
<i>unit V_{LW accum}</i> ~ <i>A_{GB}</i> + <i>A_{YFF}</i>	83.482	3.814
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{YFF}</i>	80.988	1.320
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{GB}</i>	80.579	0.911
<i>Northern Japan – Katsurazawa</i>		
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{LFC}</i> + <i>A_{YFF}</i> + <i>A_{MFF}</i>	117.25	–
<i>unit V_{LW accum}</i> ~ <i>A_{LFC}</i> + <i>A_{YFF}</i> + <i>A_{MFF}</i>	118.24	0.99
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{YFF}</i> + <i>A_{MFF}</i>	117.46	0.21
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{LFC}</i> + <i>A_{MFF}</i>	118.70	1.45
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{LFC}</i> + <i>A_{YFF}</i>	119.07	1.82
[Large watersheds]		
<i>Southern Japan – Nagase</i>		
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>unit N_B</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	148.23	–
<i>unit V_{LW accum}</i> ~ <i>unit N_B</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	149.32	1.09
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>A_{GB}</i> + <i>A_{MFF}</i>	150.53	2.30
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>unit N_B</i> + <i>A_{MFF}</i>	164.32	16.09
<i>unit V_{LW accum}</i> ~ <i>R_{length-width}</i> + <i>unit N_B</i> + <i>A_{GB}</i>	151.96	3.73
<i>Northern Japan – Taisetsu</i>		
<i>unit V_{LW accum}</i> ~ <i>A_{GB}</i> + <i>A_{YFF}</i> + <i>A_{MFF}</i>	208.08	–
<i>unit V_{LW accum}</i> ~ <i>A_{YFF}</i> + <i>A_{MFF}</i>	210.71	2.63
<i>unit V_{LW accum}</i> ~ <i>A_{GB}</i> + <i>A_{MFF}</i>	210.91	2.83
<i>unit V_{LW accum}</i> ~ <i>A_{GB}</i> + <i>A_{YFF}</i>	217.77	9.69

633 ^a GLM, generalized linear model; AIC, Akaike Information Criterion.

634 ^b ΔAIC refers to the difference between the AIC values for the best-fit model and each of the
 635 other models in the set. We examined the relative magnitudes of the factors' strengths based
 636 on changes in ΔAIC by including or excluding each variable in the best-fit model.

637

638 **Figure captions**

639

640 Figure 1. Location of the six study watersheds in southern and northern Japan. Dotted and
641 solid lines denote watershed boundaries and channel networks within the
642 boundaries, respectively. Open and closed circles represent dam locations and
643 channel segments surveyed for fieldwork, respectively.

644

645 Figure 2. Relationship between $unit V_{LW\ export}$ and precipitation or runoff parameters in the six
646 study watersheds located in southern and northern Japan, modified from the result
647 of Seo *et al.* (2012). (a) $unit V_{LW\ export} - cP_{\geq 60}$ relationship. (b) $unit V_{LW\ export} -$
648 $cD_{P_{\geq 60}}$ relationship. The ranges of comparable precipitation and water discharge
649 intensities are shaded.

650

651 Figure 3. Relationship between LW transport and storage factors and $A_{drainage}$ in the six study
652 watersheds located in southern and northern Japan. (a) $unit N_B - A_{drainage}$
653 relationship. (b) $A_{GB} - A_{drainage}$ relationship. (c) $A_{MFF} - A_{drainage}$ relationship. Closed
654 dots and solid lines belong to southern Japan, and open dots and dotted lines belong
655 to northern Japan.

656

657 Figure 4. Differences in LW accumulation features among the six study watersheds located in
658 southern and northern Japan. (a) $unit V_{LW\ accum}$. (b) Proportion of $V_{LW\ jam}$ to total
659 $V_{LW\ accum}$. (c) $unit T_{LW\ resid}$. In (a) and (c), the line within each box indicates the
660 mean value, the box ends are the means \pm standard errors, and the dots connected

661 with whiskers are the minimum and maximum values. Different letters above the
662 bars indicate significant differences based on AIC values in the GLM.

663

664 Figure 5. Differences in LW fragmentation and decomposition among the six study
665 watersheds located in southern and northern Japan. (a) Proportion of $V_{LW\ accum}$
666 affiliated with each fragmentation class to total $V_{LW\ accum}$. (b) Proportion of $V_{LW\ accum}$
667 affiliated with each decomposition class to total $V_{LW\ accum}$.

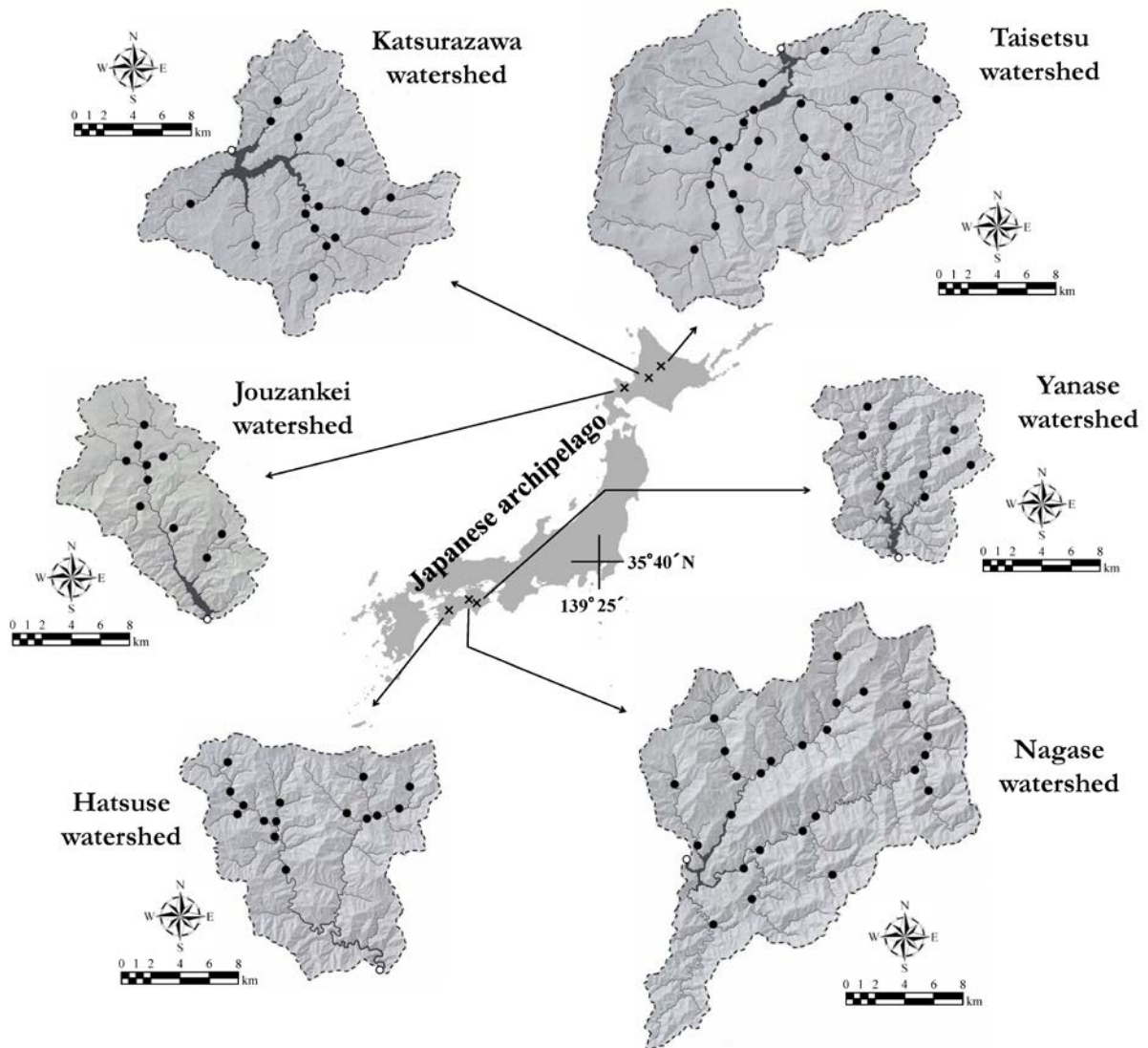
668

669 **Figures**

670

671 Figure 1.

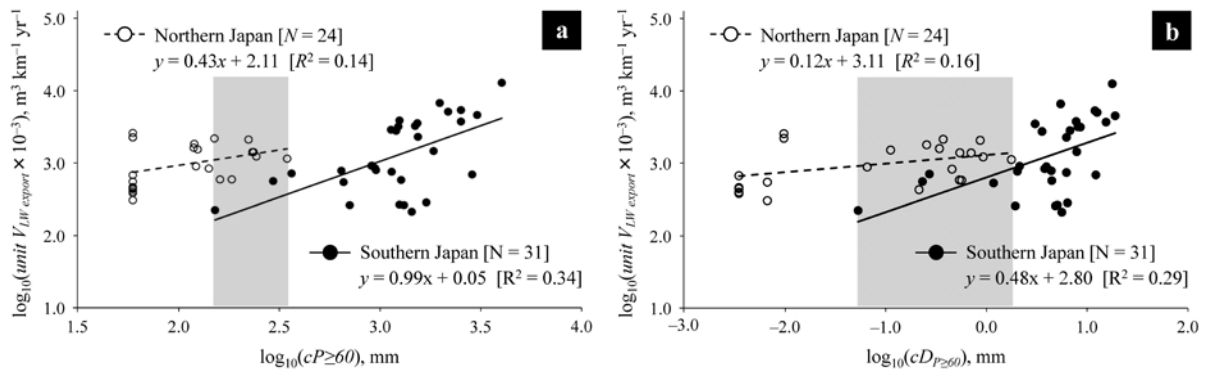
672



673

674 Figure 2.

675

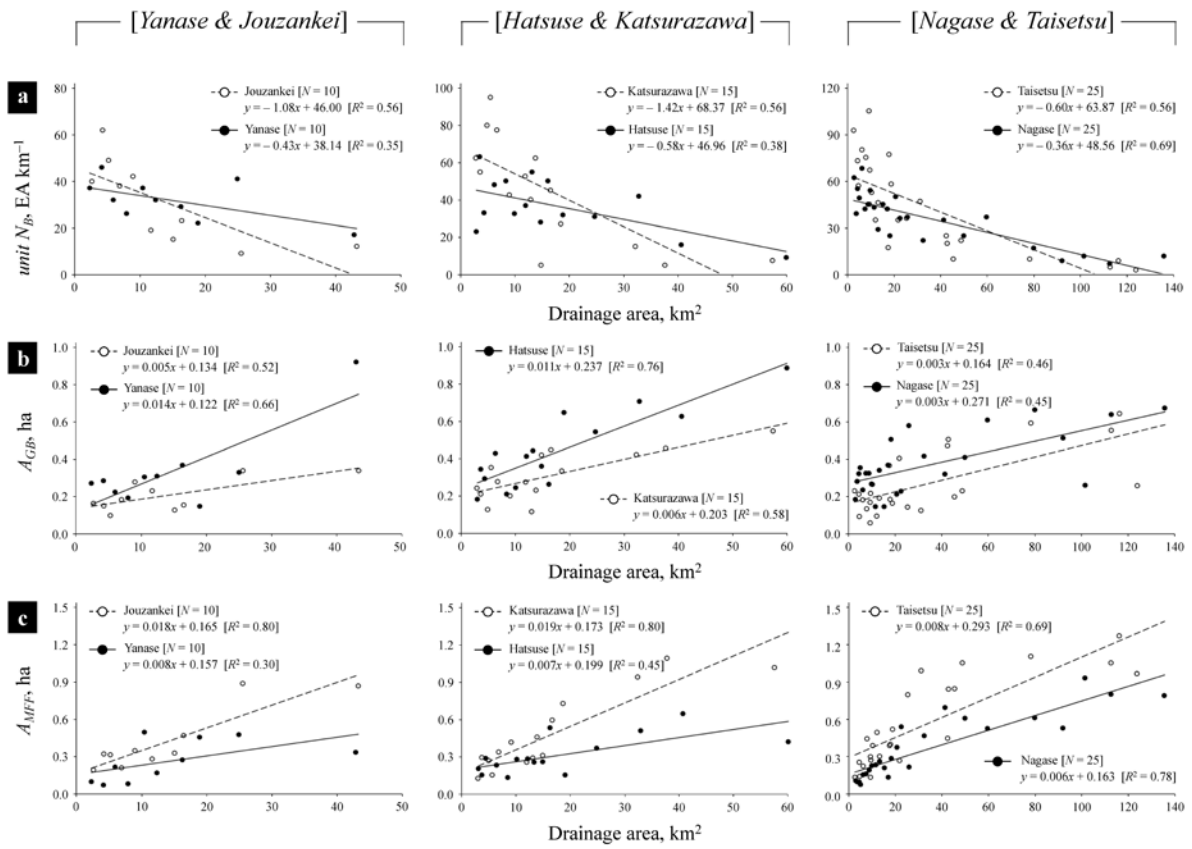


676

677

678 Figure 3.

679

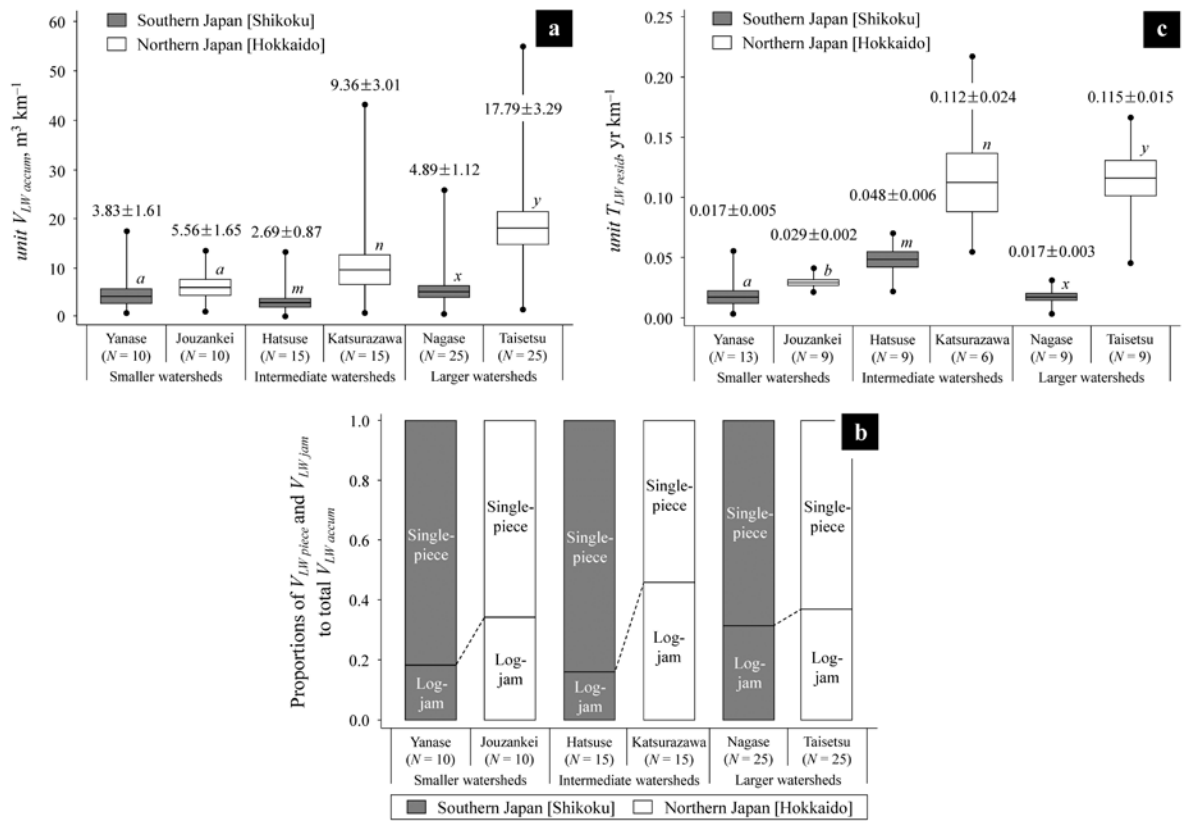


680

681

682 Figure 4.

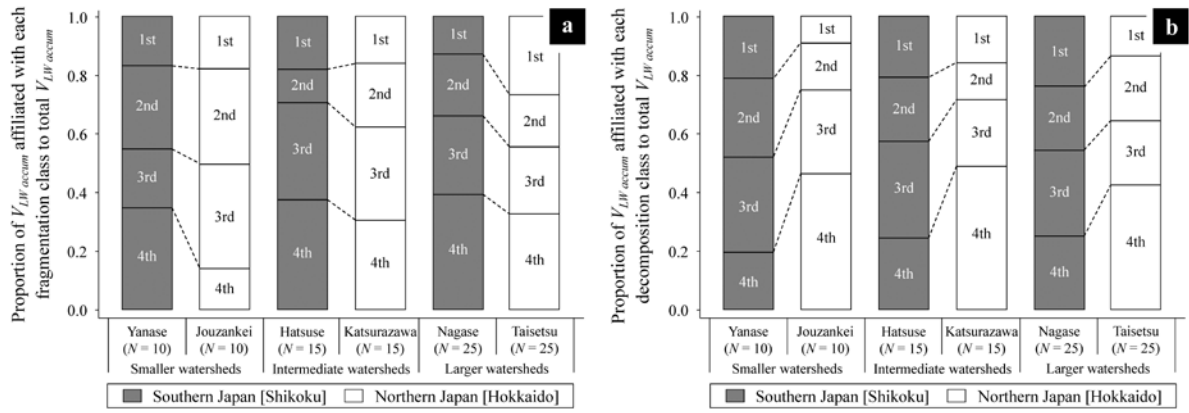
683



684

685 Figure 5.

686



687

688

689 Supplementary Material: Physical characteristics of the study segments in the six study

690 watersheds in southern and northern Japan

Watershed name	Segment No.	Drainage area (km ²)	Channel-bed gradient (%)	Mean bank-full channel width (m)	Watershed name	Segment No.	Drainage area (km ²)	Channel-bed gradient (%)	Mean bank-full channel width (m)
<i>Southern Japan</i>					<i>Northern Japan</i>				
Yanase	1	2.3	13.0	15.7	Jozankei	1	2.7	12.8	14.5
	2	4.1	11.2	17.3		2	4.2	11.3	19.6
	3	5.9	10.6	18.4		3	5.2	10.4	20.5
	4	8.0	8.5	15.2		4	6.9	9.0	19.2
	5	10.4	7.6	30.0		5	9.0	7.5	21.5
	6	12.4	7.9	27.5		6	11.7	8.9	23.1
	7	16.3	7.1	25.1		7	15.1	7.4	28.6
	8	18.9	5.9	28.5		8	16.5	6.5	24.8
	9	25.0	5.0	35.5		9	25.6	7.0	41.1
	10	42.9	4.7	45.7		10	43.3	5.9	49.4
Hatsuse	1	3.0	12.2	16.7	Katsurazawa	1	2.9	12.6	17.2
	2	3.6	10.6	17.8		2	3.6	10.5	22.1
	3	4.4	8.3	19.7		3	4.9	8.9	19.4
	4	6.3	9.0	22.9		4	5.6	7.7	23.7
	5	8.4	8.6	20.0		5	6.7	8.8	24.3
	6	10.0	7.9	24.8		6	9.1	7.5	28.8
	7	12.0	7.6	21.3		7	11.9	7.2	24.0
	8	13.2	6.9	24.4		8	13.0	7.4	27.2
	9	14.8	7.4	27.3		9	13.8	7.2	25.4
	10	16.2	6.0	30.1		10	14.8	6.7	33.6
	11	18.9	6.5	28.5		11	16.6	6.0	37.2
	12	24.7	6.1	34.0		12	18.5	6.5	41.8
	13	32.8	5.2	34.7		13	32.2	5.4	47.9
	14	40.6	4.8	47.0		14	37.6	5.0	53.2
	15	60.0	4.3	52.2		15	57.4	4.8	57.8
Nagase	1	2.7	12.5	14.7	Taisetsu	1	2.4	12.8	12.9
	2	3.6	11.3	16.4		2	4.2	12.4	16.0
	3	4.2	10.1	14.5		3	4.5	10.2	14.8
	4	4.8	10.8	17.4		4	5.9	9.0	17.4
	5	5.9	9.8	16.3		5	7.7	8.3	19.1
	6	7.3	8.4	19.6		6	9.0	7.6	20.2
	7	8.6	8.8	19.9		7	9.2	8.1	18.4
	8	9.6	7.7	21.3		8	9.4	8.4	25.3
	9	11.3	8.0	18.0		9	10.1	7.5	27.1
	10	12.9	7.3	23.3		10	11.9	6.6	26.9
	11	15.1	6.5	19.3		11	13.0	6.9	23.1
	12	16.8	7.7	24.1		12	17.4	7.4	24.5
	13	18.1	6.7	26.6		13	17.6	6.9	28.6
	14	20.5	6.2	20.9		14	18.6	6.2	29.6
	15	22.3	7.3	29.4		15	21.6	6.4	24.9
	16	25.6	6.3	36.7		16	25.2	6.7	34.3
	17	32.2	6.1	33.5		17	30.9	6.0	35.9
	18	41.1	4.8	34.6		18	42.2	6.4	39.4
	19	49.6	5.8	41.1		19	42.6	6.1	40.0
	20	59.4	4.5	44.9		20	45.2	6.5	43.2
	21	79.6	5.6	43.8		21	48.6	5.8	40.9
	22	91.8	5.1	48.6		22	78.0	5.3	51.8
	23	101.3	4.4	50.9		23	112.4	4.3	62.7
	24	112.4	3.4	47.4		24	116.1	3.8	64.6
	25	135.5	2.8	55.5		25	123.6	3.1	58.8

