HYDROLOGICAL PROCESSES
Hydrol. Process. (2015)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10473

Precipitation patterns control the distribution and export of large wood at the catchment scale

Jung Il Seo,[1] Futoshi Nakamura,[2*] Kun Woo Chun,[3] Suk Woo Kim[3] and Gordon E. Grant[4]

[1] *Department of Forest Resources, College of Industrial Sciences, Kongju National University, 54 Daehakro, Yesan, Chungcheongnamdo, 340-702, Republic of Korea*
[2] *Department of Forest Science, Graduate School of Agriculture, Hokkaido University, Kita 9 Nishi 9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan*
[3] *Department of Forest Resources, College of Forest and Environmental Sciences, Kangwon National University, 1 Kangwondaehakgil, Chuncheon, Gangwondo, 200-701, Republic of Korea*
[4] *USDA Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR, 97331, USA*

Abstract:

Large wood (LW) plays an important role in river ecosystems, but LW-laden floods may cause serious damage to human lives and property. The relationship between precipitation patterns and variations in LW distribution and export at the watershed scale is poorly understood. To explore these linkages, we examined differences in LW distribution as a function of channel morphologies in six watersheds located in southern and northern Japan and analysed the impacts of different precipitation patterns on the fluvial export of LW from river catchments. In southern Japan, intense rainfalls caused by typhoons or localized torrential downpours initiate landslides and debris flows that introduce massive amounts of LW into channels. Gravel bars formed by frequent flood events are widely prevalent, and the LW temporarily stored on these bars is frequently moved and/or broken into smaller pieces by floods. In these systems fluvial export of LW is supply-limited, with smaller accumulations and shorter residence times than in northern Japan. Conversely, in northern Japan, where typhoons and torrential downpours rarely occur, LW is mostly recruited by bank erosion, tree mortality and windthrow into channels, rather than by landslides and debris flows. Recruited pieces accumulate in log jams on valley floors, particularly on floodplains supporting mature forests, resulting in larger accumulations and longer residence times. In these watersheds fluvial export of LW is transport-limited, and the pieces gradually decompose during long-term storage as log jams. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS large wood distribution; disturbance regime; channel morphology; supply-limited; transport-limited; Japanese archipelago

Received 14 June 2014; Accepted 13 February 2015

INTRODUCTION

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

Many studies have documented the dynamics of in-stream LW in response to major runoff events caused by certain precipitation patterns (i.e. rainfall and/or snowmelt) in temperate zones. Nakamura and Swanson (1993) and Seo and Nakamura (2009) investigated the size, distribution and breakage/decay status of LW pieces introduced by landslides and/or debris flows during intense rainfall in mountain catchments, and LW dynamics in relation to geomorphic and hydrologic

*Correspondence to: Futoshi Nakamura, Department of Forest Science, Graduate School of Agriculture, Hokkaido University, Kita 9 Nishi 9, Kita-ku, Sapporo, Hokkaido 060-8589, Japan.
E-mail: nakaf@for.agr.hokudai.ac.jp

parameters. Marcus *et al*. (2002) and Moulin and Piégay (2004) quantified spatial and temporal variations in LW export associated with flood events generated by heavy rainfall and snowmelt, and discussed LW dynamics controlling fluvial export at the watershed scale. By contrast, Cadol and Wohl (2010) and Wohl *et al*. (2012) documented LW distributions in tropical streams and observed a higher transport capacity and decay rate of LW pieces in comparison with temperate streams. However, no study has specifically documented how varying precipitation regimes control the distribution and export pattern of LW in temperate zones.

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

In Japan, agencies responsible for local reservoir management remove LW pieces trapped by reservoirs, and typically estimate total annual volumes delivered to the reservoirs (see Seo *et al*., 2008, 2012; Fremier *et al*., 2010). From these databases, Seo *et al*. (2012) examined variations in LW export as a function of precipitation pattern in watersheds >20 km^2 (see Figures 3c and 3d in Seo *et al*. (2012)). They argued that LW pieces in southern and central Japan are constantly removed from channels because of repeated typhoons and heavy rainfall, resulting in supply-limited LW export. Conversely, in northern Japan, LW pieces accumulate on valley floors because opportunities to remove LW from the main channel are limited by less rainfall and corresponding floods; thus LW export is transport limited. These findings were derived from statistical models using a large database of LW export from across the Japanese archipelago, and further examination through field surveys is required to test this hypothesis. The specific objectives of this paper are to: (i) investigate differences in the physical characteristics of stream and river channels as a function of precipitation pattern in watersheds located in southern and northern Japan; and (ii) examine differences in LW distribution and relevant export as a function of precipitation pattern and channel characteristics.

STUDY SITE DESCRIPTION

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

Channel morphology in the headwaters of the six watersheds is dominated by step-pool sequences constrained by boulders, bedrock outcrops and valley walls, while braided patterns with pool-riffle sequences occur further downstream. Most of these catchments are covered by forest (91–97%) composed of mixed stands of deciduous broad-leaved trees and evergreen conifers, with partial coverage by plantation stands. The riparian zones in all watersheds are dominated by *Salix* spp., *Betula* spp., *Fraxinus mandshurica* var. *japonica* and *Alnus hirsuta*, and the maximum height and diameter at breast height of these tree species are approximately 30 m and 50 cm, respectively.

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

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

METHODS

Estimation of LW export from study watersheds

We used the annual volume of LW pieces exported from the study watershed ($V_{LW\ export}$, m^3 yr^{-1}), which was

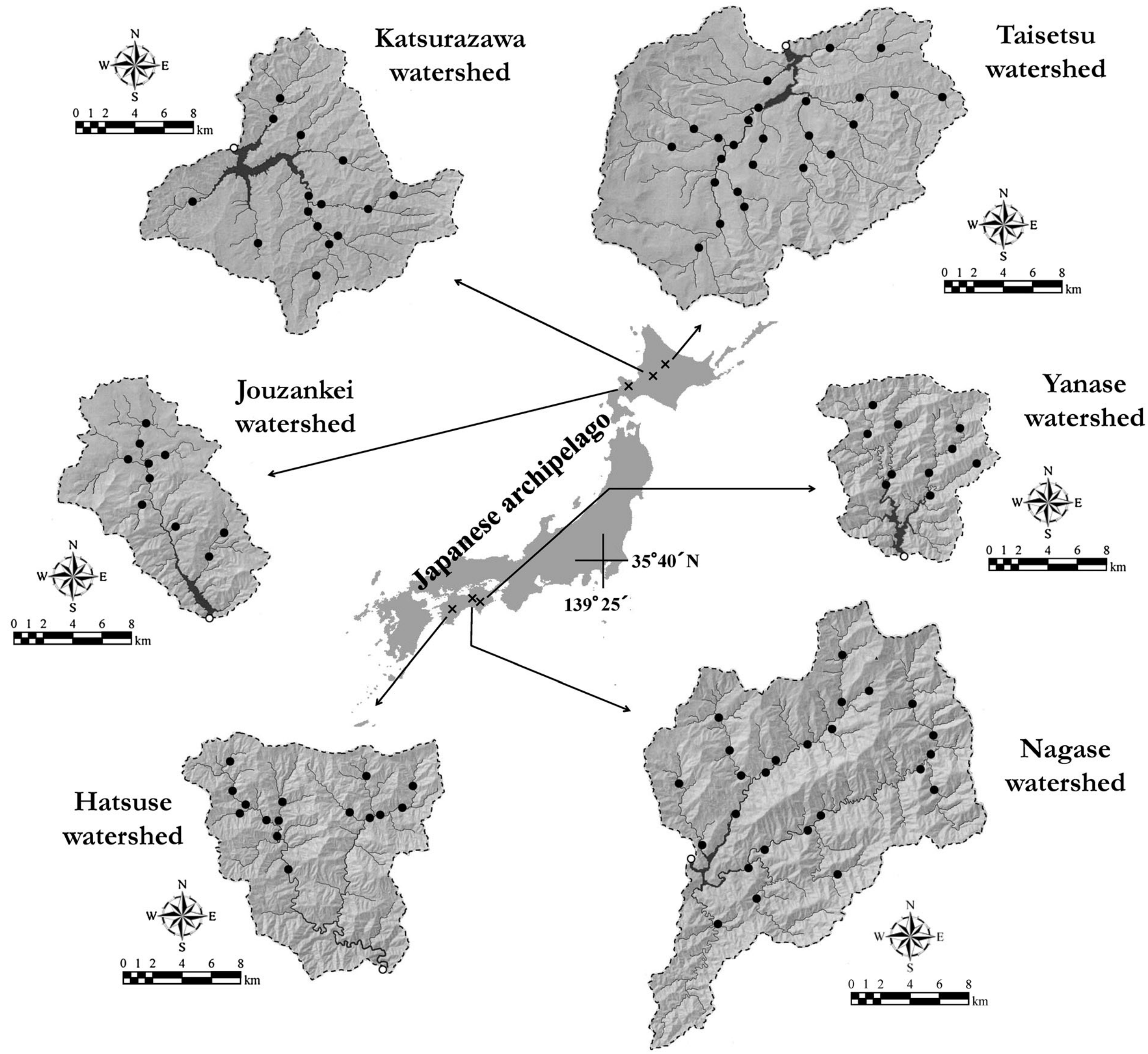

Figure 1. Location of the six study watersheds in southern and northern Japan. Dotted and solid lines denote watershed boundaries and channel networks within the boundaries, respectively. Open and closed circles represent dam locations and channel segments surveyed for fieldwork, respectively

monitored by local reservoir management offices in reservoirs (Table I). All $V_{LW\ export}$ data were divided by total channel lengths within study watersheds to express the $V_{LW\ export}$ per unit channel length (*unit* $V_{LW\ export}$, $m^3\,km^{-1}\,yr^{-1}$), making it possible to compare long-term continuous movement of LW pieces along the stream network for watersheds of different sizes. Total channel lengths were estimated using channel network data (1:25 000) derived from a digital elevation model (50×50 m resolution) in a geographic information system (GIS) (Environmental Systems Research Institute, 2007). To explore discharge dependency of $V_{LW\ export}$, we established the correspondence between precipitation and peak discharge by calculating cumulative daily precipitation greater than or equal to 60 mm ($cP{\geq}60$, mm) and cumulative water discharge per unit drainage area associated with that precipitation ($cD_{P\geq 60}$, $m^3\,s^{-1}$), based on the results of Seo *et al*. (2012).

Selection of channel segments within the study watersheds

Drainage area is a proxy for a variety of both geomorphic and hydrologic processes that control LW dynamics; specifically watershed size is associated with large variations in longitudinal patterns of channel morphology and hydrology (Nakamura and Swanson, 1993; Gurnell *et al*., 2002; Wohl and Jaeger, 2009). To explore these controls we analysed multiple channel segments (400 m in length) in each watershed that varied in upstream drainage areas: 10 segments in the Yanase and Jouzankei watersheds; 15 segments in the Hatsuse and Katsurazawa watersheds; and 25 segments; in the

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 s^{-1})
					[Southern Japan]					
Yanase	33° 35′ 34″	101.7	97.9	436–1423	91.7	394.1 ± 81.5	13	3462.1 ± 284.7	3489.6 ± 182.6	12.2 ± 0.4
Hatsuse	33° 20′ 59″	172.0	184.4	313–1456	87.9	66.8 ± 11.0	9	2773.0 ± 235.4	2709.0 ± 161.7	10.5 ± 0.4
Nagase	33° 42′ 21″	298.8	283.4	191–1893	87.9	446.1 ± 145.4	9	2640.6 ± 234.4	2735.0 ± 154.2	21.9 ± 0.7
					[Northern Japan]					
Jozankei	42° 58′ 57″	103.3	101.9	383–1302	94.4	196.8 ± 13.2	9	1390.4 ± 38.5	1340.2 ± 25.9	5.1 ± 0.1
Katsurazawa	43° 14′ 14″	150.6	144.5	185–1068	92.1	104.2 ± 21.2	6	1451.5 ± 64.0	1417.6 ± 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

[a] Annual precipitation, water discharge and LW annual export volume were expressed as the mean ± standard error.
[b] Total channel length was estimated using channel network data (1:25 000) derived from a digital elevation model (50 × 50 m resolution). In 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 data (1:25 000) derived from a digital elevation model (50 × 50 m resolution).
[c] All numerical values, except for those in the latitude, elevation range and study period columns, were rounded to the nearest 10th.
[d] Annual precipitation for long-term period includes records for the study periods and 5-year record before and after the study periods.

Nagase and Taisetsu watersheds. We carefully selected the segments to include all representative variations in lateral and longitudinal profiles (e.g. channel width, planform of floodplains, bed gradient and bed materials). Channel morphology in these segments has not been affected by artificial structures, although there are several small check dams in these catchments.

Investigation of channel segment geomorphology

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

LW sampling and measurement

LW pieces are directly recruited into the channels from hillslopes or channel banks by forest dynamics, hillslope processes and bank erosion and are then redistributed by fluvial or non-fluvial processes (Nakamura and Swanson, 1994; Seo and Nakamura, 2009). The form of storage of LW pieces recruited into and redistributed within the channel can be classified into two categories: (i) single pieces and (ii) log jams. In this study, a single piece was defined as in-stream wood that is lodged within the bankfull width and has a minimum diameter of 0.1 m and a minimum length of 1.0 m (Nakamura and Swanson, 1994). We defined a log jam as an in-stream wood accumulation composed of two or more pieces.

We first estimated the total volume of LW ($V_{LW\ accum}$, m^3) accumulated within the bankfull channel width as either single pieces or log jams. We measured the diameters at both ends for single pieces. The volume of a single-piece ($V_{LW\ piece}$, m^3) was calculated as:

$$V_{LW\ piece} = \pi \cdot \left(d1^2 + d2^2\right) \cdot \left({}^{1}/_{8}\right)$$

where $d1$ and $d2$ are the diameters at each end and l is the length. The root-wad volume was measured separately. We only measured the visible, aboveground portion of LW pieces buried in either the bank or streambed. To measure log jam volume ($V_{LW\ jam}$, m^3), we divided jam piles into multiple hexahedral shapes and then recorded their widths, lengths and heights. Importantly, we considered void spaces to constitute 30% of the measured volume (Seo and Nakamura, 2009) based on Ohuchi (1987), whose measurements ranged from 20% to 40% of the pile volume. Therefore, $V_{LW\ jam}$ was calculated as:

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

where w, l and h are the width, length and height, respectively, of a component part (hexahedral shape) of a log jam. The volumes of the components were summed to calculate the entire volume of jam. The total $V_{LW\ accum}$ comprising $V_{LW\ piece}$ and $V_{LW\ jam}$ was transformed to express the $V_{LW\ accum}$ per unit channel length (*unit* $V_{LW\ accum}$, m^3 km^{-1}).

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

Estimation of LW residence time

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

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

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

Statistical analyses

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

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

Prior to the analyses, the normality of the distributions was tested using the Kolmogorov–Smirnov test. We used $P < 0.05$ to indicate statistical significance for all tests. All statistical analyses were performed using the statistical language R version 2.15.2 (http://www.r-project.org).

RESULTS

Differences in LW export patterns between southern and northern Japan

The differences in precipitation pattern and resultant flood events between southern and northern Japan should influence LW export (Seo *et al.*, 2012). We examined the effects of precipitation intensity and water discharge on *unit* $V_{LW\ export}$ (Figure 2). Although *unit* $V_{LW\ export}$ increased with $cP\geq60$ and the associated water discharge (i.e. $cD_{P\geq60}$), the corresponding slopes of the regression models differed between southern and northern Japan (Figures 2a and 2b). In addition, in the range of comparable precipitation and runoff intensities shaded in Figures 2a and 2b, *unit* $V_{LW\ export}$ was greater in northern than in southern Japan, meaning that more LW pieces can be exported by the same level of precipitation and flood events in northern Japan.

Longitudinal changes in factors limiting LW transport in southern and northern Japan

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

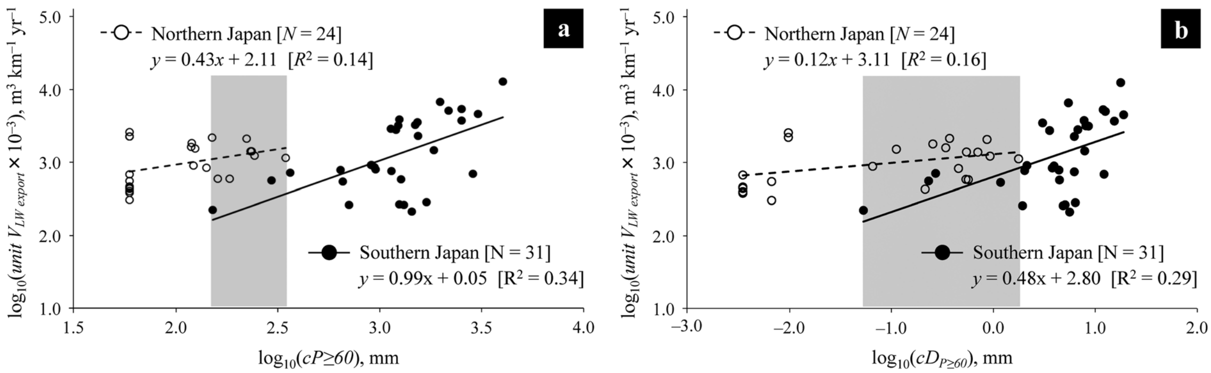

Figure 2. Relationship between *unit* $V_{LW\ export}$ and precipitation or runoff parameters in the six study watersheds located in southern and northern Japan, modified from the result of Seo *et al.* (2012). (a) *unit* $V_{LW\ export} - cP\geq60$ relationship. (b) *unit* $V_{LW\ export} - cD_{P\geq60}$ relationship. The ranges of comparable precipitation and water discharge intensities are shaded

Table II. Changes in factors limiting LW transport along the drainage area and latitudinal gradients in the three watershed groups[a,b]

Construction of parameters in the model	AIC	ΔAIC
[*Ratio of LW piece length to bankfull channel width*]		
Small watersheds		
$R_{length\text{–}width} \sim A_{drainage}$	−26.392	—
Intermediate watersheds		
$R_{length\text{–}width} \sim A_{drainage}$	−32.055	—
$R_{length\text{–}width} \sim A_{drainage} + LAT_{watershed}$	−30.279	1.776
Large watersheds		
$R_{length\text{–}width} \sim A_{drainage}$	−18.448	—
$R_{length\text{–}width} \sim A_{drainage} + LAT_{watershed}$	−17.929	0.519
$R_{length\text{–}width} \sim A_{drainage} + LAT_{watershed} + A_{drainage}{:}LAT_{watershed}$	−17.284	1.164
[*Boulder number per unit channel length*]		
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	—

[a] GLM, generalized linear model; AIC, Akaike Information Criterion; $A_{drainage}{:}LAT_{watershed}$, interaction between $A_{drainage}$ and $LAT_{watershed}$.
[b] ΔAIC refers to the difference between the AIC values for the best-fit model and each of the other models in the set. The regression model(s) with ΔAIC < 2 was considered equally influential as the best-fit model.

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

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

Longitudinal changes in factors regulating LW storage in southern and northern Japan

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

Table III. Changes in factors regulating LW storage along the drainage area and latitudinal gradients in the three watershed groups[a,b]

Construction of parameters in the model	AIC	ΔAIC
[Area of low-flow channels]		
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
[Area of gravel bars]		
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	—
[Area of young-forested floodplains]		
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
[Area of mature-forested floodplains]		
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	—

[a] GLM, generalized linear model; AIC, Akaike Information Criterion; $A_{drainage}{:}LAT_{watershed}$, interaction between $A_{drainage}$ and $LAT_{watershed}$.
[b] ΔAIC refers to the difference between the AIC values for the best-fit model and each of the other models in the set. The regression model(s) with $\Delta AIC < 2$ was considered equally influential as the best-fit model.

consisting of $A_{drainage}$ and $LAT_{watershed}$ without interaction were selected as the best predictors.

Among the channel surface planforms, A_{GB} and A_{MFF} in particular differed significantly by $LAT_{watershed}$ (Figure 3). In all watershed groups, A_{GB} was greater in southern than in northern Japan watersheds, whereas A_{MFF} was greater in northern than in southern Japan watersheds, although both A_{GB} and A_{MFF} increased with $A_{drainage}$.

Differences in LW accumulation between southern and northern Japan

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

To confirm the relative magnitude of LW fragmentation and decomposition, we calculated the proportions of $V_{LW\ accum}$ by fragmentation and decomposition class in each watershed. The proportions of $V_{LW\ accum}$ classified as the most fragmented, i.e. 3rd and 4th fragmentation classes, to total $V_{LW\ accum}$ were higher in southern compared to northern Japan watersheds (Figure 5a). By contrast, the proportions of $V_{LW\ accum}$ classified as the 3rd and 4th decomposition classes to total $V_{LW\ accum}$ were higher in northern compared to southern Japan watersheds (Figure 5b).

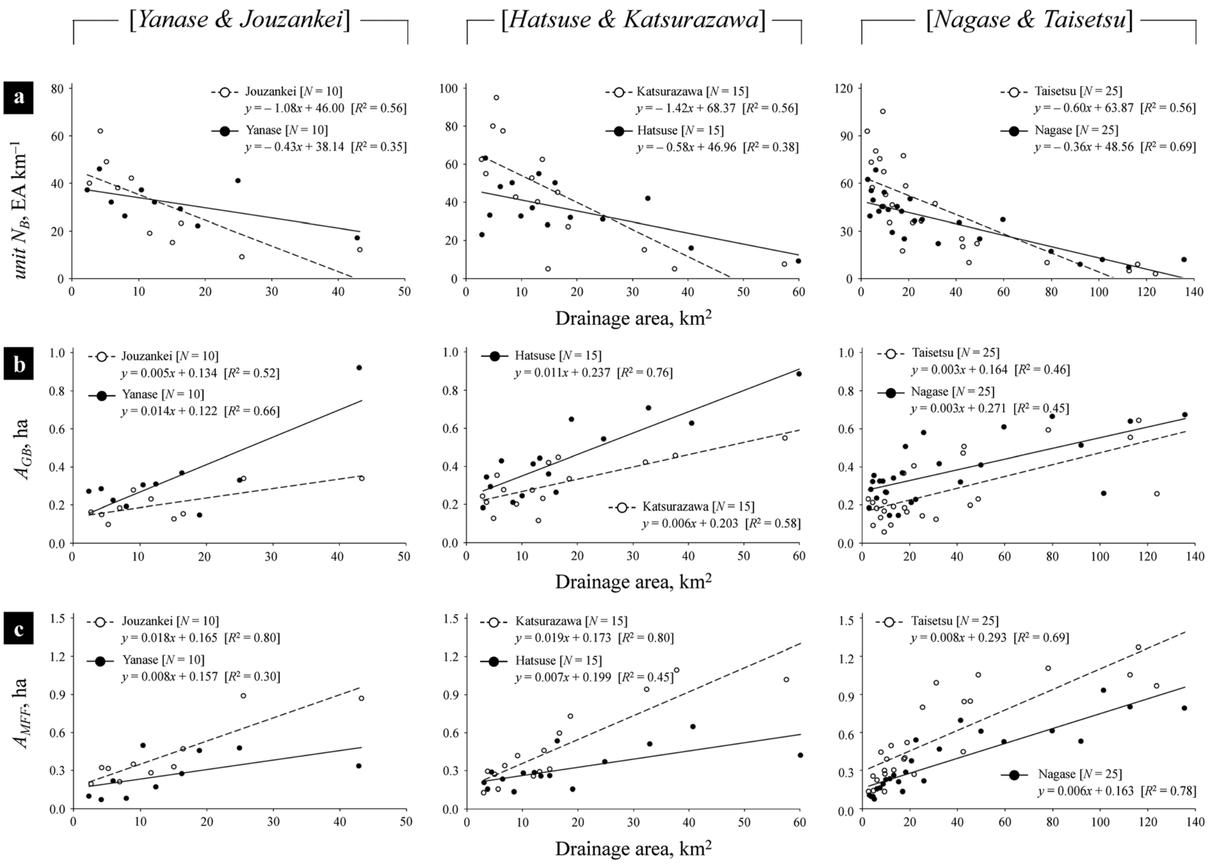

Figure 3. Relationship between LW transport and storage factors and $A_{drainage}$ in the six study watersheds located in southern and northern Japan. (a) *unit* $N_B - A_{drainage}$ relationship. (b) $A_{GB} - A_{drainage}$ relationship. (c) $A_{MFF} - A_{drainage}$ relationship. Closed dots and solid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

Table IV. Changes in *unit* $V_{LW\ accum}$ along the drainage area and latitudinal gradients in the three watershed groups[a,b]

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

[a] GLM, generalized linear model; AIC, Akaike Information Criterion; $A_{drainage}{:}LAT_{watershed}$, interaction between $A_{drainage}$ and $LAT_{watershed}$.
[b] ΔAIC refers to the difference between the AIC values for the best-fit model and each of the other models in the set. The regression model(s) with ΔAIC < 2 was considered equally influential as the best-fit model.

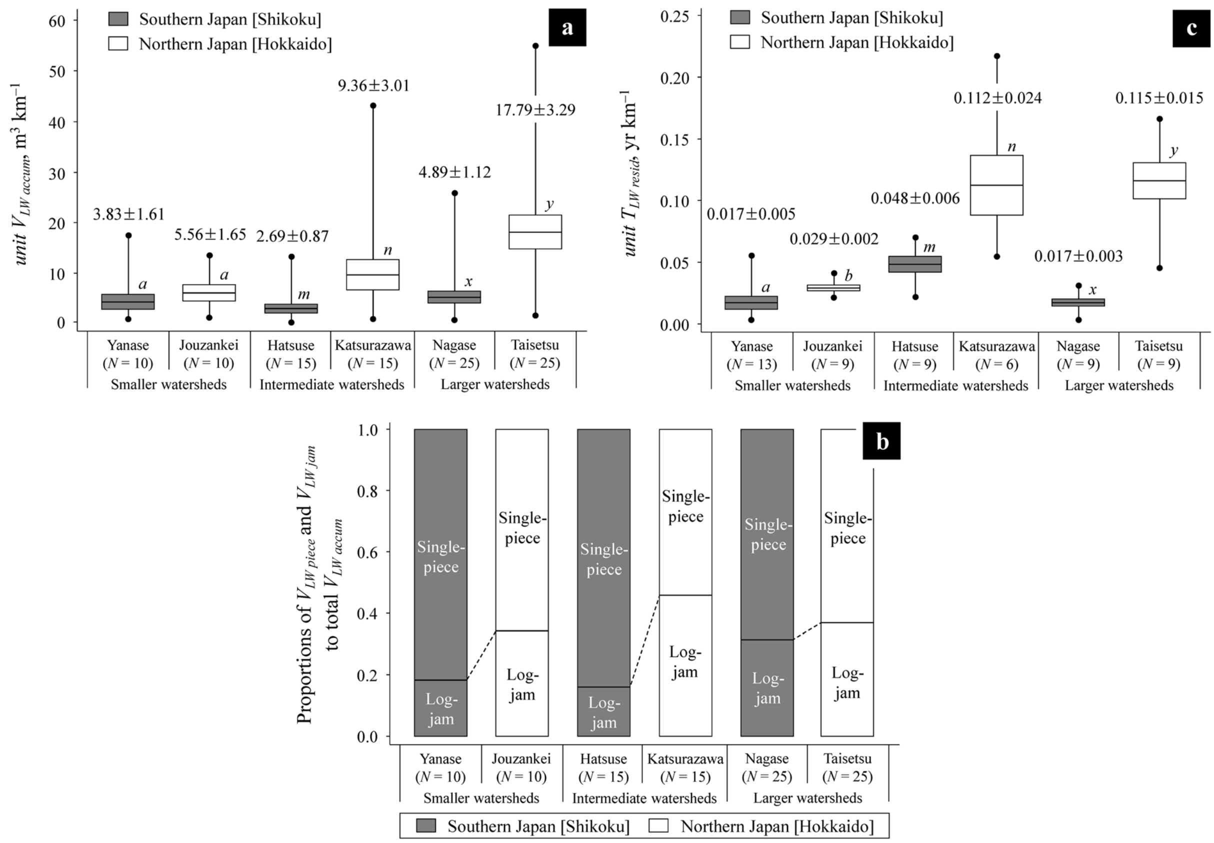

Figure 4. Differences in LW accumulation features among the six study watersheds located in southern and northern Japan. (a) *unit* $V_{LW\ accum}$. (b) Proportion of $V_{LW\ jam}$ to total $V_{LW\ accum}$. (c) *unit* $T_{LW\ resid}$. In (a) and (c), the line within each box indicates the mean value, the box ends are the means ± standard errors and the dots connected with whiskers are the minimum and maximum values. Different letters above the bars indicate significant differences based on AIC values in the GLM

Factors controlling LW accumulation in southern and northern Japan

To understand the relative importance of geomorphic factors (i.e. number of boulders, LW length–channel width ratio and areas of channel surface planforms) controlling LW transport and storage processes, models built by various combinations of parameters were compared to explain *unit* $V_{LW\ accum}$ in all watersheds (Table V). Combinations of all factors (i.e. $R_{length\text{–}width}$, *unit* N_B, A_{LFC}, A_{GB}, A_{YFF} and A_{MFF}) were influential in

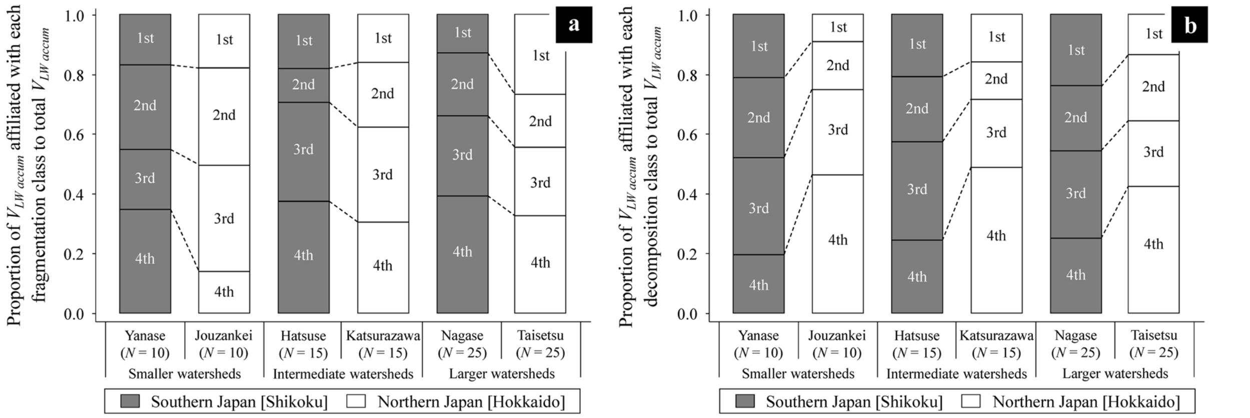

Figure 5. Differences in LW fragmentation and decomposition among the six study watersheds located in southern and northern Japan. (a) Proportion of $V_{LW\ accum}$ affiliated with each fragmentation class to total $V_{LW\ accum}$. (b) Proportion of $V_{LW\ accum}$ affiliated with each decomposition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

Table V. The influential factors in the models selected to explain *unit* $V_{LW\ accum}$ and their strengths in each study watershed[a]

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

[a] GLM, generalized linear model; AIC, Akaike Information Criterion.
[b] ΔAIC refers to the difference between the AIC values for the best-fit model and each of the other models in the set. We examined the relative magnitudes of the factors' strengths based on changes in ΔAIC by including or excluding each variable in the best-fit model.

explaining *unit* $V_{LW\ accum}$ in southern Japan watersheds, and combinations of $R_{length\text{–}width}$, A_{LFC}, A_{GB}, A_{YFF} and A_{MFF} were selected in northern Japan watersheds. Thus, the predictors selected in southern and northern Japan were identical, with the exception of *unit* N_B.

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

DISCUSSION

Based on the reservoir database, Seo *et al.* (2012) hypothesized that LW export is supply-limited in southern Japan and transport-limited in northern Japan. The LW distribution and export volumes examined in the present study at the contrasting districts (Shikoku vs. Hokkaido islands) support this hypothesis. The streams in southern Japan were characterized by a lower standing stock of LW pieces with a short residence time because of frequent removal by repeated floods (supply-limited). By contrast, streams in northern Japan featured a greater stock of LW pieces on the wide valley floors with forested floodplains, and a longer residence time because of infrequent, low-magnitude floods (transport-limited).

Differences in channel physical characteristics in relation to different precipitation patterns

Numerous studies worldwide have documented that LW dynamics are regulated by channel hydrogeomorphic characteristics, such as water discharge, LW piece length relative to channel width and LW buoyant depth relative to channel depth. All of these factors are strongly influenced by relative channel size and position within channel networks (Seo *et al.*, 2010). In small channels, the distribution of LW pieces is spatially and temporally regulated by local channel hydrogeomorphic conditions (i.e. narrow channel width and shallow flow depth), as well as by the physical characteristics of the wood itself (i.e. size and specific gravity) (Braudrick and Grant, 2000; Faustini and Jones, 2003; Seo and Nakamura, 2009). Consequently, in the absence of major floods and related disturbances, many LW pieces are retained in channels and on valley floors for years or decades (Nakamura and Swanson, 1993; Seo and Nakamura, 2009). Episodic debris flows can transport LW pieces to larger channels with lower bed gradients (Benda and Cundy, 1990; Nakamura *et al.*, 2000); debris flows are common in small steep channels in Japan such as our study watersheds. In larger channels, which are characterized by a wider valley floor and deeper flow depth, LW pieces introduced by debris flows are easily transported downstream by fluvial processes, and are stored at various depositional sites (e.g. bars or floodplains), particularly where geomorphic or hydraulic complexity is high. Overarching control on LW transport and storage by channel size is supported by our results, because all factors regulating LW transport and storage processes (i.e. $R_{length\text{–}width}$, *unit* N_B, A_{LFC}, A_{GB}, A_{YFF} and A_{MFF}) were controlled by $A_{drainage}$ (Tables II and III).

Longitudinal trends of these factors are likely to vary with runoff processes, however, particularly the type, intensity and frequency of precipitation. Wohl *et al.* (2012) demonstrated that, because tropical streams with relatively more intense and frequent rainfall have higher channel transport capacity than temperate streams, the amount of LW accumulated in tropical streams is lower than in temperate streams. The results in this study demonstrated that most of the influential factors, particularly *unit* N_B, A_{GB}, A_{YFF} and A_{MFF}, were controlled by the interaction between $LAT_{watershed}$ and $A_{drainage}$. Large boulders delivered from hillslopes by mass movements such as landslides and debris flows (Anderson and Burt, 1990; Grant and Swanson, 1995) may be immovable because of the limited stream power, resulting in channel storage for long periods of time at locations where they were initially introduced, thereby affecting channel morphology over long time scales. However, in channels where debris flows occur relatively frequently, the delivered boulders together with LW pieces can be further transported downstream by subsequent debris flows and stored at/around lower-gradient channels (Grant *et al.*, 1990; Lancaster *et al.*, 2003; Rigon *et al.*, 2008). We therefore interpret the greater number of large boulders in downstream relative to upstream locations in southern Japan as evidence of a greater frequency of rainfall-driven debris flows. In contrast, northern Japan watersheds tend to have boulders concentrated in smaller watersheds (i.e. no transport) (Figure 3). High-magnitude floods also frequently disturb geomorphic surfaces (Swanson *et al.*, 1998; Montgomery *et al.*, 2003), resulting in widely developed gravel bars and a limited extent of forested floodplains in southern Japan (Figure 3). Conversely, the extent of forested floodplains in northern Japan is greater than that of gravel bars, most likely because heavy rainfalls and floods are limited and the residence time of sediment in northern Japan is longer than that in southern Japan (Figure 4c).

Differences in LW distribution and relevant export as a function of channel physical characteristics in southern and northern Japan

The present study demonstrated that *unit* $V_{LW\ accum}$ was commonly influenced by $LAT_{watershed}$ in all watershed groups (Table IV): that is, *unit* $V_{LW\ accum}$ was substantially higher in northern Japan than in southern Japan, although there were no significant differences between the two watersheds in the small watershed group (Figure 4a). This difference is most likely because of different combinations of factors influencing *unit* $V_{LW\ accum}$ in each study watershed. The results of this study indicate that *unit* N_B and A_{GB} are the most influential factors regulating *unit* $V_{LW\ accum}$ in southern Japan (Table V). Braudrick *et al*. (1997) suggested that large boulders scattered within active channels in headwater streams could trap LW pieces as flow obstructions by reducing the channel width available for the LW pieces to pass through. In addition, Faustini and Jones (2003) addressed the relationship between LW inventory and channel morphology in boulder-rich mountain streams, and observed that large boulders provide more potentially stable depositional sites for LW pieces in transport; thus, a positive interaction exists between boulders and LW transport. In southern Japan, large boulders delivered by upstream debris flows act as roughness elements that trap LW pieces. With increasing downstream distance, these LW pieces should be stored on fluvial depositional sites in downstream channels, particularly gravel bars, which were more prevalent in southern Japan (Figure 3). These low elevation sites are particularly vulnerable to attack and inundation by rising water levels during subsequent flood events, and LW is easily refloated from these locations, resulting in relatively less LW accumulation on the valley floor (Figure 4a). During transport, LW pieces are broken into smaller pieces because of impact with the channel bed and banks, resulting in higher fragmentation rates and shorter residence times of LW in southern Japan (Figures 4c and 5a). As a consequence, in southern Japan watersheds, the fluvial export of LW is expected to be supply-limited, explaining why *unit* $V_{LW\ export}$ was lower in this area than in northern Japan for the same range of $cP{\geq}60$ and $cD_{P\geq 60}$ intensities (Figure 2).

In contrast to southern Japan, forested floodplains (particularly A_{MFF}) broadly cover the valley floors in northern Japan (Figure 3). Those geomorphic surfaces provide storage sites and thereby increase *unit* $V_{LW\ accum}$; these higher elevation and vegetated sites are less subject to attack and inundation by the less frequent high-magnitude flood events (Table V). LW depositional sites with high geomorphic complexity (e.g. lateral eddies, concave banks and woodlands and associated sheltered areas parallel to channel margins) are common in these lower-gradient channels (Hickin, 1984; Abbe and Montgomery, 1996; Piégay and Marston, 1998; Piégay, 2003; Latterell and Naiman, 2007). Because of the greater opportunity for LW lodging in these complex environments, many LW pieces form debris jams (Piégay *et al*., 1999; Gurnell *et al*., 2002). In their review of the spatial and temporal variability of LW dynamics worldwide, Seo *et al*. (2010) indicated that while LW pieces stored as debris jams can be refloated and transported by large-magnitude floods, those pieces are often retrapped by larger log jams and/or standing trees on mature stands in floodplains, resulting in long-term storage, and decomposition rather than fragmentation. Although we could not evaluate contributions of air temperature, humidity and tree species to decomposition processes, which might differently influence decomposition of LW pieces between southern and northern Japan, the decomposition rate and the relevant residence time of LW pieces in the study watersheds were higher and longer in northern Japan than in southern Japan (Figures 4c and 5b). Consequently, in northern Japan watersheds, the fluvial export of LW pieces is expected to be transport-limited, and those pieces might be easily transported if infrequent floods occur. We believe that this transport-limited situation explains why *unit* $V_{LW\ export}$ was greater in this area than in southern Japan for the same range of the $cP{\geq}60$ and $cD_{P\geq 60}$ intensities (Figure 2).

ACKNOWLEDGEMENTS

The authors thank the Water Resources Environment Technology Center and the Japanese Ministry of Land, Infrastructure and Transport for assistance in providing and collecting data on large wood. The authors also thank Yong Suk Kim and Takumi Akasaka for valuable advice in the field. This research was funded by the Water Resources Environment Technology Center and the Grants in Aid for Scientific Research (No. 23248021) from the Ministry of Education, Science & Culture, Japan. In addition, this research was conducted in part with the support of Forest Science & Technology Projects (No. S111214L050110) provided by the Korea Forest Service, Republic of Korea.

NOMENCLATURE

$V_{LW\ export}$	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, $m^3\,s^{-1}$
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 boulders 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

REFERENCES

Abbe TB, Montgomery DR. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. *Regulated Rivers: Research & Management* **12**: 201–221. DOI: 10.1002/(SICI)1099-1646(199603)12:2/3<201::AID-RRR390>3.0.CO;2-A.

Anderson MG, Burt TP. 1990. Process studies in hillslope hydrology: an overview. In *Process Studies in Hillslope Hydrology*, Anderson MG, Burt TP (eds). John Wiley & Sons Ltd: Chichester; 1–8.

Benda LE, Cundy TW. 1990. Predicting deposition of debris flows in mountain channels. *Canadian Geotechnical Journal* **27**: 409–417. DOI: 10.1139/t90-057.

Braudrick CA, Grant GE. 2000. When do logs move in rivers? *Water Resources Research* **36**: 571–583. DOI: 10.1029/1999WR900290.

Braudrick CA, Grant GE, Ishikawa Y, Ikeda H. 1997. Dynamics of wood transport in streams: a flume experiment. *Earth Surface Processes and Landforms* **22**: 669–683. DOI: 10.1002/(SICI)1096-9837(199707)22:7<669::AID-ESP740>3.0.CO;2-L.

Burnham KP, Anderson DR. 2002. *Model Selection and Multimodel Inference: A Practical Information-theoretic Approach*. Springer-Verlag: New York; 488.

Cadol D, Wohl E. 2010. Wood retention and transport in tropical, headwater streams, La Selva Biological Station, Costa Rica. *Geomorphology* **123**: 61–73. DOI: 10.1016/j.geomorph.2010.06.015.

Environmental Systems Research Institute. 2007. ArcGIS Desktop Version 9.2. Environmental Systems Research Institute: Redlands, CA.

Faustini JM, Jones JA. 2003. Influence of large woody debris on channel morphology and dynamics on steep, boulder-rich mountain streams, western Cascade, Oregon. *Geomorphology* **51**:187–206. DOI: 10.1016/S0169-555X(02)00336-7.

Fremier AK, Seo JI, Nakamura F. 2010. Watershed controls on the export of large wood from stream corridors. *Geomorphology* **117**: 33–43. DOI: 10.1016/j.geomorph.2009.11.003.

Geological Survey of Japan. 2005. Seamless digital geological map of Japan. http://riodb02.ibase.aist.go.jp/db084/index.html (in Japanese).

Grant GE, Swanson FJ. 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. In *Natural and Authropogenic Influences in Fluvial Geomorphology*, Costa JE, Miller AJ, Potter KW, Wilcock PR (eds). American Geophysical Union: Washington, DC; 83–101.

Grant GE, Swanson FJ, Wolman MG. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, western Cascades Oregon. *Geological Society of America Bulletin* **102**: 340–352. DOI: 10.1130/0016-7606(1990)102<0340:PAOOSB>2.3.CO;2.

Gurnell AM, Piégay H, Swanson FJ, Gregory SV. 2002. Large wood and fluvial processes. *Freshwater Biology* **47**: 601–619. DOI: 10.1046/j.1365-2427.2002.00916.x

Harmon ME, Franklin JF, Swanson FJ, Sollins P, Gregory SV, Lattin JD, Anderson NH, Cline SP, Aumen NG, Sedell JR, Lienkaemper GW, Cromack K, Cummins KW. 1986. Ecology of coarse woody debris in temperate ecosystems. *Advances in Ecological Research* **15**: 133–302.

Hickin EJ. 1984. Vegetation and river channel dynamics. *Canadian Geographer* **28**:111–126.

Hyatt TL, Naiman RJ. 2001. The residence time of large woody debris in the Queets River, Washington, USA. *Ecological Applications* **11**: 191–202. DOI: 10.1890/1051-0761(2001)011[0191:TRTOLW]2.0.CO;2.

Johnson SL, Swanson FJ, Grant GE, Wondzell SM. 2000. Riparian forest disturbances by a mountain flood: the influence of floated wood. *Hydrological Processes* **14**: 3031–3050. DOI: 10.1002/1099-1085(200011/12)14:16/17<3031::AID-HYP133>3.0.CO;2-6.

Keller EA, Swanson FJ. 1979. Effects of large organic material on channel form and fluvial processes. *Earth Surface Processes and Landforms* **4**: 361–380.

Lancaster ST, Hayes SK, Grant GE. 2003. Effects of wood on debris flow runout in small mountain watersheds. *Water Resources Research* **39**(6): 1168. DOI: 10.1029/2001WR001227.

Latterell JJ, Naiman RJ. 2007. Sources and dynamics of large logs in a temperate floodplain river. *Ecological Applications* **17**: 1127–1141. DOI: 10.1890/06-0963

Lienkaemper GW, Swanson FJ. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. *Canadian Journal of Forest Research* **17**: 150–156.

Marcus WA, Marston RA, Colvard CR, Gray RD. 2002. Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. *Geomorphology* **44**: 323–335. DOI: 10.1016/S0169-555X(01)00181-7.

Montgomery DR, Collins BD, Buffington JM, Abbe TB. 2003. Geomorphic effects of wood in rivers. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society: Bethesda, MD; 21–47.

Moulin B, Piégay H. 2004. Characteristics and temporal variability of large woody debris trapped in a reservoir on the River Rhone (Rhone): implications for river basin management. *River Research and Applications* **20**: 79–97. DOI: 10.1002/rra.724.

Naiman RJ, Bilby RE, Bisson PA. 2000. Riparian ecology and management in the Pacific coastal rain forest. *Bioscience* **50**(11): 996–1011. DOI: 10.1641/0006-3568(2000)050[0996:REAMIT]2.0.CO;2'.

Nakamura F, Swanson FJ. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream system in western Oregon. *Earth Surface Processes and Landforms* **18**: 43–61. DOI: 10.1002/esp.3290180104.

Nakamura F, Swanson FJ. 1994. Distribution of coarse woody debris in a mountain stream, western Cascade Range, Oregon. *Canadian Journal of Forest Research* **24**: 2395–2403. DOI: 10.1139/x94-309.

Nakamura F, Swanson FJ, Wondzell SM. 2000. Disturbance regimes of stream and riparian systems: a disturbance-cascade perspective. *Hydrological Processes* **14**: 2849–2860. DOI: 10.1002/1099-1085(200011/12)14:16/17<2849::AID-HYP123>3.0.CO;2-X.

Ohuchi Y. 1987. Timber measurement (Bassaibokunosokutei). In *Forest Measurement Lecture*, Ohsumi S (ed). Yokendo: Tokyo; 28–47 (in Japanese).

Piégay H. 2003. Dynamics of wood in large rivers. In *The Ecology and Management of Wood in World Rivers*, Gregory SV, Boyer KL, Gurnell AM (eds). American Fisheries Society: Bethesda, MD; 49–73.

Piégay H, Thévenet A, Citterio A. 1999. Input, storage and distribution of large woody debris along a mountain river continuum, the Drôme River, France. *Catena* **35**: 19–39. DOI: 10.1016/S0341-8162(98)00120-9.

Piégay H, Marston RA. 1998. Distribution of large woody debris along the outer bend of meanders in the Ain River, France. *Physical Geography* **19**: 318–340. DOI: 10.1080/02723646.1998.10642654.

Richmond AD, Fausch KD. 1995. Characteristics and function of large woody debris in subalpine Rocky Mountain streams in northern Colorado. *Canadian Journal of Fisheries and Aquatic Sciences* **52**: 1789–1802. DOI: 10.1139/f95-771.

Rigon E, Comiti F, Mao L, Lenzi MA. 2008. Relationships among basin area, sediment transport mechanisms and wood storage in mountain basins of the Dolomites (Italian Alps). In *Monitoring, Simulation, Prevention and Remediation of Dense and Debris Flows II*, De Wrachien D, Brebbia C, Lenzi MA (eds). *WIT Transactions on Engineering Sciences 60*. WIT press: Southampton; 163–172.

Robison EG, Beschta RL. 1990. Coarse woody debris and channel morphology interactions for undisturbed streams in southeast Alaska, USA. *Earth Surface Processes and Landforms* **15**: 149–156. DOI: 10.1002/esp.3290150205.

Seo JI, Nakamura F. 2009. Scale-dependent controls upon the fluvial export of large wood from river catchments. *Earth Surface Processes and Landforms* **34**: 786–800. DOI: 10.1002/esp.1765.

Seo JI, Nakamura F, Chun KW. 2010. Dynamics of large wood at the watershed scale: a perspective on current research limits and future directions. *Landscape and Ecological Engineering* **6**: 271–287. DOI: 10.1007/s11355-010-0106-3.

Seo JI, Nakamura F, Nakano D, Ichiyanagi H, Chun KW. 2008. Factors controlling the fluvial export of large woody debris, and its contribution to organic carbon budgets at watershed scales. *Water Resources Research* **44**: W04428, DOI: 10.1029/2007WR006453

Seo JI, Nakamura F, Akasaka T, Ichiyanagi H, Chun KW. 2012. Large wood export regulated by the pattern and intensity of precipitation along a latitudinal gradient in the Japanese archipelago. *Water Resources Research* **48**: W03510. DOI: 10.1029/2011WR010880.

Swanson FJ, Lienkaemper GW. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA Forest Service General Technical Report PNW-69. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station: Portland, OR.

Swanson FJ, Fredriksen RL, McCorison FM. 1982. Material transfer in a western Oregon forested watershed. In *Analysis of Coniferous Forest Ecosystems in the Western United States*, Edmonds RL (ed). *US/IBP Synthesis Series 14*. Hutchinson Ross Publishing Co: Stroudsburg, PA; 233–263.

Swanson FJ, Johnson SL, Gregory SV, Acker SA. 1998. Flood disturbance in a forested mountain landscape: interactions of land use and floods. *BioScience* **48**: 681–689.

Thevenet A, Citterio A, Piégay H. 1998. A new methodology for the assessment of large woody debris accumulations on highly modified rivers (example of two French Piedmont rivers). *Regulated Rivers: Research & Management* **14**: 467–483. DOI: 10.1002/(SICI)1099-1646(1998110)14:6<467::AID-RRR514>3.0.CO;2-X.

Wohl E, Goode JR. 2008. Wood dynamics in headwater streams of the Colorado Rocky Mountains. *Water Resources Research* **44**: W09429. DOI: 10.1029/2007WR006522.

Wohl E, Jaeger K. 2009. A conceptual model for the longitudinal distribution of wood in mountain streams. *Earth Surface Processes and Landforms* **34**: 329–344. DOI: 10.1002/esp.1722.

Wohl E, Bolton S, Cadol D, Comiti F, Goode JR, Mao L. 2012. A two end-member model of wood dynamics in headwater neotropical rivers. *Journal of Hydrology* **462–463**: 67–76. DOI: 10.1016/j.jhydrol.2011.01.061.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.