

Transport and retention of coarse woody debris in mountain streams: An in situ field experiment of log transport and a field survey of coarse woody debris distribution

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[1] Although coarse woody debris (CWD) is an important component of stream ecosystems in forested areas, the processes of CWD distribution, transport, and retention have not been clarified. In this study the distribution process of CWD pieces shorter than the bankfull width (S-CWD) is discussed using an in situ field experiment of log transport and a field survey of CWD distribution in mountain streams. The transport experiment showed that transport distance has a close relation to flow depth and also implied that the magnitude and sequence of a series of flows were important factors for S-CWD transport and retention in streams. The survey of CWD distribution indicated that in-stream obstructions played an important role in the S-CWD retention in deeper channels where S-CWD pieces were potentially transported distances more than spacing between trapping sites of CWD. Overall, the in situ field experiment and the segment-to-reach-scaled analysis using h^* (=depth/diameter) helped us understand the actual movement and distribution of CWD. *INDEX TERMS:* 1815 Hydrology: Erosion and sedimentation; 1821 Hydrology: Floods; 1824 Hydrology: Geomorphology (1625); *KEYWORDS:* coarse woody debris, in situ field experiment, mountain stream, transport and retention, critical floating depth, sequence of high flow events

1. Introduction

[2] Coarse woody debris (CWD) is an important component of most stream ecosystems in forested areas because CWD can influence the morphology and ecology of streams. For example, CWD influences the abundance and the relative proportions of fish and invertebrates in streams [Elliott, 1986; Smock *et al.*, 1989; Fausch and Northcote, 1992] by retaining food, such as leaf and twig litter [Bilby and Likens, 1980; Jones and Smock, 1991; Webster *et al.*, 1994], and forming habitats, such as refuges and spawning sites [House and Boehne, 1986; Everett and Ruiz, 1993; Inoue and Nakano, 1998]. However, CWD can be moved by high flow events, thus possibly altering the functions of individual CWD pieces. Therefore, to fully understand the roles of CWD in streams, it is important to understand transport and retention of CWD.

[3] Most studies on CWD distribution have focused on the relations between the geomorphic features in streams and the amount and depositional form of CWD without considering the transport mechanisms [Keller and Swanson, 1979; Lienkaemper and Swanson, 1987; Bilby and Ward, 1991; Nakamura and Swanson, 1994]. These studies showed that CWD pieces longer than the bank-full width (L-CWD) were stable and influenced channel morphology and stream ecosystems over the long term. CWD pieces shorter than the bank-full width (S-CWD) also play important ecological roles in streams [Jones and Smock, 1991; Ehrman and Lamberti, 1992]. However, S-CWD is usually

unstable and more easily transported than L-CWD; that is, the effects of S-CWD on stream ecosystems change dynamically. Therefore, in order to understand distribution patterns and geomorphic and ecological roles of CWD, not only the distribution of L-CWD but also the transport mechanisms for S-CWD should be examined. Especially, in regions where S-CWD is dominant in streams, such as afforestation areas in southwestern Japan, S-CWD dynamics is a serious problem to be solved.

[4] Although a few studies have been made on S-CWD transport using flume experiments and numerical simulations [Ishikawa *et al.*, 1989; Fujita and Kurokawa, 1993; Braudrick *et al.*, 1997; Braudrick and Grant, 2000], actual transport of S-CWD in mountain streams remains poorly understood because field measurements on the transport of S-CWD are difficult to carry out during floods. Flow conditions during debris flows and large floods, whose recurrence intervals are several years to many decades, are too complicated for investigating S-CWD movement. However, in the case of moderate floods, which only slightly alter channel morphology, there is a possibility that S-CWD movement can be monitored. Furthermore, to assess the ecological roles of S-CWD, we need to discuss not only the impact of a long-term structure of S-CWD on the stream ecosystems, but also S-CWD transport with a timescale equivalent to the life histories of fish and invertebrates, i.e., with recurrence intervals of a few months to several years.

[5] There is a growing awareness that it is essential to conduct in situ field experiments on S-CWD dynamics and to consider S-CWD movement when trying to understand CWD distribution. The objective of this study is to explain

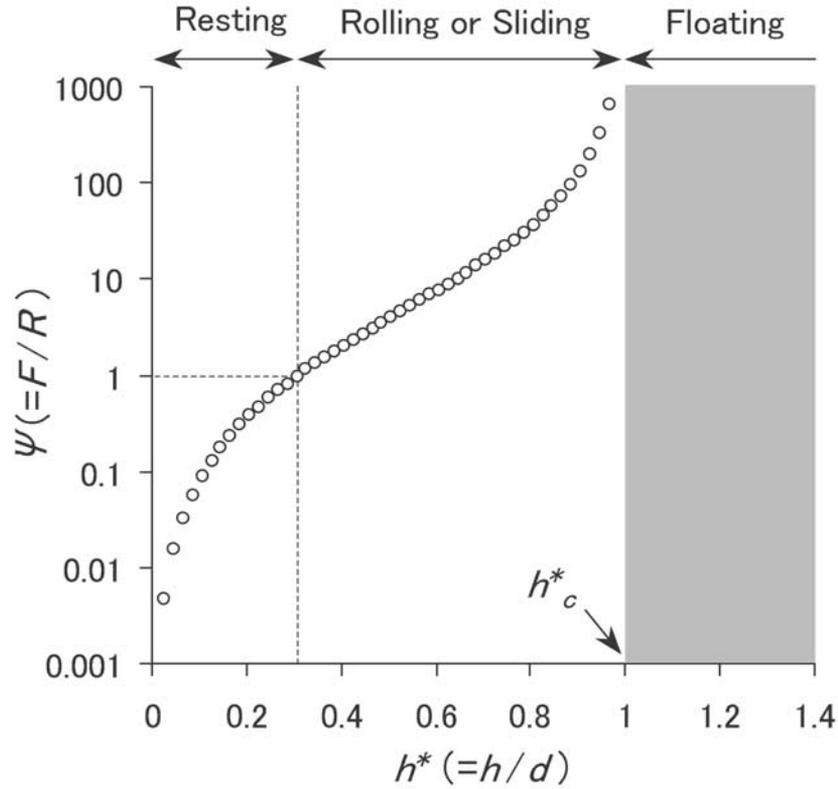


Figure 1. An example of the relationship between the nondimensional water depth (h^*) and the nondimensional force (Ψ) and transport regimes. The threshold for movement of logs is $\Psi = 1$, and the threshold for transport by floating is h_c^* . Assuming that the density of log is equivalent to the water, h_c^* is 1. Parameters were $\rho = 1000 \text{ kg m}^{-3}$, $\sigma = 1000 \text{ kg m}^{-3}$, $k = 15$, $\mu = 1.0$, $C_d = 0.8$, $C_H = 70$, $\alpha = 0.040 \text{ rad}$, and $\theta = 0.785 \text{ rad}$.

the process of CWD distribution in mountain streams using a field survey of CWD distribution and an in situ field experiment of S-CWD transport. First, we conducted an in situ field experiment to analyze S-CWD transport mechanisms and examined the actual movement, i.e., transport distance of logs, for about 1 year. Then, we made a field survey of CWD distribution to document the actual situations of S-CWD and L-CWD retained in a channel. Finally, we compared the results of the experiment and the survey, and here we discuss the pattern and formation process of CWD distribution in streams.

2. Viewpoints on Analysis of Log Transport Distance

[6] *Ishikawa et al.* [1989], *Braudrick et al.* [1997], and *Braudrick and Grant* [2000] developed theoretical models for S-CWD entrainment based on the balance of forces on individual S-CWD pieces by flowing water. Using these models, we focused on several important points to discuss the results produced in our field experiment of log transport and the survey of CWD distribution.

[7] The forces acting on S-CWD in streams are hydrodynamic (F) and resistance (R). The hydrodynamic force comprises the drag force and the lifting force. However, the lifting force is negligible because most S-CWD pieces are not submerged [*Braudrick and Grant*, 2000]. We assume that the shape of the S-CWD is a cylindrical log of which

the diameter and the length are d and l , respectively. According to *Braudrick and Grant* [2000], F is

$$F = \frac{1}{2} C_d \rho (l h \sin \theta + A_{\text{sub}} \cos \theta) U^2, \quad (1)$$

and R is

$$R = \left(g \sigma \frac{\pi l d^2}{4} - g \rho A_{\text{sub}} l \right) (\mu \cos \alpha - \sin \alpha), \quad (2)$$

where C_d is the drag coefficient of the log in water, ρ is the density of water, h is the water depth, θ is the angle of log relative to flow, U is the flow velocity, g is the gravity, σ is the density of the log, μ is the coefficient of friction between the log and the channel bed, α is the channel bed slope angle, and A_{sub} is the submerged area of the log perpendicular to length:

$$A_{\text{sub}} = d^2 \left\{ \frac{1}{4} \cos^{-1} \left(1 - \frac{2h}{d} \right) - \frac{1}{8} \sin \left[2 \cos^{-1} \left(1 - \frac{2h}{d} \right) \right] \right\}. \quad (3)$$

[8] In addition, we use the following relations:

$$U = C_H \sqrt{h \sin \alpha}, \quad (4)$$

$$l = kd, \quad (5)$$

$$h^* = \frac{h}{d}, \quad (6)$$

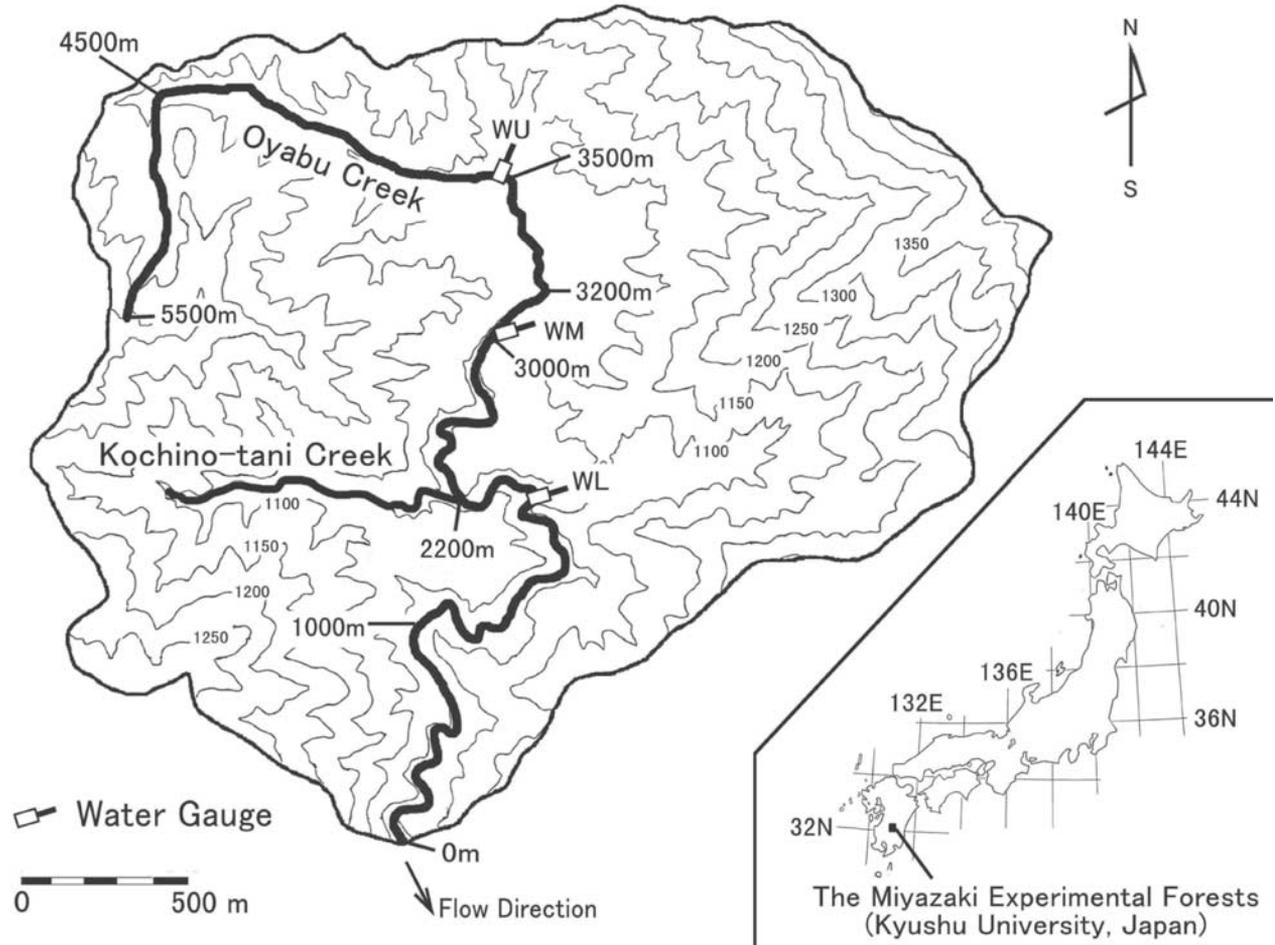


Figure 2. Location of study sites in Oyabu basin, the Miyazaki Experimental Forests of Kyushu University, southwestern Japan. Oyabu Creek was the main stream for the log transport experiment, and Kochino-tani Creek was the branch stream for the coarse woody debris (CWD) distribution survey. Three stream gauges (GU, GM, and GL) were placed along the stream.

where C_H is Chézy's coefficient, k is the constant which varies depending on the log, and h^* is the nondimensional water depth.

[9] Then, the combination of equations (1)–(6) gives the nondimensional force ($\Psi = F/R$):

$$\Psi = \frac{F}{R} = \frac{2C_d \rho C_H^2 h^* \sin \alpha (k h^* \sin \theta + \beta(h^*) \cos \theta)}{g k (\pi \sigma - 4\beta(h^*) \rho) (\mu \cos \alpha - \sin \alpha)}, \quad (7)$$

where $\beta(h^*)$ is a function of nondimensional water depth:

$$\beta(h^*) = \frac{1}{4} \cos^{-1}(1 - 2h^*) - \frac{1}{8} \sin[2 \cos^{-1}(1 - 2h^*)]. \quad (8)$$

[10] Equation (7) indicates that the nondimensional force (Ψ) is a function of the nondimensional water depth (h^*). In other words, log transport regimes (resting, rolling/sliding,

Table 1. Characteristics of Study Streams

	Log Transport Experiment, Oyabu Creek	CWD Distribution Investigation, Kochino-tani Creek
Watershed area, km ²	5.30	0.86
Length of study section, m	5500	1080
Stream order ^a	1–4	3
Bank-full width, m average (range)	9.0 (2.0–20.0)	6.6 (3.2–16.5)
Gradient, % average (range)	4.0 (0.4–25.0)	5.3 (1.5–16.1)
Channel morphology ^b	1, ^c cascade/step pool 2, step pool/plane bed 3, step pool 4, plane bed/pool riffle	step pool/plane bed

^aFrom map 1:5000.

^bClassifications according to *Montgomery and Buffington* [1997].

^cStream order.

Table 2. Wood Density and Porosity of Logs Used in the Transport Experiment

Porosity, %	Wood Density, kg m ⁻³		
	Air-Dried	Saturated ^a	Transported by Flood ^b
67–71	440–630	1150–1170	more than 860

^aThe value was calculated using the porosity data and the specific density of wood substance (1500 kg m⁻³).

^bReference data for the density of logs transported by flood, measured immediately after a flood in a forested stream, western Japan [Nakashima and Yamanaka, 1999].

floating) are interpreted by h^* . Figure 1 shows an example of the relationships between Ψ and h^* . First, if the hydrodynamic force (F) is less than the resisting force (R), $\Psi < 1$, the log remains stationary. Then, if F is greater than R with the result that h^* increases, $\Psi > 1$, the log begins to move by sliding or rolling. Finally, if h^* is beyond the threshold for floating (h_c^*), $R = 0$ and $\Psi = \infty$, the log is transported by floating. The h_c^* depends on σ , for example, $h_c^* = 1.0$ when $\sigma = \rho$ or $h_c^* = 0.5$ when $\sigma = 0.5\rho$.

[11] This study focuses on S-CWD transport distance in a stream. A physically based model for transport distance, which linked the above entrainment model with a model for S-CWD velocity and transport duration, would be a good analysis tool. However, it is very difficult to develop and verify such a model for transport distance because S-CWD velocity is affected by complex flow patterns, which quickly fluctuate spatially and temporally in a stream, and transport duration is influenced by the duration of flood flow above a critical depth and the S-CWD stopping mechanism, including accidental factors. Here we emphasize that h^* is a useful index in analyzing the effects of flows on the transport distance of S-CWD. The h_c^* , especially, is an important value for the floating threshold that largely determines whether S-CWD is transported long distances.

[12] In the field experiments of log transport it is difficult to accurately measure the water depth at the log deposition site during high flows and to know the log density (σ) at the moment of floating, which greatly controls h_c^* . Therefore we

have chosen to estimate the representative water depth at deposition for each segment and to focus on results at the reach to segment scale.

[13] We note that the above mentioned concept cannot be applied to resting logs trapped by in-stream obstructions, such as large boulders and other logs, because obstructions alter the resisting force and violate assumptions in the entrainment model. Therefore comparing the results of the experiment of log transport in a stream with few obstructions and the results of the survey of CWD distribution in a stream with obstructions is necessary in order to understand the transport and retention of CWD.

3. Methods

3.1. Study Sites

[14] The study was conducted in two mountain streams, Oyabu Creek and Kochino-tani Creek, in the Oyabu basin in the central Kyushu Range, Japan (Figure 2). Both creeks flow through the Miyazaki Experimental Forests of Kyushu University (32°22'N, 131°09'E, 990–1479 m high).

[15] The 5.30-km² Oyabu basin is underlain by sedimentary rocks, shale, phyllite, and green-stone from the Cretaceous Period [Tanaka and Iwamatsu, 1993]. The slope of the basin is very steep: 30% of the area has a gradient of more than 30°. The channels in Oyabu and Kochino-tani Creeks are constrained by streamside hillslopes. The streambeds are composed mostly of gravel, cobble, and bedrock. Bars and large boulders occur in several places.

[16] The forest is composed largely of mixed stands of deciduous broad-leaved trees; beech (*Fagus crenata* Bl.), oak (*Quercus mongolica* var. *grosseserrata* Rehd. et Wils.) and Japanese cherry birch (*Betula grossa* Sieb. et Z.), and evergreen coniferous trees; and fir (*Abies firma* Sieb. et Z.) and hemlock (*Tsuga sieboldii* Carr.). These trees, occupying the forest overstory, are 20–30 m tall.

[17] The climate of the basin is classified as a cool temperate zone; the annual mean temperature is 13.6°C. The basin receives 3500 mm of precipitation annually, mostly as frontal rain from June to October. It also receives heavy rain brought by typhoons several times a year.

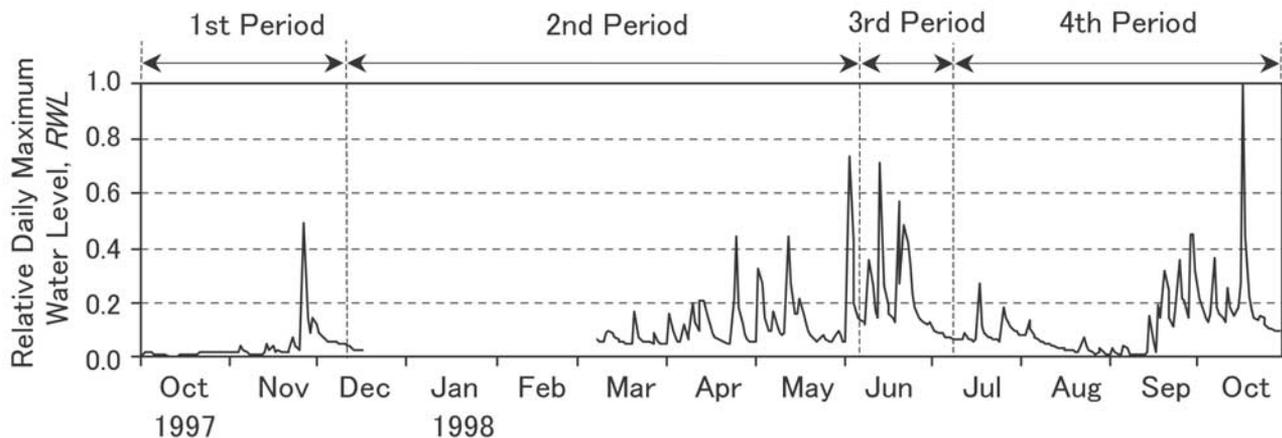


Figure 3. Relative daily maximum water level (RWL) in Oyabu Creek from 1 October 1997 through 30 October 1998. The values were calculated using the data of the stream gauges (maximum = 1, minimum = 0).

Table 3. Features of the High-Flow Events Relating Log to Transport^a

Period	Date	Discharge		Time, hour		
		Peak, $\text{m}^3 \text{s}^{-1}$	Specific, ^b $\text{m}^3 \text{s}^{-1} \text{km}^{-2}$	After Beginning to Peak ^c	After Peak to Inflection Point ^d	In Excess of Antecedent Peak to Peak
First	26 Nov. 1997	7.2	3.5	24	3	N/A
Second	2 June 1998	10.8	5.3	14	4	4 ^e
Third	13 June 1998	10.5	5.1	9	3	0 ^f
Fourth	17 Oct. 1998	14.4	7.0	6	4	2 ^g

^aThese were estimated using data at the 3000-m point in Oyabu Creek.

^bSpecific discharge is defined as peak discharge divided by catchment area.

^cTime after beginning of runoff to peak of each high-flow event ($S_i - P_i$ in Figure 4).

^dTime after peak to inflection point on recession curve ($P_i - I_i$ in Figure 4).

^eTime interval between the point at which the discharge of the second event surpasses the peak of the first event and the peak of the second event ($An_2 - P_2$ in Figure 4).

^fPeak of the third event was below the peak of the second event.

^gTime interval between the point at which the discharge of the fourth event surpasses the peak of the second event and the peak of the fourth event ($An_4 - P_4$ in Figure 4).

[18] As the basin is steep in the mountainous areas and soil is thin, the water level of the channel immediately rises after rain starts and rapidly declines after rain stops. Thus the difference of discharge between low flow and peak flow is large. This is a typical pattern of rainfall-runoff in the mountain regions of southwestern Japan.

3.1.1. Log Transport Experiment: Oyabu Creek

[19] A field experiment of log transport was conducted in Oyabu Creek (Figure 2). As many riparian trees along the stream had been cleared, CWD was scarce in the stream. Neither CWD nor boulders blocked the stream. The experimental section of the stream was 5500 m long and it was a first- through fourth-order stream. Mean bank-full width and mean gradient of the experimental section were 9.0 m and 4.0%, respectively (Table 1). The water levels of Oyabu Creek were observed using three stream gauges (GU, GM, GL, for upper, middle, and lower, respectively) distributed along the stream (Figure 2).

3.1.2. CWD Distribution Investigation: Kochino-tani Creek

[20] CWD distribution was investigated in Kochino-tani Creek, a branch stream of Oyabu Creek (Figure 2). Kochino-tani Creek drains a 0.86-km² watershed and is the only creek in the Oyabu basin that has been excluded from forest operations for more than 60 years. It is covered with 100- to 200-year-old natural forests [Aragami, 1987]. As the structure of the stand supplying CWD to the channel is similar all along the stream, the size and amount of CWD entering the stream is similar along the research section. The research section in the Kochino-tani Creek was 1080 m long and was a third-order stream. Mean bank-full width and mean gradient of the research section were 6.6 m and 5.3%, respectively (Table 1). The research section was divided into the 54 twenty-meter-long sample units.

3.2 Field Experiment on Log Transport

[21] We used 63 similar sized logs in this experiment. Branches and other irregularities on the log surfaces were removed. About 10 vinyl plastic number tags for identification were attached on each log using a staple gun. The mean diameter of the logs was 14 cm (± 4 cm

standard deviation), and the length was 1.7 m (± 0.4 m standard deviation). The length was decided based on the minimum bank-full width in the experimental section, lest logs should span the channel and trap other logs. Wood density and porosity of logs are shown in Table 2.

[22] Before the experiment, we made a topographic survey of the channel and set bench marks at 10- to 50-m intervals to document the positions of logs in the channel. We placed the logs at 38 points from 2260 to 5260 m in the experimental section on 1 October 1997 when the water level was low. The logs were installed perpendicular to the flow at the center of shallower sites such as riffles, where the streambed was relatively flat and the water depth was less than 5 cm. Each log was in contact with the streambed and was not moving.

[23] We identified the locations and depositional form of logs four times over the following year: 9 December 1997, 3 June 1998, 8 July 1998, and 30 October 1998. The transport distances of logs during each period were measured based on the distance from each log to the nearest bench mark. The depositional form was classified into two types depending on deposition condition. The first type, grounded, is that

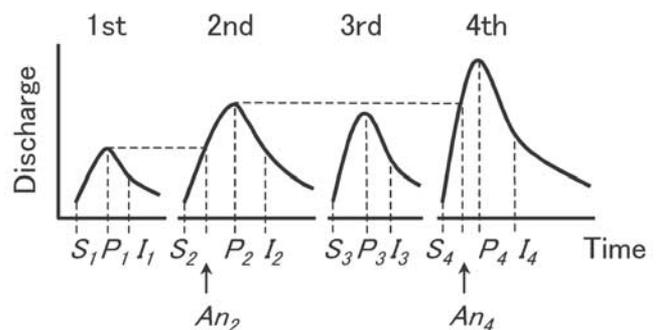


Figure 4. A definition sketch related to Table 3. S_i , P_i , and I_i are the times of beginning, peak, and inflection point on the recession curve of the i th runoff event, respectively. An_i is the time when the discharge of the i th runoff event surpasses the peak of the highest previous event.

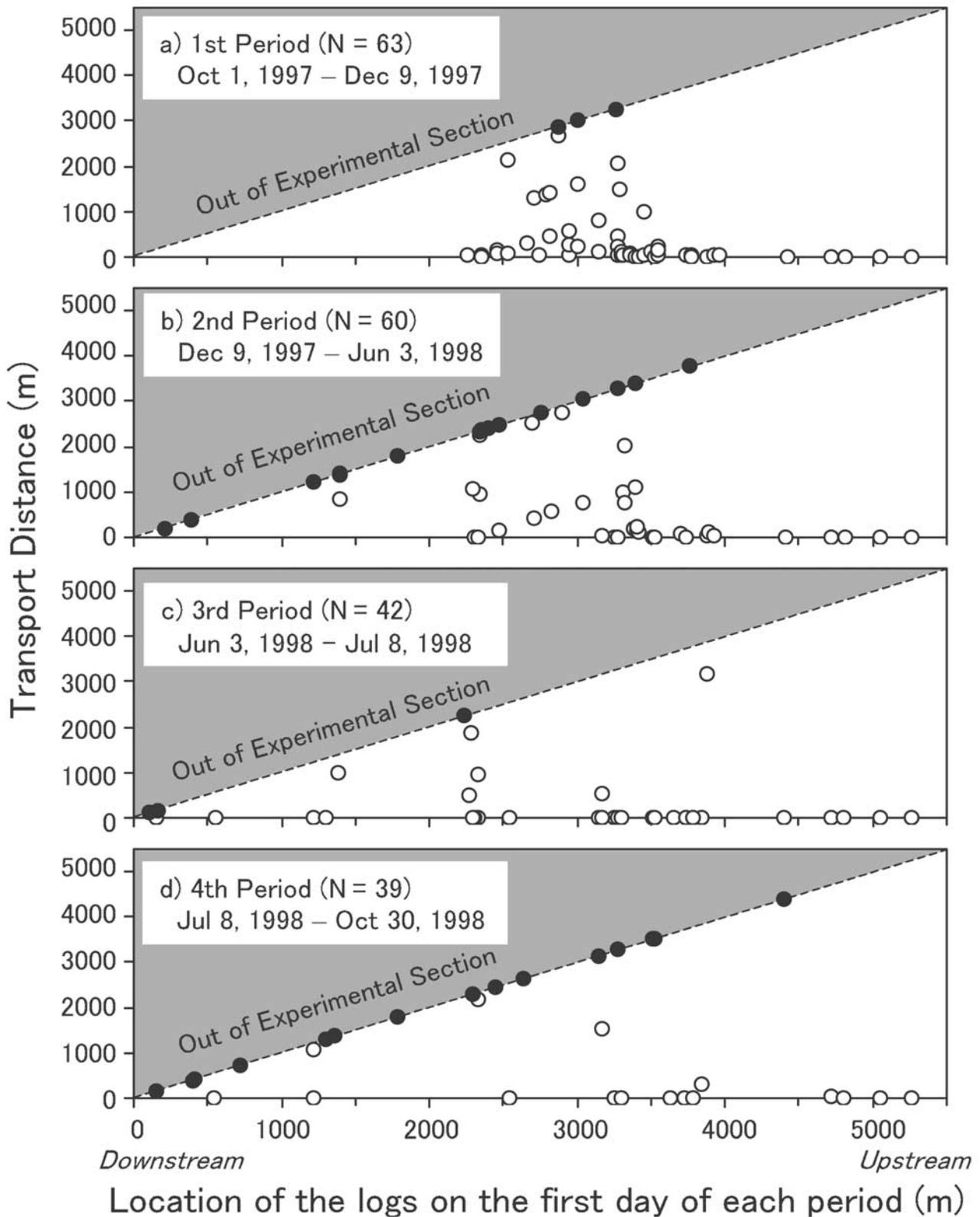


Figure 5. Transport distances of logs in the periods: (a) first period, (b) second period, (c) third period, and (d) fourth period. Open circles indicate logs remaining within the experimental section, and solid circles indicate logs transported out of the experimental section. Oblique lines show the distances the logs were transported to the lowest point of the experimental section. Note that the data of the transport distances of the logs located above 2200 m on the first day of the period were used in the log transport analysis (Figures 6, 8, and 12).

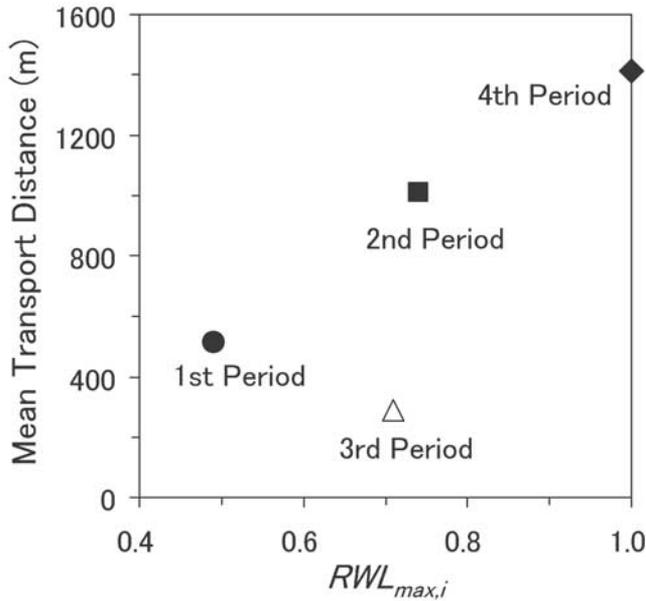


Figure 6. Relationship between the maximum RWL and the mean transport distance in each period.

of logs grounded individually on gravel, bars, and bedrock; the second type, trapped, is that of logs trapped individually by cobble, streamside and eroded roots of riparian trees, and partially buried sediments.

[24] We did not touch the logs throughout these surveys because changes in depositing conditions might influence the retransport of logs. Some logs were transported out of the experimental section and the locations of these logs were recorded as the lowest point of the experimental section.

[25] To compare the results with equation (7), a site-specific log movement model, we needed to know the actual water depth at the site the log was deposited. Because it is impossible to do this with sufficient accuracy, we attempted a macroscopic analysis using the representative water depths of the segments at peak flows to discuss the transport distances of logs at segment to reach scale. The representative water depths of the segments were estimated by the following procedure:

1. A point 3000 m above the bottom of the experimental section was selected as the reference point to determine the maximum discharge during each period. This point was located at the center of a 200-m straight reach (Figure 2). According to channel types described by *Montgomery and Buffington* [1997], the channel morphology around this point was classified as a plane bed type, and the gradient and cross section were almost uniform. According to the intensive measurement at 2-m intervals, the mean (\pm standard deviation), maximum, and minimum bank-full width around this point were 9.5 (\pm 0.5) m, 10.7 m and 8.8 m, respectively.

2. The maximum water level of each period at 3000 m was measured using the stream gauge GM (Figure 2) and flow markers, such as leaf litter deposition.

3. The maximum discharge at 3000 m was calculated by multiplying the cross-sectional area of flow and the velocity estimated from Manning’s equation. The Manning’s roughness coefficient of this reach was calculated from discharge measurements to be 0.061.

4. The specific discharge at 3000 m was calculated by dividing the maximum discharge by the catchment area.

5. The experimental section was divided into 24 segments. The segments were defined as the channel between confluences of tributaries into the main channel. We assumed that the discharge was constant throughout

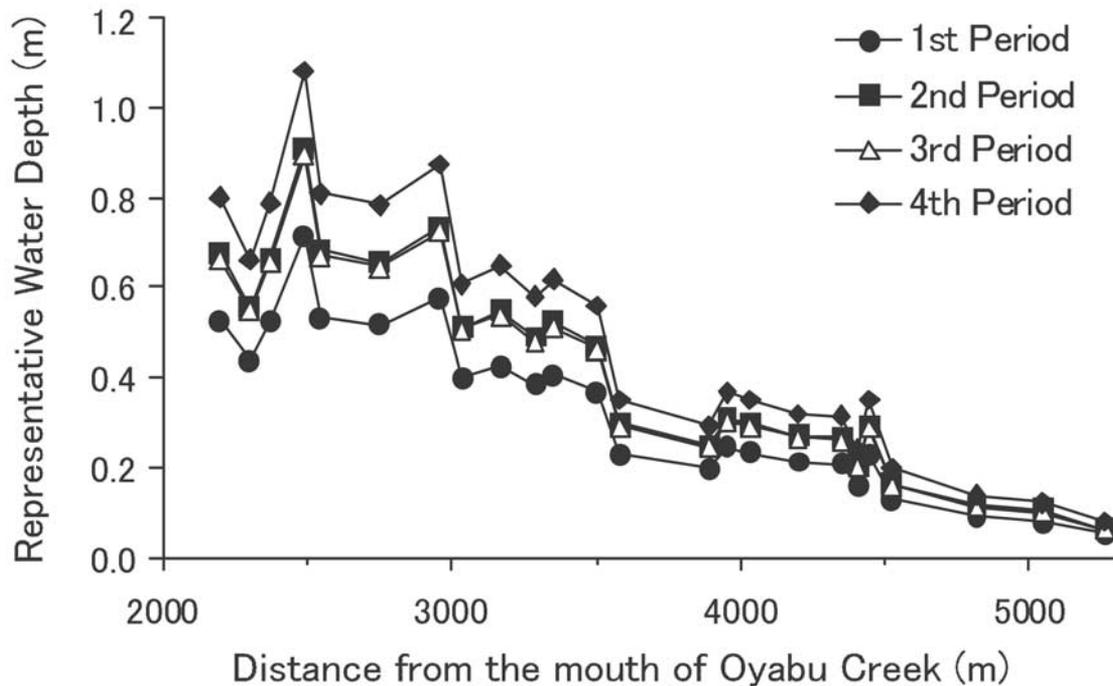
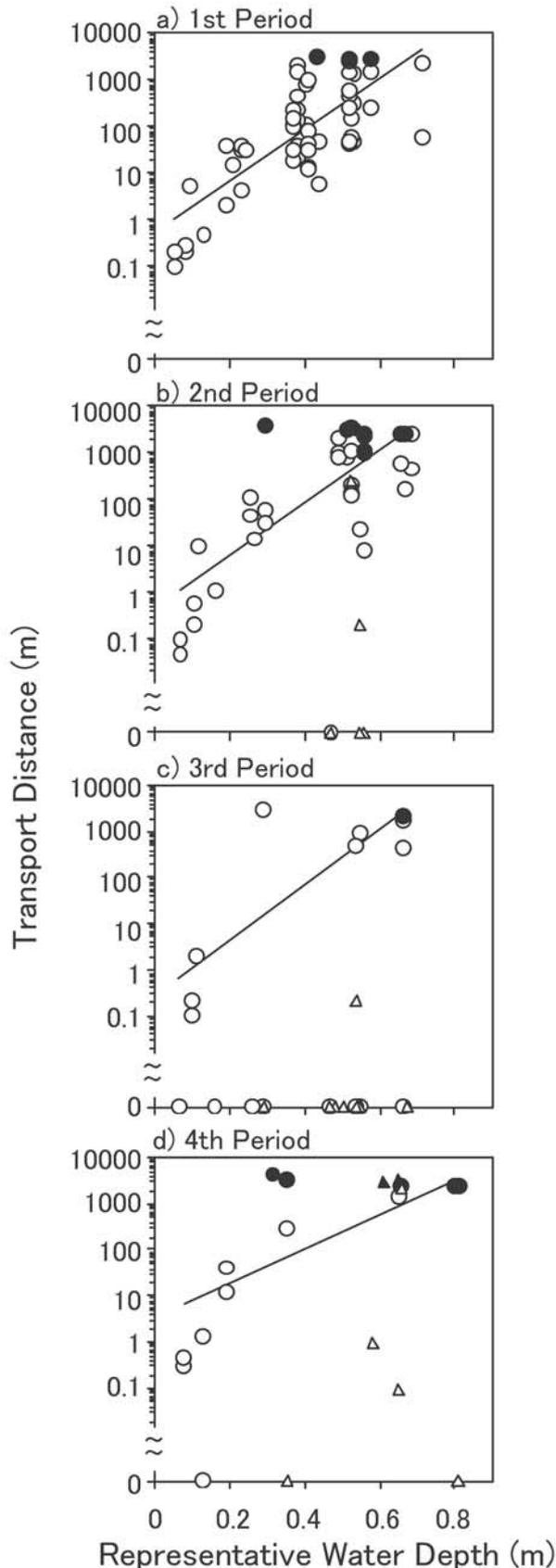


Figure 7. Representative water depth of segments at maximum flow in each period.



each segment because tributaries are the major water sources for the main channel.

6. The maximum discharge of each segment was calculated by multiplying the specific discharge and the catchment area of the segment.

7. The representative water depth of each segment was calculated using the mean bank-full width, mean gradient, and maximum discharge of the segment by assuming the segment as a rectangular channel. Manning's equation was used in the calculation and the calculated values were checked against stream gauge data.

3.3. Field Survey of CWD Distribution

[26] Field surveys of CWD distribution in the research section of Kochino-tani Creek were made at low flow during 3–9 March 1998. We measured the lengths of CWD pieces in their entirety and diameter at the midpoint (at least 1 m in length and 10 cm in diameter) and surveyed locations of CWD pieces in the research section. The volume of CWD was calculated assuming a cylindrical shape.

[27] The depositional form of CWD was divided into three classes: (1) individual, in which CWD is deposited individually on the streambed; (2) jam associated, in which two or more pieces of CWD touch each other; and (3) fallen tree, in which CWD has one end in contact with the streambed and the other extending onto the hillslope.

[28] Additionally, the class of jam-associated CWD was classified into three types depending on in-stream obstructions related to jam formation: channel constriction, large boulder, or standing tree.

4. Results

4.1. Log Transport in Oyabu Creek

4.1.1. Fluctuation of Water Level During the Experiment

[29] Figure 3 shows the relative daily maximum water level (RWL) at 3000 m in Oyabu Creek. The values were

Figure 8. (opposite) Relationships between the representative water depth of segments and the transport distances of logs in each period: (a) first period, (b) second period, (c) third period, and (d) fourth period. Circles show “grounded” logs on the first day of the period: open circles, logs retained within the experimental section during the period; solid circles, logs transported out of the experimental section. Triangles show “trapped” logs on the first day of the period: open triangles, logs retained within the experimental section during the period; solid triangles, logs transported out of the experimental section. The regression lines are fitted excluding unmoved grounded logs (transport distance = 0 m) and all trapped logs: (a) $y = 0.52e^{12.75x}$, $r^2 = 0.58$, $N = 60$; (b) $y = 0.45e^{13.01x}$, $r^2 = 0.65$, $N = 37$; (c) $y = 0.26e^{13.97x}$, $r^2 = 0.71$, $N = 9$; (d) $y = 3.84e^{8.32x}$, $r^2 = 0.61$, $N = 15$. These equations show that the relationship between the transport distance and the water depth is exponential. However, they are not very useful for prediction because of the poor fit (low r^2). This implies that the complexity of flow can be closely related to the log transport.

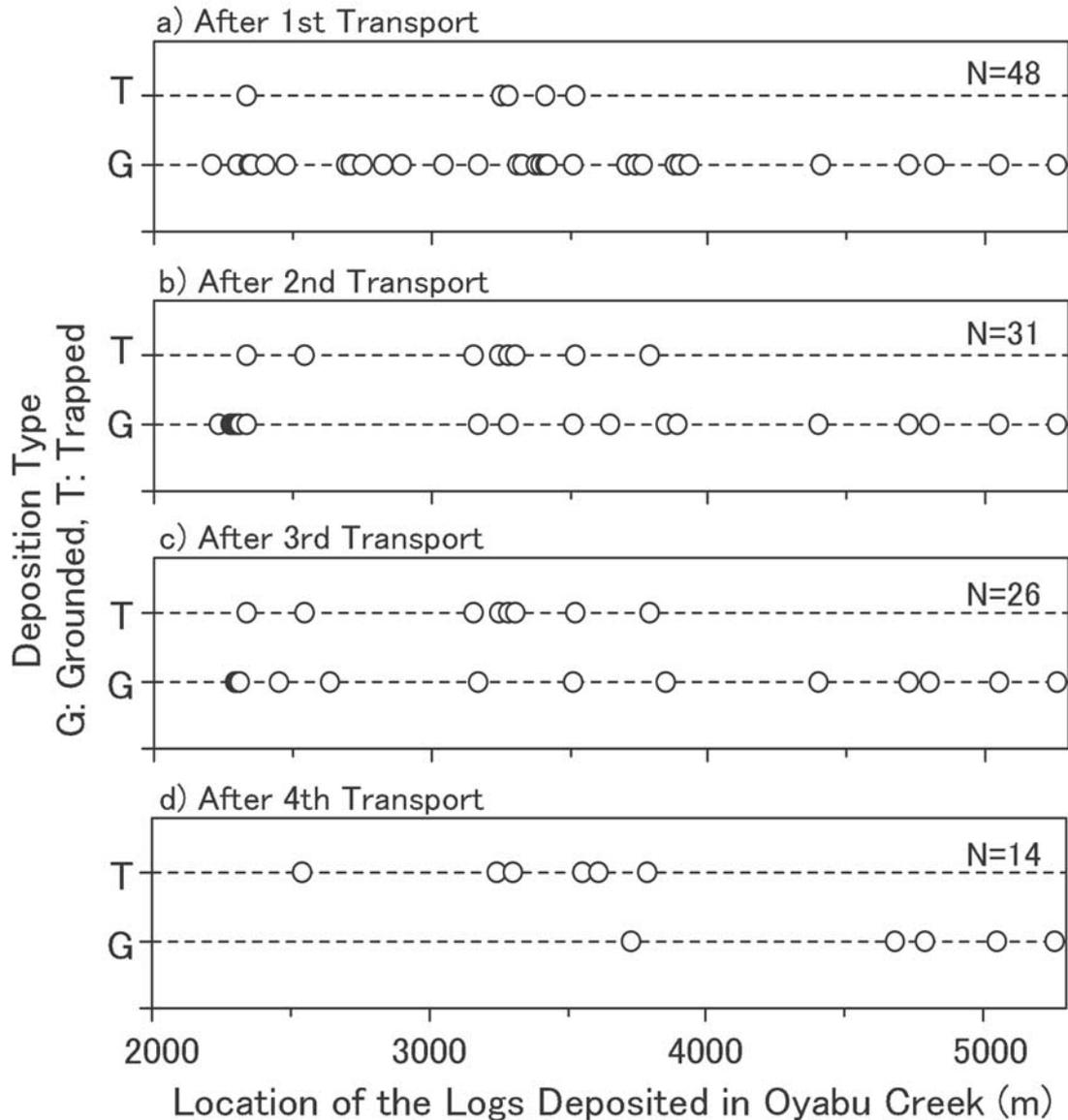


Figure 9. Location and depositional form of the logs after maximum flow in each period. The depositional form is classified into two types: G, grounded; T, trapped.

calculated based on the data at the GM stream gauge and were checked using the data of the other gauges. The water level on the missing days in the second period was inferred to be less than the peak water levels in April and May of the second period, based on precipitation data [Miyazaki *Experimental Forests of Kyushu University*, 2000]. The largest RWL occurred on 17 October 1998 in the fourth period. The smallest RWL occurred on 26 November 1997 in the first period. The maximum RWL of the third period was slightly less than that of the second period. The order of the maximum RWL of the periods was

$$RWL_{\max,1} < RWL_{\max,3} < RWL_{\max,2} < RWL_{\max,4},$$

where $RWL_{\max,i}$ was the maximum RWL of measurement period i .

[30] Some features of these high flow events are shown in Table 3. The time after the water level began to increase

until it peaked ranged from 6 to 24 hours. It took 3–4 hours for the discharge to decrease by half after peak. To help understand Table 3, the definitions of time intervals are visually shown in Figure 4.

4.1.2. Transport Distances of Logs

[31] Figure 5 shows the transport distances of the logs in each period. The transport distances of the logs varied greatly. Logs below 3500 m tended to move long distances, but most logs above 3500 m were not transported far.

[32] In the analysis of the log transport hereinafter, only the transport distances of the logs above 2200 m on the first day of the period were considered, in order to minimize the bias of logs moving out of the experimental section.

[33] Figure 6 shows the relationship between the $RWL_{\max,i}$ and the mean transport distance. The mean transport distance increased with the $RWL_{\max,i}$, except for the third period. Incidentally, most logs below 2200 m were

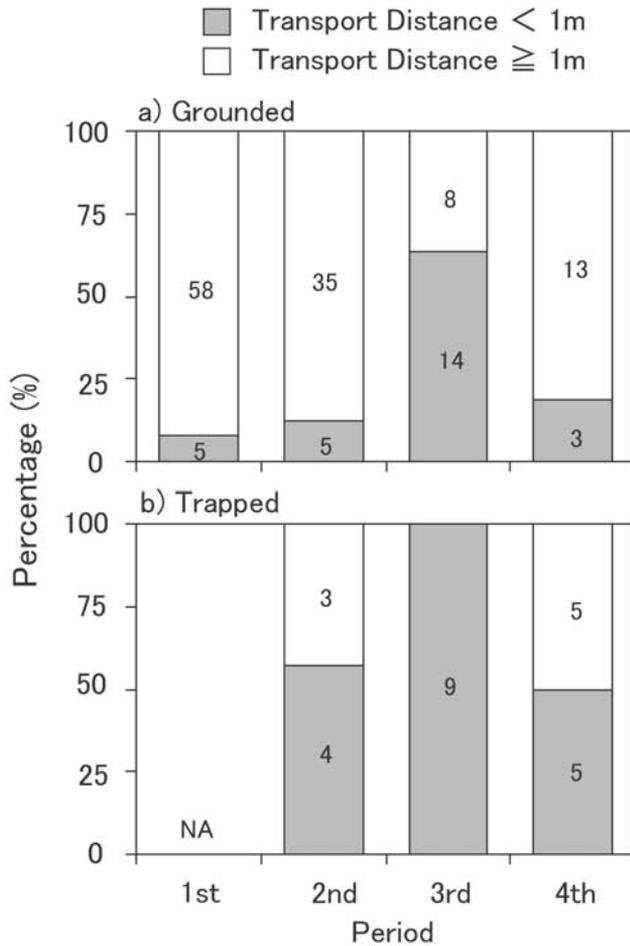


Figure 10. Response of the logs to maximum flow in each period: (a) grounded logs; (b) trapped logs. The numbers inside the bars are the numbers of the logs. NA means not applicable.

transported out of the experimental section except for during the third period.

4.1.3. Peak Water Depth of Segment and Transport Distances of Logs

[34] Figure 7 shows the representative water depth of the segments at maximum flows. The water depth at maximum flows tended to increase downstream.

[35] Figure 8 shows the relationship between the representative water depth of the segments where the logs were located on the first day of the period and the transport distance of logs above 2200 m. In the first period the transport distance tended to increase exponentially with the representative water depth of the segment. In the other periods the relations between the transport distance and the representative water depth of the segment were also exponential, excluding unmoved grounded logs and all trapped logs (Figure 8). The number of unmoved logs in the third period was the greatest among all periods despite the fact that $RWL_{max,3}$ was obviously greater than the $RWL_{max,1}$ (Figure 3).

4.1.4. Depositional Forms and Responses of Logs to Peak Flows

[36] All the logs in each period were deposited individually; that is, no logs were touching others in their final

resting places at each measurement period. Figure 9 shows the location and depositional form of the logs after maximum flow in each period. Most logs (85%) were grounded on the gravel, bars, and bedrock by transport of the first period. After that, the percentage of grounded logs decreased gradually and was equivalent to trapped logs in the fourth period. This pattern was remarkable in the lower section, below about 3500 m. Figure 10 shows response of the logs to maximum flow in all periods. In the first, second, and fourth periods the percentage of logs not transported (transport distance <1 m) was at most 19% for the grounded type and 57% for the trapped type. In contrast, in the third period, the percentage of the logs transported <1 m was over 60% for the grounded type and 100% for the trapped type.

4.2. Distribution of CWD in Kochino-tani Creek

[37] The research section of Kochino-tani Creek contained 176 CWD pieces. Almost all CWD pieces were S-CWD (83% of the total). The mean and maximum values for CWD length in the research section were 3.5 and 14 m, respectively. The mean and maximum values for CWD diameter were 27 and 80 cm, respectively.

[38] Figure 11 shows the numbers, volumes, and depositional forms of CWD in the sample units in the research section. The number pattern was similar to the volume pattern, except for several units with a few large CWD pieces. For example, the size of the piece at 820 m was 14 m in length and 70 cm in diameter. The upper reach had more sample units where S-CWD pieces were deposited than the lower reach: 15 units in the upper and eight units in the lower. However, the number of S-CWD pieces in the upper reach was less than the number in the lower reach: 60 in the upper and 86 in the lower. The volumes of S-CWD in the upper and lower reach were 11.9 and 16.8 m³, respectively. The dominant depositional forms in the upper and lower reaches were distinctly different. The dominant form in the upper reach was the “individual,” 46 pieces in 15 units, but in the lower reach the majority was “jam-associated,” 78 pieces in only four units. CWD jams were located at only five units in the whole research section. The CWD jams of the “channel constriction” type, which were made by some L-CWD pieces, trapped a large number of S-CWD: 49 pieces (34% of all S-CWD).

[39] In the research section the dominant feature of the S-CWD distribution was that S-CWD was individually deposited at frequent intervals in the upper reach and they locally accumulated in CWD jams in the lower reach. L-CWD also showed a similar tendency.

5. Discussion

5.1. Effect of Peak Flow and Flow Sequence on Log Transport

[40] In this study, we regarded the $RWL_{max,i}$ as an index of the magnitude of the peak flow during individual time periods in the experiment. The magnitude of the third period was nearly equal to the second period (Figure 3, Table 3), but many grounded logs, which were easy to transport compared with trapped logs, were unmoved in the third period (Figures 8c and 10). This result has two possible interpretations. One is that the hydrodynamic

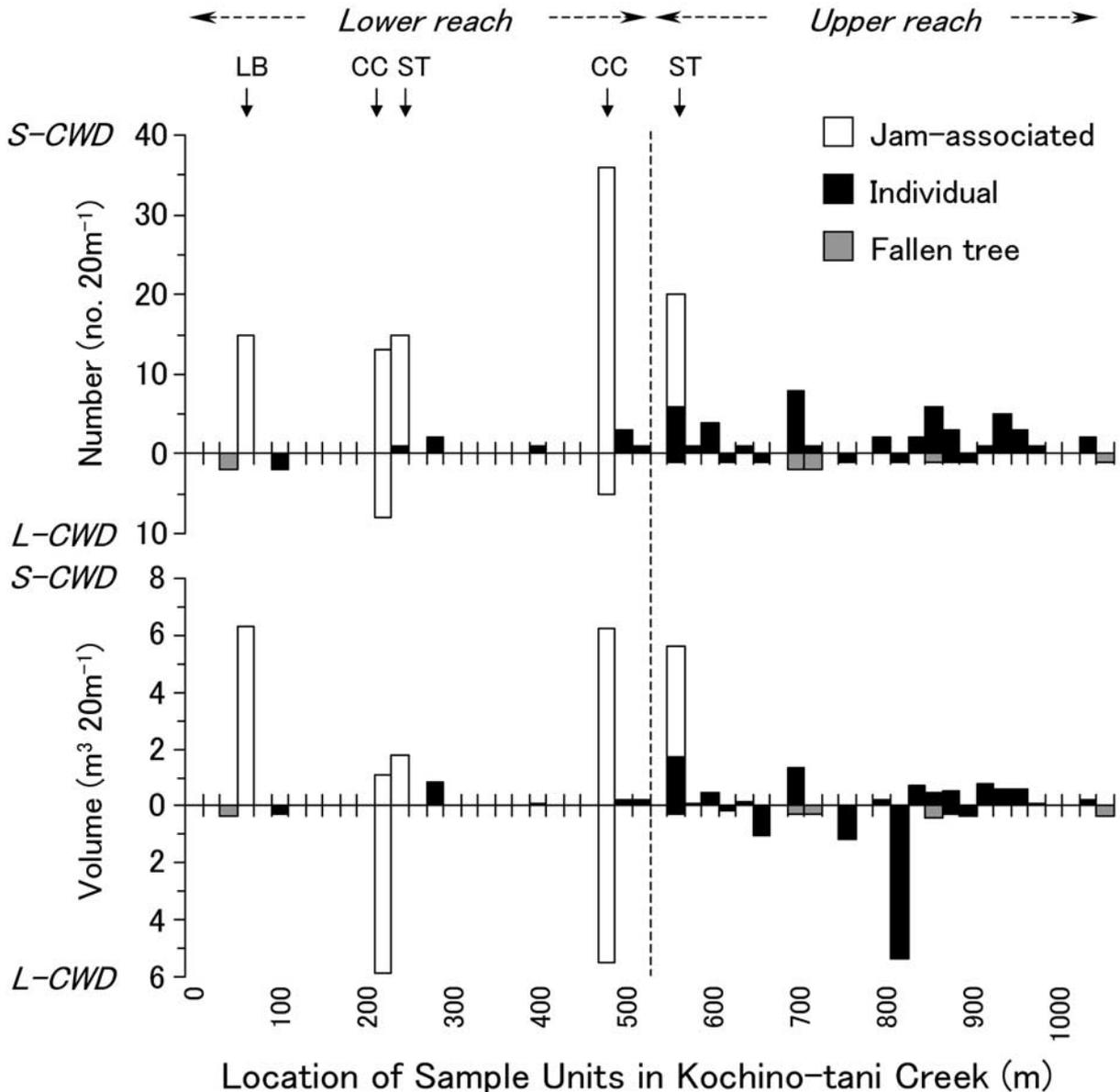


Figure 11. Number, volume, and depositional forms of S-CWD and L-CWD in the Kochino-tani Creek. The dashed line shows the middle of the research section. The depositional form of CWD is divided into three classes: jam-associated, individual, and fallen tree. Furthermore, jam-associated is classified into three types: CC, channel constriction; LB, large boulder; ST, standing tree.

force (F) acting on logs at the peak in the third period was less than the resisting force (R) when the logs stopped in the second period. The alternative interpretation is that the logs transported in the second period were located above the water surface at the peak in the third period. Either of these interpretations could explain the marked decrease in transport distance in the third period (Figure 6). Strictly speaking, this analysis should also account for log orientation to flow or drag coefficient (C_d) in comparing the log movement in the first and third periods.

[41] We conclude that the sequence of high-flow events can be very important for log transport. Moreover, judg-

ing from the slight difference between $RWL_{\max,2}$ and $RWL_{\max,3}$, the response of logs to flows may be quite sensitive to stage. In a related example, *Bilby* [1984] observed a similar relationship between flow magnitude and log movement in a headwater stream with logging debris. In previous studies, however, the effects of a series of flows on log movement were not examined because most flume experiments were usually made under steady flow conditions [*Ishikawa et al.*, 1989; *Braudrick et al.*, 1997; *Braudrick and Grant*, 2000] and because direct observations and field measurements of log transport were difficult in streams. Our results imply that analyzing the magnitude and the sequence of a series

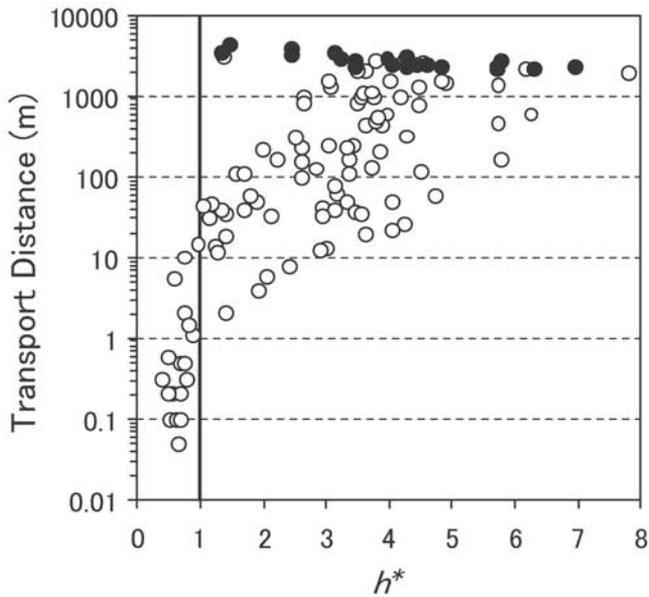


Figure 12. Relationship between the nondimensional water depth at segment scale and the transport distances of logs. In this analysis the density of the logs is equivalent to water; that is, the threshold value for floating (h_c^*) is 1. Open circles indicate logs retained within the experimental section; solid circles indicate logs transported out of the experimental section.

of flows is important to clarify the S-CWD dynamics in streams.

5.2. Effect of Critical Floating Depth on Log Movement

[42] In the analysis of log transport distance, the non-dimensional water depth for each log (equation (6)) is macroscopically expressed as

$$h^* = \frac{h_s}{d}, \quad (9)$$

where h_s is the representative water depth of the segment at the maximum flow of the period. In addition, the threshold for floating is

$$h_c^* = \frac{h_c}{d}, \quad (10)$$

where h_c is the critical floating depth of each log. It is difficult to determine h_c precisely because the density of the log varies with the moisture condition of the log deposition sites, for example, on gravel above the water surface or under flowing water. Here we tried evaluating robustly the effects of the critical floating depth on log movement at the segment scale. Judging from the density of CWD pieces transported by floods [Nakashima and Yamanaka, 1999] (Table 2), CWD pieces deposited in a channel typically contain high percentages of water. If we assume that the average density is equivalent to the water, then h_c is equal to the diameter of the logs; that is, the threshold for floating is

$$h_c^* = 1. \quad (11)$$

[43] Figure 12 shows the relationship between h^* (equation (9)) and the transport distances of the logs in all periods, excluding the unmoved logs and trapped logs in Figure 8. The logs moved at most 10 m downstream and were retained in the segments when $h^* < 1$. On the other hand, the logs were potentially transported over 1000 m and were transported out of the segments when $h^* > 1$. It is implied that the water depth relative to log diameter is an important factor for log transport in actual streams. However, to analyze the log transport distance in more detail, it is necessary to consider the site-specific water depth, the log orientation to flow as Ishikawa *et al.* [1989] and Braudrick and Grant [2000] pointed out, and the log transport duration.

[44] Here we tried a preliminary study on the log transport duration and the log velocity. In Figures 6, 8, and 10, it is noted that the discharge in excess of the antecedent flow peak is closely related to the mean transport distance of the measurement period. Therefore we assume that on the average the transport duration in a runoff event is equivalent to the time interval between the point at which the discharge level of the event surpasses the peak of the highest previous event and the peak of the runoff event. In the second period, for example, the tentative maximum log velocity is 0.26 m s^{-1} in a calculation using the maximum log transport distance (3766 m) and the duration (4 hours, $An_2 - P_2$ in Figure 4). This estimated value is substantially smaller than the representative water velocity of each segment at the beginning point of the duration (An_2 in Figure 4), which ranges from 0.96 to 1.67 m s^{-1} . The discrepancy implies that log transport is strongly affected by other factors such as complexity of flow related to channel morphology. In addition, the discrepancy may arise in part from difficulty in analyzing the critical floating depth and in understanding log stopping mechanisms.

5.3. Log Retention in the Channel at the Reach Scale

[45] The above discussion suggests that the channel's ability to retain logs is primarily a function of the water depth at the maximum flow in a channel. According to the depth of maximum flow in each measurement period (Figure 7), the experimental section above the 2200-m point was divided into four reaches, 2200–3200 m, 3200–3500 m, 3500–4600 m, and 4600–5500 m from the lowest point. Figure 13 shows the proportion of retained logs and the range of the maximum water level of each reach. In the 4600–5500 m reach, all logs remained and the proportion of retained logs was 100% during the experiment because the water depth in the reach was less than the mean diameter of the logs, which indicated the critical floating depth of logs, at all flow peaks. In contrast, in the 2200–3200 and 3200–3500 m reaches, most logs were rapidly transported out of the reaches and the proportion remaining finally dropped to 4% because the water depth was much greater than the mean diameter. In the 3500–4600 m reach, where the depth was approximately twice as large as the mean diameter, the proportion remaining in the reach decreased more gradually compared with the lower reaches (2200–3200 and 3200–3500 m) and reached only 43%. The results imply that the logs tend to be retained for a long time in a reach shallower than the critical floating depth and are immediately transported out of a

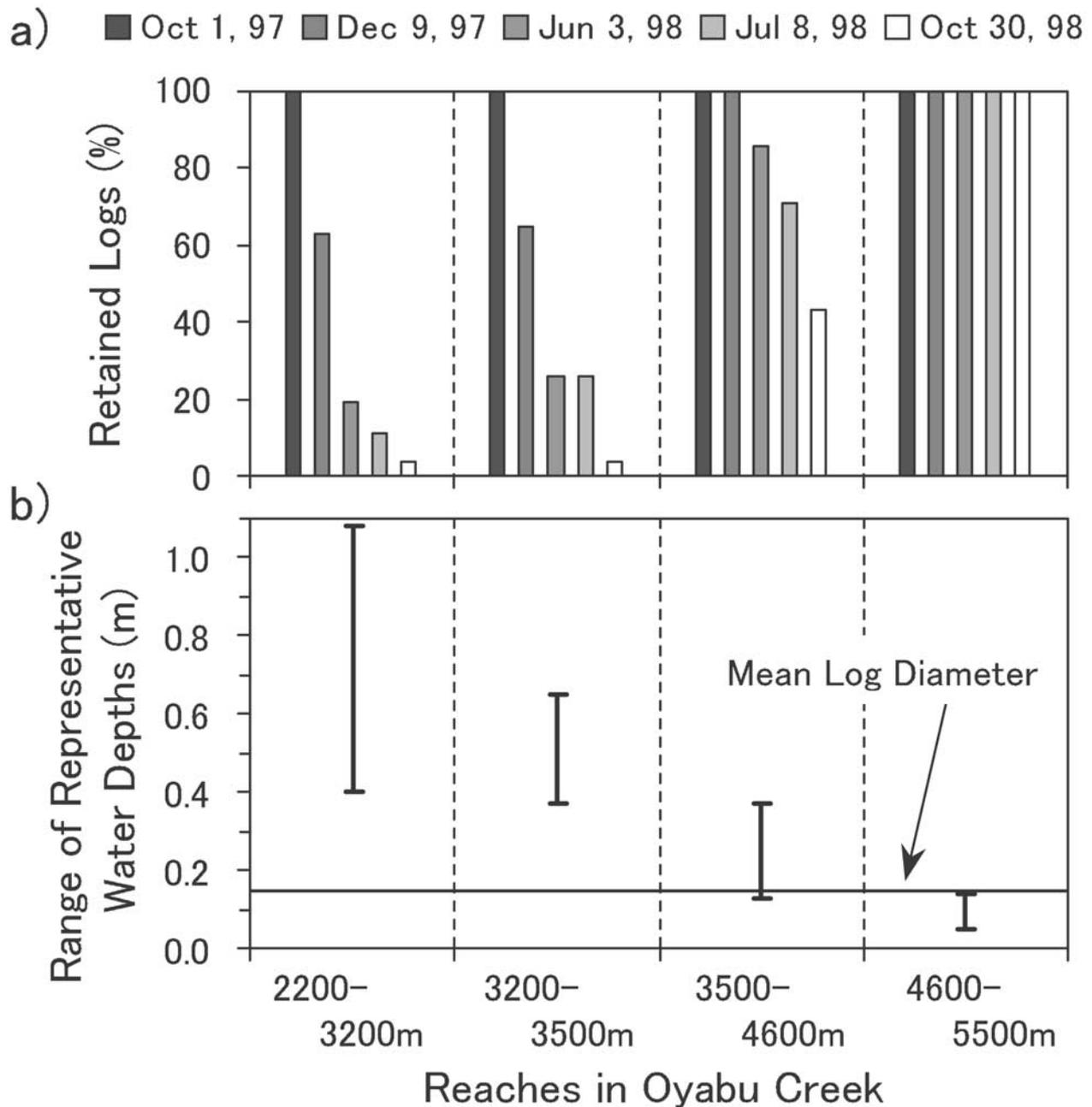


Figure 13. Log retention in the channel at the reach scale: (a) proportion of retained logs and (b) the range of representative water depths of the segments in each reach. Note that in the reach 4600–5500 m, the representative water depths were below the mean diameter of logs (14 cm) during the experiment, and all logs were retained in the reach.

reach deeper than the critical floating depth. However, even if the logs are deposited in the deeper reach, trapping by in-stream obstructions would make the logs reside longer in the reach (Figure 9).

5.4. Verification of S-CWD Distribution Pattern in Kochino-tani Creek

[46] Most CWD were S-CWD (83%) in Kochino-tani Creek. Therefore the results of the log transport experiment are useful to discuss the distribution of CWD pieces along the stream.

[47] We examined the effects of the water depth on the S-CWD distribution pattern. To understand the variations of water depth at flow peaks along Kochino-tani Creek, the water depths of three peak flows (the specific discharges 5.0 , 7.0 , and $10.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$) were estimated by the procedure used to calculate the representative water depth of the segment in the experimental section. These flow discharges were not particularly high (the recurrence interval is less than about 5 years) and the value of $7.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ is equal to the specific discharge of the maximum flow (17 October 1998) during the experiment

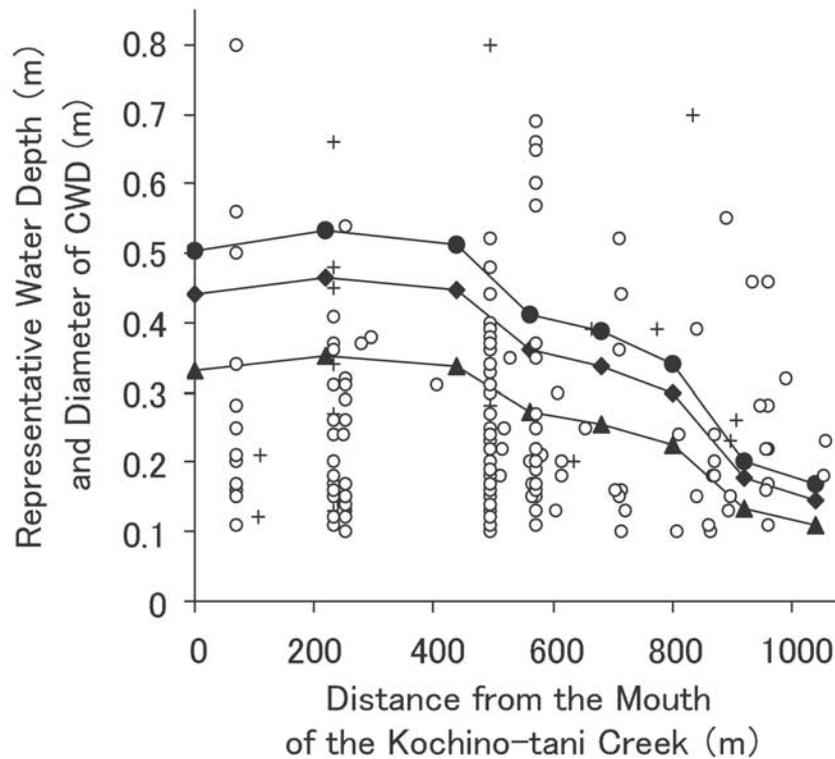


Figure 14. Variations of representative water depth at flow peaks and diameters of CWD pieces along Kochino-tani Creek. The water depths were estimated using high flows with different specific discharges: $5.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ (curve with triangles), $7.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ (curve with diamonds), and $10.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ (curve with circles), which recurrence intervals were equal to about 0.5, 1.0 and 5.0 years, respectively. The diameters of CWD pieces are plotted according to S-CWD (circles) and L-CWD (plus signs).

in Oyabu Creek. Figure 14 shows the water depth of the peak flow and the diameter of CWD pieces along Kochino-tani Creek. The water depth increased downstream, and the diameters of most CWD pieces were smaller than the water depth at the peak flow (recurrence interval is about 1.0 year) in the lower reach. In contrast, the diameters of many CWD pieces were greater than the water depth in the upper reach. Therefore the upper reach's ability to retain S-CWD pieces was greater than the lower reach's ability in Kochino-tani Creek. From this estimation we would predict that the number of units retaining S-CWD and the amount of S-CWD in the upper reach are greater than in the lower reach. However, the results of the survey of S-CWD distribution (Figure 11) show that although a great number of units have S-CWD in the upper reach, the amount of S-CWD is not greater. The direct cause of this was the existence of CWD jams in the lower reach, which were not formed in the experimental section.

[48] In the upper reach, relatively shallower depths were insufficient for the transport of S-CWD entering the channel. In other words, the transport distances were short relative to space at trapping sites, channel constrictions, large boulders, or standing trees. Therefore S-CWD pieces were individually deposited at frequent intervals in the upper reach (Figure 11).

[49] In the lower reach, S-CWD pieces were easily transported because of the greater depth. Therefore very few individual S-CWD pieces were retained in the channel.

Judging from the results shown in Figure 9, to retain S-CWD in the outflow dominant reach, flow-resistance factors other than the friction of the channel bed are necessary. Channel constrictions, larger boulders, and standing trees have important roles in impeding flow and acted to trap transported S-CWD and form CWD jams in the lower reach. CWD jams themselves can also be effective trapping sites [Keim *et al.*, 2000]. CWD jams at channel constriction points, some of which were composed of L-CWD, trapped a great number of S-CWD by blocking the channel. For this reason, S-CWD pieces were locally accumulated in CWD jams in the lower reach (Figure 11).

[50] Consequently, the distribution of S-CWD pieces is primarily determined by a combination of water depth at flow peaks and in-stream obstructions. In-stream obstructions related to CWD jam formation have an important role in the distribution of S-CWD in deeper channels where S-CWD is potentially transported significant distances, i.e., more than the spacing between trapping sites. In steep mountain regions like Japan, where the difference of discharge between low flow and peak flow is large and the response of discharge to rainfall is so quick, these trapping mechanisms may be critical to CWD distribution in streams.

6. Conclusions

[51] Although CWD distributed in streams has been recognized by ecologists and stream managers to be an

important factor for fish and aquatic invertebrates [Bilby, 1981; Molles, 1982; Murphy and Koski, 1989; Fausch and Northcote, 1992], controls on the spatial pattern of CWD have been poorly understood. To understand the interaction between the activity of aquatic organisms and the abiotic environment created by CWD, it is essential to clarify the mechanisms of transport and retention of CWD. In this study we focused on the dynamics of S-CWD, which has received little study so far [Braudrick and Grant, 2000; Keim et al., 2000], and investigated the transport and retention of S-CWD using an in situ field experiment of log transport and a survey of CWD distribution in a relatively undisturbed stream. This study led to the following results:

1. The transport distance of log exponentially increases with the representative water depth of the segments at peak flows.

2. The sequence of a series of flows influences log transport, and flow magnitude greater than the previous flows is necessary for retransport of most logs.

3. Logs are not transported far (at most 10 m) and are retained individually as long as the water depth of the segment at peak flows is less than the diameters of the logs.

4. Logs are easily transported out of a reach of which the water depth at peak flows is greater than the log diameter. A large amount of S-CWD, however, is locally accumulated in CWD jams by obstructions, such as channel constrictions, large boulders, and standing trees in the stream.

[52] We conclude that the critical floating depth of S-CWD and the magnitude and sequence of a series of flows are key factors for S-CWD movement. Also, we recognize in-stream obstructions as important trapping mechanisms for CWD distribution in steep mountainous areas like Japan because they serve to accumulate S-CWD in reaches where S-CWD potentially would be transported distances greater than the spacing between the trapping sites. While the stability of S-CWD is lower than that of L-CWD in streams [Lienkaemper and Swanson, 1987], the retention time of S-CWD in reaches increases when S-CWD is deposited within a reach shallower than its critical floating depth and when S-CWD is trapped by in-stream obstructions.

[53] Our results based on the in situ field experiment and field survey of transport and retention of S-CWD should be useful information for riparian management and investigation of ecological processes related to S-CWD in stream ecosystems. In addition, these results indicate that improvements in understanding S-CWD transport will probably require approaches that consider the more actual shape of CWD (e.g., CWD with rootwad) or CWD orientation relative to flow [Ishikawa et al., 1989; Braudrick and Grant, 2000]. CWD transport models linked with more precise hydrological and hydraulic models are needed to clarify the long-term dynamics of CWD.

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