DYNAMICS OF WOOD TRANSPORT IN STREAMS: A FLUME EXPERIMENT

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ABSTRACT

The influence of woody debris on channel morphology and aquatic habitat has been recognized for many years. Unlike sediment, however, little is known about how wood moves through river systems. We examined some dynamics of wood transport in streams through a series of flume experiments and observed three distinct wood transport regimes: uncongested, congested and semi-congested. During uncongested transport, logs move without piece-to-piece interactions and generally occupy less than 10 per cent of the channel area. In congested transport, the logs move together as a single mass and occupy more than 33 per cent of the channel area. Semi-congested transport is intermediate between these two transport regimes. The type of transport regime was most sensitive to changes in a dimensionless input rate, defined as the ratio of log volume delivered to the channel per second (Q_{log}) to discharge (Q_w); this ratio varied between 0·015 for uncongested transport and 0·20 for congested transport. Depositional fabrics within stable log jams varied by transport type, with deposits derived from uncongested and semi-congested transport regimes having a higher proportion of pieces oriented normal to flow than those derived from congested transport. Because wood input rates are higher and channel dimensions decrease relative to piece size in low-order channels, we expect congested transport will be more common in low-order streams while uncongested transport will dominate higher-order streams. Single flotation models can be used to model the stability of individual pieces, especially in higher-order channels, but are insufficient for modelling the more complex interactions that occur in lower-order streams. © 1997 by John Wiley & Sons, Ltd.

INTRODUCTION

Large woody debris (LWD), commonly defined as logs greater than 1 m long or 0·1 m in diameter, is a major element of stream morphology in forested fluvial systems of the Pacific Northwest and elsewhere. LWD has been shown to cause local scour (Beschta, 1983; Lisle 1986; Bilby and Ward, 1991), and to increase pool frequency (Hogan, 1987; Robison and Beschta, 1990; Montgomery *et al.*, 1995) and hydraulic roughness (Lienkaemper and Swanson, 1987; Montgomery and Buffington, 1993). However, little is known about the dynamics of LWD movement, in particular its interaction with sediment transport. Because it moves only occasionally during large floods (MacDonald *et al.*, 1982; Gregory, 1991), most accounts have been anecdotal and have not discussed the mechanisms of movement in any detail.

Studies in the Pacific Northwest indicate that LWD creates scour pools that provide rearing and resting habitat for salmonids and other fish (Harmon *et al.*, 1986; Lisle, 1986). Much of the wood in Pacific Northwest streams was removed during the last half century in an attempt to decrease obstructions to upstream salmonid migration and river navigation (Sedell and Froggatt, 1984). LWD was also salvaged from streams as timber or removed during log drives, the latter being a common method for transporting logs downstream. With the growing recognition of the ecological importance of LWD over the last 20 years, various governmental agencies have tried to restore streams by deliberately adding wood and growing streamside forests to provide

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long-term recruitment of wood for streams. An understanding of how logs move during flood events, and of the interactions among wood movement, sediment transport, and channel and riparian zone disturbance processes, would help to improve the effectiveness of logs added for ecological value.

Fluvial transport of LWD also poses hazards to human life and property, particularly in countries like Japan where many communities lie at the mouths of steep, forested mountain streams. During large floods and debris flows, these streams transport high concentrations of LWD that dramatically increase the destructive power of such events (Ishikawa, 1989). The Japanese government spends an enormous amount of money trying to protect cities from so-called 'floating log disasters', yet little is known about the physical dynamics of LWD transport. An understanding of the dynamics of LWD transport would help in the design of more effective engineering systems for managing LWD in order to better protect people and property.

The long residence time of *in situ* wood (MacDonald *et al.*, 1982; Gregory, 1991), the modest movement during even 10-year floods (Grant, 1987; Lienkaemper and Swanson, 1987) and the logistical difficulties of making measurements during flood flows all point to a need for flume experiments to understand the dynamics of wood transport. Flume experiments provide a controlled environment where fluvial transport of wood under a range of conditions can be analysed and replicated.

Beginning with a discussion of how wood moves in streams, we present an analytical model that predicts flow conditions required to entrain individual pieces, and describe the results of a series of flume experiments at the Public Works Research Institute (PWRI), Tsukuba, Japan. These experiments examined wood movement as a function of flow conditions, channel morphology, and wood size and input rate. Results of these experiments provide insight into how the depositional fabric of wood accumulations can be used to infer transport dynamics.

HOW DOES WOOD MOVE IN STREAMS?

LWD can be transported in channels by debris flows or stream flow. Debris flow transport of LWD dominates steep, low-order channels. Debris flows entrain LWD lying in their paths, and transport pieces to lower-gradient channels (Keller and Swanson, 1979; Nakamura and Swanson, 1993). This paper primarily addresses fluvial transport of LWD, but interactions between debris flows and streams are an important aspect of LWD transport, particularly as a mechanism for delivering large volumes of wood to streams.

Previous studies on fluvial transport of LWD mapped wood distributions through time in first- to fifth-order streams (Toews and Moore, 1982; Grant, 1987; Lienkaemper and Swanson, 1987; Gregory, 1991; Nakamura and Swanson, 1993). During these studies, when no floods had return intervals greater than 10 years, most wood movement resulted from either the break-up of individual jams (Grant, 1987) or the remobilization of pieces introduced between flood events (Lienkaemper and Swanson, 1987). LWD moves further in large streams than in small streams, and smaller pieces move further than larger pieces (Grant, 1987; Lienkaemper and Swanson, 1987). These patterns imply that piece length relative to channel width is an important factor in wood transport. Rootwads inhibit LWD movement, make pieces more stable, and are therefore an important factor in wood transport (Grant, 1987); however, they were not considered in this study in order to simplify the experiments. In reaches where pieces move occasionally, the pieces tend to accumulate in jams that are quite stable (Grant, 1987; Hogan, 1987). Minimum ages for wood accumulations, calculated by dating nurse trees growing on them, average 50 years in a third-to-fourth-order old-growth forest stream in Oregon, with a maximum age of 150 years (Gregory, 1991). Similarly, in Redwood Creek, California, the jams can be up to 150 years old (MacDonald *et al.*, 1982).

DIFFERENCES BETWEEN SEDIMENT AND WOOD TRANSPORT IN STREAMS

The physics of wood transport differs from that of sediment transport because of differences in shape, density and size of the mobile constituents. Wood is rod-shaped rather than spherical, so the force on the cross-sectional area of the particle is greater for wood than for sediment. Because wood is elongate, with its length often the same dimension as the channel width, pieces have a higher probability of encountering the channel margin than do inorganic sediments, which are often many orders of magnitude smaller than the channel width. The higher probability of encountering the channel margin makes wood more likely to be deposited in shallow areas, or to become lodged against bed or bank obstructions.

Table I. Densities of common species of wood in the Pacific Northwest
at 12 per cent moisture content (USDA Wood Handbook, 1974)

Common name	Species	Density (kg m^{-3})
Douglas fir	*Pseudotsuga menziesii*	537
Sitka spruce	*Picea sitchensis*	449
Western hemlock	*Tsuga heterophylla*	506
Western red cedar	*Thuja plicata*	359
Bigleaf maple	*Acer macrophyllum*	537
Black cottonwood	*Populus trichocarpa*	392
Old-growth redwood	*Sequoia sempervirens*	449

Unless waterlogged, wood is typically less dense than water (Harmon *et al.*, 1986; Table I), causing buoyant forces to be much greater than for inorganic sediments. Because it floats, once entrained wood will continue to move in wide, straight channels unless the water shallows below the threshold for flotation. For coarse inorganic sediments, however, the threshold for transport is defined by the critical shear stress rather than by the threshold for flotation; large variations in shear stress across and along a channel mean that particles are repeatedly entrained and deposited over short distances (Hassan and Church, 1984)

Braudrick and Grant (in preparation) have developed three equations that can be used to analyse the flotation threshold for wood of different densities (ρ_{wood}):

$$\cos^{-1}\left(\frac{r-d_c}{r}\right) - \frac{r-d_c}{r^2}\sqrt{2d_c r - d_c^2} = \frac{\pi\rho_{wood}}{\rho_{water}} \tag{1}$$

for $\rho_{wood} < 500\,\mathrm{kg\,m}^{-3}$

$$r = d_c \tag{2}$$

for $\rho_{wood} = 500\,\mathrm{kg\,m}^{-3}$

$$\sin^{-1}\left(\frac{d_c - r}{r}\right) + \frac{d_c - r}{r^2}\sqrt{2d_c r - d_c^2} = \pi\left(\frac{\rho_{wood}}{\rho_{water}} - \frac{1}{2}\right) \tag{3}$$

for $\rho_{wood} > 500\,\mathrm{kg\,m}^{-3}$

where r is the log radius, d_c is the critical depth at flotation, and ρ_{water} is the density of water. Figure 1 shows the numerical solutions to these equations, with d_w divided by log diameter (D_{log}) plotted against ρ_{wood}/ρ_{water}. The density of wood depends upon the type of wood (species, heartwood versus sapwood) and state of decay. The more advanced the decay, the more easily water saturates logs, increasing density. Density of dry wood varies among species in the Pacific Northwest, but is generally between 350 and 500 kg m^{-3} (Forest Products Laboratory, 1974; Table I).

Wood may move prior to flotation if the force of the water acting upon it is sufficient to overcome the frictional resistance of the log with the bed. Piece length with respect to channel width is an important factor in predicting LWD transport (Bilby, 1983; Lienkaemper and Swanson, 1987), indicating the importance of interactions between wood pieces and the channel. The presence of rootwads may make wood more stable, particularly if the piece is anchored to the bank. Channel roughness may also influence wood transport; sand bars and boulders in streams can inhibit wood movement by causing grounding. For these reasons, Equations 1, 2 and 3 address only some of the forces acting on logs in streams. The flume experiments described below examine the more complex situations typically found in natural streams. In particular, we examine the effect of piece size, input rate and channel geometry on the transport dynamics of wood.
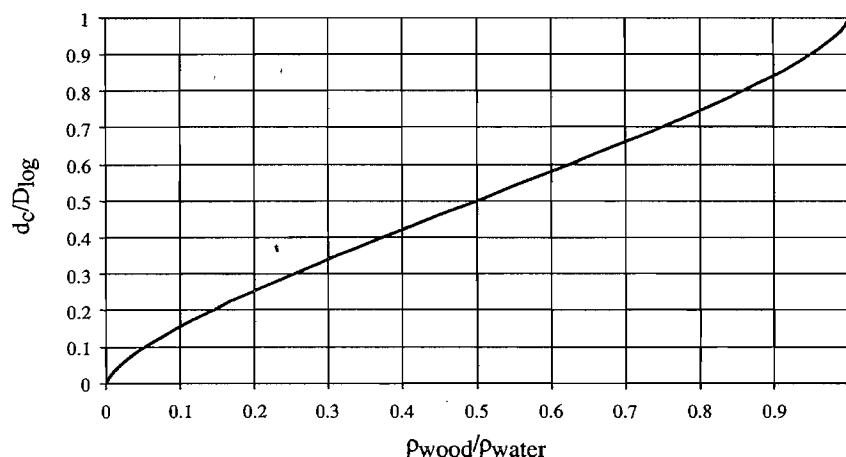
Figure 1. Dimensionless plot of critical floating depth/log diameter (d_c/D_{log}) versus wood density/water density $(\rho_{wood}/\rho_{wood})$ (after Braudrick and Grant, in preparation)

Table II. Flow conditions for the five experiments at PWRI. The submerged log depth assumes the dowels had a density of $500\,kg\,m^{-3}$. The average channel depth was calculated using $Q=AV$, with A representing the average depth multiplied by the width

Run	Log diameter (m)	Log length (m)	Log input rate (logs s^{-1})	Average channel depth (m)	Flow (m^3 s^{-1})
1	0·004	0·4	5	0·027	0·012
2	0·004	0·4	5	0·023	0·009
3	0·002	0·2	5	0·015	0·0045
4	0·004	0·4	1	0·023	0·009
5	0·002	0·2	1	0·015	0·0045

METHODS

We used a mobile-bed flume at PWRI, 15 m long by 1 m wide, with a gradient of 0·01. Two sizes of round wooden dowels (4 cm by 40 cm and 2 cm by 20 cm) were used to simulate logs in five different experiments (Table II). Before each run, the bed of the flume was uniformly covered with a smooth 10 cm thick bed of sand with an average grain size of approximately 1 mm. Water was released in the flume for 30 min, allowing channel morphology and sediment transport to reach equilibrium. The flow was scaled to maintain the Froude number below 1. In each experiment, 200 dowels were released at rates of either five per second or 5 per 5 s. The experiment was repeated five times, three times for the larger dowel size and twice for the smaller dowel size. A video camera suspended over the flume 2–3 m upstream of the flume outlet recorded the movement of dowels through a 1 m^2 area. The video tape was sampled on a video edit machine at 5 s intervals and the number of dowels present and transported through the 1 m^2 area during each 5 s time step were counted. Channel bed elevations were measured at 0·5 m intervals along the flume after each run. Water depth was measured prior to log addition for runs 2 and 3 only.

TYPES OF LOG TRANSPORT

In these flume experiments, individual logs moved by rolling, sliding or floating. When flow was deep enough, flotation was the most common mode of transport observed. Pieces often rolled when they encountered a shallow section of the flume or as they were remobilized from bars where they had been deposited. Although the extent of rolling may have been exaggerated by using smooth cylindrical dowels with no roots or limbs, many
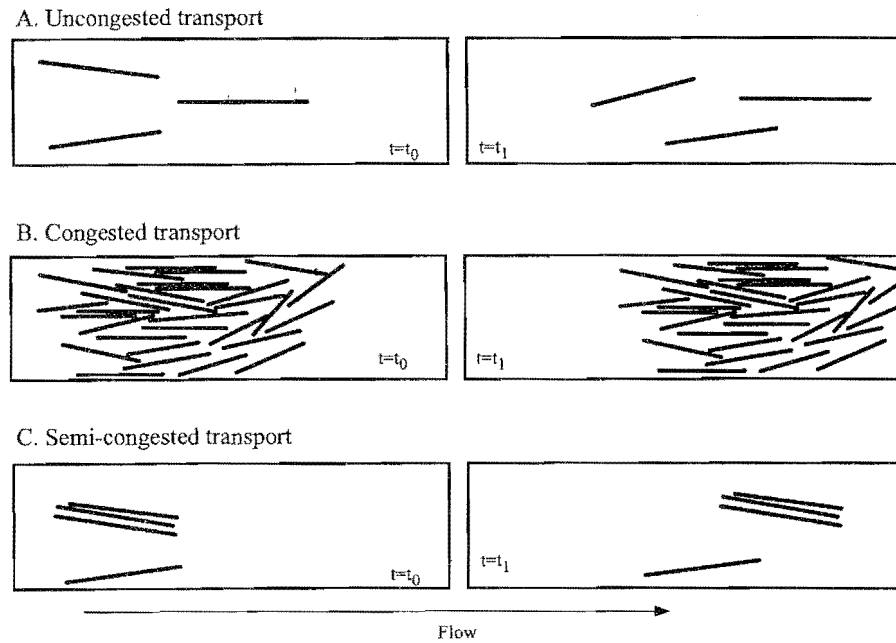
A. Uncongested transport

B. Congested transport

C. Semi-congested transport

Flow

Figure 2. Wood transport regimes. The figures on the left are position at an initial time (t_0) and the figures on the right are the same logs at a later time step (t_1)

natural conifer logs are cylindrical. In natural settings, however, sliding may be more common. Sliding occurred when a large mass of moving logs encountered stationary logs and pushed them downstream.

Previously deposited pieces were remobilized when other logs eroded bars by redirecting flow or whole stationary logs were struck by moving logs. Newly deposited logs diverted flow, causing scour around other logs and reinitiating movement. Remobilization often began with logs rolling or pivoting until they were in deeper water and could float downstream. Large groups of logs moving downstream often remobilized logs in their path, pushing them down the flume.
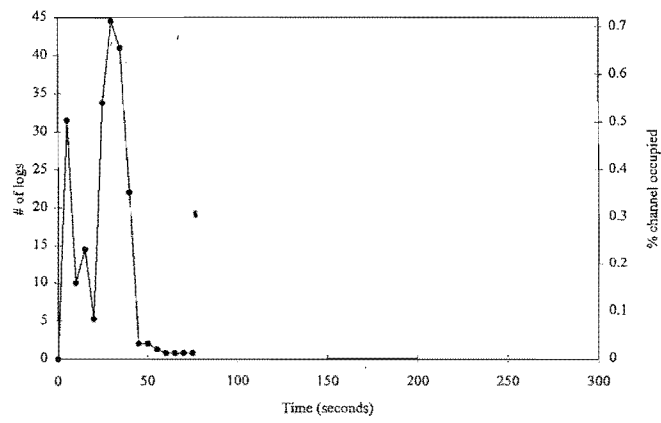
We observed three distinct transport regimes: uncongested, semi-congested and congested transport (Figures 2 and 3). Transport was uncongested when piece-to-piece contact between logs occurred rarely or not at all during movement. During uncongested transport, logs typically occupied less than 10 per cent of the $1 m^2$ sampling area at any time, and the logs responded to obstacles and cross-channel velocity gradients by rotating or rolling independently of other logs. Transport was uncongested at the beginning of each experiment, when log concentrations were low (Figures 3A–D), and throughout run 5 (Figure 3E).

Transport was congested when logs moved as a single mass occupying more than 33 per cent of the sampling area. During congested transport, the spacing between logs was small, with many piece-to-piece contacts, so logs were unable to move independently of each other, and there was little rotation or pivoting of individual logs. Under these conditions, the entire mass of logs moved as a single translatory plug spanning the channel. Some pivoting occurred on the outside of the moving mass during congested flow, with little movement in the interior. Congested transport occurred in runs 1 and 2 (Figures 3A and B).
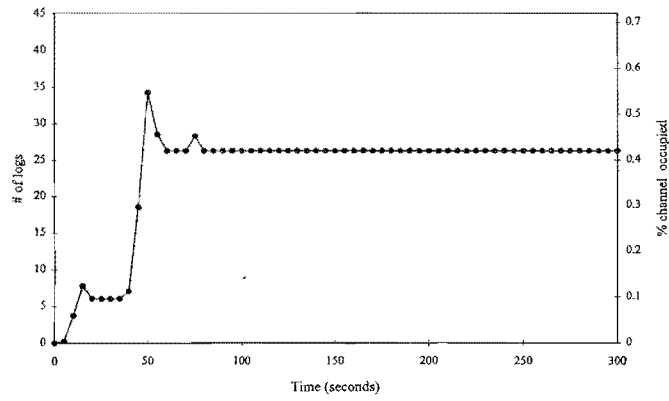
Semi-congested transport was intermediate between these two transport types and occurred when logs occupied 10 to 33 per cent of the channel area. During semi-congested transport, some of the logs moved as individuals and others moved in clumps (usually consisting of three to five pieces). Semi-congested transport dominated runs 3 and 4 (Figures 3C and D). In run 3, transport was semi-congested in a section of the sampling window where a log-defended bar cut the effective width of the channel in half. The logs travelled through this restricted area in clumps, but the clumps broke up below the bar and pieces moved as individuals, indicating that transport may have been uncongested in parts of the channel that were not sampled on video.

Two primary patterns of wood transport and deposition were observed within these dominant transport regimes: pulsed movement, which occurred when a cohort of logs moved together (Figures 3A–C), and the
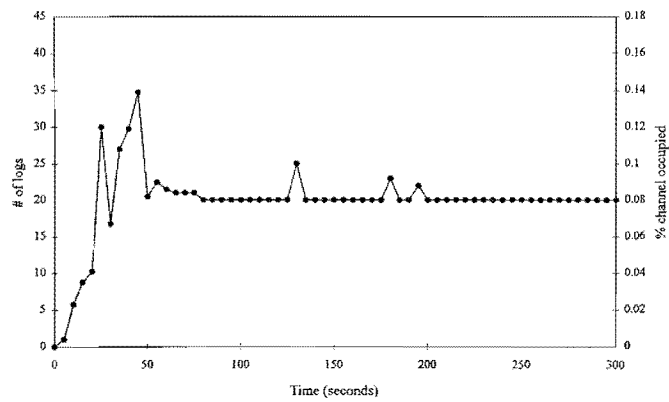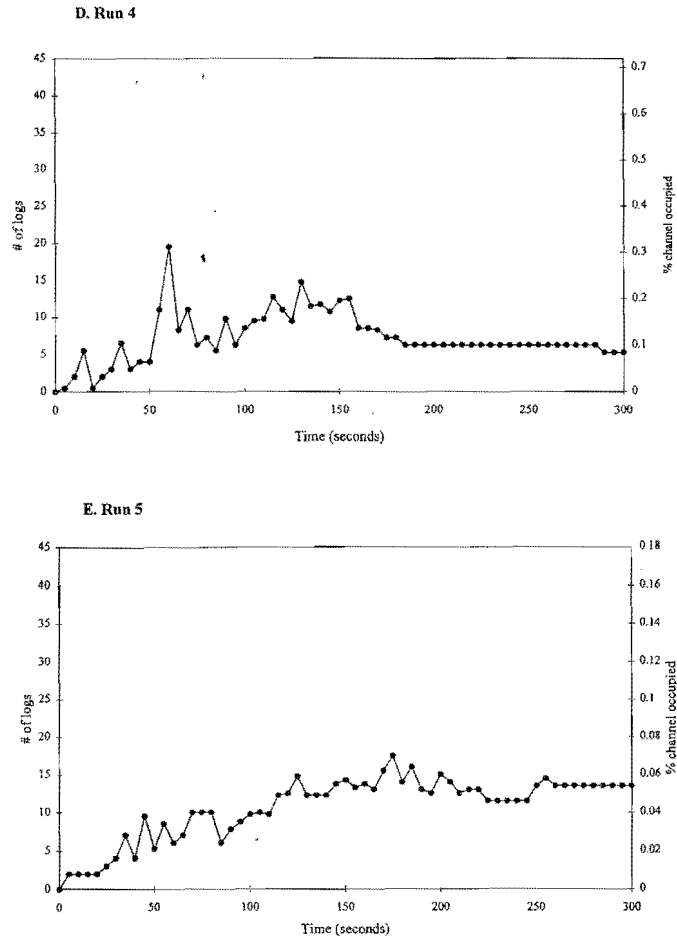
A. Run 1

B. Run 2

C. Run 3

Figure 3. Relation between the number of logs passing through the sampled window (1 m²), the percentage of the channel area covered by logs, and time, for the five experiments

gradual accretion of wood to subaqueous bars (Figures 3D and E). These patterns of wood transport were influenced by the prevailing transport regime. Wood moved in pulses during congested transport (runs 1 and 2) and semi-congested transport (run 3), and accretion of pieces to bars occurred during uncongested transport (run 5) and semi-congested transport (run 4). Pulses were congested or semi-congested, depending on the proportion of the channel area occupied by the cohort. The peak number of logs in the sampled area was higher in run 3 than in run 2, but because the pieces were smaller in run 3, the pulses did not occupy enough area to cause congested transport. Pulses moved through the flume (run 1) or stopped, resulting in the formation of jams that remained stable for the remainder of the experiment (runs 2 and 3). Pulsed movement resulted in the highest piece transport rates, and was responsible for the largest temporal variation in number of pieces sampled per unit time.

FACTORS CONTROLLING WOOD TRANSPORT REGIME

We hypothesized that the three transport regimes could be described by three dimensionless ratios: the relative log input rate, which is the volumetric log input rate divided by the discharge (Q_{log}/Q_w); the relative log length, which is the log length divided by the channel width (L_{log}/w_c); and the relative log diameter, which is the log diameter divided by the average depth of the channel (D_{log}/d_w) (Figure 4).

Of these three ratios, only relative log input rate distinguished between transport regimes. As this ratio increased, transport became more congested. The boundary between uncongested and semi-congested
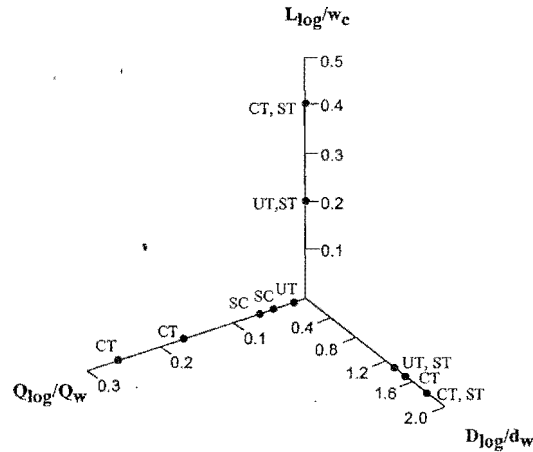
Figure 4. Values of L_{log}/w_c (log length/channel width), D_{log}/d_w (log diameter/channel depth), and Q_{log}/Q_w (volumetric log input rate/ flow) for each run. Data points are labelled with the maximum transport type during each experimental run. UT is uncongested transport, ST is semi-congested transport, and CT is congested transport; Q_{log}/Q_w is the only ratio that differentiates between each transport type

transport was broadly defined between Q_{log}/Q_w values of 0·015 and 0·06. The transport became congested at Q_{log}/Q_w values between 0·07 and 0·20. The L_{log}/w_c and D_{log}/d_w were higher for congested transport (0·4 and 1·5, respectively) than for uncongested transport (0·2 and 1·34, respectively) but did not separate these two regimes from semi-congested transport. These results imply that the transport type may be most sensitive to changes in the log input rate relative to the discharge.

PATTERNS OF WOOD DEPOSITION

Floating wood is likely to be deposited where the wood hits an obstruction, the stream shallows over bars, or pieces encounter a narrow reach of channel. When floating wood passes over a bar, the depth of water may no longer be sufficient to float the log, causing deposition. When a channel is constricted by bedrock outcrops or slope failures, the channel width may become less than the piece length, and deposition or lodging occurs. Obstructions, such as boulders and standing trees, can block wood from being transported downstream by reducing the width of channel available for wood to pass through. A stream with frequent narrow reaches, bars and obstructions promotes wood deposition, and wood will be transported less frequently and for shorter distances than in a stream without these features.

We propose that the inherent ability of a channel to retain wood of a given size is a function of the stream's 'debris roughness', which varies with D_{log}/d_w and L_{log}/w_c. Wood floats until D_{log}/d_w drops below the critical value for flotation for a given density (Figure 1). Similarly, floating wood is deposited or lodged when L_{log}/w_c increases above either 0·5 in wide reaches (Abbe *et al.*, 1993), or 1 in narrow, constrained reaches (Lienkaemper and Swanson, 1987). The debris roughness can be measured at a point or series of points within a channel, but it is used to characterize a stream reach, similarly to hydraulic roughness. Other factors can also influence the debris roughness, such as the presence of other logs and the log transport regime.

We tested some aspects of debris roughness to patterns of wood deposition in these experiments. Because the PWRI flume had a fixed width with varying depth, we were not able to examine the effect of varying L_{log}/w_c within a run. Since L_{log}/w_c ranged from 0·2 and 0·4 in our experiments, i.e. below depositional threshold indicated by field studies (Abbe *et al.*, 1993), we hypothesize that L_{log}/w_c will not influence deposition greatly. Therefore, changes in debris roughness within each run should be controlled primarily by changes in D_{log}/d_w. Maps of water depth before log addition for runs 2 and 3 show the morphology of the flume over a 4·5 m section near the outlet (Figures 5A and B). Both maps show a subaqueous, mid-channel bar, with the deepest flow along the flume walls. The density of the dowels in this experiment was approximately 500 kg m^{-3}, and Equation 2 and Figure 1 show that logs should float until depth drops below half the log diameter ($D_{log}/d_w = 2·0$). In runs 2 and 3,
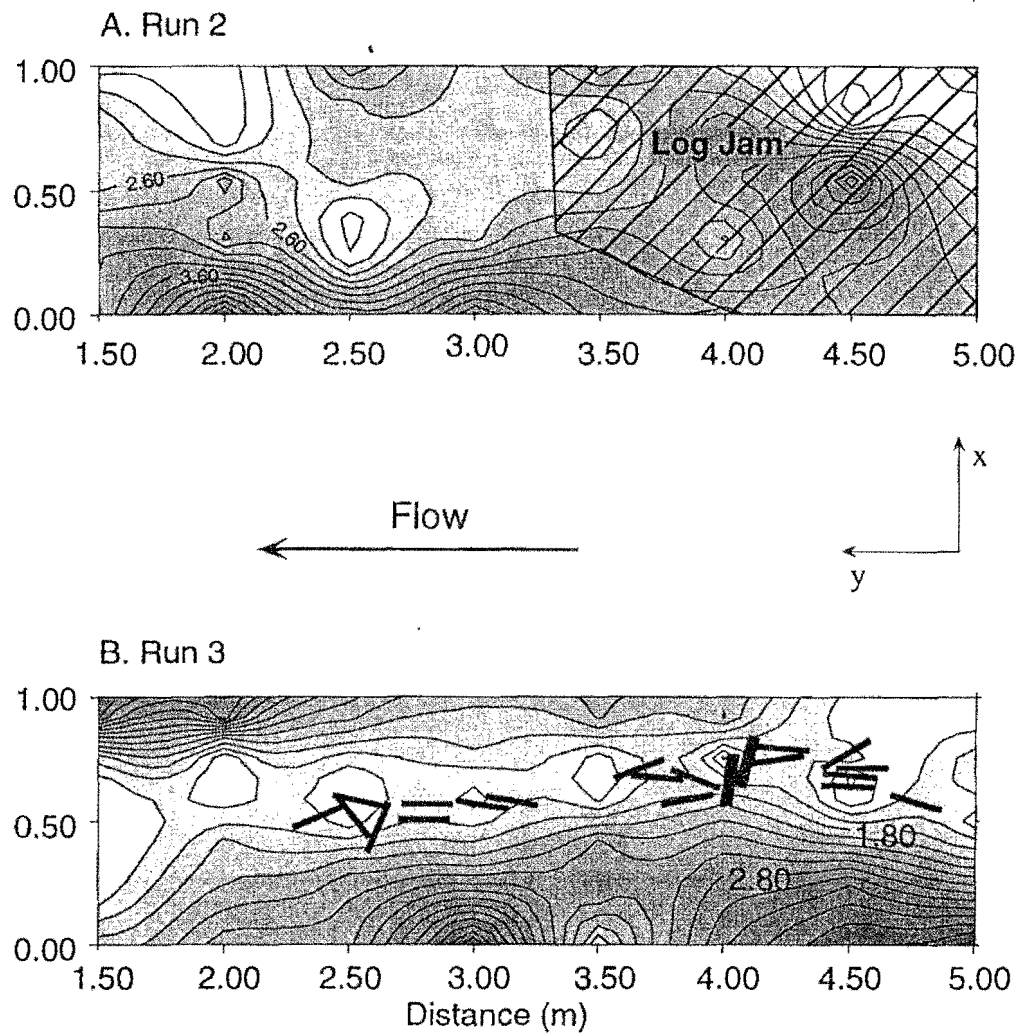
Figure 5. Water depth (in centimetres) prior to log addition, and wood location at the end of the experiment for runs 2 (a) and 3 (b). The contour interval is 0·2 cm, with shading increasing with depth; flow is from right to left; the log jam in run 2 is indicated by the grid pattern

logs were deposited where depth prior to log addition was 2·4 cm ($D_{log}/d_w = 1·67$) and 1·4 cm ($D_{log}/d_w = 1·25$), respectively (Figures 5A and B). The pieces should still float in both runs when D_{log}/d_w is less than 2, so deposition should not occur. Cross-sections of bed elevation at the point of deposition before logs were added to the flume and after wood was removed for runs 2 and 3 indicate that bed elevation increased during both experiments (Figures 6A and B). This shallowing could cause piece deposition, or could have occurred after
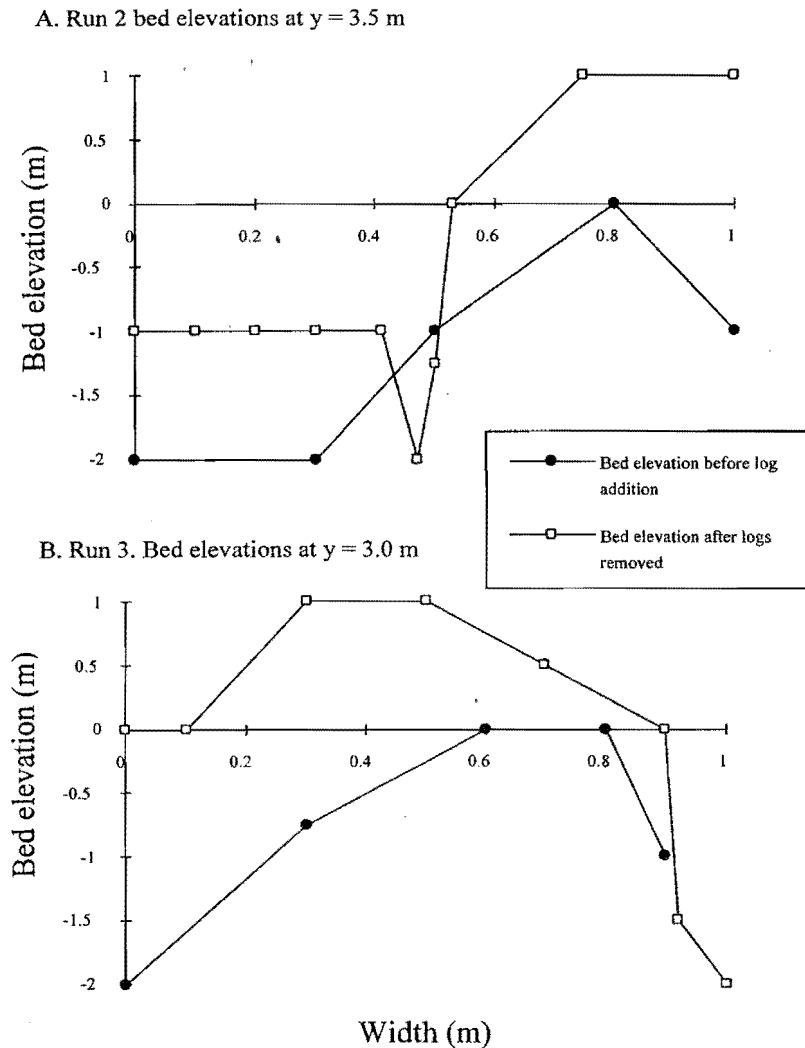
A. Run 2 bed elevations at y = 3.5 m

B. Run 3. Bed elevations at y = 3.0 m

Width (m)

Figure 6. Cross-sections of bed elevation before log addition and after log removal. (a) $y = 3\cdot5$ m for run 2; (b) $y = 3\cdot0$ m for run 3

wood deposition. Because we do not have water depth data during any of the experiments we cannot directly calculate D_{log}/d_w, but infer that the depth decreased sufficiently during the experiment to cause wood deposition.

MODES OF TRANSPORT INFERRED BY DEPOSITIONAL FABRICS OF LOG JAMS

We observed a correlation between transport regime and depositional fabric of log jams deposited following each run. We measured dowel orientations taken from photographs (runs 2 and 3) and from maps (runs 4 and 5) at the conclusion of the experiments; run 1 had few logs left in the flume and was not considered in this analysis. These orientations were plotted as rose diagrams (Figures 7 and 8). Since the dowels had no roots or distinguishable ends, all of the rose diagrams are symmetrical and assume that 0° is downstream (Figures 7 and 8). Runs 3 and 5 could be broken into three sections, with the orientation of each section measured separately.

Results indicate that orientations of dowels can be used to infer transport type by comparing the proportion of flow-parallel to flow-normal pieces. Congested transport (run 2, Figure 8A) results in most pieces oriented roughly 30° to the flow, seen in some debris flows. Fabric of elongate particles in debris flows tends to parallel

A. Run 2 (congested)
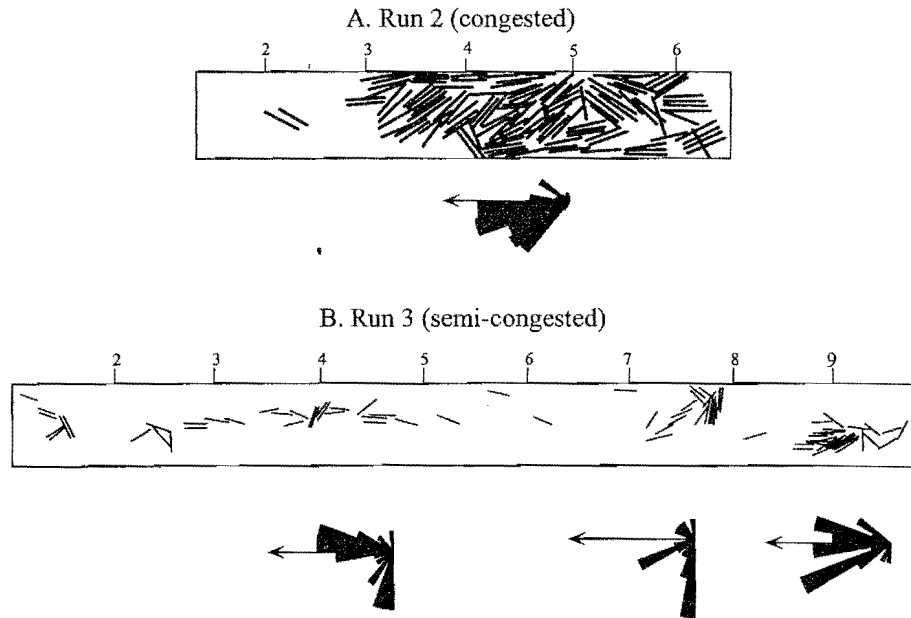

B. Run 3 (semi-congested)

Figure 7. Dowel locations and orientations after runs 2 and 3. Maps were taken from photographs at PWRI. Map of run 2 does not show the entire flume because photographs of the entire flume were not taken. Rose diagrams representing the entire jam of run 2 and three sections of run 3 are shown

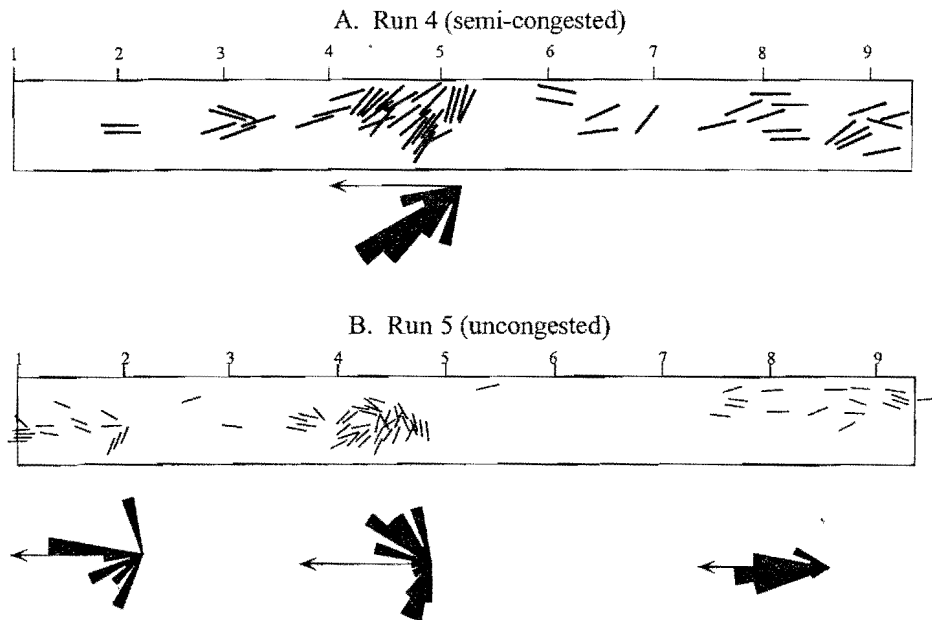A. Run 4 (semi-congested)

B. Run 5 (uncongested)

Figure 8. Dowel locations and orientations after runs 4 and 5. Location and orientation were recorded immediately after the run, and not obtained from photographs. Maps were copied from maps recorded at PWRI. Rose diagrams representings runs 4 and 5 are shown

the margin of the flow wave; thus, at the toe of the deposit, particles are oriented perpendicular to the channel and at the lateral margins, the particles are parallel to the channel (Major and Voight, 1986; Major and Iverson, 1993).

Semi-congested transport (run 3, Figure 7B) left a log levee, with pieces oriented parallel to flow along roughly the same flow-line (Figure 7B, far left). The deposits upstream became a source of mobile wood by re-entrainment, after introduction of pieces 'had ceased, resulting in a more loosely clustered fabric.

Accumulations resulting from uncongested (run 5, Figure 8B) and semi-congested transport (run 4, Figure 8A) had logs oriented parallel to flow at their downstream ends and normal to flow upsteam, similar to the bar-apex jam described by Abbe et al. (1993). During these runs, as logs gradually accreted to bars, slow accumulation allowed individuals or clumps of two or three logs to roll and pivot to a flow-normal orientation. Pieces in the upstream reach of the flume were often oriented parallel to flow, but these pieces were deposited as individuals where pivoting did not occur.

DISCUSSION

Flume experiments have been used to study the mechanics of sediment transport and the consequences for channel morphology (e.g. Langbein and Leopold, 1968; Dietrich et al., 1989; Lisle et al., 1991). Our experiments provide a preliminary picture of the dynamics of LWD transport and of how wood deposits can be used to infer wood transport processes in streams. They also suggest the direction for further field and flume studies in order to clearly describe wood transport.

Wood enters streams by various mechanisms: individual trees or snags enter due to windthrow, tree mortality, or both; large streamside slides and floodplain erosion can cause large quantities of logs to be delivered en masse, as can debris flows. Pieces delivered via windthrow and tree mortality enter the channel as intact or broken pieces, and undergo further breakdown from decay and mechanical erosion until they are floated or entrained by other moving debris during a flood (Nakamura and Swanson, 1993). We propose that these pieces will move largely by uncongested transport and that their stability can be predicted by 'using Equations 1, 2 and 3, or a force balance equation between the wood and water. Streamside slides contribute many trees at one time, which may be immediately redistributed if the flow is high enough. This redistribution can occur as either semi-congested or uncongested transport, depending on the input rate and piece size relative to channel geometry. Debris flows in forested regions typically carry large numbers of logs at their snout that travel as congested transport (Major and Voight, 1986). Where debris flows enter higher-order streams, logs may continue to be transported downstream, or they may be deposited as relatively immobile blockages where they can cause temporary damming, followed by a dam break flood (Coho, 1993). Remobilization of wood jams is a significant modifier of channel morphology in Pacific Northwest streams (Coho, 1993) and in streams in the eastern United States (Hack and Goodlett, 1960; Kochel et al., 1987). Under these circumstances, transport continues as congested or semi-congested.

The type of transport will also change with position in the channel network. Debris flows initiate in low-order tributaries, and remobilized wood jams are most common in first- and second-order streams, but can occur in up to fifth-order streams (Coho, 1993). Consequently, congested transport might be expected to dominate in first- through to fourth-order channels, depending on the drainage network structure. Transport may also be congested in higher order streams if logs are bunched by obstructions, such as bedrock, boulders or bridge abutments. Large dynamic jams can exist in large streams: the Great Raft on the Red River (a tributary of the Mississippi) was over 320km long prior to snags being removed in the 1830s (McCall, 1988). Channel-spanning jams and debris flows are rare in large rivers, however, so we expect congested transport to be uncommon.

High-order streams have large floodplains that can be eroded by high flows, bringing riparian trees into the channel. Because of the low input rates, high flows, and wide and deep channels relative to piece size, uncongested transport should be the dominant type of transport in the lower reaches of the channel network. Uncongested and possibly semi-congested transport may also occur in the upper reaches of the channel network during high flows and low input rates, when congested transport cannot occur.

To discover the causal mechanism for changes in transport regime, we may look to the literature on heterogeneous coarse sediment transport, which reveals a similar trend to that seen in these flume experiments (Reid and Frostick, 1987; Iseya and Ileda, 1987; Lisle et al., 1991). Iseya and Ileda (1987) noted three different bed states during a flume experiment – smooth, transitional and congested – resulting from particle–particle

interaction; these states are analogous to the wood transport regimes (uncongested, semi-congested and congested) seen in our experiments. Reid and Frostick (1987) noted two separate regimes of sediment transport – loosely clustered and open-plane bed – in Turkey Brook, England. These two studies found that congestion was caused by an increase in interaction of particles. Iseya and Ikeda (1987) proposed that an increase in coarse sediment supply increases the interaction among particles, creating increased congeston. Reid and Frostick (1987) see similar results (although they only have two regimes) and suggest that kinematic wave theory (Langbein and Leopold, 1968) may provide an explanation for the patterns observed. We do not have enough data to prove or disprove the applicability qf kinematic wave theory to wood transport, but congestion certainly increases with increases in particle interaction, suggesting that kinematic wave theory may explain changes in wood transport regime.

Field studies show that deposited piece size increases with stream size (Bilby and Ward, 1989; Abbe *et al.*, 1993). Bilby and Ward (1989) found that piece length, diameter and volume increased with increasing stream width. Abbe *et al.* (1993) found that key members of wood jams – pieces that initiate a jam – had D_{log}/d_w and L_{log}/w_c (at bankfull) greater than 0·5 on the Queets River, Washington. These studies, and the results of our flume experiment, indicate that the debris roughness of a stream could be quantified from a knowledge of channel geometry, and tree height and diameter. Further flume and field studies are needed to quantify the relative importance of D_{log}/d_w and L_{log}/w_c, and perhaps other factors (i.e. obstruction spacing, sinuosity) as well (Nakamura and Swanson, 1994).

Because congestion may increase with decreasing stream order, fabrics of deposits might be expected to change throughout a stream network. In low-order streams, deposits with flow-parallel pieces would be expected along reaches where debris flow input of pieces is common, and flow-normal pieces would be expected where pieces are input and transported individually. As stream order increases, more and more of the deposits should have their pieces oriented normal to flow, unless they are deposited on the lateral margins of the stream where they can be deposited parallel to flow. Remobilized jams may retain some of their congested character when redeposited.

Floating log disasters occur when a high concentration of logs is transported downstream by a flood or debris flow. More than 19 000 logs overran the channel in a single disaster in Japan in 1990 (Ishikawa *et al.*, 1991). These concentrations resemble congested transport seen in these experiments. To prevent such disasters, the transport rate of the logs needs to be reduced. If log traps can be built to keep Q_{log}/Q_w below 0·15, and concentration and log transport rates low, thereby causing wood to move via uncongested and semi-congested regimes (Figure 4), the extent of these disasters could be reduced.

Restoring streams to improve aquatic habitat requires the reintroduction of wood into streams where the wood has been removed by salvage, log drives and removal of streamside forests. Often, the distribution and structure of wood accumulations before human influences is unknown. Our studies showed how wood structure and transport should change as a function of position within the channel network; this geomorphic context needs to be understood to guide effective placement of wood for long-term stability. A quantitative understanding of how wood moves in streams is needed to assess the stability of wood added, and to prevent congested transport from posing threats to communities and structures downstream.

CONCLUSIONS

These experiments provide a preliminary picture of the dynamics of wood transport in streams. Wood was transported via three transport regimes – uncongested, semi-congested and congested – which can be distinguished by the degree of interaction among pieces. These transport regimes are analogous to transport regimes seen in the transport of coarse-grained, heterogeneous, inorganic sediments. Wood was deposited in the shallowest areas of the flume, but we lacked the resolution of bottom elevation measurements to accurately test the theoretical model posed in the first part of the paper. Wood deposits resulting from uncongested and semi-congested transport tended to have a majority of their pieces oriented normal to flow. The results of these experiments suggest a framework for expanding particle transport models to include woody debris.

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