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Transport and deposition of large woody debris in streams: a flume experiment

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Abstract

Large woody debris (LWD) is an integral component of forested streams of the Pacific Northwest and elsewhere, yet little is known about how far wood is transported and where it is deposited in streams. In this paper, we report the results of flume experiments that examine interactions among hydraulics, channel geometry, transport distance and deposition of floating wood. These experiments were carried out in a 1.22-m-wide × 9.14-m-long gravel bed flume using wooden dowels of various sizes as surrogate logs. Channel planforins were either self-formed or created by hand, and ranged from meanders to alternate bars. Floating pieces tended to orient with long axes parallel to flow in the center of the channel. Pieces were deposited where channel depth was less than buoyant depth, typically at the head of mid-channel bars, in shallow zones where flow expanded, and on the outside of bends. We hypothesize that the distance logs travel may be a function of the channel's debris roughness, a dimensionless index incorporating ratios of piece length and diameter to channel width, depth and sinuosity. Travel distance decreased as the ratio of piece length to both channel width and radius of curvature increased, but the relative importance of these variables changed with channel planform. Large pieces can move further than our debris roughness models predict if greater than 50% of the active channel area is deeper than the buoyant depth of the piece, or if momentum is high enough to carry pieces across shallows. Our debris roughness model allows first-ordcr prediction of the amount of wood transport under various channel geometries. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Woody debris; Channel morphology; Flume experiments; Wood transport

1. Introduction

Large woody debris (LWD) is an integral geomorphic and ecologic component of forested streams. Wood is often seen as a relatively immobile component of streams, since most studies on wood dynamics have focused on relatively small streams where piece length is longer than channel width, and large floods capable of moving wood are infrequent. Recent floods in the Pacific Northwest and California, however, resulted in significant wood movement in many large and small streams. Extensive new accumulations of wood and addition of new wood to existing log jams in streams, and the collection of wood in reservoirs and lakes, attest to the high rates of wood transport during these recent floods.

LWD can have profound effects on the morphology of forested streams (Montgomery et al., 1995, 1996; Hogan et al., 1999), but has received compara-

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tively little study by geomorphologists relative to the other components of fluvial systems. LWD contributes to both sediment erosion (Beschta, 1983) and deposition (Hogan et al., 1999), creating pools and storing large volumes of sediment (Assani and Petit, 199.5; Thompson, 1995; Hogan et al., 1999). The removal of wood from streams alters stream morphology, increasing the sediment transport rate, and causing pools to shallow (Smith et al., 1993a,b; Lisle, 199.5). In small streams, steps due to LWD

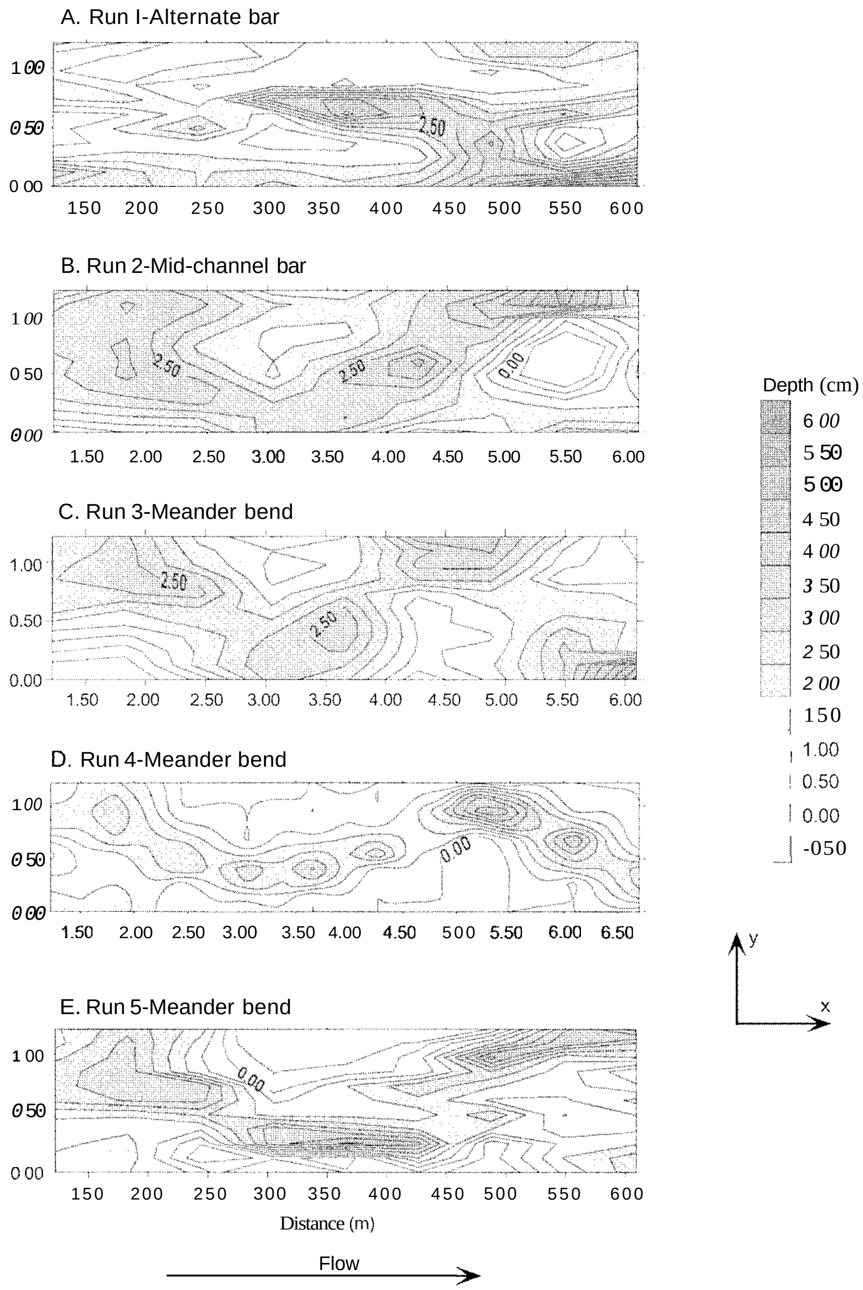


Fig. 1. Contour maps of depth for each run.

jams can account for a significant portion of the head loss in streams (Marston, 1982; Thompson, 1995). In order to assess these potential effects of wood on the morphology of streams, we need to understand where wood will deposit and how long it will remain in a given reach.

Moving wood can be a geomorphic hazard in communities adjacent to forested mountain streams. Wood dramatically increases the destructive power of floods and debris flows, by increasing the force imparted to structures and riparian forests, and accumulating behind bridge abutments and culverts, causing backwater flooding. This is of particular concern in Japan and other countries where high population densities occur along mountain streams. Models that predict when and where wood will be entrained or deposited, and factors that promote wood deposition could mitigate such destructive events.

Wood enhances aquatic habitat by creating refugia that serve as resting and rearing habitat (Harmon et al., 1986; Lisle, 1986), and by providing nutrients to the stream (Harmon et al., 1986). Because stream management practices in the past resulted in removal of in-stream wood and logging of streamside forests, many streams in the Pacific Northwest and elsewhere have low densities of wood compared with historic levels (Sedell and Froggatt, 1984; Harmon et al., 1986). Currently, stream restoration programs are seeking to improve aquatic habitat and other aquatic functions by adding wood back to streams. Because we lack quantitative models of wood transport and deposition, these expensive efforts to replace wood typically do not consider wood stability and movement potential in their design.

Wood primarily moves during large floods when safety and logistical constraints impede direct measurement of transport dynamics. To overcome this, we tested a quantitative model predicting wood transport distance and depositional location using flume experiments. Flume experiments, which have historically been used primarily to study sediment transport in streams, are increasingly being used to

Table 1
Piece sizes, flow hydraulics, and channel pattern used in these experiments, by run

Run	Length (m)	Diameter (cm)	Channel pattern	Mean depth (cm)	Mean Froude number
1A	0.3	1.27	Alternate bars[a]	1.49	1.12
1B	0.6	1.27	Alternate bars[a]	1.49	1.12
1C	0.3	2.54	Alternate bars[a]	1.49	1.12
1D	0.6	2.54	Alternate bars[a]	1.49	1.12
2A	0.3	1.27	Mid-channel bar	1.95	1.05
2B	0.6	1.27	Mid-channel bar	1.95	1.05
2 c	0.3	2.54	Mid-channel bar	1.95	1.05
2D	0.6	2.54	Mid-channel bar	1.95	1.05
3A	0.3	1.27	Meander-bend	1.46	1.35
3B	0.6	1.27	Meander-bend	1.46	1.35
3c	0.3	2.54	Meander-bend	1.46	1.35
3D	0.6	2.54	Meander-bend	1.46	1.35
4A	0.3	1.27	Meander-bend	1.59	1.32
4B	0.6	1.27	Meander-bend	1.59	1.32
4 c	0.9	1.27	Meander-bend	1.59	1.32
4D	0.3	2.54	Meander-bend	1.59	1.32
4E	0.6	2.54	Meander-bend	1.59	1.32
4F	0.9	2.54	Meander-bend	1.59	1.32
5A	0.3	1.27	Meander-bend	1.62	1.24
5B	0.6	1.27	Meander-bend	1.62	1.24
5C	0.9	1.27	Meander-bend	1.62	1.24
5D	0.3	2.54	Meander-bend	1.62	1.24
5E	0.6	2.54	Meander-bend	1.62	1.24
5F	0.9	2.54	Meander-bend	1.62	1.24

[a] Indicates that the channel was self formed.

study wood movement and hydraulics as well (e.g. Ishikawa, 1989; Gippel et al., 1996; Braudrick et al., 1997; Braudrick and Grant, 2000).

In this paper, we report on a series of flume experiments on wood transport conducted at the St. Anthony Falls Hydraulic Laboratory, Minneapolis, MN. These experiments were designed to test a semiquantitative model of wood transport by fluvial process based upon piece and reach-average channel characteristics. Because thresholds of movement and deposition have not previously been quantified, our studies focused on the simple case of transport and deposition of individual logs. Interactions among multiple pieces can both increase and decrease piece transport: piece-to-piece collisions can entrain previously deposited pieces, while immobile pieces can obstruct moving pieces, causing deposition, and formation of log jams (Abbe and Montgomery, 1996; Braudrick et al., 1997). Here, we neglect these more complex dynamics in order to develop simple physical models to describe movement of individual pieces. We also emphasize fluvial processes while recognizing that wood transport by debris flows may involve other mechanisms (Braudrick et al., 1997).

2. Background and theory of wood transport

Previous field studies on fluvial transport of LWD inferred transport relations from mapped temporal changes in LWD distribution in first- to fifth-order streams (Toews and Moore, 1982; Hogan: 1987; Lienltaemper and Swanson, 1987; Bilby and Ward, 1989; Gregory, 1991; Nakamura and Swanson, 1994; Young, 1994). These studies showed that LWD moves farther and more frequently in large ($\geq$ fifth order) than small ($<$ fifth-order) streams (Bilby, 1985; Lienkaemper and Swanson, 1987; Bilby and Ward, 1989, 1991), smaller pieces move farther than larger pieces (Lienkaemper and Swanson, 1987; Young, 1994), and most mobile pieces are shorter than bankfull width (Nakamura and Swanson, 1994). These studies suggest that piece length relative to average channel width (L_{log}/w_{av}) is a good first-order approximation of the likelihood of piece movement, and the distance it will travel once in motion.

Other piece characteristics besides length can affect both the distance a piece travels and its frequency of transport. Rootwads can inhibit LWD movement by anchoring pieces to the bed or bank, increasing drag and thereby decreasing mobility (Abbe and Montgomery, 1996). Piece diameter strongly influences depth of flow required to entrain and transport logs, thereby influencing distance traveled (Bilby and Ward, 1989; Abbe el al., 1993; Braudrick et al., 1997; Braudrick and Grant, 2000). Pieces tend to stop when the channel depth is approximately half the piece diameter (Abbe et al., 1993).

Channel morphology is also a factor in determining the distance a piece travels. Wood is often deposited in wide, sinuous reaches, where channel curvature and alternate bar morphology promote frequent contact between the wood and the channel

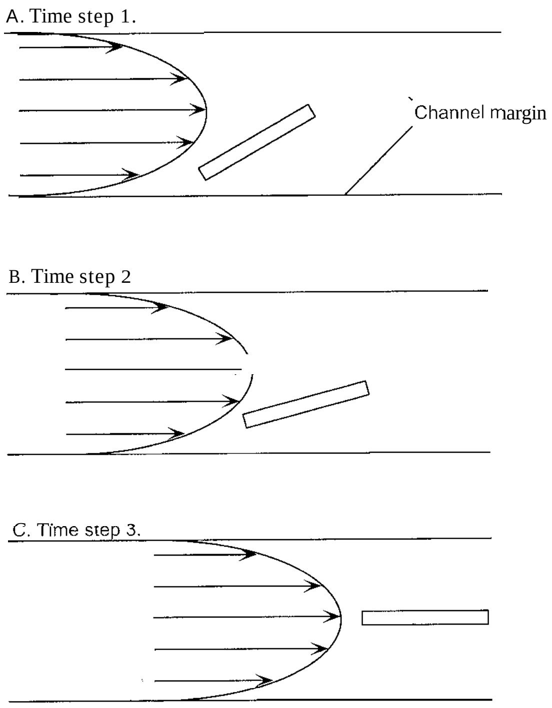


Fig. 2. Schematic diagram showing velocity field across a hypothetical channel, and its effect on piece orientation. In time step 1, the velocity is higher at the downstream end of the piece than the upstream end of the piece. Because one end of the piece is moving faster than the other end, the piece rotates toward a more flow-parallel orientation as shown in time step 2. Since the velocity field still varies across the piece, the piece continues to rotate toward the flow-parallel orientation shown in time step C, where the piece has achieved a stable orientation.

margins (Nakamura and Swanson, 1994). In narrow, straight reaches, on the other hand, high shear stresses, deep flows, and limited bar development cause pieces to flush through (Nakamura and Swanson, 1994). Pieces tend to deposit on the outside of bends and the head of islands and bars (Nakamura and Swanson, 1994; Abbe and Montgomery, 1996). Pieces also tend to lodge against large boulders and other immobile pieces, forming log jams (Nakamura and Swanson, 1994).

Previous field studies provide a basis for a quantitative model of wood movement and deposition. Braudrick et al. (1997) defined those in-stream factors that promote wood deposition and inhibit wood

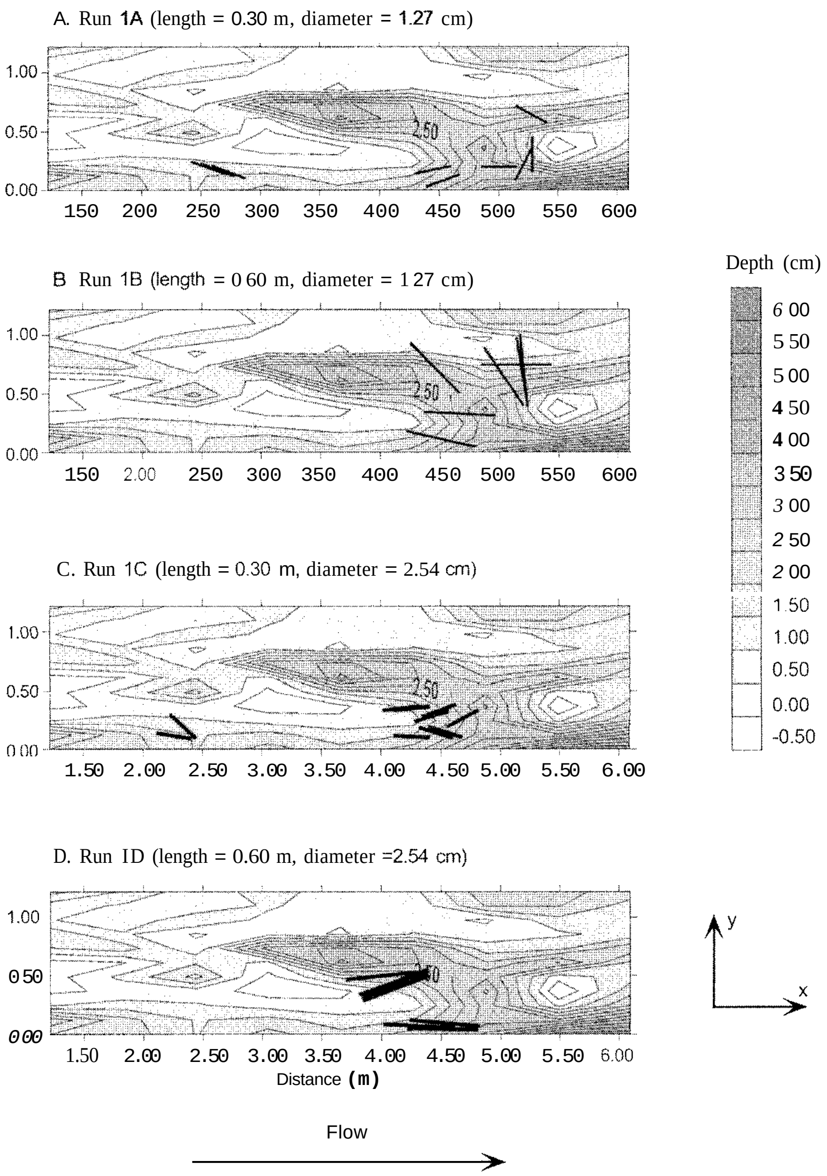


Fig. 3. Maps of water depth and depositional location of pieces for runs 1A–1D

transport as a stream's *debris roughness*. The debris roughness is a reach-average value that is the sum of all factors tending to extract wood from the flow, much as hydraulic roughness extracts kinetic energy from the flow. Field evidence suggests that three channel characteristics — channel width, sinuosity and channel depth — and two woody debris characteristics — piece length and piece diameter — influence wood deposition (e.g. Lienkaemper and Swanson, 1987; Bilby and Ward, 1989, 1991; Abbe et al., 1993; Nakamura and Swanson, 1994; Young, 1994). We propose that three dimensionless ratios based on these piece and channel characteristics describe the probability that wood will be deposited: piece length to mean channel width (L_{log}/w_{av}), piece length to the mean radius of curvature (L_{log}/R_c), and buoyant

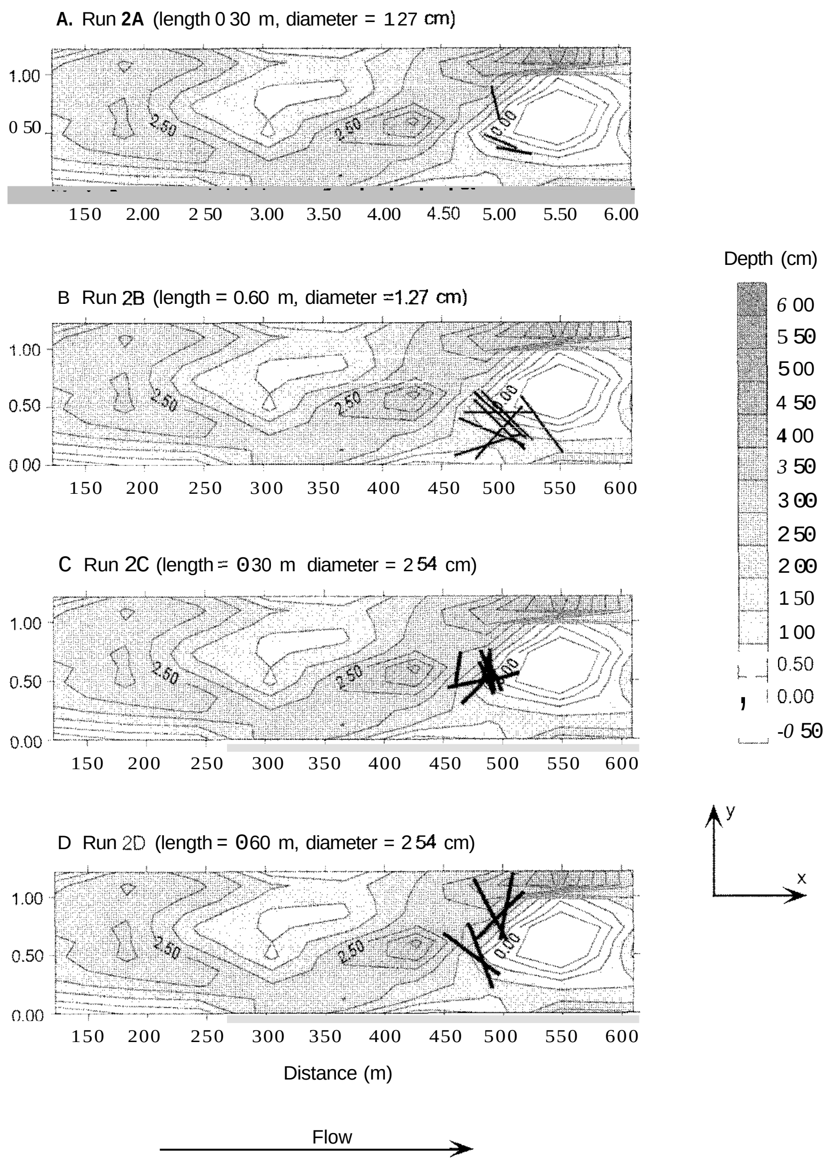


Fig. 4. Maps of water depth and depositional location of pieces for runs 2A–2D

depth to average channel depth (d_b/d_{av}). Buoyant depth (d_b), the depth at which flotation occurs for pieces of a given diameter and density, is used as a proxy for piece diameter and accounts for varied wood densities of the dowels used in these experiments (Braudrick et al., 1997; Braudrick and Grant, 2000). We also define the radius of curvature of the channel (the radius of a circle that best defines the bend of the channel) as a proxy for sinuosity.

Using these dimensionless ratios, we construct a simple equation for debris roughness (DR):

$$\mathrm{DR} \propto \left(a_1 \frac{L_{\log}}{w_{\mathrm{av}}} + a_2 \frac{L_{\log}}{R_{\mathrm{c}}} + a_3 \frac{d_{\mathrm{b}}}{d_{\mathrm{av}}} \right) \qquad (1)$$

where a_1, a_2 and a_3 are coefficients that vary according to the relative importance of each variable. Other factors that could be included in a debris

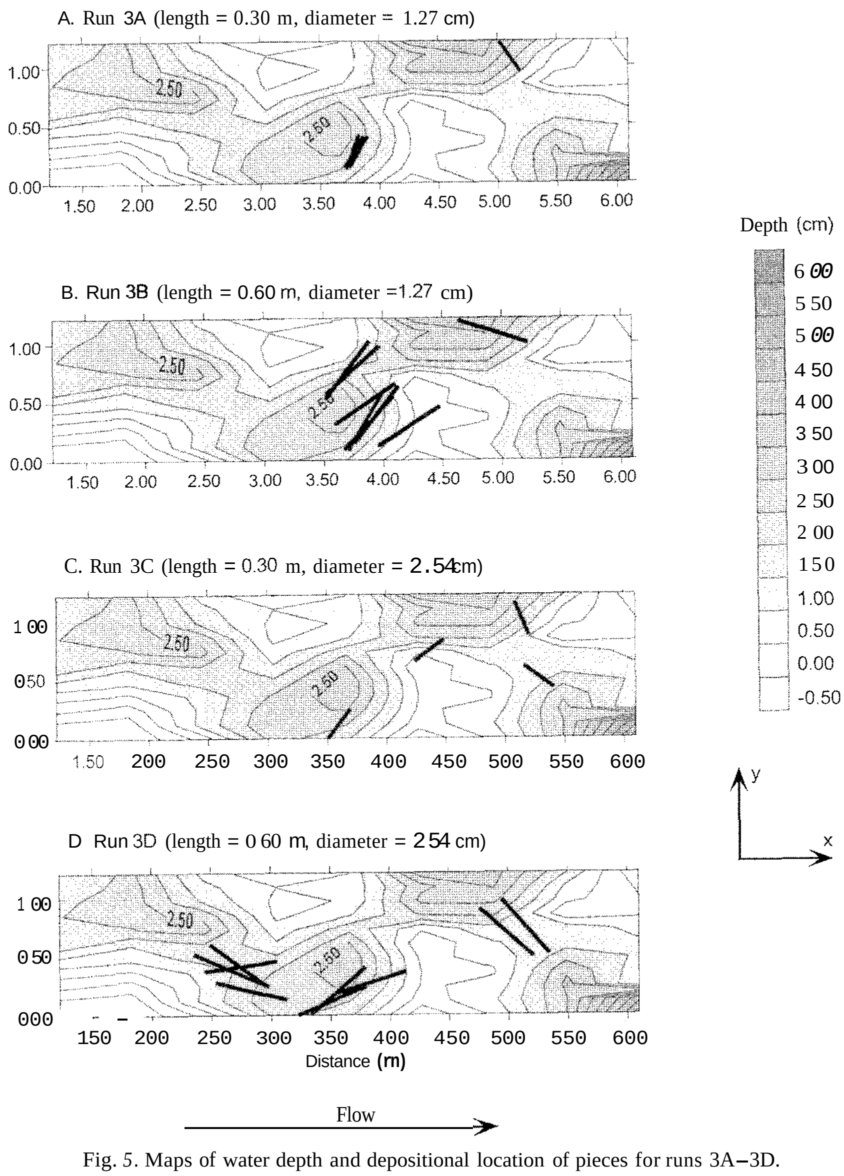


Fig. 5. Maps of water depth and depositional location of pieces for runs 3A–3D.

roughness equation include the hydraulic relative roughness D_{84}/d_{av}, where D_{84} is the 84th percentile of the grain size distribution, and local constrictions in width; however, we neglect these factors

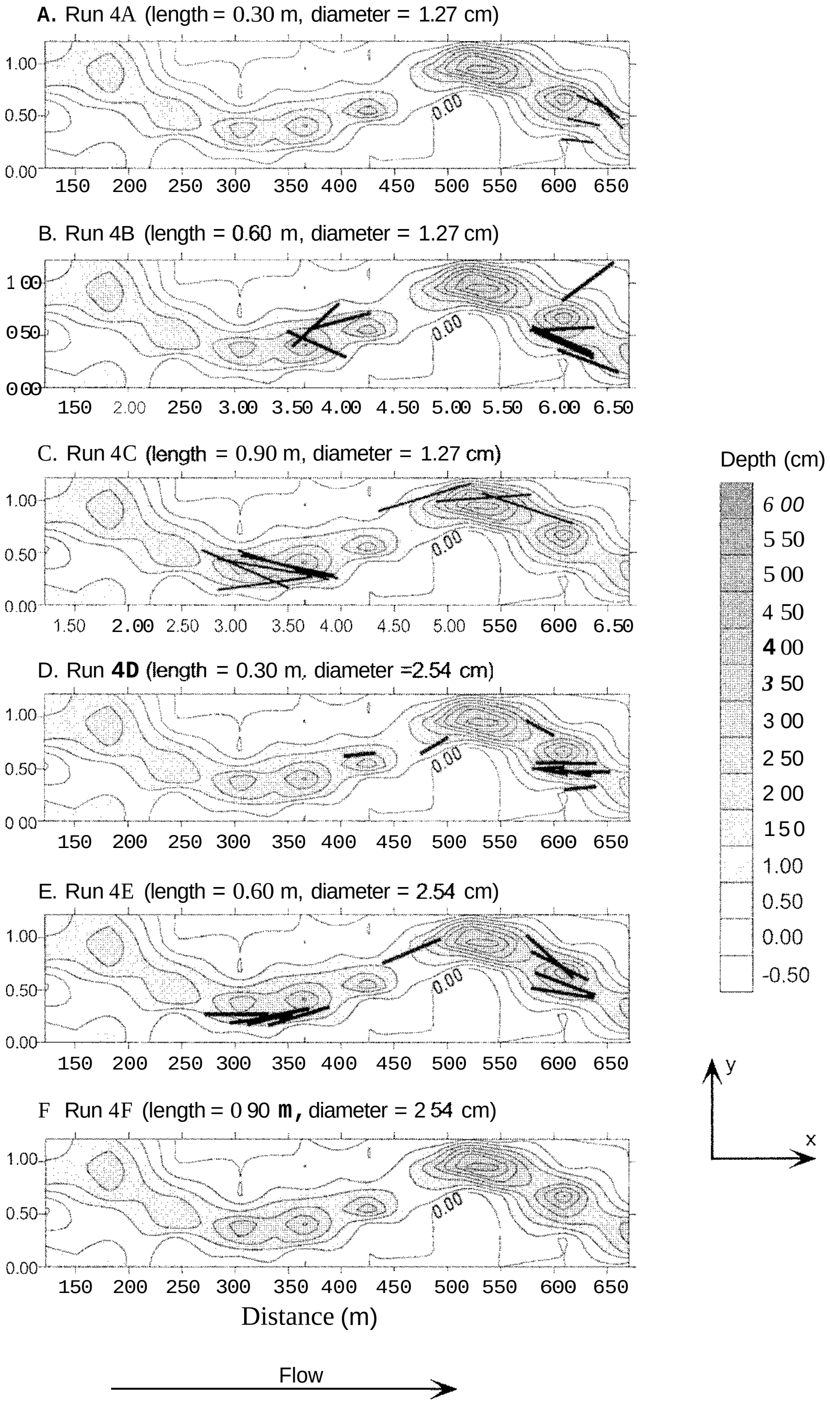


Fig. 6. Maps of water depth and depositional location of pieces for runs 4A–4F

in this initial analysis. While reach-average values, such as those used in Eq. (1), should generally predict the relative ability of streams to transport wood, local conditions can sometimes be more im-

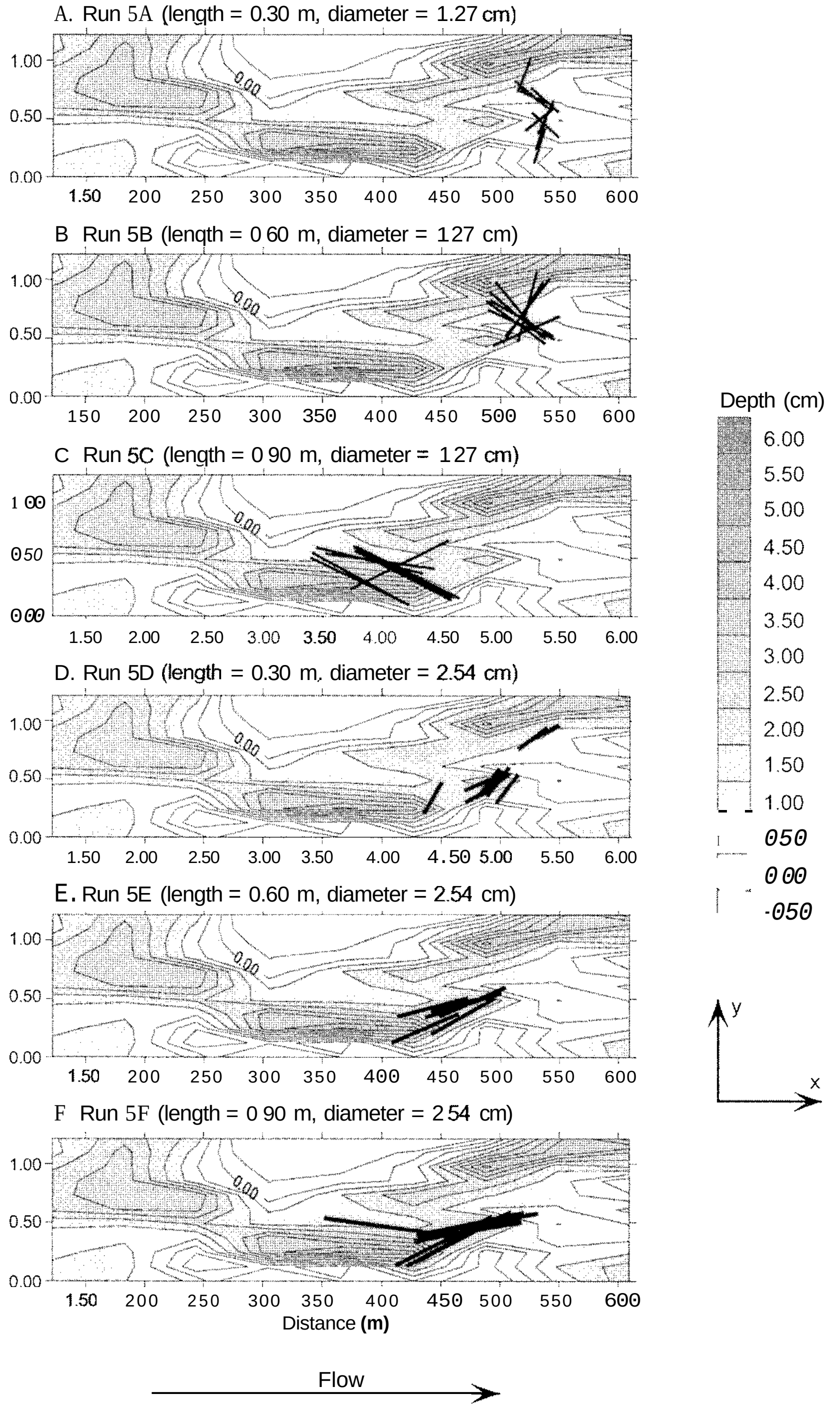


Fig. 7. Maps of water depth and depositional location of pieces for runs 5A–5F.

Table 2
Experimental conditions, percent of pieces retained, and distance traveled by run

Run	L_{log}/w_{av}	L_{log}/w_{min}	d_b/d_{av}	L_{log}/R_c	Maximum L_{log}/R_c	Mean transport distance (m)	% Tranported through flume
1A	0.53	0.97	0.57	0.18	0.50	4.78	10
1B	1.05	1.94	0.42	0.36	1.00	5.67	30
1C	0.53	0.97	1.03	0.18	0.50	4.39	0
1D	1.05	1.94	1.17	0.36	1.00	4.82	10
2A	0.29	0.91	0.35	0.26	0.18	6.48	70
2B	0.58	1.82	0.41	0.51	0.36	5.55	20
2C	0.29	1.00	0.78	0.26	0.18	5.09	0
2D	0.58	2.00	0.90	0.51	0.36	6.02	50
3A	0.26	0.27	0.47	0.19	0.39	5.96	60
3B	0.52	0.53	0.53	0.38	0.76	4.53	10
3C	0.26	0.27	1.05	0.19	0.39	6.13	60
3D	0.52	0.53	1.20	0.38	0.76	4.21	10
4A	0.28	0.50	0.50	0.24	0.30	6.77	50
4B	0.56	1.00	0.48	0.47	0.60	5.74	10
4C	0.84	1.50	0.47	0.71	0.90	4.24	0
4D	0.28	0.50	0.96	0.24	0.30	5.91	0
4E	0.56	1.00	1.10	0.47	0.60	4.85	0
4F	0.84	1.50	0.87	0.71	0.90	7	100
5A	0.34	0.51	0.49	0.24	0.20	5.47	0
5B	0.69	1.02	0.48	0.47	0.40	5.50	10
5C	1.03	1.53	0.46	0.71	0.60	4.35	0
5D	0.34	0.53	0.94	0.24	0.20	5.16	0
5E	0.69	1.02	1.08	0.47	0.40	5.71	40
5F	1.03	1.53	0.85	0.71	0.60	4.86	0

portant that reach-average conditions. This is particularly true where there are local obstructions, such as log jams, or an abnormally sharp bend.

Flume experiments allow us to vary the constituents of Eq. (1) over a relatively wide range to test their relative importance. Here we report results from a series of experiments designed to predict how these first-order controls on piece transport distance and depositional location varied in relation to different channel morphologies and piece sizes.

3. Methods

We conducted flume experiments at the University of Minnesota's St. Anthony Falls Hydraulic Laboratory, Minneapolis, MN. The flume was 1.22 m wide and 9.14 m long, with a fixed slope of 1%. The sediment for all experiments was pea gravel with D_{50} of approximately 8 mm. Cylindrical wooden dowels with densities ranging from 436 to 735 kg/m^3 were used to simulate logs. Dowel density varied even among pieces of equal diameter. Flow depth was measured with a point gauge. Average velocity was measured using a float and stopwatch. A coordinate system was created with X along the flume length, Y measured across the flume

Table 3
Results of regression analysis of distance traveled for all runs

Independent variable	Coefficient	Standard error	P value	R^2
Constant	5.117	0.196	0.000	
d_b/d_{av}	0.197	0.114	0.087	0.008
Constant	6.019	0.163	0.00	
L_{log}/w_{av}	– 1.013	0.255	0.000	0.063
Constant	5.960	0.154	0.000	
L_{log}/R_c	– 1.027	0.268	0.000	0.055

Each independent variable was run separately. N = 235 and Z as elevation. We measured both water surface and bed elevations at intervals of 0.60 m in the X direction, and 0.15 m in the Y direction, with finer measurement intervals in areas of complex morphology.

Channel morphology was either self-formed or created manually; the latter permitted construction of a range of channel configurations. There were five channel morphologies used in these experiments. Run 1 had alternate bars and was the only self-formed channel morphology. Run 2 had one-meander bend and an emergent mid-channel bar. Runs 3, 4 and 5 were all meander-bend channels where run 3 had the highest sinuosity and lowest radius of curvature, run 4 had emergent bars, and run 5 had submerged bars (Fig. 1). In every case, water was run through the flume until a stable channel configuration was formed, and sediment transport had ceased. Wood pieces were introduced into the top of the flume, oriented parallel to the flume length, and the coordinates of the ends of the pieces were recorded after deposition. After the location was noted, the pieces were removed from the flume so that piece–piece interactions did not play a role in the experiments.

For each channel morphology either 4 (2 lengths × 2 diameters; runs 1, 2 and 3) or 6 (3 lengths × 2 diameters; runs 4 and 5) dowel length and diameter combinations were used (Table 1). For each diameter/length combination, ten trials were conducted. A criterion for dowel movement of at least 1 m downstream from the entry point was used to eliminate feed effects; on this basis, five of the pieces in run 1 were excluded from the analysis. Backwater effects from the tailgate started to affect flow beyond 7 m, so only data from the upstream-most 7 m were used. The distance traveled was measured from the point of introduction to the midpoint of the deposited piece. Average channel width was calculated by

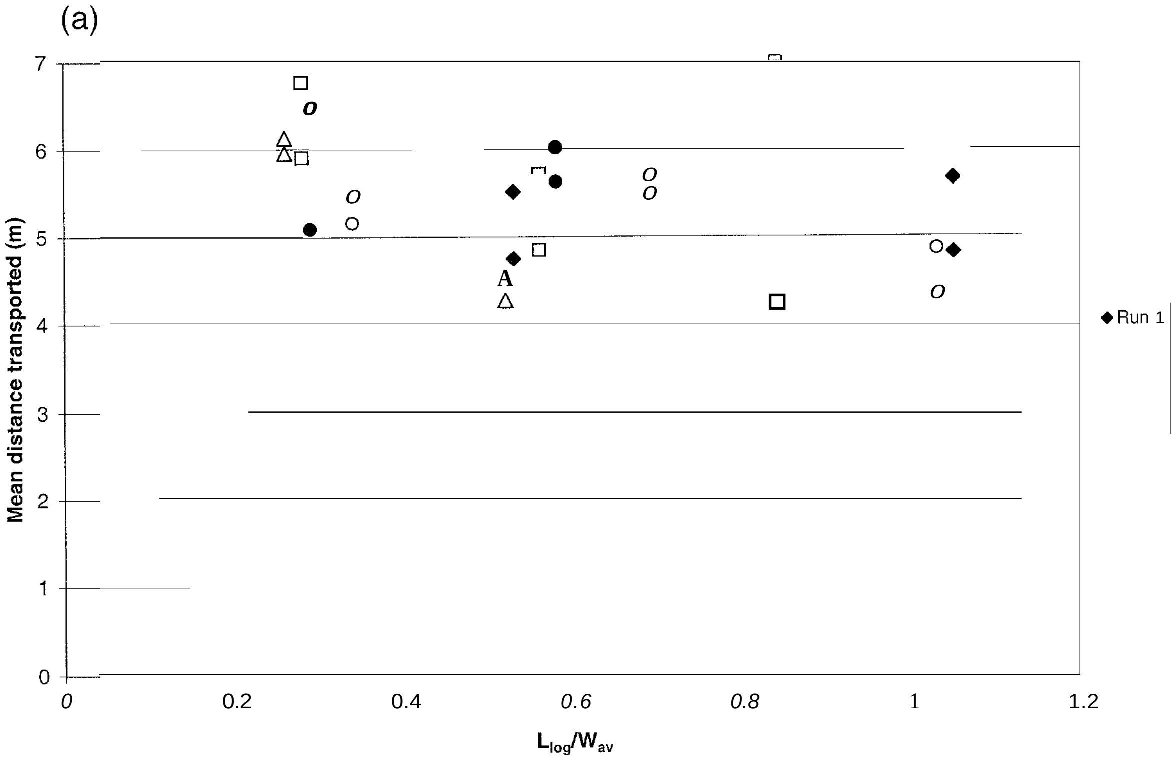
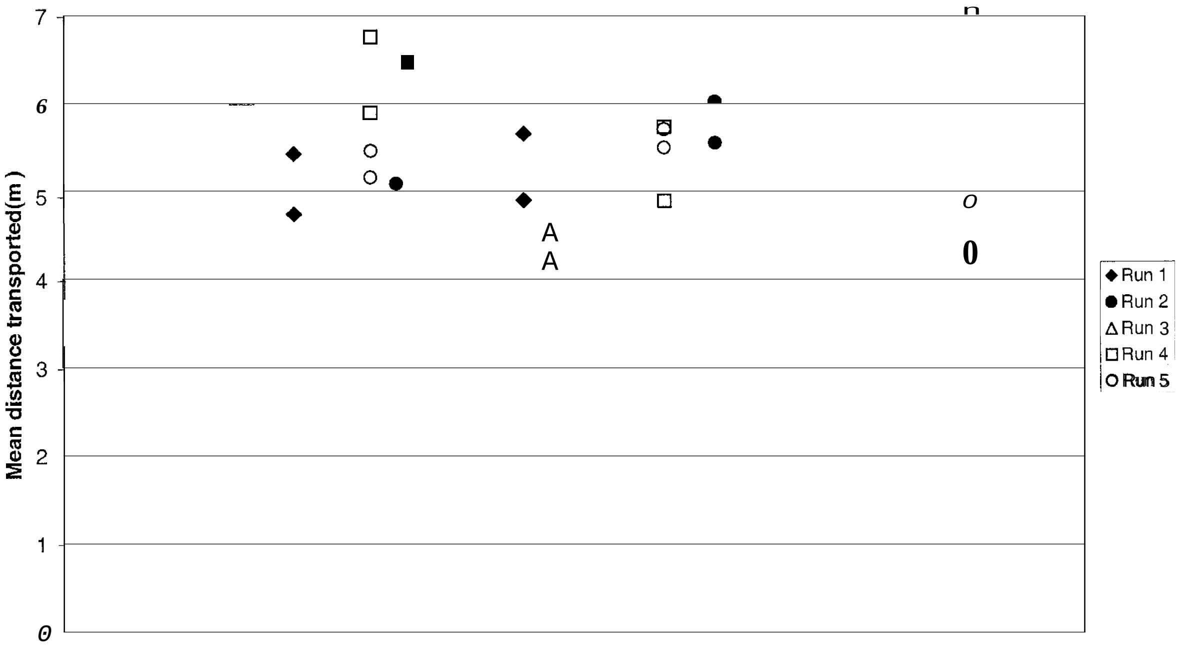


Fig. 8. (a) Mean distance traveled vs. L_{log}/w_{av} for each run. (b) Mean distance traveled vs. L_{log}/R_c for each run. (c) Mean distance traveled vs. d_b/d_{av} for each run.



measuring the wetted channel width at 0.5 m intervals. Radius of curvature was measured at the apex of the most sinuous bend in the run.

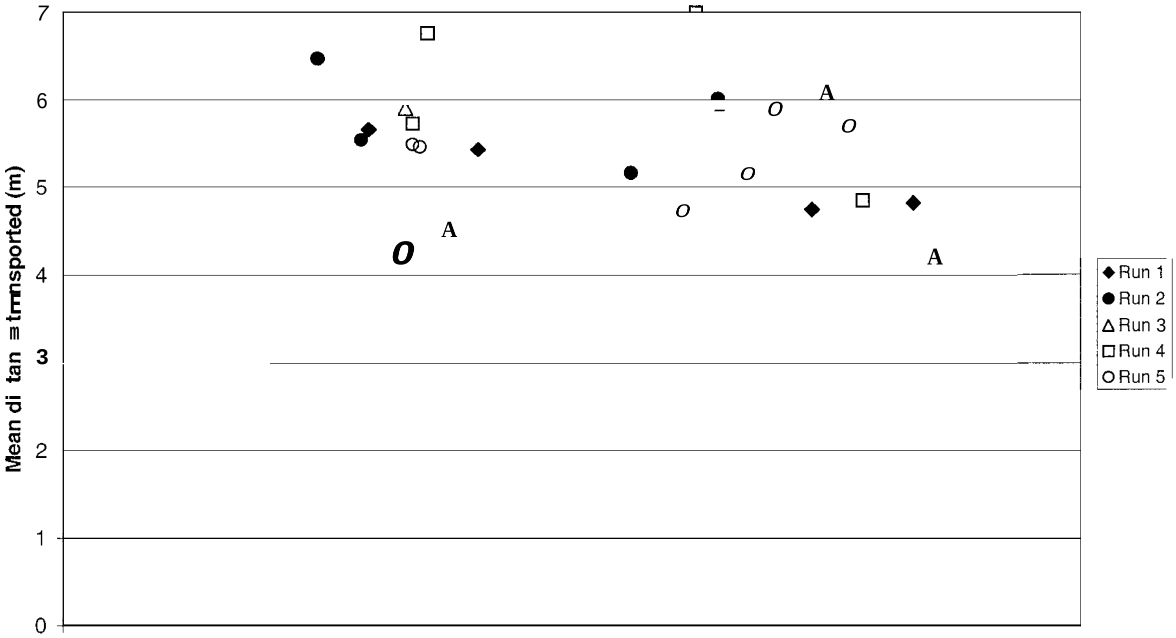
4. Results

4.1. Piece movement and depositional location

In all runs, moving pieces tended to align themselves parallel to flow throughout their passage down the flume. Flow-parallel orientation was preserved by the nonuniform cross-channel velocity distribution (Fig. 2) and, to a lesser degree, by lateral shock waves created by the near-critical flows, which tended to shunt pieces towards the center of the channel. Pieces moved at about the velocity of the flow unless contact with the bed or banks reduced piece velocity.

Piece depositional location and orientation are shown in Figs. 3–7, with each log representing a separate trial (removed after deposition so that piece interactions did not occur). Depositional orientation reflected the manner in which the piece was deposited. Pieces floated parallel to flow until their downstream ends encountered the bed or banks, whereupon they would begin to pivot or roll. Pieces lodged normal to flow if the upstream end of the piece also became lodged against the bed during pivoting (runs 1, 2 and 5, Figs. 3, 4 and 7). If the upstream end of the piece did not lodge against an obstruction, the piece rolled or pivoted into a flow parallel position along the margin of the channel (runs 1 and 2, Figs. 3 and 4) or on the outside of bends (runs 3, 4 and 5, Figs. 5, 6 and 7).

Depositional location was similar among trials within each run, and occurred where local water depth was less than the buoyant depth of the logs. Depositional locations included: (1) submerged bar



crossovers where the flow expanded (run 1, Fig. 3); (2) shallow bars, either as submerged bar heads (run 5, Fig. 7), bar tails (run 1 Fig. 3), or mid-channel bars (run 2, Fig. 4); or (3) on the outside of bends (runs 3, 4 and 5, Figs. 5, 6 and 7) in meander-bend channels.

The effects of piece length and diameter on depositional location varied between runs. In runs 2, 3 and 5 (Figs. 4, 5 and 7), pieces tended to deposit in the same types of locations regardless of piece length or diameter. Shorter, smaller diameter pieces were transported further onto bars than longer, larger diameter pieces (run 5, Fig. 7), and were generally more likely to be transported through the flume (runs 2 and 3, Figs. 4 and 5, Table 2). Piece length appears more important in controlling final piece location in meander-bend runs (runs 3–51, and diameter appears a more critical factor in runs with well-developed alternate bars with corresponding expansion zones and crossovers between bars (run 1).

An interesting result is shown in run 4F, where all of the pieces were transported through the flume even though they were the longest, largest diameter piece combination used. Pieces in this run were slowed, but did not stop when they encountered the banks and bed. To a lesser degree pieces in run 2D also moved much further than we predicted, with a high percentage of pieces transported through the flume in spite of these being the longest and largest diameter pieces for the given set of hydraulic conditions. The relatively uniform flow depth coupled with high piece momentum allowed them to overcome the obstructions, as discussed later.

4.2. Effects of debris roughness on distance traveled and piece retention

We hypothesized that the distance wood travels might be described by the channel's debris roughness (Eq. (1)). Although regression analysis show a significant inverse relationship between the components of debris roughness (Table 3), very low R^2 values (below 0.10) indicate that the predictive value of the results is low. In general, meander bend morphologies (runs 3–5, Fig. 8, hollow symbols) show a better trend of decreased distance traveled with increases in L_{log}/R_c and L_{log}/w_{av} than alternate bar and mid-channel bar morphologies.

Considering the retention of pieces in the channel rather than distance traveled, we see no relation between piece retention (the percentage of trials where the logs deposited in the flume) and either L_{log}/R_c, L_{log}/w_{av} or d_b/d_{av} (Fig. 9). The majority of runs with low retention values had low values of L_{log}/R_c and L_{log}/w_{av}. However, some runs with equally low values had 100% retention in the flume, particularly, the smaller pieces in runs 2, 4 and 5. For example, run 4D had 100% retention of pieces in spite of relatively small L_{log}/R_c and L_{log}/w_{av}. However, L_{log}/R_c and L_{log}/w_{av} did affect distance transported in run 4D, as the pieces moved past the first bend and deposited in the second. Retention results are strongly influenced by the relatively short flume length, as discussed below.

5. Discussion

Pieces consistently floated down the flume parallel to flow in the center of the channel. On bends pieces tended to get pushed to the outside of the bend (where flow is deepest), and still maintained a flow parallel orientation. Once piece movement begins, flow parallel orientation and topographic steering tends to promote continued transport, even in rough, sinuous channels. This orientation limits potential deposition sites for wood to bar heads, the outside of bends, and zones where flow shallows. Moving wood will most likely not deposit in straight narrow reaches.

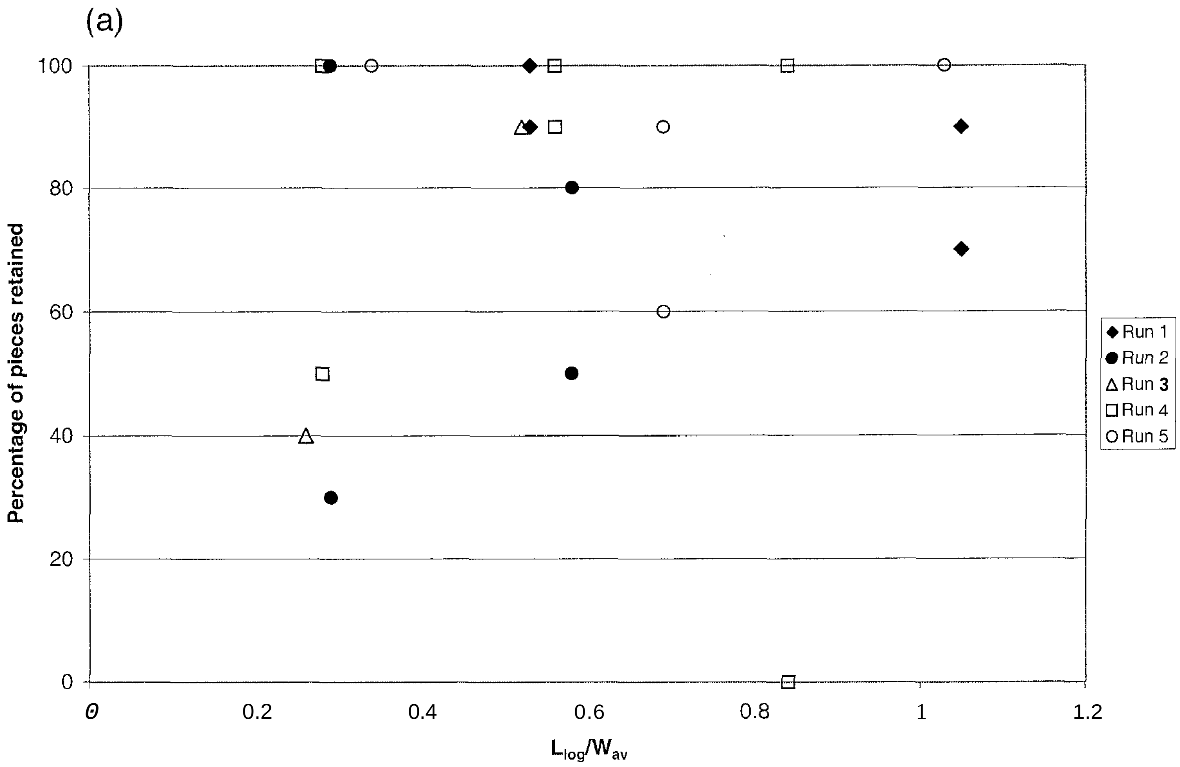


Fig. 9. (a) Percent of pieces retained vs. L_{log}/w_{av} for each run. (b) Percent of pieces retained vs. L_{log}/R_c for each run. (c) Percent of pieces retained vs. d_b/d_{av} for each run.

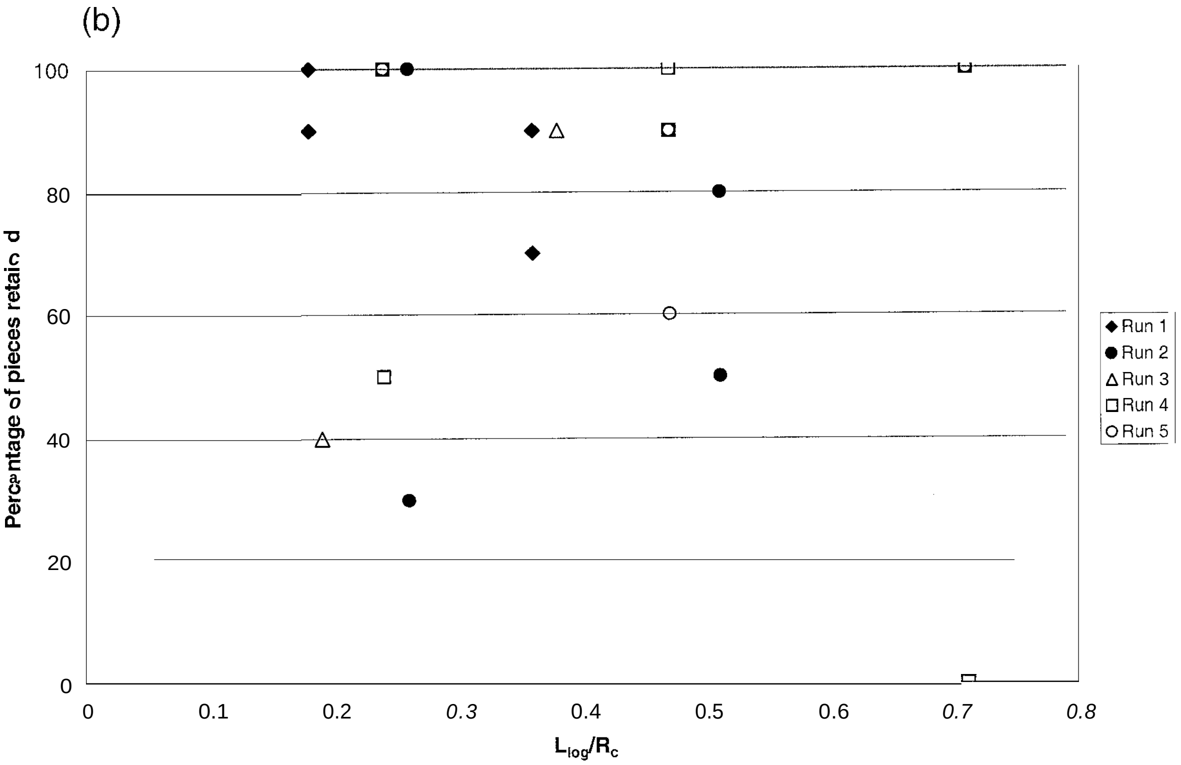


Fig. 9 *(continued)*.

Wood deposition sites in the flume — the outside of bends, heads of islands and bar crossovers—generally resembled depositional sites observed in the field (Nakamura and Swanson, 1994). Often, pieces would roll up onto bars, where depth was very shallow. Rolling would be less common in the field, where presence of rootwads, limbs, and vegetation on bar surfaces would tend to inhibit piece rotation. We have, however, observed large logs both with and without rootwads rolling onto bar heads during flood flows.

While the terms in our debris roughness model were significantly correlated with distance traveled for pieces, R^2 values are so low that the results are not particularly useful from a predictive standpoint. The two most likely reasons for this are the importance of local rather than reach average conditions in promoting wood deposition, and the limited length of channel over which deposition could occur. Because individual pieces are typically long relative to channel width, and float deep in the water column, they "sense" topographic irregularities, such as abrupt variations in channel width or depth. Such variations may exert first-order controls on where deposition actually occurs, but are obscured by use of reach averaged dimensionless variables, such as L_{log}/R_c, d_b/d_{av}, etc. A related factor that limits the predictive power of the debris roughness relationship in our experiments was the relatively short length of flume over which the experiments were conducted. Each run had only from one to three primary depositional sites; if pieces were not trapped at these locations, they passed through the flume. A longer flume with more depositional sites may be necessary to achieve higher R^2 values. Local variations, particularly, in flow depth and the velocity field, can have a profound influence on piece movement and these variations can not be predicted using reach-average values.

We were surprised that d_b/d_{av} did not significantly affect travel distance since previous work had demonstrated the strong dependence of piece diame-

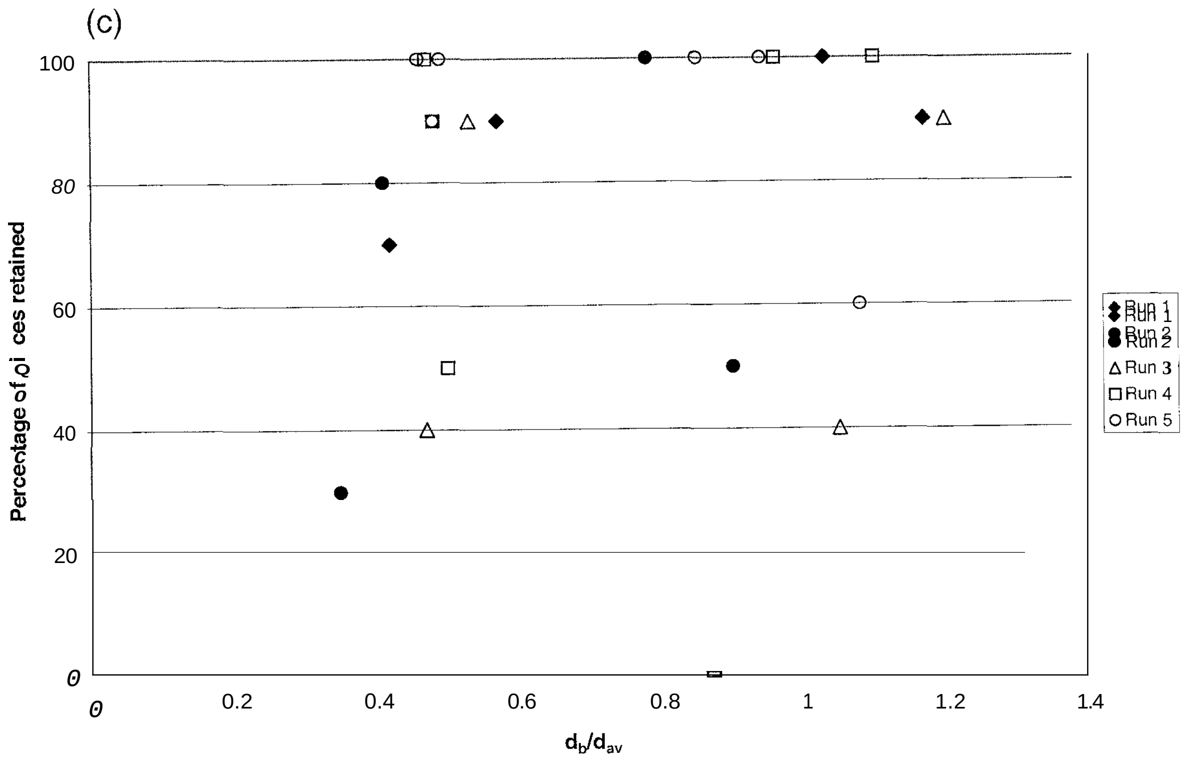
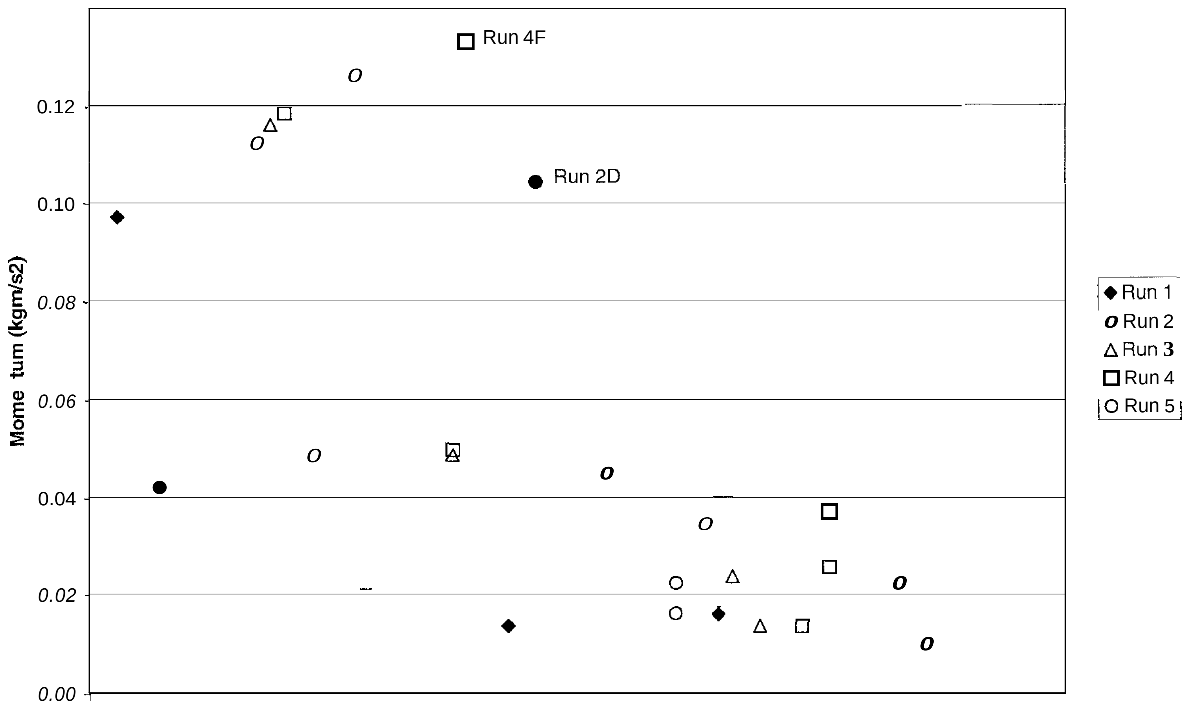


Fig. 9 *(continued)*.

ter on entrainment (Abbe et al., 1993; Braudrick and Grant, 2000). We expected that runs where average depth was less than buoyant depth would have much shorter travel distances than where average depth was greater than buoyant depth. It appears that for the types of channels examined, d_b/d_{av} has to be significantly greater than 1 to affect piece movement. The absence of a relation between d_b/d_{av} and distance traveled could be due to the propensity for pieces to align themselves parallel to flow in the center of the channel. Most of our runs (except run 4) had asymmetric cross-sections. Hence, even though $d_b/d_{av} > 1$, over some fraction of the cross-section, the thalweg where the channel was deepest had depths sufficient to float the piece. Because pieces tended to stay aligned parallel to flow in the deepest sections of the channel, shallow bars had little effect on piece movement. The one run in which diameter significantly influenced piece transport was run 1, where pieces deposited in a zone of abrupt flow expansion and shallowing. The diameter ratio may be most important where shallowing occurs over the entire cross-section. The primary influence of d_b/d_{av} is its effect upon the threshold for the initiation of wood movement (Braudrick and Grant, 2000).

Our model suggests that, all things being equal, smaller pieces will move farther than larger pieces if channel geometry is constant. In these experiments, the difference in transport distance between shorter and longer pieces was less than predicted; however, we were particularly surprised by the high mobility of the very large pieces in run 4F (where all of the pieces moved through the flume in spite of their being the largest pieces in all runs). We do not believe these to be anomalous results, as during the February, 1996 flood in the western Cascades, OR, we observed many large logs (i.e. $>$30 m long) traveling long distances down relatively narrow (i.e. $<$ 30 m wide) channels. Two factors can make larger pieces more mobile than smaller pieces: the higher momentum of larger moving pieces, and reduced influence of local changes in the depth and velocity fields. For pieces moving at the same velocity, momentum increases with increasing piece size (momentum = mass times velocity). Each time a moving piece encounters the bed or banks, its velocity is reduced and momentum is extracted. Larger pieces have higher mass and, therefore, higher momentum, which allows them to overcome frictional resistance offered by obstructions, such as individual bed particles, shallow bars and banks. Longer pieces also integrate a wider range of water velocities and water depths than shorter pieces, reducing the influence of local reductions in velocity and depth. It is difficult to discern which of these two factors is more important; however, theoretically, both should affect piece movement. We refer to the condition when piece size and velocity overwhelms the effect of bed obstructions as *momentum-maintained transport*.

Because momentum is dissipated every time a piece encounters the bed, momentum should dominate piece transport when a high percentage of the channel area has water depth (d_w) greater than the buoyant depth of the log, and there are few locations where the logs encounter the bed. Fig. 10 is a plot of the percent of the active channel area where $d_w > d_b$ vs. the momentum of the piece (with velocity equal to the average flow velocity). Because water velocities were approximately equal in these experiments (Table 1), momentum is essentially a measure of piece size. The majority of runs have momentum below 0.06 kg m/s, particularly, those with a high percent of their channel area deeper than buoyant depth. The two runs where our debris roughness model did not accurately predict distance transported, runs 2D and 4F, had high momentum, and over 50% of their channel area with $d, > d_b$. Run 4F had a well-defined thalweg, with few shallow



bars, so both velocity and percent channel area where $d_w > d$, were high. The same flow conditions were able to trap smaller logs (e.g. run 4A–C) so the effect was not due solely to d_w/d_b. Since the thalweg was well defined, there were few shallow bars to trap the pieces in run 4, and piece momentum was able to overcome debris roughness.

Shallow regions of the channel are essentially zones of high friction that are distributed within the deeper zones of no friction (where the piece does not encounter the bed). In general, longer pieces are more likely to encounter these high friction zones, simply because their length spans a greater percentage of the active channel, or because increasing L_{log}/w_{av} and L_{log}/R_c forces pieces out of the thalweg where flow depth may be greater than d_b, thereby increasing their probability of deposition. This effect is offset, however, by piece mass (as discussed above), and the hydraulic steering that tends to align long pieces with the flow rather than across it (Fig. 2).

Pieces may be deposited on the channel bed or against or along the banks. Banks may trap pieces, causing deposition, even though the thalweg is sufficiently deep to float the logs. High L_{log}/R_c and/or L_{log}/w_{av} result in flow paths that force the piece toward the banks where depth is shallow enough for deposition to occur, or where banks, vegetation, or immobile logs project into the current. Bank-dominated deposition occurred in runs 3–5 in our experiments, and may have been promoted by gently sloping banks that tended to ramp wood out of the flow. Bed-dominated deposition occurs because thalweg depth shallows at bar crossovers and mid-channel bars or islands, and flow depth is no longer sufficient to float the logs. Bed-dominated deposition occurred in run 1 and to a lesser extent run 2. Momentum-maintained transport can dominate, if the distribution of potential deposition sites is infrequent (e.g. a large portion of the channel area has $d_w > d_b$). Momentum-maintained transport will be less common in channels with many bank and bed irregularities because the number of potential deposition sites is very high and momentum is constantly dissipated.

Based upon relative values of L_{log}/w_{av}, D_{log}/d_{av} and L_{log}/R_c, and this inferred susceptibility to momentum-maintained transport, we can predict the general debris roughness of various natural stream types based upon our experiments (Table 4). We expect that the highest piece retention will occur in

Table 4
Theoretical description of debris roughness and depositional location based upon channel type

Field example	D_{log}/d_{av}	L_{log}/R_c	L_{log}/w_{av}	Bed or bank dominated?	Debris roughness	Depositional location
Low-gradient headwater streams	High	High	High	Both	Very High	In-situ
Multiple thread streams	High	High	High	Both	Very High	Bar and island heads, outside of bends, floodplains
Sinuous, unconstrained streams	High	High	Low	Both	High	Outside of bends, bar heads
Third- to fourth-order streams	High	Low	High	Both	High	Floodplains, bar heads
> Fifth-order unconstrained streams	High	Low	Low	Bed	Low	Island heads, bar crossovers
Sinuous constrained streams	Low	High	High	Bank	High[a]	Outside of bends, floodplains
Large sinuous streams with extensive floodplains	Low	High	Low	Bank	Low[a]	Outside of bends, floodplains
Straight constrained streams	Low	Low	High	Bank	Low[a]	Floodplains, vegetated surfaces
Large streams	Low	Low	Low	Neither	Very Low	Bridge abutments

[a]Indicates potential site for momentum-maintained transport.

channels with large values of L_{log}/w_{av}, D_{log}/d_{av} and L_{log}/R_c. These high values are typically found in either small channels where initiation of wood movement is rare, or multiple-thread (braided) streams. Other channel types where D_{log}/d_{av} is high include unconstrained meandering streams, medium-sized streams with nonuniform cross-sections, and streams that receive very large trees as input (such as redwoods). In these channels, the potential for momentum-maintained transport is low and the distances pieces travel should be controlled by L_{log}/w_{av}, D_{log}/d_{av} and L_{log}/R_c, and deposit on bar and island heads, bar crossovers, the outside of bends, and on floodplains. If D_{log}/d_{av} is low, such as constrained streams and large rivers, deposition should be mostly along banks, the outside of gently sloping bends, and on floodplains. In the largest streams where all 3 components of Eq. (1) are small, we expect there to be very few potential deposition sites. In these larger streams, pieces often deposit on bridge abutments, which provide the only significant obstructions in the stream. Presence of bedrock, bank irregularities, vegetation and immobile wood will substantially influence these general trends, however.

5.1. *Contrast between debris and hydraulic roughness*

Both debris and hydraulic roughness are somewhat idealized parameters that integrate a wide range of factors promoting extraction of either mass (debris roughness) or energy (hydraulic roughness) from the flow. In both cases, it is often difficult to measure the influence of individual factors, so that, in practice, a composite value for the entire stream is assigned. For example, the well-known Manning's roughness coefficient is such a composite variable, incorporating flow resistance due to skin, form, spill, channel curvature, and even the effect of standing vegetation in the channel. The debris roughness of a channel similarly involves factors that include flow hydraulics (width and depth), topographic irregularities of the bed and banks, and channel planform, all in relation to the size of wood pieces likely to be moving. In the same manner that hydraulic roughness varies with discharge, so will the factors influencing debris roughness change with flow. It is unlikely that either hydraulic or debris roughness can be rigorously quantified for natural channels. Both concepts, however, have great utility for generally characterizing channel conditions, and predicting trends in energy dissipation or wood trapping efficiency, respectively. Our experiments are only the first attempts to quantify debris roughness, and we believe that they demonstrate that the general form of the relation is valid. Future research should help more clearly define the complex factors promoting wood deposition in rivers.

6. Conclusions

These experiments tested a quantitative model for wood retention and distance traveled based upon ratios between piece and channel geometries. We observed that once moving, wood can be efficiently transported by streams because of its ability to stay in the thalweg and align itself parallel to flow. In all of our runs, deposition sites were similar to those seen in the field. We found that distance traveled is significantly related to the ratios of the piece length to the average channel width and maximum radius of curvature of the channel; however, the R^2 values were extremely low, perhaps due to the wide spatial variability of potential deposition sites. Surprisingly distance traveled and piece retention were not related to the ratio of a log's buoyant depth to average flow depth: the proportion of channel area where flow depth is greater than buoyant depth may be more important than the average. Large pieces can move further than smaller pieces if the distribution of potential deposition sites is infrequent, which allows the higher momentum of these large pieces to overwhelm debris roughness. These results allow first-order prediction of the relative transport efficiency or retentiveness of different channel types.

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