AN ABSTRACT OF THE THESIS OF

Christian A. Braudrick for the degree of Master of Science in Geology presented on May 13, 1997. Title: Entrainment, Transport, and Deposition of Large Woody Debris in Streams: Results from a Series of Flume Experiments

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Although there has been extensive research on the geomorphic and ecologic role of large woody debris (LWD) in streams, the dynamics of LWD in streams are poorly known due to various measurement difficulties during floods. In this thesis I present the results of two flume experiments on the dynamics of wood in streams. The first experiment examined the effects of piece interaction on wood transport, while the second evaluated a theoretical model predicting the threshold of movement, and factors controlling the deposition of individual logs. Flume experiments allow us to model the wood movement under a variety of piece geometries, piece concentrations, and hydraulic conditions.

The first experiment showed that logs moved in three distinct transport regimes; congested, semi-congested, and uncongested transport. During congested transport the logs move as a single mass and occupy > 33 % of the channel area. Uncongested transport occurs when the logs are moving as individuals and occupy < 10 % of the channel area.

Semi-congested transport is intermediate between these two transport regimes and occurs when wood moves in clumps of 2-3 logs. Transport regime was dependent upon the ration of the volumetric input rate of pieces to the flow, and to a lesser degree, the ratios of the piece length to channel width and piece diameter to channel depth. The transport regime was reflected in the deposit. Congested transport deposits have a higher portion of their pieces oriented parallel to flow than uncongested and semi-congested transport. We expect that congested transport will occur in low-order channels where input rates are high and channel geometry is small relative to piece size. Uncongested transport will dominate large channels where input rates are lower relative to flow and channel geometry is large relative to piece size.

Our theoretical model and these experiments indicate that the entrainment of individual logs was dependent upon the angle of the piece, and the presence/absence of rootwads. Although previously noted as a first-order control on piece movement, piece length had little effect on the entrainment threshold, but did affect the distance transported. The distance transported decreased with increases in the ratios of the piece length to average channel width (L_{log}/w_{av}), the piece length to the radius of curvature (L_{log}/R_c), and the piece diameter relative to average depth (D_{log}/d_{av}). These three ratios comprise the debris roughness. Increased debris roughness caused a general decrease in distance transported. Pieces with high debris roughness can travel further than predicted if they have high momentum, and over 50 % of their channel area deeper than the depth at which the piece floats. These results indicate that flume experiments and theoretical models, tools that have been extensively used to study sediment dynamics, are a useful in examining wood dynamics.

Entrainment, Transport, and Deposition of Large Woody Debris in Streams: Results from a Series of Flume Experiments

by

Christian A. Braudrick

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Although my name is on the title page this thesis, it is a comprised of two papers that are not solely mine. I would like to thank my co-authors; Gordon Grant, Yoshiharu Ishikawa, Hiroshi Ikeda, and Julia Jones. Although not a member of my committee, and not an author of any of the papers, Fred Swanson provided reviews of the first manuscript, and was always willing to discuss wood in streams, and his insights became an integral part of my thinking. His interest and support throughout my time here are greatly appreciated. Julia Jones was extremely helpful and understanding of my total lack of statistical skills. She was very helpful in both reviewing both papers, and giving a crash course in Systat. I would also like to thank everyone at the St. Anthony Falls Hydraulic Laboratory, particularly Gary Parker for their assistance during my stay there. A very special thanks goes to Gordon Grant. His willingness to take me on as a graduate student allowed this long, arduous process to happen. Gordon painstakingly helped improve my writing and thought processes, and I am a much improved scientist thanks to his help. Lastly, I would like to thank my family and friends for their support and encouragement. I am forever indebted to them for their love and wit, both of which kept me sane in Corvallis.

Contribution of Authors

Yoshiharu Ishikawa provided the flume, and helped with the design of the first manuscript. Hiroshi Ikeda helped develop our theories on the factors which might influence the bunching of wood, and wood dynamics as a whole in the first experiment. Julia Jones helped with the statistical analysis of the second manuscript. Gordon Grant designed the first experiment, helped design the second, and was instrumental in the interpretation of the data.

Table of Contents

List of Figures

List of Figures (continued)

List of Tables

Table | Page

List of symbols and their units

A_1 - Submerged rootwad area parallel to piece length (m^2)

A_2 - Submerged bole area parallel to piece length for pieces with rootwads (m^2)

A_3 - Submerged rootwad area perpendicular to piece length (m^2)

A_{sub} - Submerged log area for pieces without rootwads (m^2)

C_d - Coefficient of drag between the log and flow

d_{av} - Average water depth (m)

d_b - Buoyant depth (m)

D_{log} - Log diameter (m)

d_w - Water depth (m or cm)

g - Gravity

L_{log} - Log length (m)

Q_{log} - Volumetric log input rate (m^3/s)

Q_w - Flow (m^3/s)

r - Log radius (m)

R_c - Radius of curvature (m)

U - Flow velocity

V_1 - Submerged volume parallel to piece length (m^3)

V_2 - Submerged bole volume parallel to piece length for pieces with rootwads (m^3)

V_{rw} - Total rootwad volume (m^3)

w_{av} - Average channel width (m)

w_c - Channel width (m)

w_{min} - Minimum channel width (m)

α - Angle of bed (slope)

μ_{bed} - Coefficient of friction between the wood and the bed

ρ_{log} - Piece density (kg/m^3)

ρ_w - Water density (kg/m^3)

θ - Piece angle with respect to flow

Entrainment, Transport, and Deposition of Large Woody Debris in Streams: Results From a Series of Flume Experiments.

Chapter 1: Introduction

Large woody debris (LWD) is an integral ecological and geomorphic component of forested streams. Most of the research on LWD focuses on its geomorphic and ecologic roles and assumes that wood is a stable component of streams. Scientific interest in LWD is multi-disciplinary because wood is important for ecology and morphology of streams, and poses a geologic hazard. Most of the focus of LWD research is on the ecological role of wood because it provides vital habitat for salmonids and other aquatic organisms by creating backwaters and other slow-water zones(e. g. Harmon *et al.*, 1986). In order to improve salmonid habitat, various governmental agencies are spending millions of dollars per year adding wood to streams in order to replenish some of the wood that has historically been removed by log drives, salvage, and for navigation. Wood is also an important geomorphic component of forested streams (Montgomery *et al.*, 1993; Hogan, 1995, Montgomery *et al.*, 1996). Wood contributes to both erosion and deposition of sediment in forested streams (Hogan, 1995), increases pool frequency (Hogan, 1987, Robison and Beschta, 1990, Montgomery *et al.*, 1995) and hydraulic roughness (Lienkaemper and Swanson, 1987, Montgomery and Buffington, 1993). In countries like Japan, where many communities lay at the base of steep-forested mountain streams, wood is viewed as a potential hazard, where floods and debris flows carrying wood tend to be far more destructive than those without wood (Ishikawa, 1989).

Previous research on wood dynamics in streams has focused on measuring wood movement through time in streams (Toews and Moore, 1982; Grant, 1987; Lienkaemper and Swanson, 1987; Gregory, 1991; Nakamura and Swanson, 1993). These studies occurred in relatively small channels where wood moves infrequently, and none had a flood with a recurrence interval greater than ten years. The lack of wood movement during these studies has added to the perception of wood as a stable component of forested streams. However, during the February, 1996 flood in the western Cascades, Oregon many large logs were observed moving down channels of all sizes. In spite of the importance of LWD across a range of disciplines, we know little about when wood moves, how wood moves, and how far wood moves once in motion. It is particularly striking that we know so little about wood dynamics, yet are spending so much money adding wood to streams. It is hard to imagine that in 1997 we could undertake what is essentially a large engineering project with such a paucity of data on the physics of the components. In this thesis we seek to investigate some of the dynamics of woody debris using methods similar to those used to study inorganic sediment dynamics. Because it is difficult and often hazardous to measure wood movement during floods we have little data on thresholds of wood movement and deposition. A similar problem exists for inorganic sediment which has been overcome by using theoretical models and flume experiments (e.g., Langbein and Leopold, 1968; Dietrich *et al.*, 1989; Lisle *et al.*, 1991). Physically-based models and flume experiments are a vital component of our present understanding of sediment dynamics in streams, but have not been used extensively in wood studies and as a consequence we know little about wood dynamics at a variety of scales and hydraulic conditions.

Approaches to understanding wood and sediment dynamics differ because sediment is inorganic and falls under the realm of geologists and engineers, whereas wood is an organic component of forested streams which, until recently, has been largely ignored by geologists, and has mostly been studied by fisheries biologists who, for the most part, have not taken a process based look at how wood moves in streams. Because wood has been largely ignored by geologists and engineers, similar analytical tools have not been used to study sediment and wood.

Wood differs from sediment in shape, size, and density. Wood is rod-shaped rather than spherical, and can be much longer than the channel width. This means that wood can have part of its length on the banks, or even be suspended over the channel. Because pats of pieces can lay outside the channel margin, vegetation can play a large role by increasing the stability of pieces lodged upstream of trees, and providing locations for wood to deposit. We do not seek to model the effects of vegetation, nor do we seek to model pieces suspended over the channel in the papers which comprise this thesis. While the density of wood varies, it is commonly less than the density of water, and flotation plays a major role in both the entrainment and transport of wood in streams. We therefore can use similar methods to study wood and sediment if we keep in mind these differences.

The quantification of wood dynamics, particularly assessing wood stability and deposition is an integral part of understanding the geomorphic and ecologic role of wood, and in the assessment of potential hazards posed by LWD. Because of the infrequency of movement and the difficulty in measuring wood dynamics during large floods, flume experiments provide an excellent tool in quantifying the movement and deposition of wood under a variety of hydraulic conditions and channel morphologies, yet have received little use in the study of LWD dynamics.

This thesis is comprised of two papers that report the results of two separate flume experiments which seek to enhance our understanding of the entrainment, transport, and deposition of wood in streams. The first experiment was conducted at the Public Works Research Institute (PWRI), Tsukuba, Japan, and investigates how pieces interact during transport. In particular, we investigate the input rates and hydraulic characteristics which cause large groups of logs to travel downstream as a large mass rather than as individual pieces or groups of 2-3 logs. The second paper, conducted at the Saint Anthony Falls Hydraulic Laboratory, reports results of experiments which test physical and theoretical models of entrainment and deposition of individual logs in streams.

Chapter 2

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 of the dynamics of wood transport in streams through a series of flume experiments and observed three distinct transport regimes: uncongested, congested, and semi-congested transport. During uncongested transport, the logs move without piece-to-piece interactions and generally occupy < 10 % of the channel area. In congested transport, the logs move together as a single mass and occupy >33 % of the channel area. Semi-congested transport is an 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 0.14 for uncongested transport and 0.28 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 that congested transport is more common in low-order streams and that uncongested transport would dominate higher-order streams. Simple flotation models can be used to model the stability of individual pieces, especially in higher order channels, but are insufficient for modeling the more complex interactions that occur in lower-order streams.

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 increase pool frequency (Hogan, 1987, Robison and Beschta, 1990, Montgomery *et al.*, 1995), and hydraulic roughness (Lienkaemper and Swanson, 1987, Montgomery and Buffington, 1993). Little is known about the dynamics of LWD movement, however, 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 (c.f. Sedell and Froggatt, 1984). LWD was also salvaged from streams as timber or removed during log drives, the latter a common method for transporting logs downstream. With the growing recognition of the ecological importance of LWD over the last twenty years, various governmental agencies have tried to restore streams by deliberately adding wood and growing streamside forests to provide long-term recruitment of wood for streams. Understanding how logs move during flood events and interactions among wood movement, sediment transport, and channel and riparian zone disturbance processes would help improve the effectiveness of logs added for ecological values.

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 an event (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. Understanding the dynamics of LWD transport would help in designing more effective engineering systems for managing LWD to better protect people and property.

The long residence time of *in situ* wood (MacDonald *et al.*, 1982, Gregory, 1991), modest movement during even ten-year events (Grant, 1987, Lienkaemper and Swanson, 1987) and 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 analyzed 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 on 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 the 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 delivery of 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 breakup of individual jams (Grant, 1987) or the remobilization of pieces introduced between flood events (Lienkaemper and Swanson, 1987). LWD moves farther in large streams than in small streams, and smaller pieces move farther 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), but 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 that grow 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 sediment 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 scale 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 makes wood more likely to be deposited in shallow areas, or to become lodged against bed or bank obstructions.

Unless waterlogged, wood is typically less dense than water (Harmon *et al.*, 1986; Table 1), causing buoyant forces to be much greater than for inorganic sediments. Because it floats, once wood starts to move in large, straight channels, it will continue to move unless the water shallows below the threshold for flotation. For coarse inorganic sediments, however, the threshold for transport is defined by its 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).

The flotation threshold for wood is given by:

$$\cos^{-1}\left(\frac{r-d_b}{r}\right)-\frac{r-d_b}{r^2}\sqrt{2d_b r-d_b{}^2}=\pi\frac{\rho_{\log}}{\rho_w} \tag{2.1}$$

Where r is the log radius, d_b is the depth at which flotation occurs, and ρ_{log} and ρ_w are the densities of wood and water, respectively. When ρ_{log} = 500 kg/m^3 the d_b = r.

Figure 2.1 shows the numerical solutions to equation 2.1, with d_b divided by the log diameter (D_{log}) plotted against ρ_{log}/ρ_w. The density of wood depends upon the type of wood (species, heartwood versus sapwood) and the state of decay. The more advanced the decay the more easily water saturates the log, increasing the density. The density of dry wood varies among species in the Pacific Northwest, but is generally between 350 kg/m^3 and 500 kg/m^3 (Forest Products Laboratory, 1974) (Table 2.1).

Table 2.1. Densities of common tree species in the Pacific Northwest (Forest Products Laboratory, 1974)

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

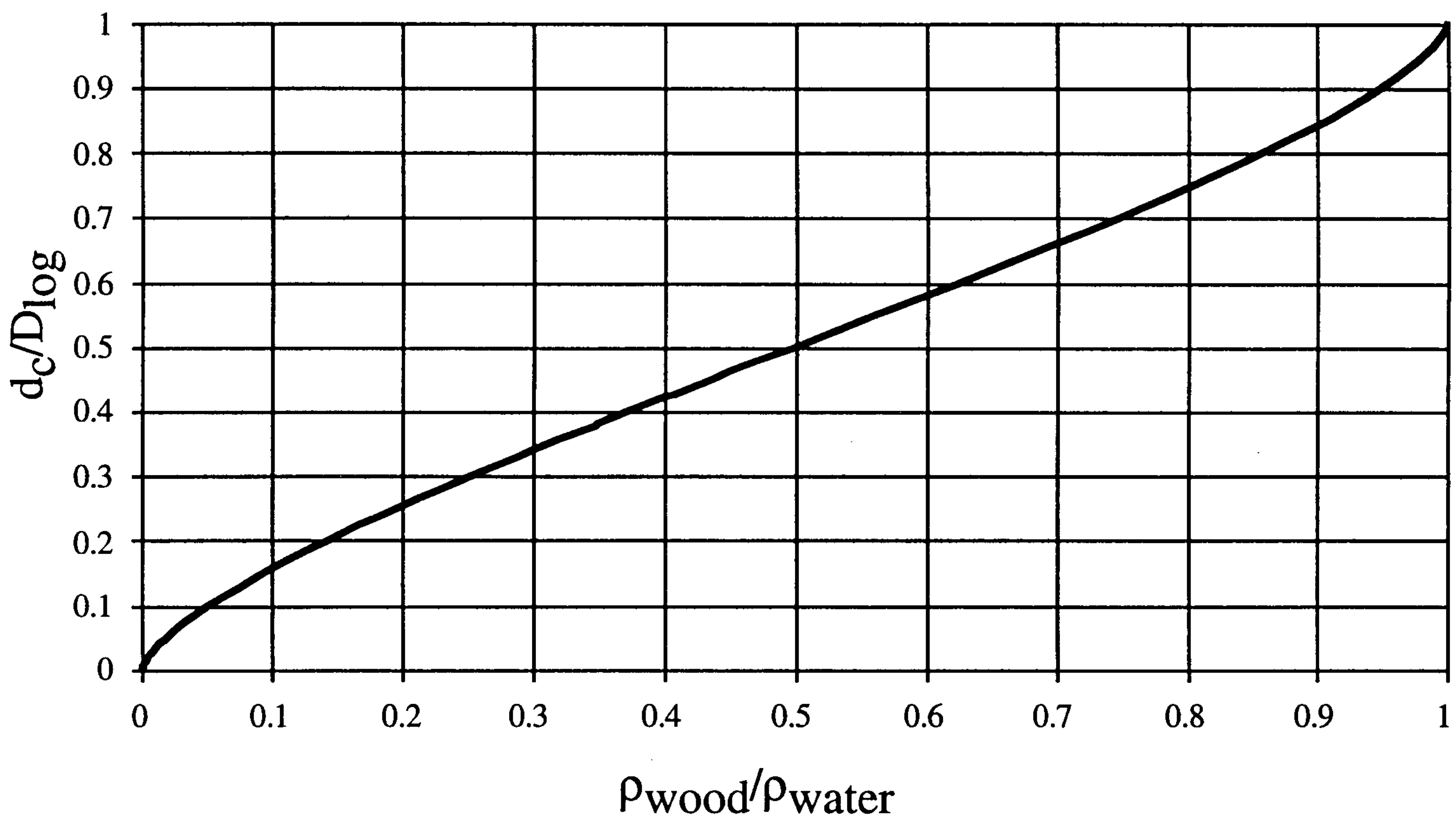

Figure 2.1. dimensionless plot of flotation thresholds for wood of different piece densities and diameters.

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 wood is anchored to the bank. Channel roughness may also influence wood transport; sand bars and boulders in streams can inhibit wood movement by causing it to run aground. For these reasons, equation 2.1 addresses 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.

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 2.2). Before each run, the bed of the flume was uniformly covered and smoothed with a 10-cm thick bed of sand with an average grain size of approximately 1 mm. Water was released in the flume for 30 minutes, allowing the channel morphology and sediment transport to reach equilibrium. The flow was scaled to maintain Froude number below 1. In each experiment, two hundred dowels were released at rates of either 5 per second or 5 per 5 seconds. The experiment was repeated 5 times, three times for the larger dowel size and twice for the smaller dowel size. A video camera was suspended over the flume 2 to 3 m upstream of the flume outlet; it recorded the movement of dowels through a 1 m^2 area . The video tape was sampled on a video edit machine at 5-second intervals. The number of dowels in the 1 m^2 area and the number of dowels that passed through the area during the 5-second 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.

Table 2.2. Experimental Conditions

Run	Log diameter (m)	Log length (m)	Log input rate (logs/sec)	Average channel depth (m)	Flow (m^3/sec)
1	0.04	0.4	5	0.027	0.012
2	0.04	0.4	5	0.023	0.009
3	0.02	0.2	5	0.015	0.0045
4	0.04	0.4	1	0.023	0.009
5	0.02	0.2	1	0.015	0.0045

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 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 flow direction changed or 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.

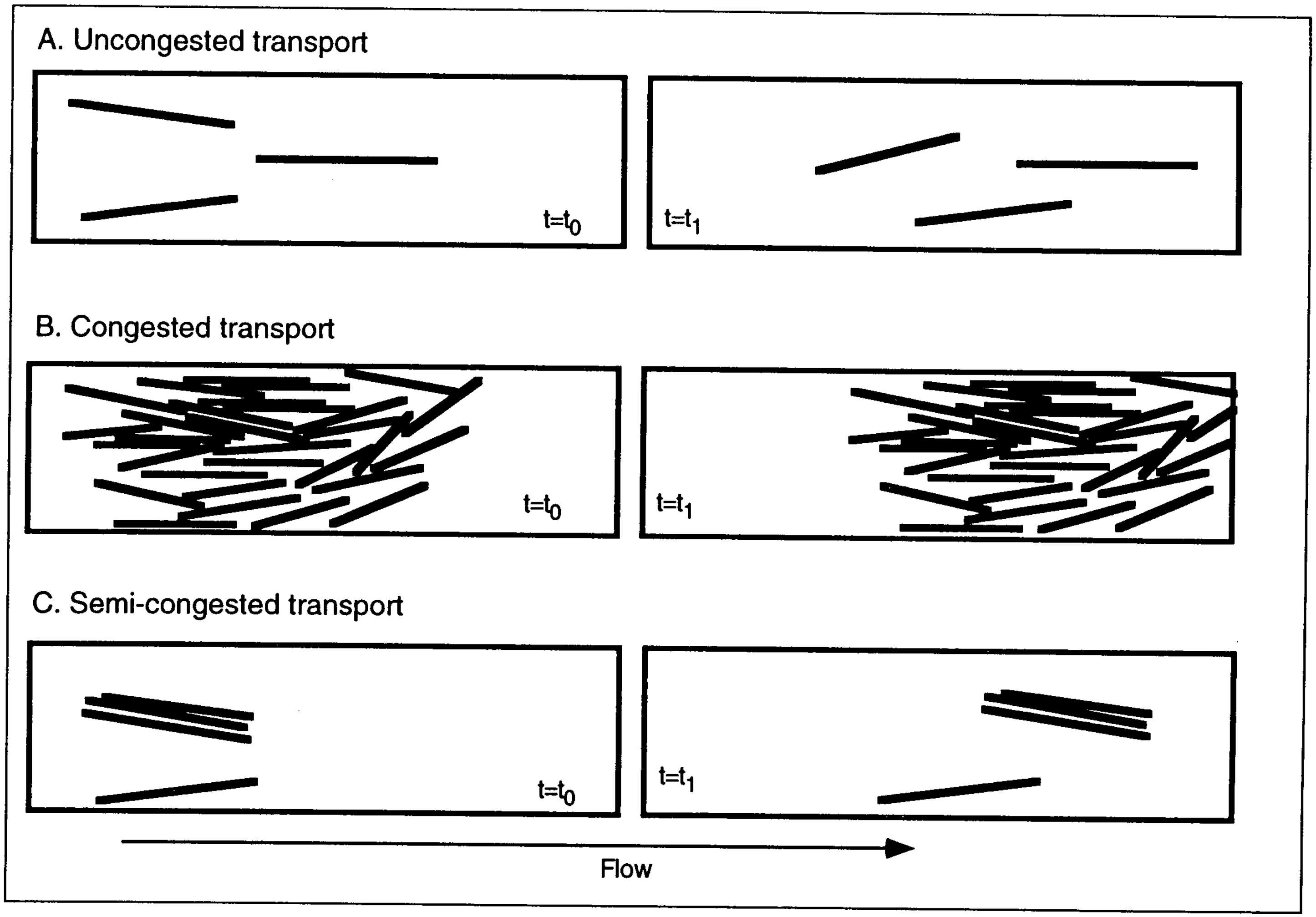

Figure 2.2. Schematic diagram of wood transport regimes. The figures on the left show pieces at time step t_0, and the figures on the right show pieces at time step t_1 for uncongested, semi-congested, and congested transport.

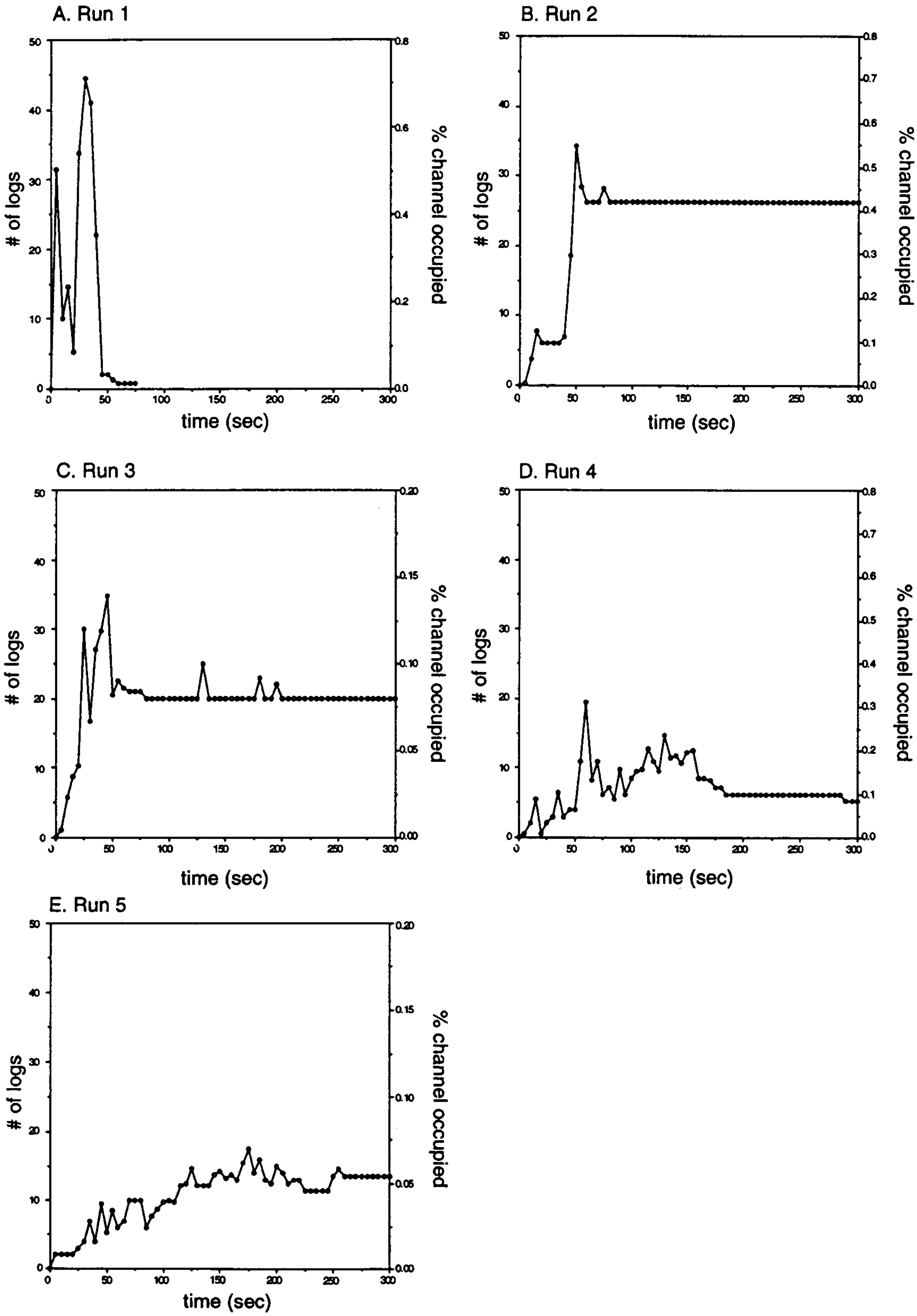

Figure 2.3. Plots of percent channel are occupied and the number of logs versus time for all five runs.

We observed three distinct transport regimes; uncongested, semi-congested, and congested transport (Figures 2.2 and 2.3). 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 concentration was low (Figures 2.3A-2.3D), and throughout run 5 (Figure 2.3E).

Transport was congested when the 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 the 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 that spanned 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 2.3A and 2.3B).

Semi-congested transport was intermediate between these two transport types and occurred when the 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 3-5 pieces). Semi-congested transport dominated runs 3 and 4 (Figures 2.3C and 2.3D). 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 traveled through this restricted area as a clump, but the clumps broke up below the bar and moved as individuals, indicating that transport may have been uncongested in parts of the channel that were not sampled on the 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 2.3A, 2.3B, and 2.3C), and the gradual accretion of wood to subaqueous bars (Figures 2.3D and 2.3E). 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 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 flow (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 2.4).

Of these three ratios, the only that distinguished among transport regime was the relative log input rate. As this ratio increased, transport became more congested. The boundary between uncongested and semi-congested transport was broadly defined between Q_{log}/Q_w 0.015 and 0.06. The transport became congested at Q_{log}/Q_w values between of 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 uncongested transport (0.2 and 1.34, respectively) but did not separate those two regimes from semi-congested transport. These results imply that

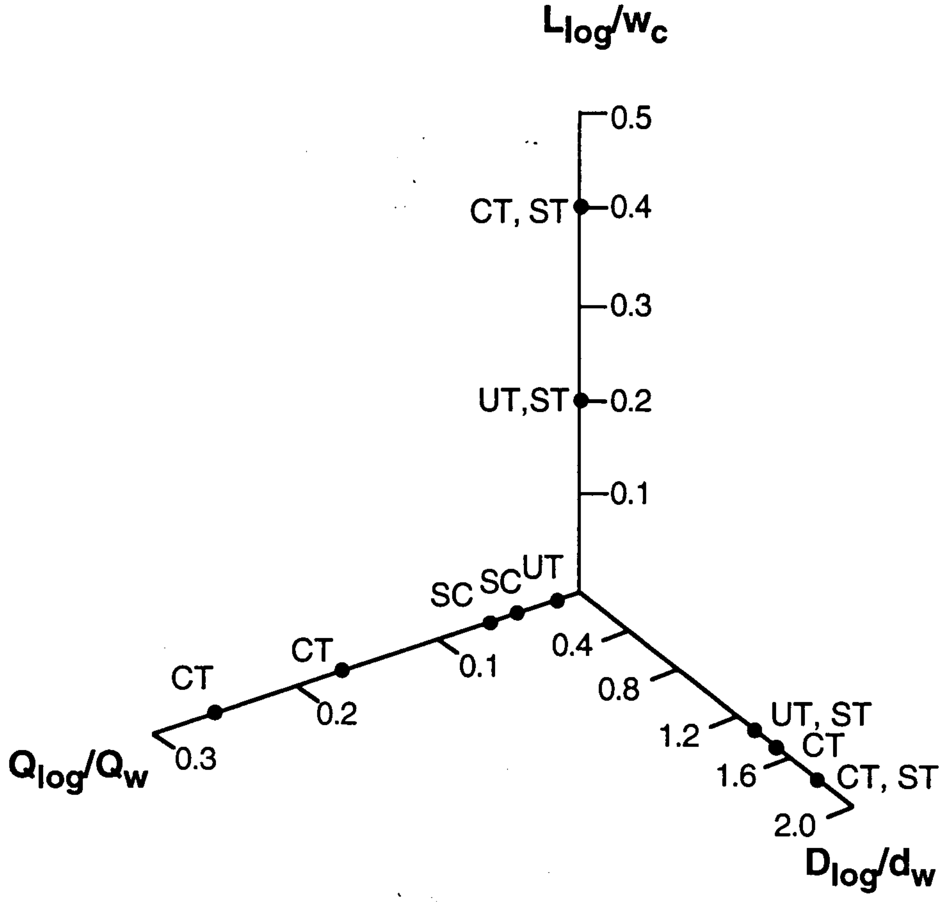

Figure 2.4. Values of the dimensionless ratios by run. Data points are labelled by transport type, and represent the maximum values for each run. UT is uncongested transport, ST is semi-congested transport, and CT is congested transport.

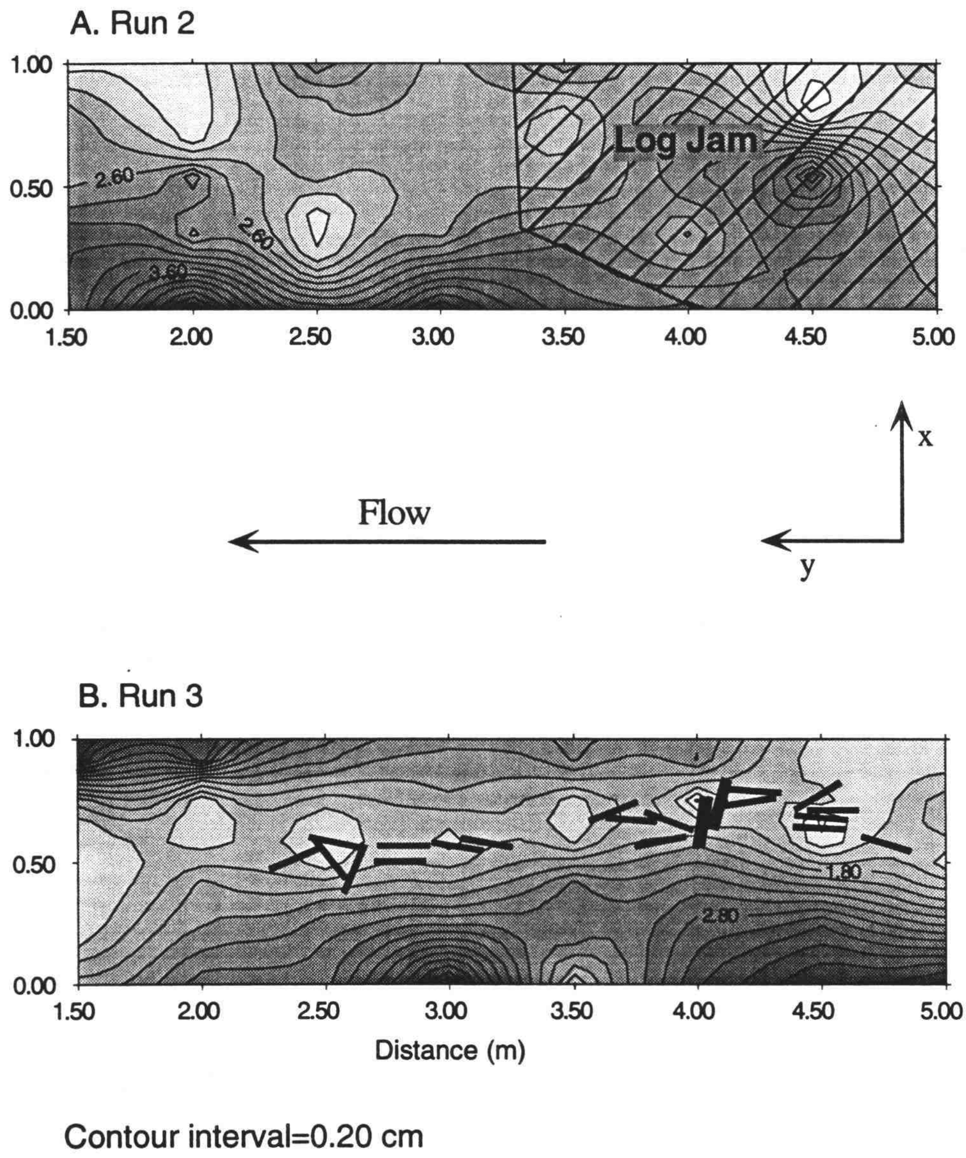

Figure 2.5. Water depth (cm) prior to log addition and piece location at the end of the experiment for runs 2 and 3.

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 the stream. When floating wood passes over a bar, the depth of the water may no longer be sufficient to float the log, and the log is deposited. When a channel is constricted by bedrock outcrops or slope failures, the channel width may become less than 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 the wood to pass through. A stream with frequent narrow reaches, bars, and obstructions promotes wood deposition, and the 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 2.1). Similarly, floating wood is easily deposited or lodged when L_{log}/w_c increases above 0.5 (Abbe *et al.*, 1993). 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, similar to hydraulic roughness. Other factors can also influence the debris roughness, such as the presence of other logs, and the congestion of the flow.

We would like to test the applicability of debris roughness to the patterns of wood deposition in these experiments. The PWRI flume had a fixed width with varying depth, and we were therefore not able to examine the effect of varying L_{log}/w_c within a run. However, since L_{log}/w_c is below depositional thresholds indicated by field studies (Abbe *et al.*, 1993) we hypothesize that L_{log}/w_c will have less of an effect in these experiments. Therefore, changes in debris roughness within each run should be controlled by changes in

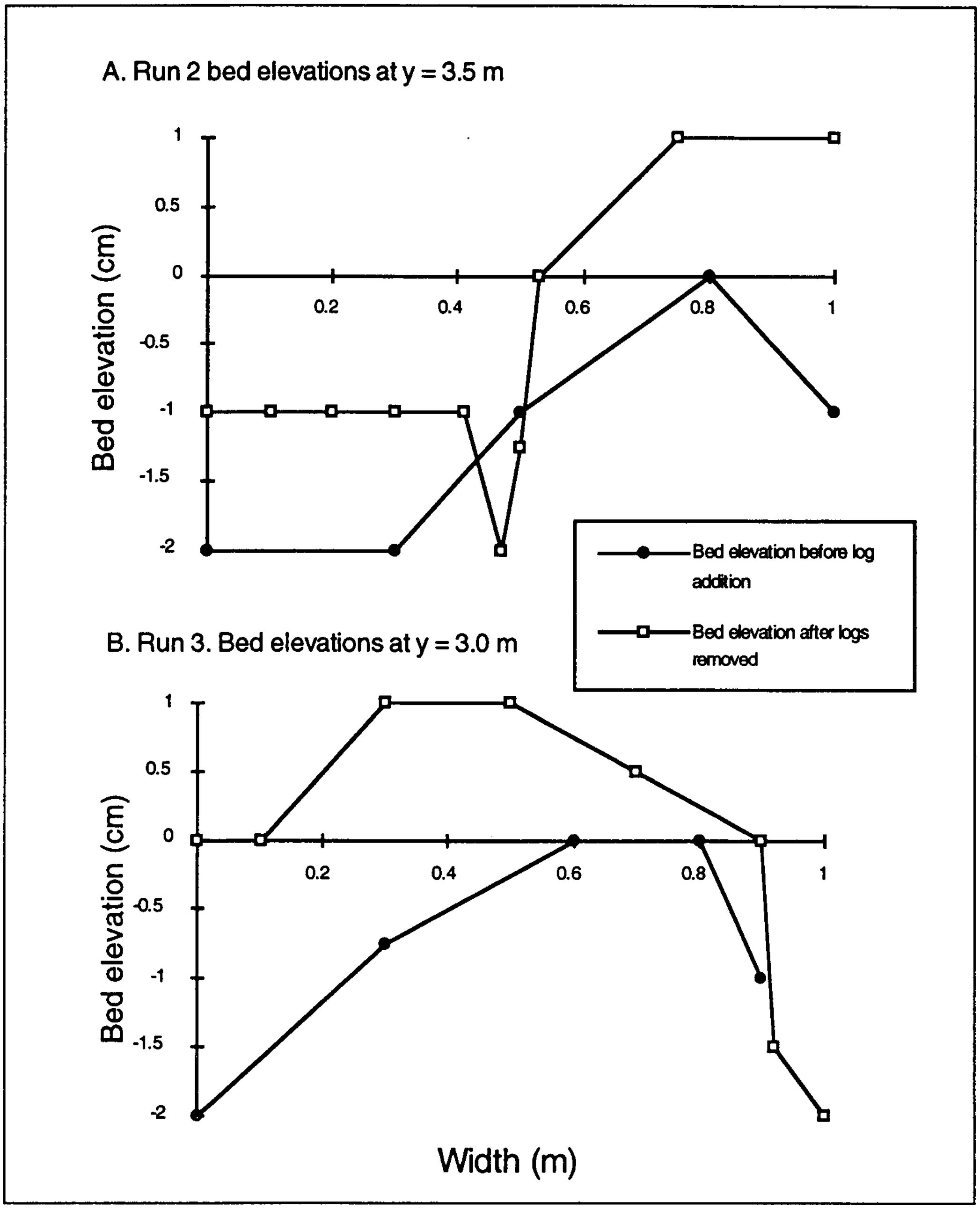

Figure 2.6. Cross-sections of bed elevation before log addition and after log removal.

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 2.5A, 2.5B). 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 1 and Figure 2.1 show that the logs will float until the depth drops below half the log diameter ($D_{log}/d_w = 2.0$). In runs 2 and 3, the logs were deposited where the 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 2.5A and 2.5B). 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 the logs were added to the flume and after the wood was removed for runs 2 and 3 indicate that the bed morphology changed during both experiments (Figures 2.6A and 2.6B). Changes in bed elevation could either cause wood deposition, or could have been caused by scour after deposition. Unfortunately, we do not have water depth data during any of the experiments, so we can only guess that the depth decreased sufficiently during the experiment, to allow wood deposition.

Modes of transport inferred by depositional fabrics of log jams

We observed a correlation between the transport regime and the 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 were plotted as rose diagrams (Figures 2.7 and 2.8). Since the dowels had no roots or distinguishable ends, all of the rose diagrams are symmetrical and assume that 0 degrees is the flow direction (Figures 2.7 and 2.8). Runs 3 and 5 could be broken into three sections, with the orientation of each section measured separately.

The orientations of the dowels in this flume experiment indicate transport type and patterns of transport may be discerned from the deposit by comparing the proportion

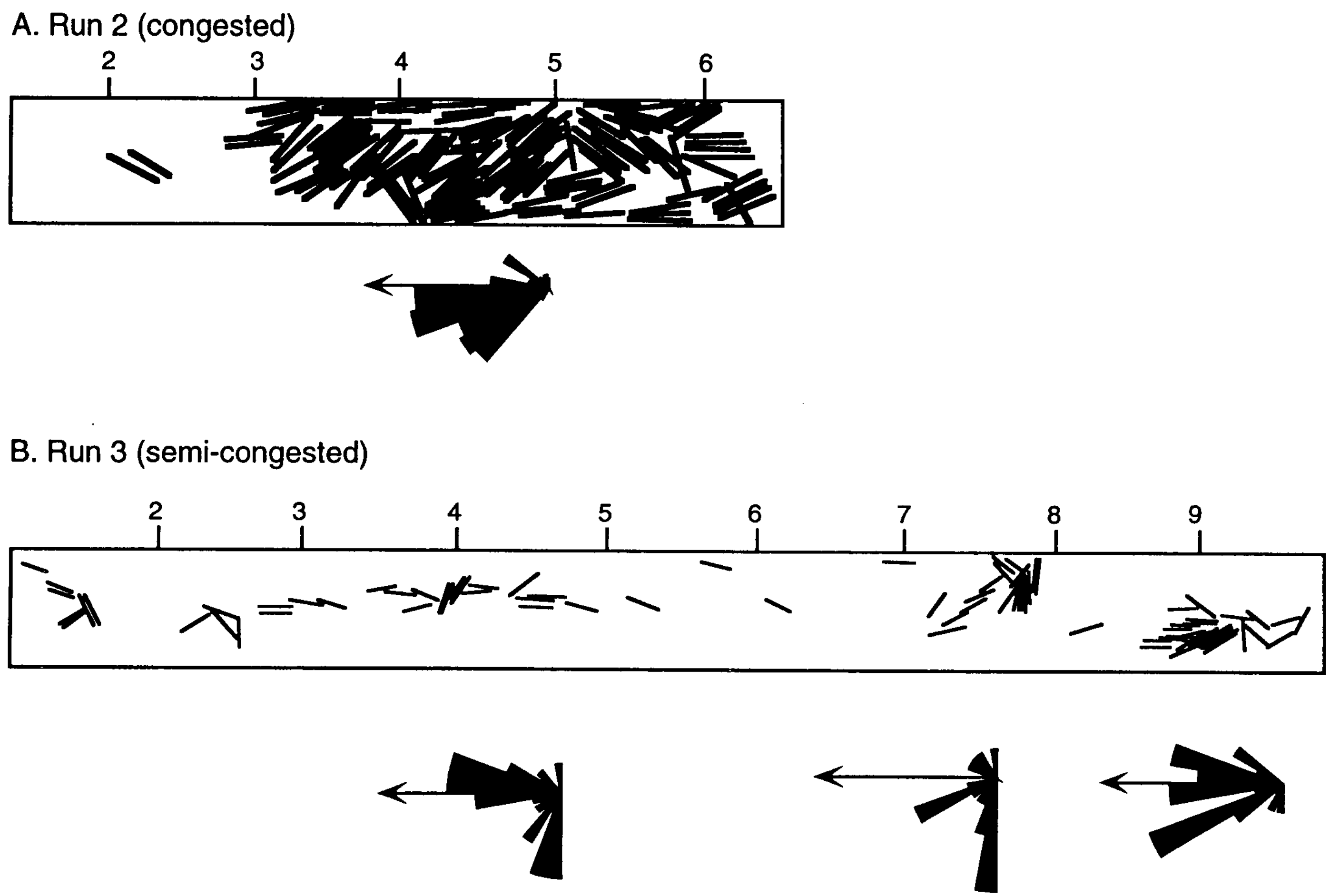

Figure 2.7. Dowel locations and rose diagrams of orientation for runs 2 and 3. Both maps are overlays of photographs taken after the runs.

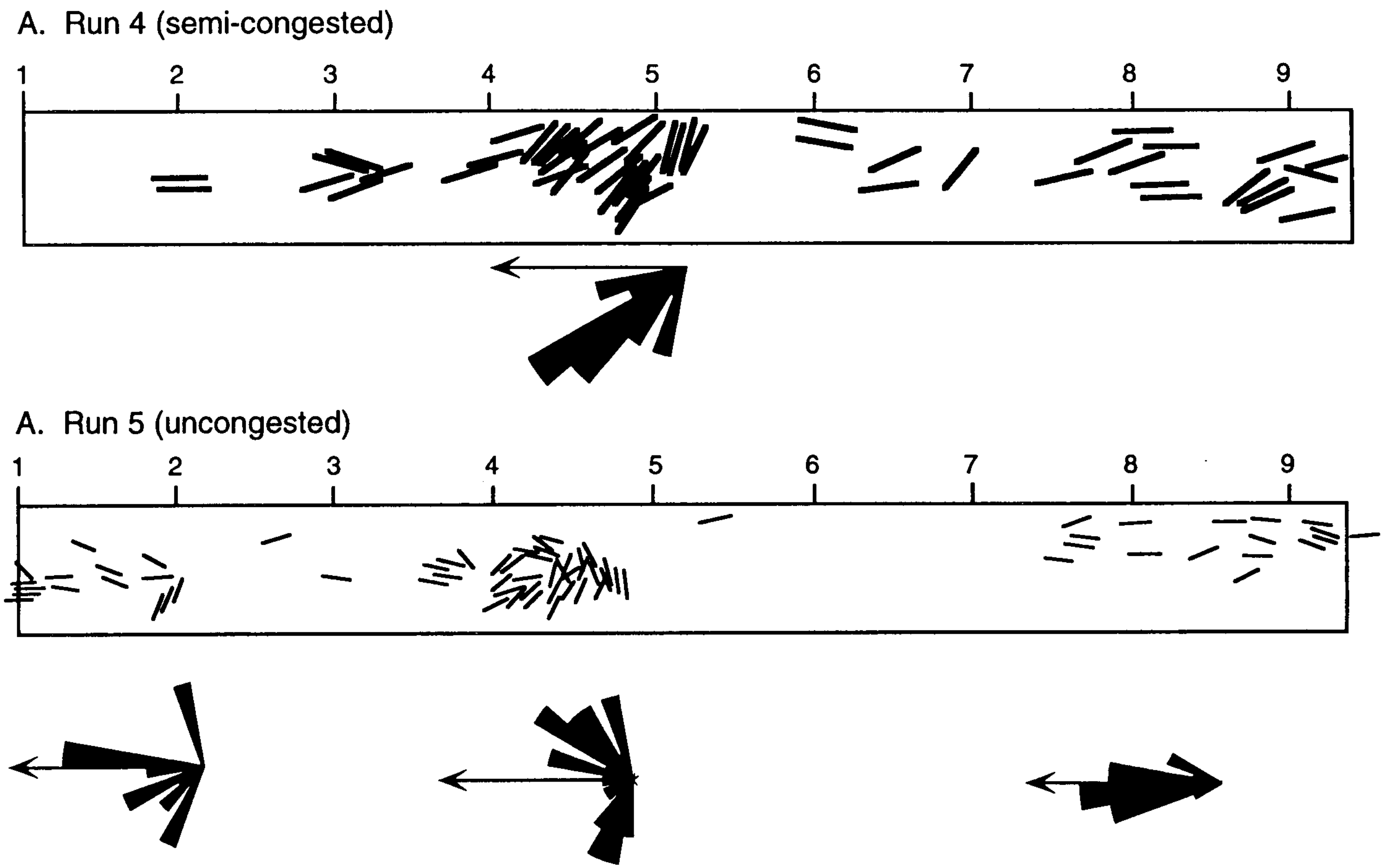

Figure 2.8. Dowel locations and rose diagrams of orientation after runs 4 and 5. Loctaion and orientation were mapped immediately after the run.

of flow-parallel pieces to the proportion of pieces that are flow-normal. The congested transport deposit (run 2, Figure 2.8A) had most pieces oriented roughly 30 degrees to the flow, with few pieces oriented normal to flow. Fabric of elongate particles in debris flows tends to parallel the margin of the flow wave; thus, at the toe of the deposit, the 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). Congested transport may be similar to plug flow seen in some debris flows.

Semi-congested transport (run 3, Figure 2.7B) left a log levee, with pieces lying parallel to flow along roughly the same flow-line (Figure 2.7B, far left). The deposits upstream acted as a source of mobile wood after introduction of pieces had ceased, therefore these loosely clustered deposits were not considered as a semi-congested fabric.

The accumulations resulting from uncongested (run 5, Figure 2.8B) and semi-congested transport (run 4, Figure 2.8A) where logs gradually accreted to bars, had logs oriented parallel to flow at their downstream ends and pieces oriented normal to flow upstream, similar to the bar-apex jam described by Abbe *et al.* (1993). The slow accumulation of pieces in these runs allowed the pieces to roll and pivot to a flow-normal orientation. Pieces in the upstream reach of the flume often were oriented parallel to flow, but were not in contact with each other so that pivoting could not occur.

Discussion

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

Wood enters streams by various mechanisms: as individual trees or snags due to windthrow, tree mortality, or both; by large streamside slides and floodplain inundation; or by debris flows. Pieces delivered via windthrow and tree mortality enter the channel as intact or broken pieces, 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 largely move 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 result 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 which travel as congested transport (Major and Voight, 1986). Where debris flows enter higher order steams 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.

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 they can occur in up to fifth-order streams (Coho, 1993). Consequently, congested transport might be expected to dominate in first- through 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 320 km long prior to snags were 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.

Higher 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 will both occur in the upper reaches of the channel network during high flows and low input rates.

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 Ikeda, 1987, Lisle *et al.*, 1991). Iseya and Ikeda (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 pieces. Iseya and Ikeda (1987) proposed increases in coarse-sediment supply, which increase the interaction among particles as the mechanism for the increase in gravel congestion (Iseya and Ikeda, 1987). They suggest that an increase in coarse sediment supply increases the interaction among the particles, creating increased congestion. 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 of kinematic wave theory to wood transport, but congestion certainly increases with increases in particle interaction, suggesting that kinematic wave theory 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. 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 decrease in stream order, fabrics of the 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 pieces 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 carried by a flood or debris flow are transported downstream. 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 concentration and log transport rates low, thereby causing wood to move via uncongested and semi-congested regimes (Figure 2.4), the extent of these disasters could be reduced.

Restoring streams to improve aquatic habitat requires reintroducing 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, and likely locations for wood deposition. A quantitative understanding of how wood moves in streams is needed to asses 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 models 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. Results of these experiments suggest a framework for expanding particle transport models to include woody debris.

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Chapter 3

Entrainment and Deposition of Large Woody Debris in Streams: A Flume Experiment.

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Abstract

Large woody debris is an integral component of forested, fluvial systems of the Pacific Northwest and elsewhere, yet little is known about when wood moves and how far it moves once in motion. In this paper we report theoretical models of entrainment, and a series of flume experiments examining interactions among hydraulics and channel geometry, as factors determining entrainment and transport distance. These experiments were carried out in a 1.22 m wide by 9.14 m long flume using dowels of various sizes as surrogate logs.

Theoretical models and these experiments indicate that entrainment of pieces was influenced by the angle of the piece and the presence/absence of rootwads. Pieces without rootwads oriented parallel to flow and all pieces with rootwads were the most stable, and pieces without rootwads oriented at 45 and 90 degrees to flow were the least stable. Although previously reported as the most important factor in piece stability, piece length did not significantly affect the threshold of movement unless the piece was oriented parallel to flow.

However, piece length did affect the transport distance, which decreased with increases in the ratio of piece length to both channel width and the radius of curvature. The debris roughness--the sum of the ratios of piece length to channel width, piece length to the radius of curvature and piece diameter to average depth--generally decreased with increased transport distance. Pieces can move further than our debris roughness models predict if they have high momentum and greater than 50 % of the active channel area deeper than the depth at which the piece floats. We propose that the debris roughness is an effective model in predicting a streams resistance to wood transport.

Introduction

Large woody debris (LWD) is an integral component of forested streams in the Pacific Northwest and elsewhere, yet there is little quantitative data available on hydraulic conditions governing wood entrainment and deposition. This is due, in part, to the fact that LWD tends to move during large floods, when safety and logistical constraints make field measurements difficult. Flume experiments have been used to study sediment transport for over eighty years, and have contributed greatly our present knowledge of sediment transport, but have received little use as a tool to improve our understanding of LWD movement in streams.

In this paper we report the results of a series of flume experiments conducted at the Saint Anthony Falls Hydraulic Laboratory, in which we examined both entrainment and deposition of individual logs in streams. These experiments were designed to test a simple entrainment model based on the balance of forces exerted on individual logs, and a theoretical model that takes into account the piece and channel characteristics that promote wood deposition. The interaction among multiple pieces can play an important role in both entrainment and deposition. Stationary pieces can be entrained when they are impacted by moving pieces, or by the diversion of flow from other stationary pieces (Braudrick *et al.*, in press). Previously deposited pieces can obstruct the transport path of moving pieces, causing deposition, which results in the formation of jams (Grant, 1987; Abbe and Montgomery, 1996). Because thresholds of movement and deposition have not previously been quantified, we decided to begin with the simple case of individual logs.

Improving our knowledge of wood transport dynamics will enhance our understanding of the ecologic and geomorphic role of LWD. Wood enhances aquatic habitat by creating refugia which 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). Governmental agencies are seeking to improve aquatic habitat by adding wood back to streams at great financial cost. Understanding factors contributing to wood stability will help make stream restoration more ecologically effective at a lower cost.

LWD can have profound effects on the morphology of forested streams (Montgomery *et al.*, 1993; Hogan, 1995, Montgomery *et al.*, 1996) but has received little study by geomorphologists relative to the other components of fluvial systems. LWD contributes to both sediment erosion (Beschta, 1983) and deposition (Hogan, 1995), both creating pools and storing large volumes of sediment (Assani and Petit, 1995; Hogan, 1995; Thompson, 1995).The removal of wood from streams alters stream morphology, increasing the sediment transport rate, and causing pools to shallow (Smith *et al.* 1993 a and b; Lisle, 1995). In small streams, steps due to LWD jams can account for a significant portion of the head loss in streams (Marston, 1982; Thompson, 1995). Wood is a relatively stable component of forested streams, often remaining in place for a century or more (MacDonald *et al.*, 1982; Gregory, 1991).

After reviewing previous work on LWD transport, we present a simple force balance model for wood movement and results of experiments designed to predictions of wood transport. We then extrapolate these results to the field predicting the efficiency of different stream types to either retain or pass woody debris.

Previous Research

Ishikawa (1989) conducted the first flume experiment on LWD dynamics, observing the movement of groups of logs through artificial constrictions and across alluvial fans. He found that piece angle with respect to flow altered the stability of pieces, with flow-parallel pieces being the most stable. All pieces were trapped upstream of constrictions where piece length was three times the width of the constriction, and were passed through the constriction where piece length was two-thirds the width of the constriction.

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; Grant, 1987; Hogan, 1987; Lienkaemper and Swanson, 1987; Bilby and Ward, 1989; Gregory, 1991; Nakamura and Swanson, 1994; Young, 1995). These studies showed that LWD moves farther in large (≥ fifth-order) than small (< fifth-order) streams (Bilby and Ward, 1989), smaller pieces move farther than larger pieces (Grant, 1987; Lienkaemper and Swanson, 1987; Young, 1993), frequency of piece movement increases with increasing stream size (Bilby, 1985; Lienkaemper and Swanson, 1987; Bilby and Ward, 1989; 1991), and most mobile pieces are shorter than bankfull width (Nakamura and Swanson, 1994). Taken together, 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. Pieces tend to be stable when piece length is greater than one-half bankfull width in large rivers (Abbe *et al.*, 1993), or greater than bankfull width in smaller rivers (Lienkaemper and Swanson, 1987). However no models exist which predict how piece length effects stability over a range of stream sizes.

Other factors 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 increasing drag, thereby decreasing mobility (Grant, 1987; Abbe and Montgomery 1996). The piece diameter strongly influences the depth of flow required to entrain and transport logs, thereby influencing distance travelled (Bilby and Ward, 1989; Abbe *et al.*, 1993). Pieces tend to stop when the channel depth is approximately half the piece diameter (Abbe *et al.*, 1993; Braudrick *et al.*, in press). Pieces tend to be stable when greater than half their length is outside the channel area (Lienkaemper and Swanson, 1987), because less of the piece is exposed to the flow.

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 margins. 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 (Grant, 1987; Nakamura and Swanson, 1994).

In a previous flume experiment Braudrick *et al.* (in press) defined debris roughness as the factors which wood to stop. Debris roughness is a function of channel geometry relative to piece geometry. Piece length relative to the average channel width (L_{log}/w_{av}) and piece diameter relative to channel depth (D_{log}/d_w) contributed to debris roughness (Chapter 2, this study), but theoretically any stream factor that promotes deposition increases the debris roughness.

Theoretical background

Entrainment

We consider wood entrainment in relation to a force balance model acting on wood in streams. For the case of a simple cylindrical log laying on a planar bed stream The total resistance force (F_r), which is the gravitational force minus the buoyant force, is equal to:

$$F_r = \left(g\rho_{log} L_{log} \frac{\pi D_{log}^{2}}{4} - g\rho_w L_{log} A_{sub} \right) \mu_{bed} \mathrm{Sin}\alpha \qquad (3.1)$$

where L_{log} is the piece length, ρ_{log} and ρ_w are the densities of wood and water respectively, D_{log} is piece diameter, μ_{bed} is the coefficient of friction between the wood and the bed, α is the angle of the bed (equal to the slope at low values of α), g is gravity, and A_{sub} is the submerged area of the log. μ_{bed} is equal to 0.466 for wood laying in water on a fine sand bed (Ishikawa, 1989). A_{sub} is a function of water depth (d_w)and diameter and is equal to:

$$A_{sub} = \left(Cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right) - Sin\left(Cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right)\right)\right)\frac{D_{log}^{\ 2}}{8} \tag{3.2}$$

The driving force (F_D) acting on the log is equal to:

$$F_D = \frac{U^2}{2}\rho_w C_d\left(L_{log}d_w Sin\theta + A_{sub}Cos\theta\right) \tag{3.3}$$

where U is the water velocity, C_d is the drag coefficient, and θ is the piece orientation with respect to the flow. Gippel *et al.* (1996) found that C_d is 1.05 for pieces oriented parallel to flow, 0.80 for pieces oriented at 45 degrees to flow, and 1.0 for pieces oriented normal to flow. The piece moves when the driving force is equal to the resistance force, which is given by equation 3.4.

$$\left(g\rho_{log}L_{log}\frac{\pi D_{log}^{\ 2}}{4} - g\rho_w L_{log}A_{sub}\right)\mu_{bed}Sin\alpha = \frac{U^2}{2}\rho_w C_d\left(L_{log}d_w Sin\theta + A_{sub}Cos\theta\right) \tag{3.4}$$

Equations 3.2 and 3.4 indicate that entrainment is a function of four piece characteristics: piece length, piece density, piece diameter, and orientation, and three hydraulic characteristics: slope, velocity, and channel depth (Figure 3.1). If the piece is oriented at 90 degrees to flow $A_{sub}Cos\theta$ equals zero, and piece length is canceled out, and does not affect the entrainment threshold. However, piece length does effect the stability of pieces at other orientations.

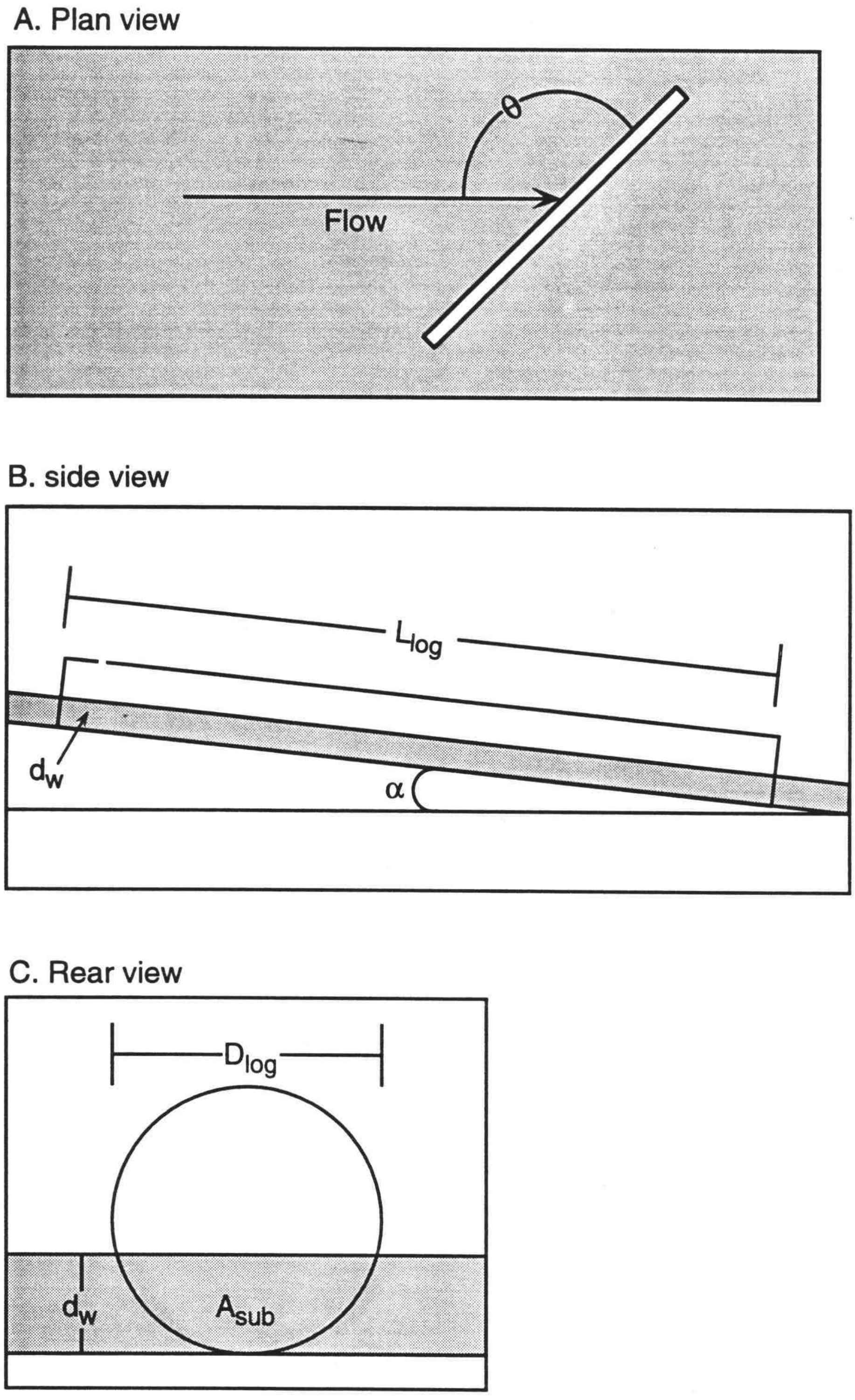

Figure 3.1. Schematic diagram of some of the components of the force balance of a cylindrical log with a rootwad.

If a rootwad is attached to the piece, the piece is elevated off the bed a certain height dependent on the ratio of piece length to rootwad diameter. This effectively reduces the buoyant force because less water is displaced, and increases the gravitational force per unit bed area, since the entire mass is bourne on less basal area. The force balance acting on pieces with rootwads is:

$$\left(g\rho_{\log}\left(L_{\log}\frac{\pi D_{\log}^{2}}{4}-V_{rw}\right)-g\rho_w\left(V_1+V_2\right)\right)\mu_{bed}Sin\alpha =$$

$$\frac{U^2}{2}\rho_w C_d\left(\left(A_1+A_2\right)Sin\theta + A_3 Cos\theta\right) \tag{3.5}$$

where the left-hand side of the equation is the resistance force, and the right-hand side is the driving force, and V_{rw} is the rootwad volume, V_1 and V_2 are the submerged volumes of the bole and rootwad, respectively, A_1 and A_2 are the submerged areas of the bole and rootwad in cross-section, respectively, A_3 is the submerged area perpendicular to piece length, and all other variables are as defined previously (Figure 3.2).

If the rootwad diameter is large relative to piece diameter, A_1 and A_2 are generally lower than the submerged area for a piece without a rootwad. Accordingly, V_1 and V_2 are lower than the submerged volume of a piece without a rootwad. This suggests that pieces with rootwads will be more stable than pieces without rootwads.

Often the non-rootwad end of the piece can float, which causes pivoting and hence torque to become an important factor in piece movement. This causes longer pieces to have a lower entrainment threshold than shorter pieces because torque is the cross-product of force and the length of the lever arm. So depending on their orientation relative to the channel, long pieces with rootwads may be more or less stable than shorter pieces with rootwads.

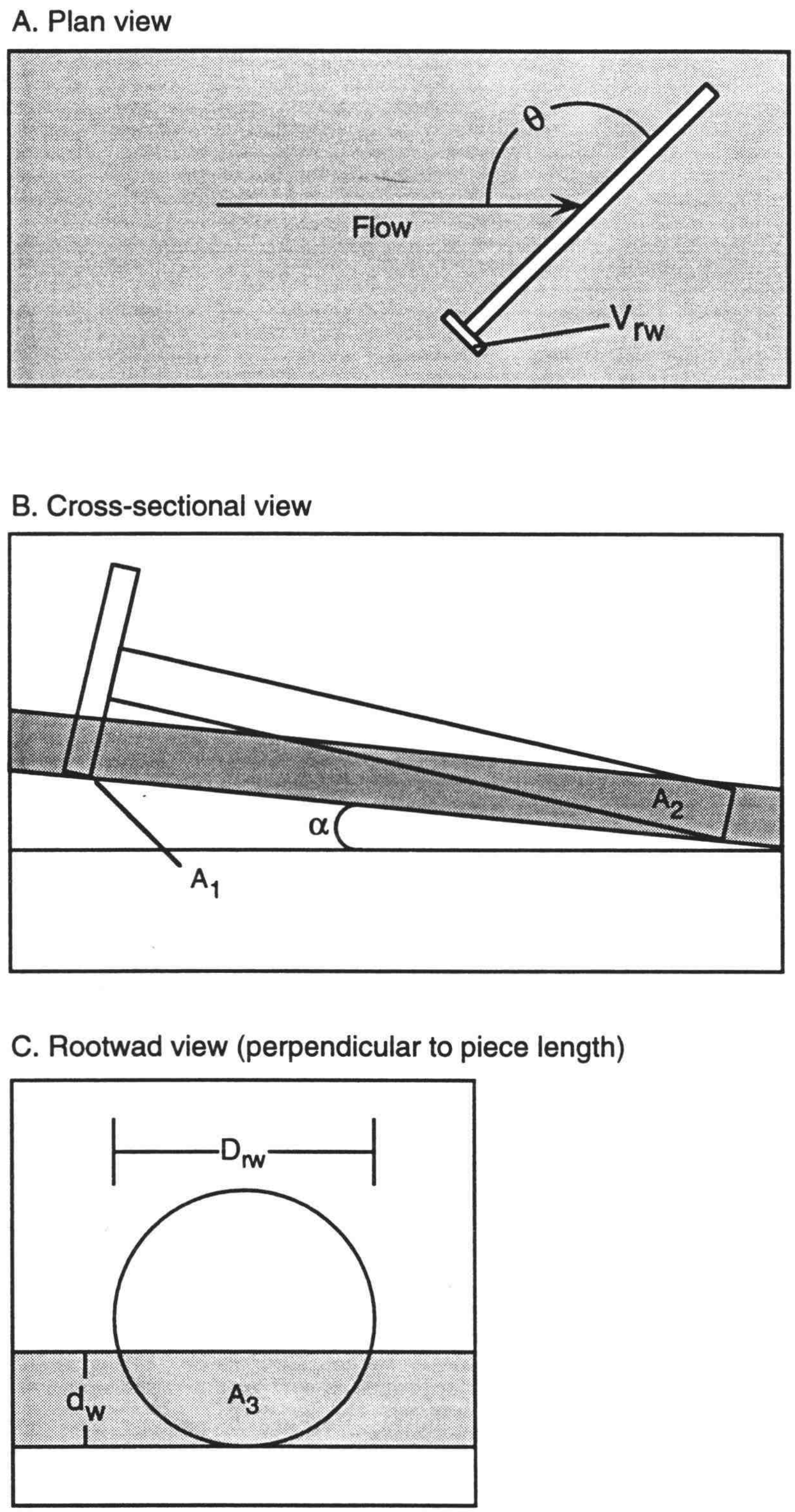

Figure 3.2. Schematic diagram of some of the components of the force balance of a cylindrical log with a rootwad.

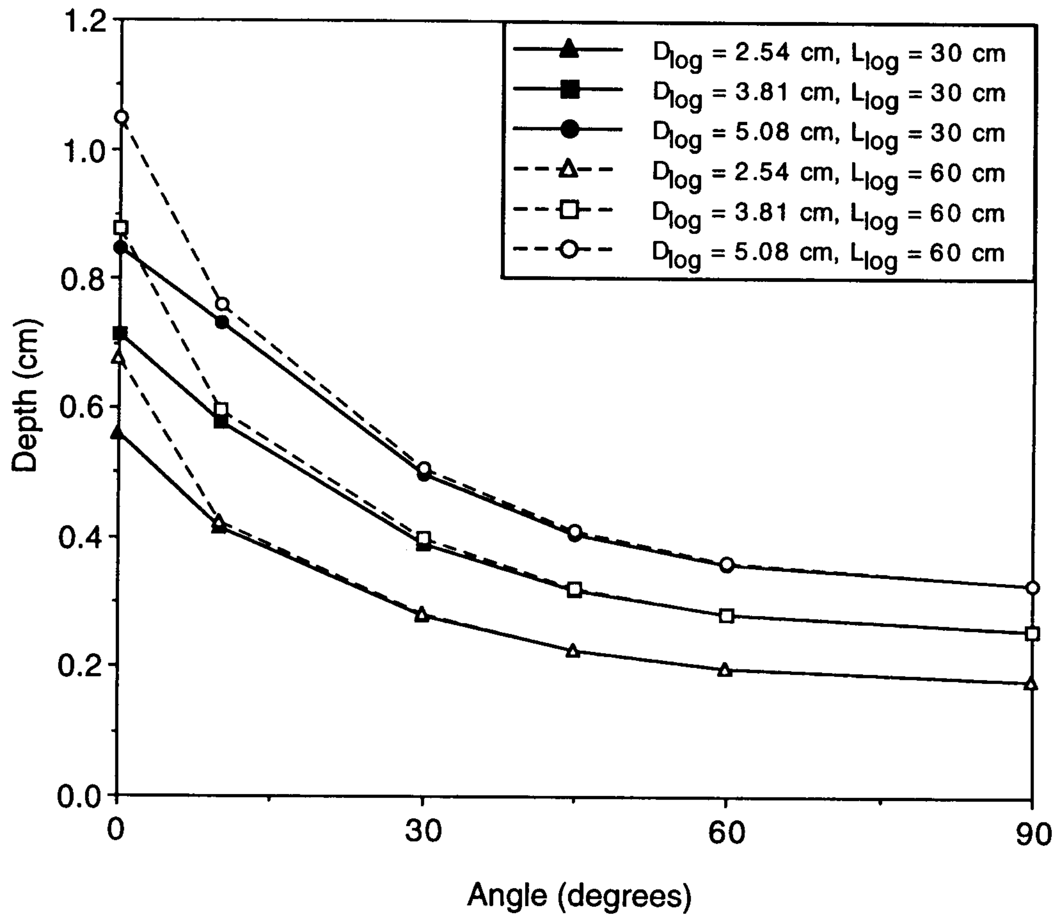

Figure 3.3. Theoretical plot of entrainment depth of logs of 2 length classes and three diameter classes based upon equation 3.4. Piece sizes are similair to those used in the experiments.

Numerical simulation of depth of entrainment for pieces without rootwads, similar in size to those used in these experiments, as a function of piece angle show that the importance of length class decreases as piece orientation changes from flow-parallel to flow-normal (Figure 3.3). The larger the diameter of the piece, the greater the depth required for entrainment. Equation 3.4 indicates that large diameter pieces oriented parallel to flow should be the most stable, and stability will decrease as the piece is rotated towards ninety degrees. Piece length should have some effect, but the magnitude of the effect is less than the effect of orientation. Equation 3.5 indicates that pieces with rootwads will be more stable than pieces without rootwads, due to a reduced buoyant force, and less surface area exposed to the flow.

Deposition

We can use evidence from field studies to define a series of dimensionless ratios among piece size, channel geometry, and flow hydraulics that should affect the probability that a piece will become deposited; these we define as the debris roughness of a stream reach. L_{log}/w_{av} and D_{log}/d_w both contribute to the distance a piece travels, but other dimensionless ratios should affect deposition as well. Because of the propensity of wood to deposit on the outside of bends, channel sinuosity is also a factor in the debris roughness of a channel. We propose that the ratio of the piece length to the radius of curvature of the bend (L_{log}/R_c) is the best way to quantify this effect. The higher L_{log}/R_c the less likely a piece would be to pass through a bend, because the piece ends may become lodged against the bank as flow patterns push it to the outside of the bend.

Debris roughness (DR) can be described as:

$$DR \propto \left(a_1 \frac{L_{log}}{w_{av}} + a_2 \frac{L_{log}}{R_c} + a_3 \frac{D_{log}}{d_{av}} \right) \qquad (3.6)$$

where a_1, a_2, and a_3 are coefficients which according to the relative importance of each variable.

The ratio of the piece length to the minimum width of a reach (L_{log}/w_{min}) can determine whether or not a piece will be able to pass through a given section, and may be a more appropriate predictor than L_{log}/w_{av} for certain stream types. We would also expect that a channel with uniform depth would have a lower debris roughness than a channel with a varied depth, if the depth is below the buoyant threshold of the piece. We hypothesize that the percent of the active channel area whose depth is greater than the depth at which the piece becomes buoyant (d_b) is the best way to evaluate the effect of uniform versus varied depth.

Methods

We conducted these experiments at the University of Minnesota's St. Anthony Falls Hydraulic Laboratory, Minneapolis, MN. The flume was 1.22 m (4 ft) wide and 9.14 m (30 ft) long. The base of the flume had a fixed slope of 1%. The sediment for all experiments was pea gravel with D_{50} of approximately 8 mm. Cylindrical wooden dowels of known density (ranging from 436-735 kg/m^3) were used to simulate logs. Rootwads were constructed by gluing wooden cabinet doorknobs, essentially a disk with a cylindrical base, onto the end of the dowels. All depth were measured with a point gauge. Velocity was measured using a float and stopwatch. A coordinate system was created with X along the flume length, Y measured across the flume, and Z as elevation.

Entrainment experiments

We constructed a uniform 5 cm thick planar bed of sediment with a 1% slope for the entrainment experiments. The center of the dowels were placed 3 m from the top of the flume, and 0.61 m from the sidewall in order to minimize wall and inflow effects. At the beginning of each experiment the flow was set below the threshold of movement, as predicted by equation 3.4, and gradually raised until the piece moved. We then measured the velocity and depth at the initial location of the piece. We measured the initiation of movement of pieces, not whether they moved down the channel, and defined movement as piece displacement greater than one-half log length downstream. Six pieces were used in these experiments representing two length classes (0.30 m and 0.60 m), two diameter classes (2.54 cm and 3.78 cm), and two lengths with rootwads (both with diameters of 2.54 cm and lengths of 0.30 m and 0.60 m, Table 3.1). This ensured that we could evaluate the effects of piece length, diameter, and rootwads on the initiation of transport. Pieces were placed in the flume either parallel, 45 degrees, or perpendicular to flow, with the rootwad at the upstream end of the piece. For statistical purposes each experiment was repeated at least 5 times.

Table 3.1. Experimental conditions for the entrainment experiments.

Run	Angle	Length (m)	Length class	Diameter (cm)	Diameter class	Rootwad diameter (cm)
1	0	0.3	1	2.54	1	N/A
2	45	0.3	1	2.54	1	N/A
3	90	0.3	1	2.54	1	N/A
4	0	0.6	2	2.54	1	N/A
5	45	0.6	2	2.54	1	N/A
6	90	0.6	2	2.54	1	N/A
7	0	0.3	1	3.81	2	N/A
8	45	0.3	1	3.81	2	N/A
9	90	0.3	1	3.81	2	N/A
10	0	0.6	2	3.81	2	N/A
11	45	0.6	2	3.81	2	N/A
12	90	0.6	2	3.81	2	N/A
13	0	0.3	1	2.54	1	3.81
14	45	0.3	1	2.54	1	3.81
15	90	0.3	1	2.54	1	3.81
16	0	0.6	2	2.54	1	3.81
17	45	0.6	2	2.54	1	3.81
18	90	0.6	2	2.54	1	3.81

Deposition experiments

For these experiments, channel morphology was either self-formed or created by hand; the latter permitted construction of bars with a variety of channel configurations. In either case, water was run through the flume until a stable channel configuration was formed, when water surface elevations were measured. 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 a finer measurement interval in areas where the morphology was more complex. Pieces were introduced into the top of the flume (X = 0.60 m, Y = 0.60 m) 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 interactions did not play a role in the experiments. For each channel morphology either 4 (2 lengths and 2 diameters, runs 1, 2, and 3) or 6 pieces were used (3 lengths and 2 diameters, runs 4 and 5, Table 3.2). Each piece was run through the flume 10 times. After 7 m, backwater effects from the tailgate started to affect flow, so only data from the upper 6 m were used. The distance travelled was measured from the point of introduction to the midpoint of the piece. Average channel width was calculated by measuring the active channel width at 0.5 m intervals. Radius of curvature was measured at the apex of the most sinuous bend in the run.

Table 3.2. Piece sizes used in the deposition experiments, by run.

Run	Length (m)	Length class	Diameter (cm)	Diameter class
1.1	0.3	1	1.27	1
1.2	0.6	2	1.27	1
1.3	0.3	1	2.54	2
1.4	0.6	2	2.54	2
2.1	0.3	1	1.27	1
2.2	0.6	2	1.27	1
2.3	0.3	1	2.54	2
2.4	0.6	2	2.54	2
3.1	0.3	1	1.27	1
3.2	0.6	2	1.27	1
3.3	0.3	1	2.54	2
3.4	0.6	2	2.54	2
4.1	0.3	1	1.27	1
4.2	0.6	2	1.27	1
4.3	0.9	3	1.27	1
4.4	0.3	1	2.54	2
4.5	0.6	2	2.54	2
4.6	0.9	3	2.54	2
5.1	0.3	1	1.27	1
5.2	0.6	2	1.27	1
5.3	0.9	3	1.27	1
5.4	0.3	1	2.54	2
5.5	0.6	2	2.54	2
5.6	0.9	3	2.54	2

For Experiment 2, we tested the hypothesis that the distance traveled would decrease with increases in L_{log}/w_{av}, L_{log}/w_{min}, D_{log}/d_w, and L_{log}/R_c. A regression was developed using distance travelled as the dependent variable and L_{log}/w_{av}, L_{log}/w_{min}, D_{log}/d_w, and L_{log}/R_c as the independent variables, with N=240.

Results

Entrainment

Figures 3.4-3.6 evaluate the effects of the two hydraulic driving forces acting on the piece: the water depth/buoyant depth for the piece in the absence of a rootwad (d_w/d_b) and velocity (U_w) at which piece movement occurred for the various runs in the entrainment experiments. The buoyant depth was calculated using equations developed by Braudrick *et al.* (in press, chapter 2 of this thesis). We used d_w/d_b instead of d_w alone in order to evaluate the influence of depth regardless of piece density. Pieces should float when $d_w/d_b = 1$. It is clear from these figures that pieces oriented at 0 degrees are more stable than pieces oriented at 45 and 90 degrees, for all lengths and diameters, and regardless of whether or not pieces had a rootwad. Pieces without rootwads oriented at 45 and 90 degrees tend to move prior to their flotation threshold, and pieces without rootwads oriented at 0 degrees and pieces with rootwads tend to move after their flotation threshold (Table 3.3). There is little difference in d_w/d_b between piece lengths for pieces of equal diameter (Table 3.3).

Pieces oriented at 45 and 90 degrees tended to pivot and roll toward 0 degrees, while moving down the flume. Often pivoting and rolling was the first stage of movement. Pieces oriented at 0 degrees tended to float at one end, pivot slightly and roll down stream. Pieces without rootwads oriented at 0 degrees were further stabilized by the bunching of sediment downstream of the piece, which increased piece stability. The role of a deformable bed downstream of the piece affects pieces with other orientations as well, and makes it difficult to test equations 3.4 and 3.5 because the resistance provided by the sediment is unknown

Pivoting was also very important for pieces with rootwads, particularly those oriented at 45 and 90 degrees. These pieces rolled downstream, pivoted towards 0 degrees, and stabilized just downstream of their initial location. Under flow conditions observed, stability of pieces with rootwads is essentially controlled by their stability at 0

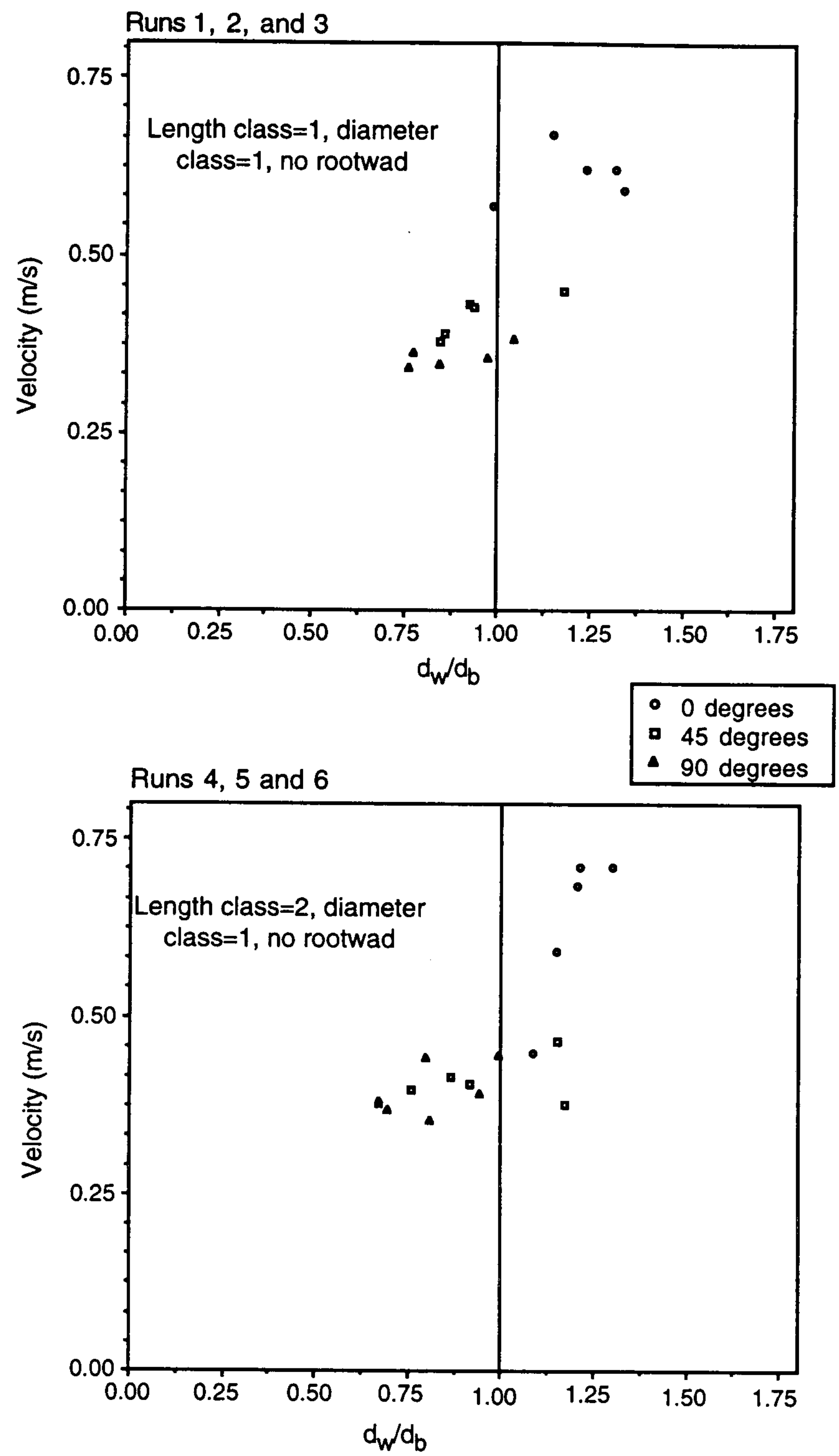

Figure 3.4. Velocity and d_w/d_b for pieces without rootwads in diameter class 1. The vertical line indicates d_w/d_b =1.

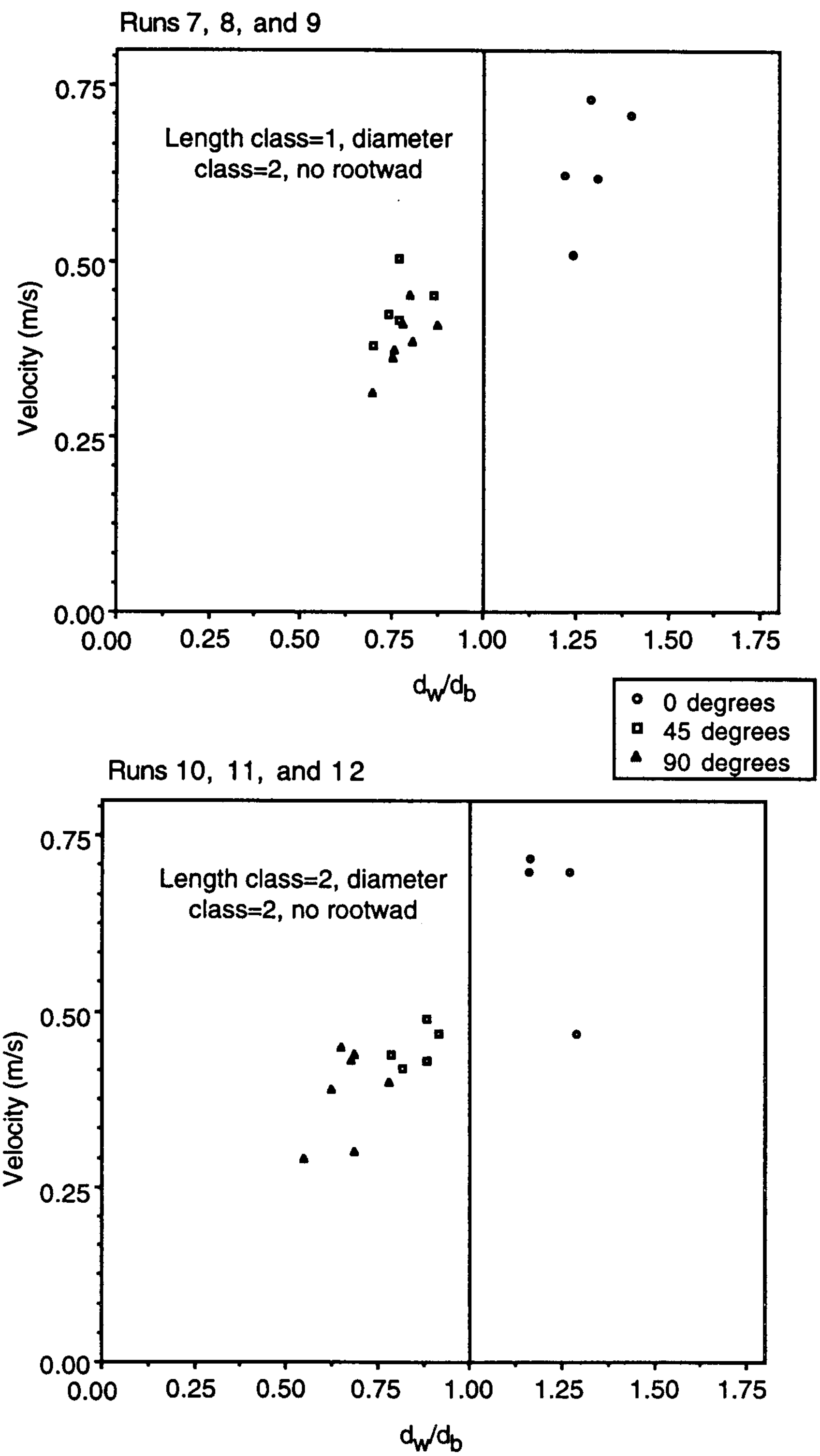

Figure 3.5. Velocity and d_w/d_b for pieces without rootwads in diameter class 2. The vertical line indicates $d_w/d_b = 1$.

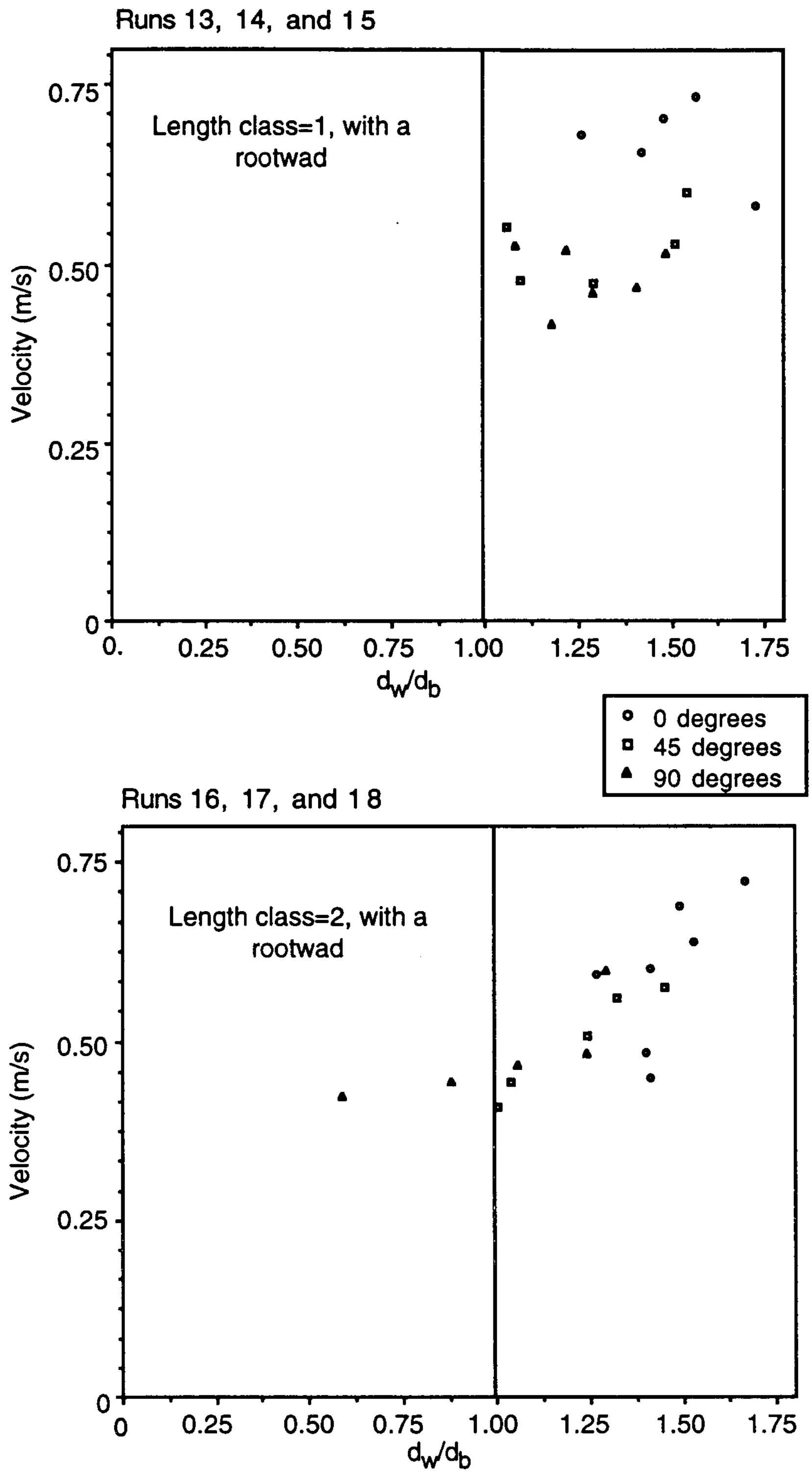

Figure 3.6. Velocity and d_w/d_b for pieces with rootwads in diameter class 1. The vertical line indicates $d_w/d_b = 1$.

degrees. Movement of rootwad pieces oriented at 0 degrees began with flotation of the non-rootwad end, which reduced the normal force, then the rootwad would move forward while still in contact with the bed.

Table 3.3. Mean depth as a percentage of d_b at time of movement for all runs.

Run	length class	diameter class	rootwad	angle	mean depth as a % of d_b at flotation
1	1	1	no	0	134
2	1	1	no	45	95
3	1	1	no	90	88
4	2	1	no	0	122
5	2	1	no	45	97
6	2	1	no	90	80
7	1	2	no	0	129
8	1	2	no	45	77
9	1	2	no	90	78
10	2	2	no	0	135
11	2	2	no	45	83
12	2	2	no	90	65
13	1	1	yes	0	145
14	1	1	yes	45	121
15	1	1	yes	90	131
16	2	1	yes	0	149
17	2	1	yes	45	143
18	2	1	yes	90	132

We can compare the results of our entrainment experiments for pieces without rootwad to the entrainment depth and velocity predicted by the model. We can use drag coefficients presented by Gippel *et al.* (1996), μ_{bed} equal to 0.5, which is slightly higher than the value of 0.466 found for logs laying on a fine sand bed (Ishikawa, 1989), and Manning's n equal to 0.013 (the average value calculated for all runs). Figures 3.7-3.10 show the calculated and observed values of depth and velocity. While the force balance equations correctly predict the relative stability of the pieces, the experimental results plot at higher velocities and depths than the equations predict. We believe that this discrepancy

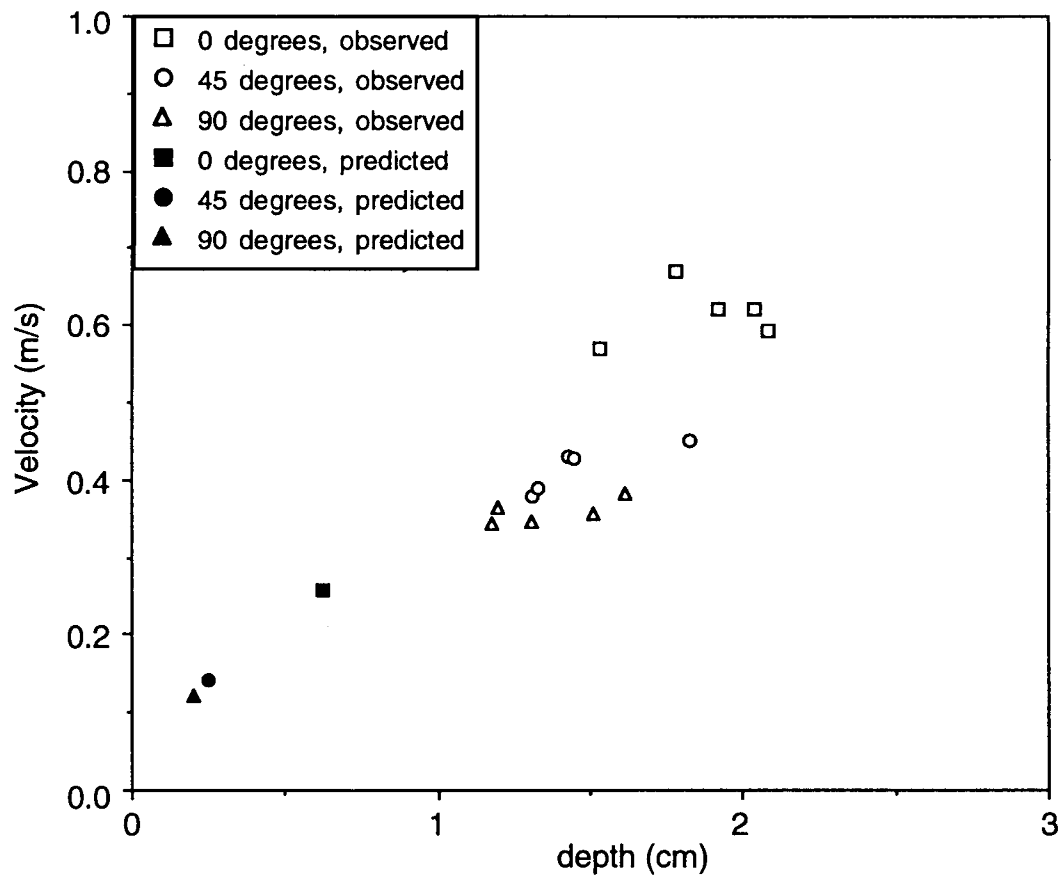

Figure 3.7. Observed (hollow symbols) and predicted (filled symbols) depths and velocities at entrainment for pieces in length class 1 and diameter class 1, without rootwads.

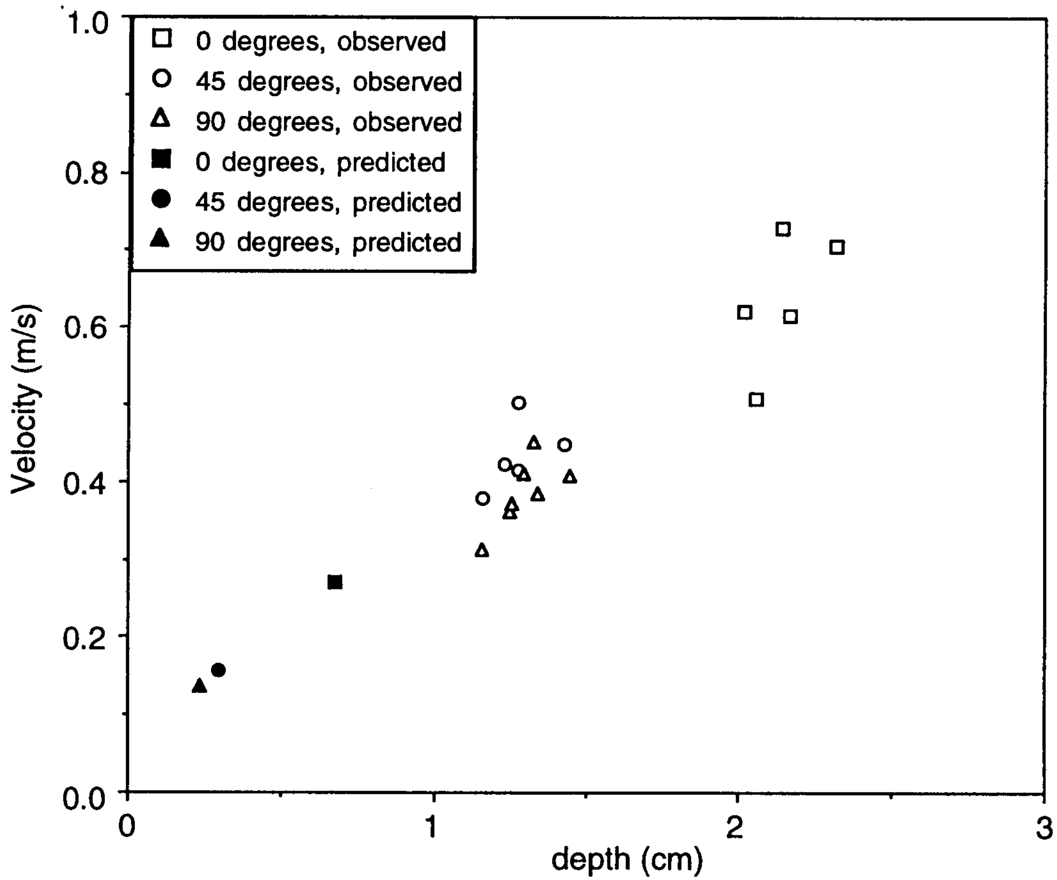

Figure 3.8. Observed (hollow symbols) and predicted (filled symbols) depths and velocities at entrainment for pieces in length class 1 and diameter class 2, without rootwads.

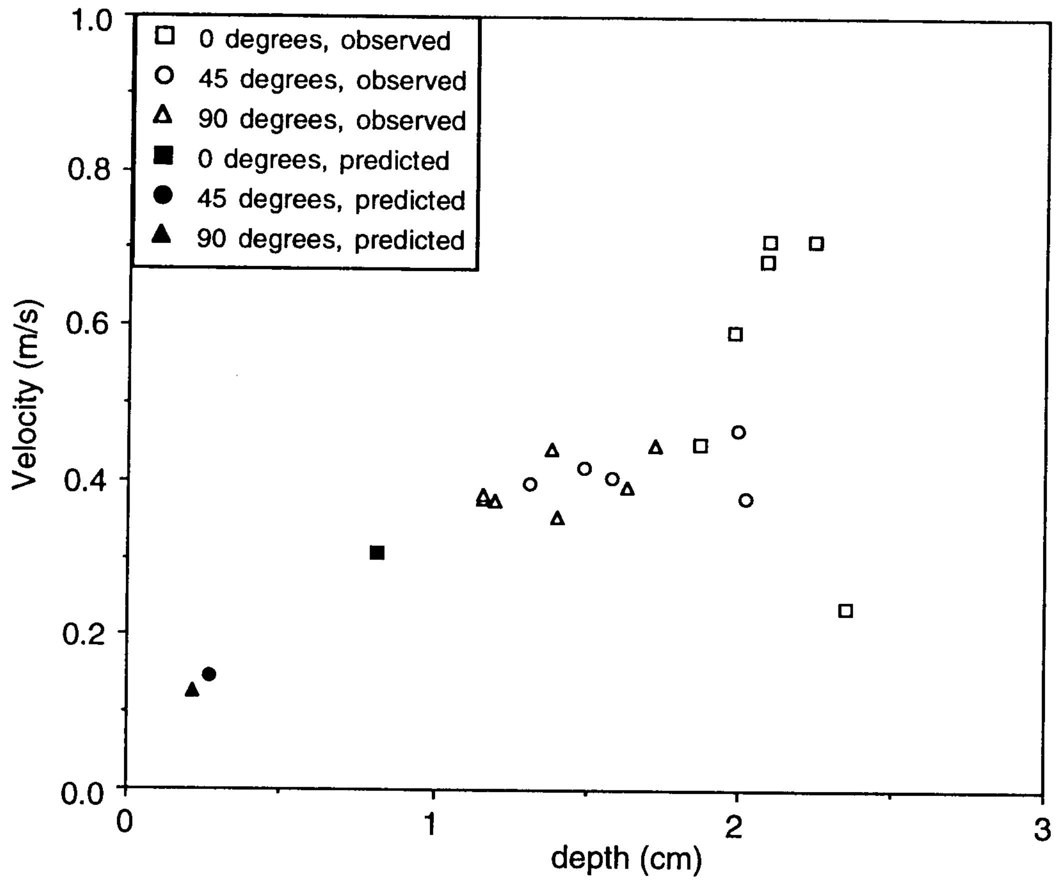

Figure 3.9. Observed (hollow symbols) and predicted (filled symbols) depths and velocities at entrainment for pieces in length class 2 and diameter class 1, without rootwads.

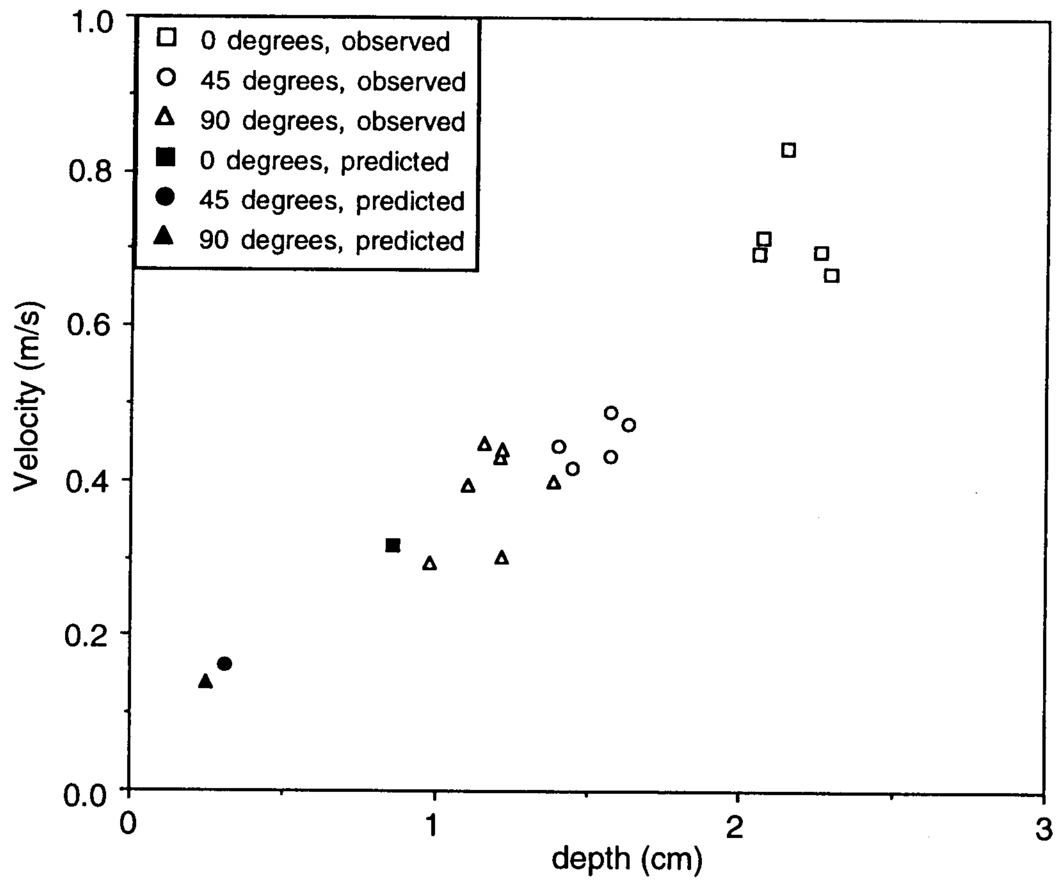

Figure 3.10. Observed (hollow symbols) and predicted (filled symbols) depths and velocities at entrainment for pieces in length class 2 and diameter class 2, without rootwads.

is due to resistance of the gravel bed. Because we wanted the bed to remain immobile we had to use a relatively large grain size in our flume experiments. Dimensional analysis shows that if we are modeling logs that are 15 m long, using grain size of 8 mm in the flume models sediment diameters of 20 cm. This large grain size impedes log entrainment and increases the force required to move them. However, the force-balance equations do accurately predict the relative importance of piece size and orientation on entrainment.

Piece transport and deposition

There were 5 channel morphologies used in the deposition 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 relatively uniform depth, and run 5 had flow coming up onto the bars (Figure 3.11). Deposition location for each piece in the 5 runs is shown in figures 3.12-3.16.

Pieces tended to align themselves parallel to flow while traveling down the flume in all runs regardless of their initial orientation at the time of input. This occurred in all runs, due to the cross channel velocity distribution (Figure 3.17) and, to a lesser degree, lateral shock waves created by near critical flows that tended to shift pieces towards the center of the channel.

Once the downstream ends of pieces encountered obstructions they tended to pivot or roll. Pieces lodged normal to flow if the upstream end of the piece also became lodged against an obstruction during pivoting (runs 1, 2, and 5, Figures 3.12, 3.13, and 3.16). 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, Figures 3.12 and 3.13) or on the outside of bends (runs 3, 4, and 5; Figures 3.14, 3.15,

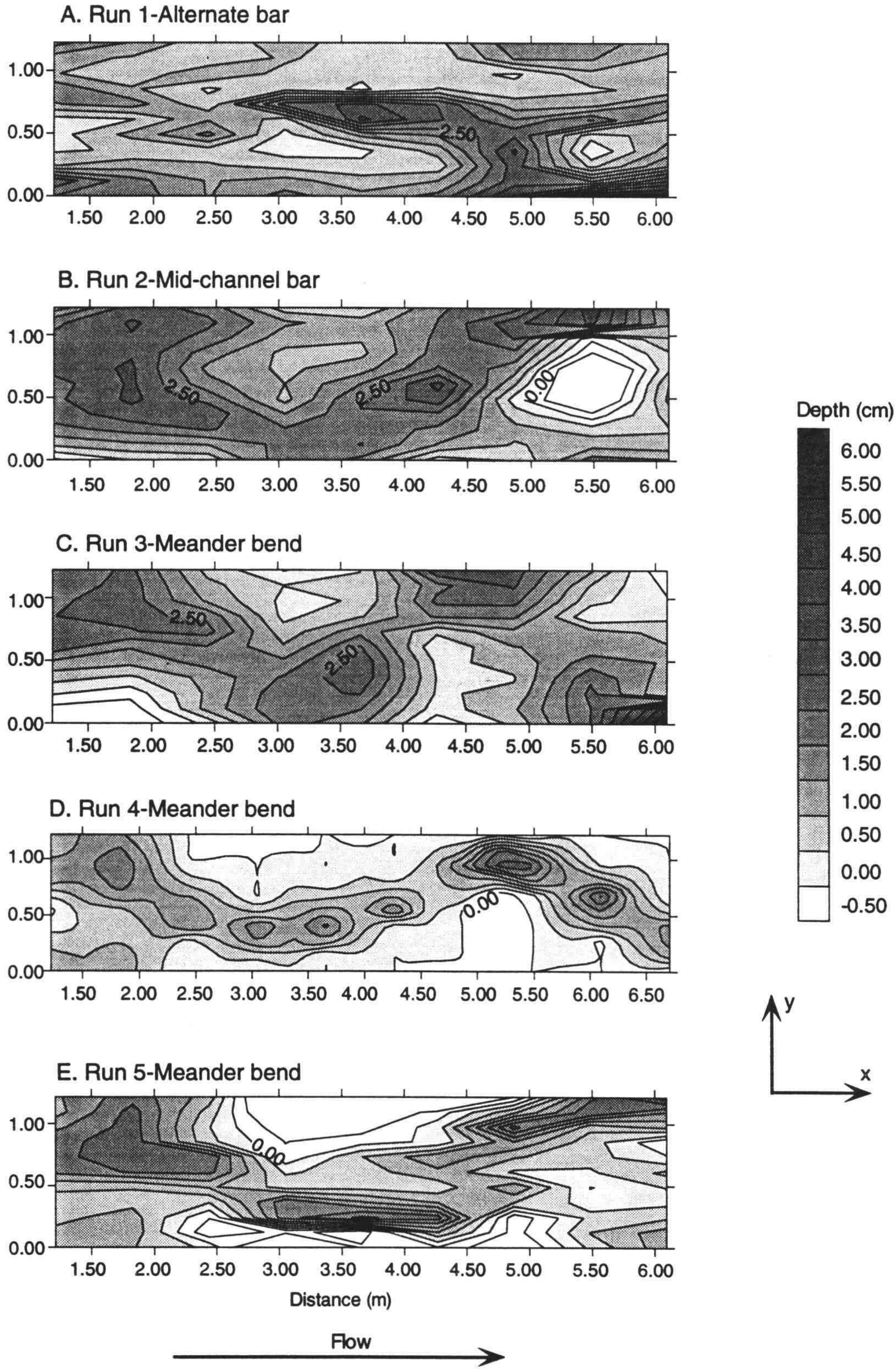

Figure 3.11. Contour maps of water depth for each of the 5 runs.

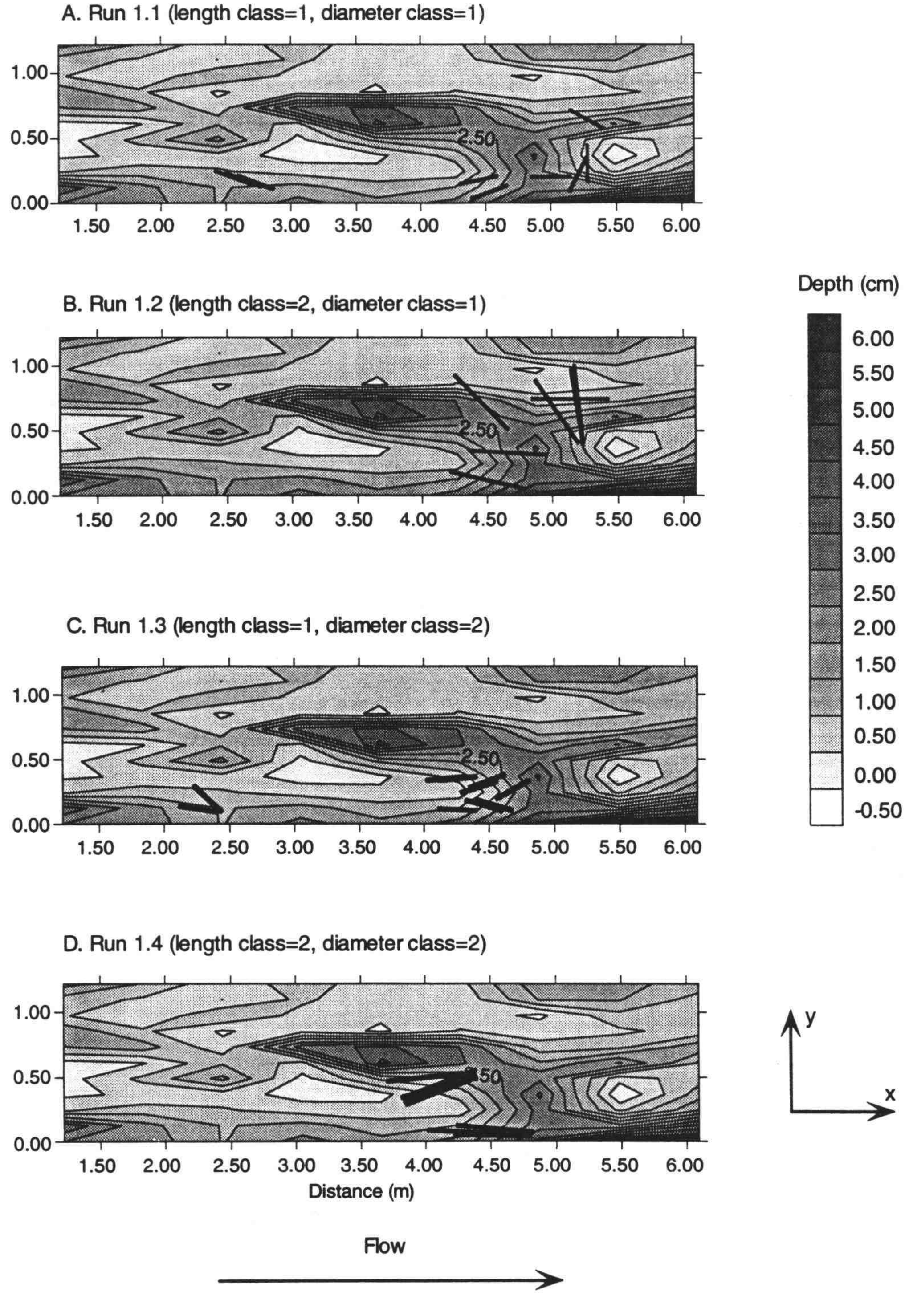

Figure 3.12. Maps of water depth and depositional location of pieces for runs 1.1-1.4.

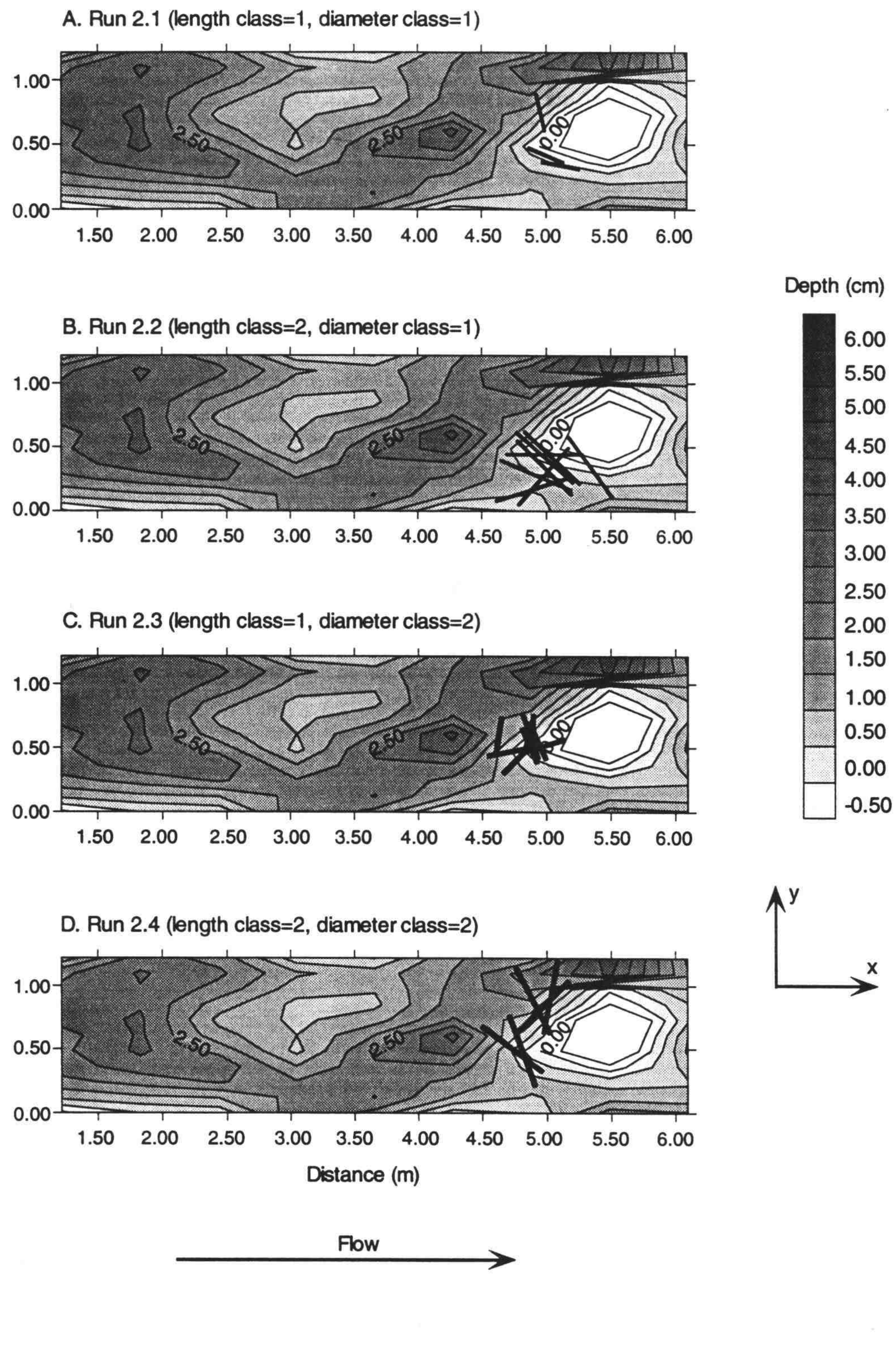

Figure 3.13. Maps of water depth and depositional location of pieces for runs 2.1-2.4.

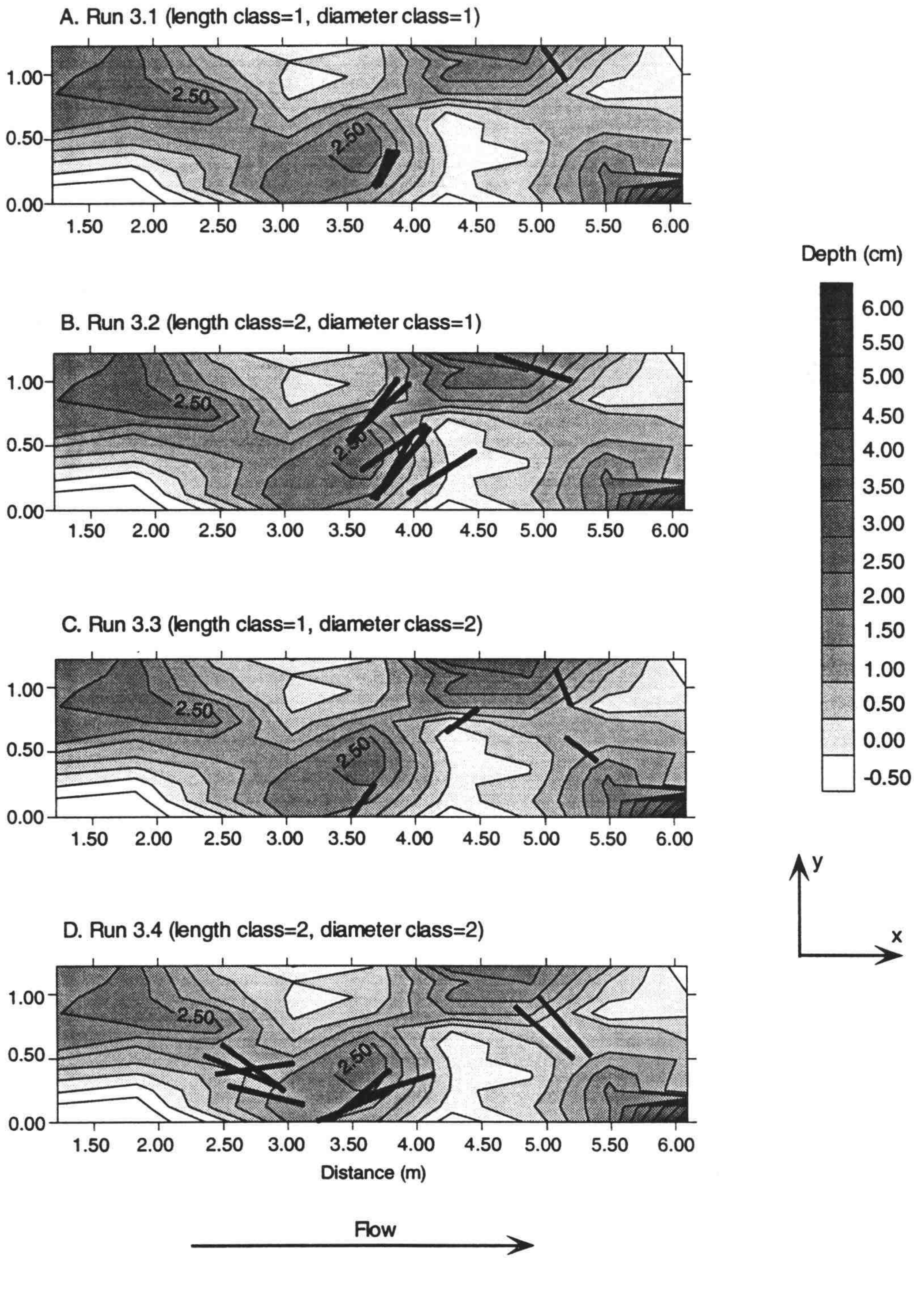

Figure 3.14. Maps of water depth and depositional location of pieces for runs 3.1-3.4.

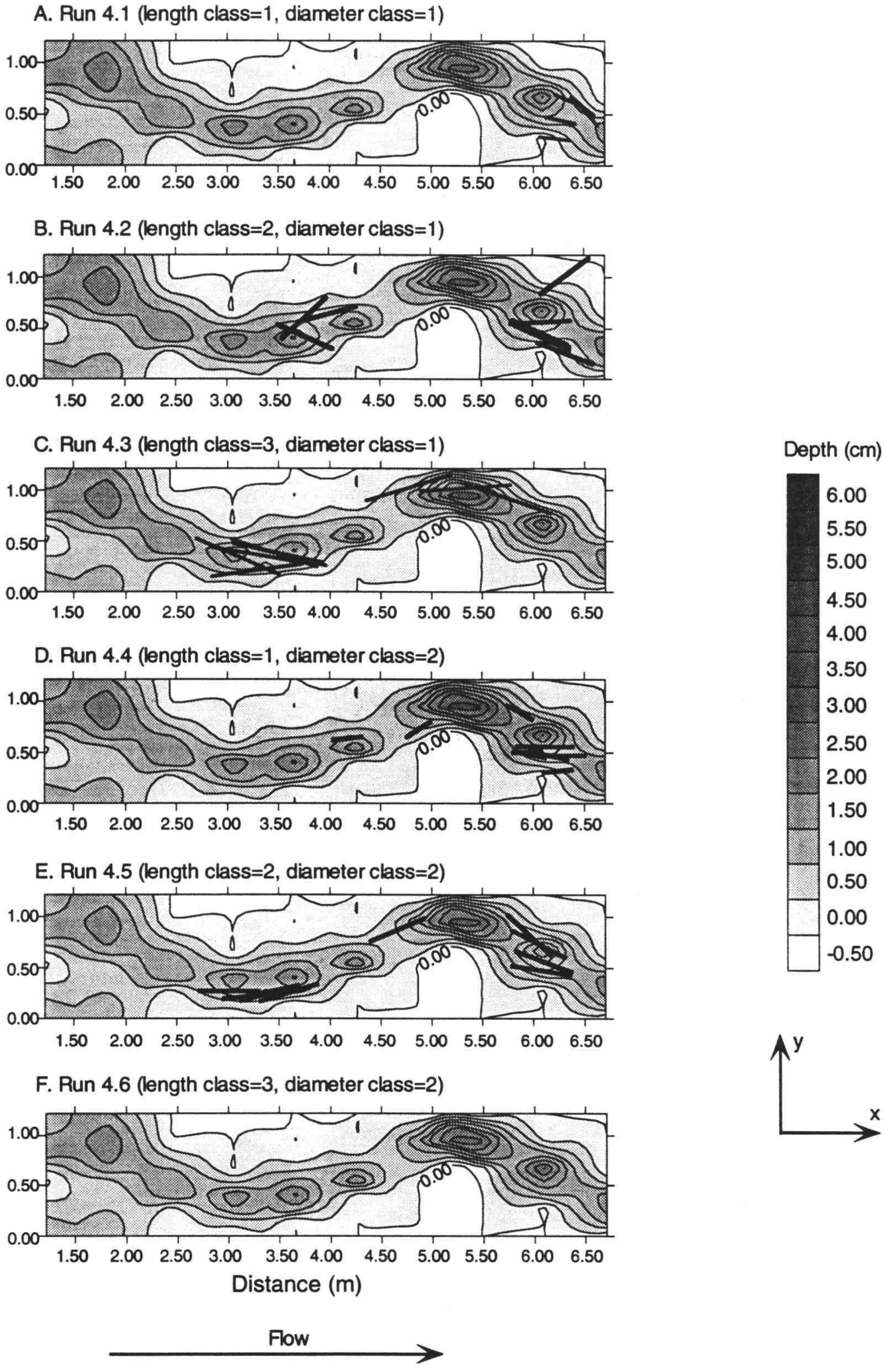

Figure 3.15. Maps of water depth and depositional location of pieces for runs 4.1-4.6.

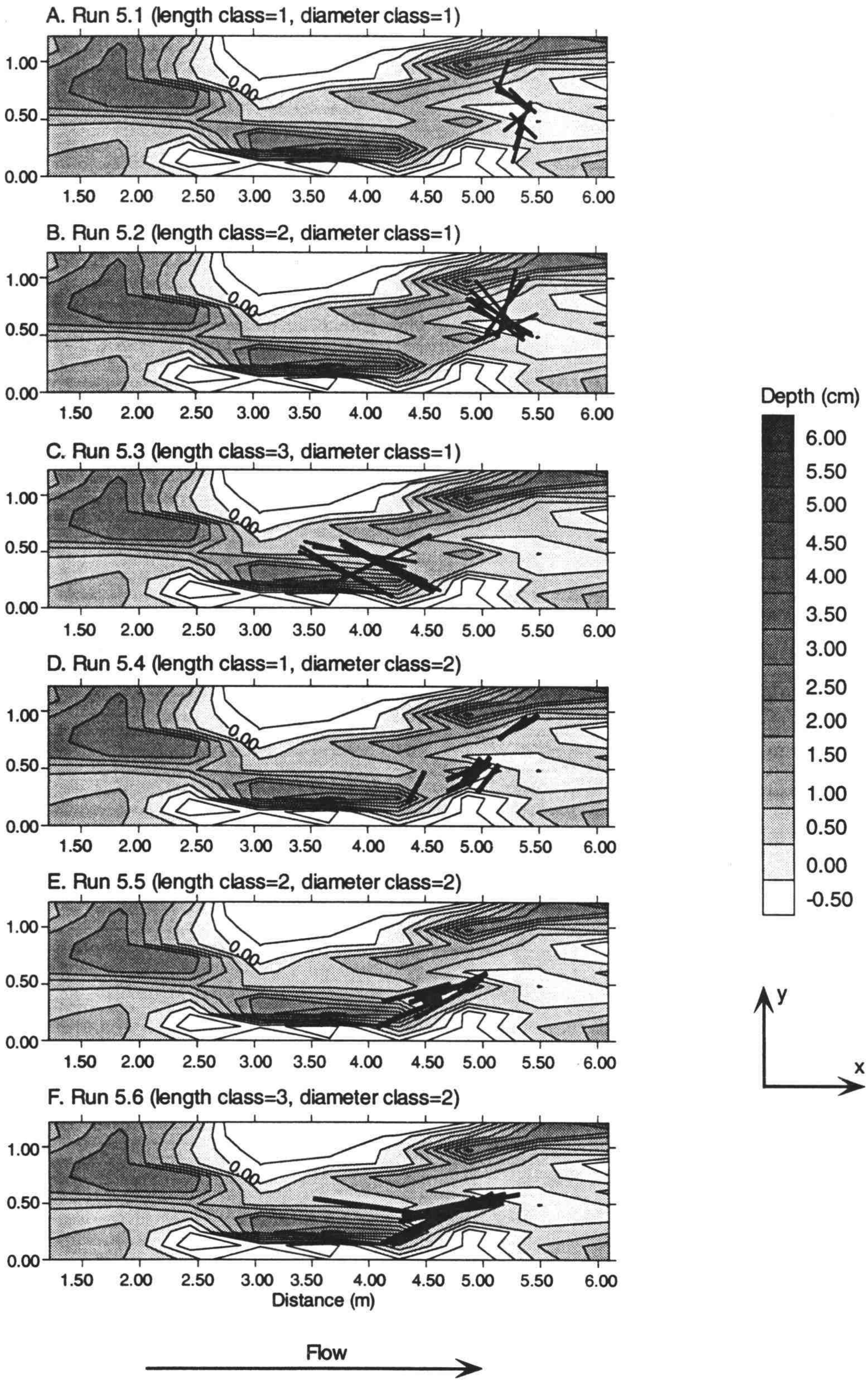

Figure 3.16. Maps of water depth and depositional location of pieces for runs 5.1-5.6.

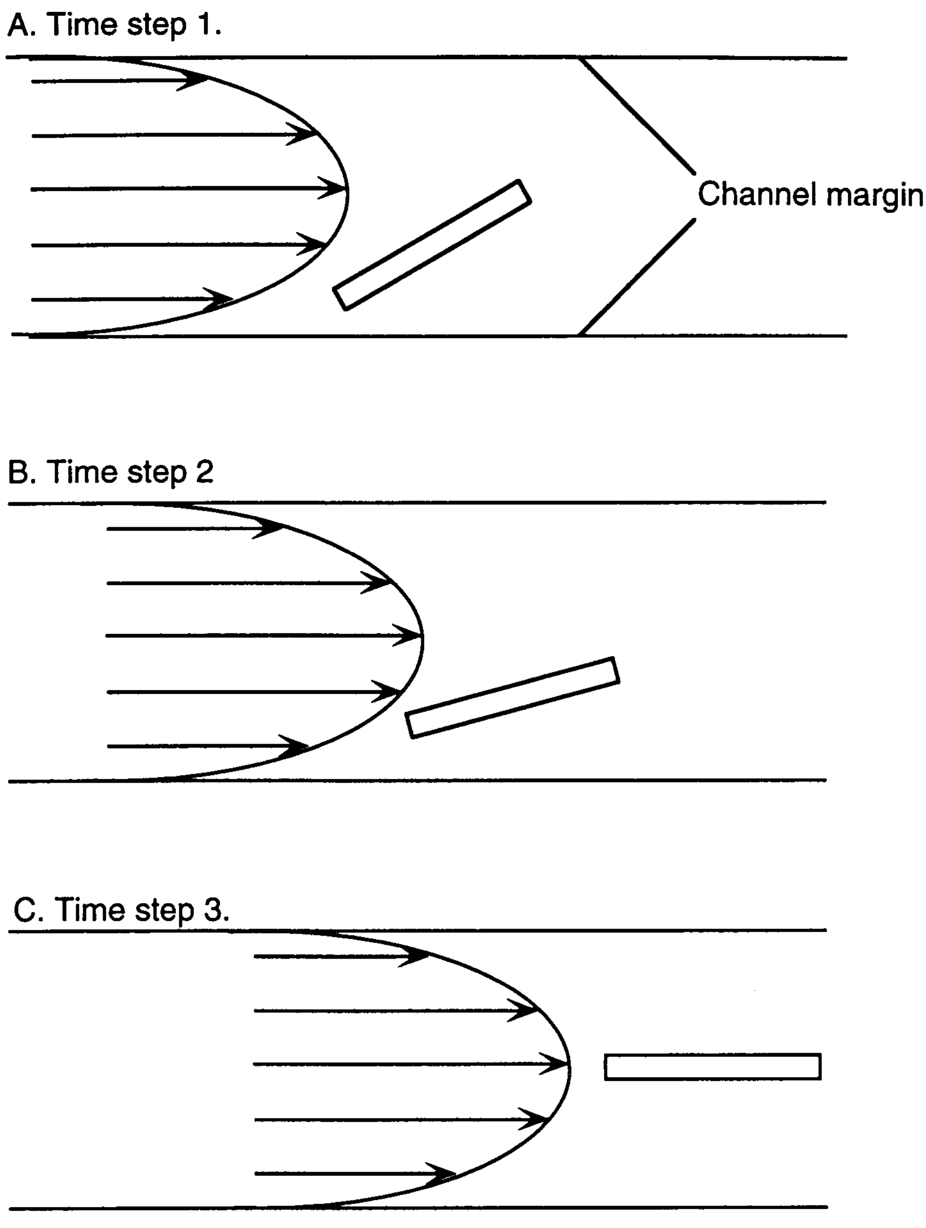

Figure 3.17. Schematic diamgram showing velocity field accross a channel, and its effect on piece orientation. In time step 1, the velocity is higher at the downstream end of the piece than the upstream end of the piece. Because one end of the piece is moving faster than the other end, the piece rotates toward a more flow-parallel orientation as shown in time step 2. Since the velocity field still varies accross 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.

and 3.16). Rolling was somewhat pronounced because the pieces were smooth cylinders without rootwads.

Distance travelled decreased with increasing piece length in all runs except run 1, run 2.4, and run 4.6. All of the pieces in run 4.6 (length class = 3, diameter class = 2) passed through the flume, and 50 % of the pieces passed through the flume in run 2.4 (length class = 2, diameter class = 2). In general, distance travelled decreased with increased D_{log}/d_{av} within runs. Larger diameter pieces lodged on bars where the depth was still sufficient to float the smaller diameter pieces. In run 1 (alternate bars, Figure 3.12) diameter class was the sole determinant of distance travelled, with pieces in diameter class 1 traveling further than pieces in diameter class 2.

Several channel features inhibited piece movement including: the presence of shallow bars, high sinuosity, and shallow expansion zones. Shallow bars, either submerged bar heads (run 5, Figure 3.16) or mid-channel bars (run 2, Figure 3.13) were common deposition sites for pieces. In runs with meandering channels, high sinuosity caused pieces to deposit on the outside of bends (runs 3, 4, and 5, Figures 3.14, 3.15, and 3.16). Pieces also deposited in shallow zones where the flow expanded (run 1, Figure 3.12). Once the flow expands, the depth shallowed, and at least part of the piece comes into contact with the bed.

In general the distance travelled decreased with increased length or diameter class within each run (Figure 3.18). For the deposition experiments, the distance traveled was significantly related to L_{log}/w_{av}, L_{log}/R_c, and the interaction between these two variables (Table 3.4). Distance travelled decreased as either L_{log}/R_c or L_{log}/w_{av} increased, but increased when both L_{log}/R_c and L_{log}/w_{av} were high, indicating that channels that are narrow and sinuous relative (and hence relatively deep) are more likely to pass pieces. Long distances traveled were achieved under two distinct conditions of piece diameter and width. Pieces with low L_{log}/w_{av} and D_{log}/d_{av} tended to travel longer distances (gray boxes in runs 3, 4, and 5, Figure 3.18), but the pieces that most consistently travelled the

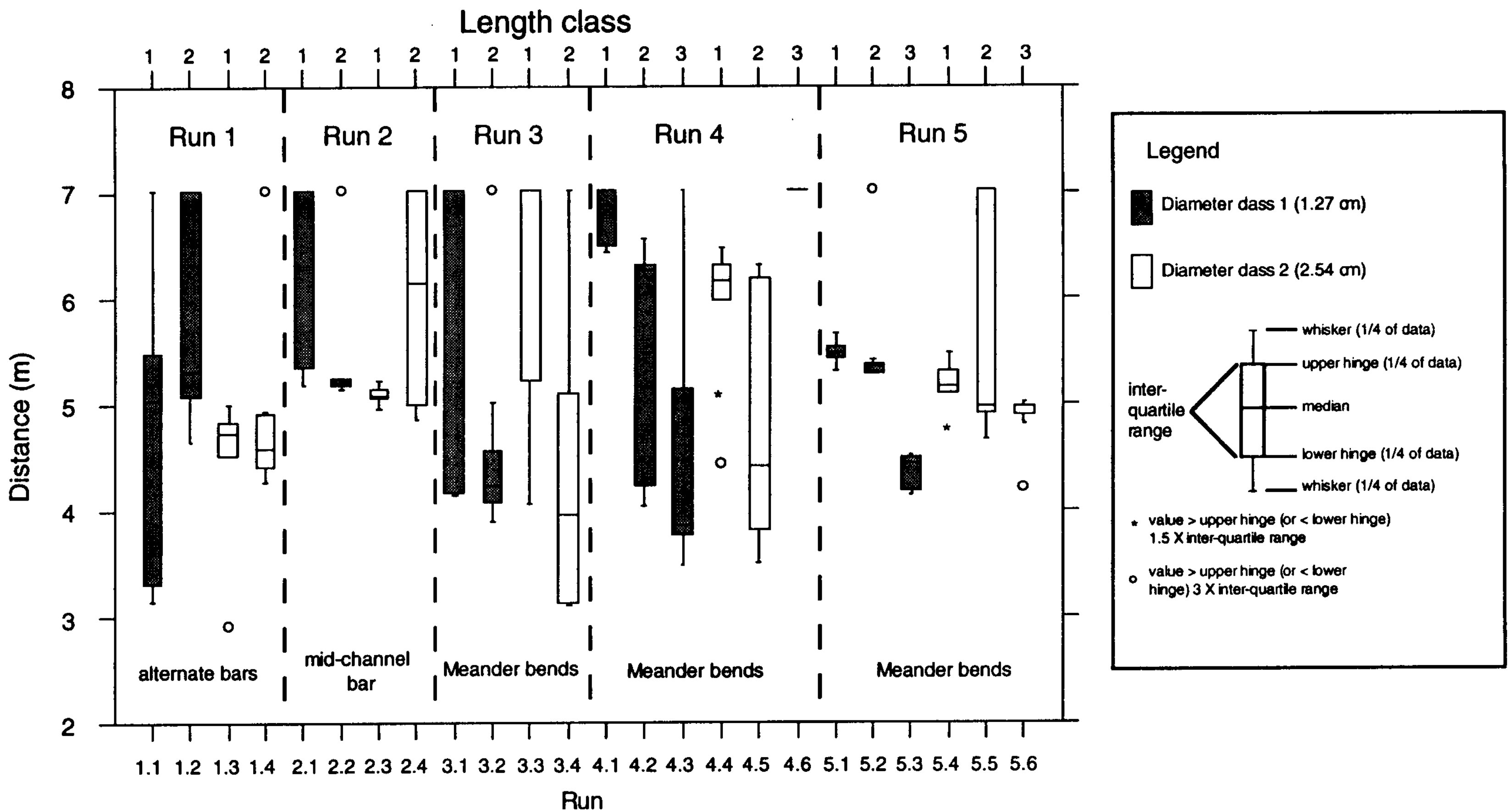

Figure 3.18. Box plot of distance travelled for all runs in experiment 2. The legend is as per Wilkinson *et al.* (1996).

entire length of the flume were long, large-diameter pieces in run 4.6 (Figure 3.18, Table 3.5).

Table 3.4. Results of distance travelled model. F-ratio = 6.622

Dependent Variable	Coefficient	Standard error	P-value
Constant	7.061	0.439	0.000
L_{log}/w_{av}	-3.333	0.790	0.000
L_{log}/w_{min}	0.435	0.228	0.057
D_{log}/d_{av}	-0.099	0.171	0.562
L_{log}/R_c	-2.482	0.891	0.006
L_{log}/w_{av}* L_{log}/R_c	3.405	1.142	0.003

Assuming debris roughness is the sum of L_{log}/R_c, L_{log}/w_{av}, and D_{log}/d_{av} (i. e. the coefficient are all equal to 1 in equation 3.6), we see a general trend of decreasing mean distance travelled with increased debris roughness (Figure 3.19, Table 3.5). Again run 4.6 does not fit into this model, it had the furthest distance travelled with the second-highest debris roughness.

Statistical analysis, shows decreased distance travelled with increased L_{log}/w_{av} or L_{log}/R_c (Table 3.4), and a general trend in decreasing trend in mean distance travelled with increasing debris roughness, indicate that debris roughness is a useful tool in predicting the likelihood that pieces will be retained. The exceptions, particularly run 4.6, indicate that high momentum can allow large pieces to travel further than our model predicts under certain conditions.

Table 4. Dimensionless ratios which contribute to debris roughness, debris roughness and distance travelled for the deposition experiments

Run	L_{log}/w_{av}	L_{log}/w_{min}	D_{log}/d_{av}	L_{log}/R_c	debris roughness	mean distance travelled (m)	% passed through flume
1.1	0.53	0.97	0.85	0.50	1.88	4.78	10
1.2	1.05	1.94	0.85	1.00	2.9	5.67	30
1.3	0.53	0.97	1.70	0.50	2.73	4.39	0
1.4	1.05	1.94	1.70	1.00	3.75	4.82	10
2.1	0.29	0.91	0.65	0.18	1.12	6.48	70
2.2	0.58	1.82	0.65	0.36	1.59	5.55	20
2.3	0.29	1.00	1.30	0.18	1.77	5.09	0
2.4	0.58	2.00	1.30	0.36	2.24	6.02	50
3.1	0.26	0.27	0.87	0.39	1.52	5.96	60
3.2	0.52	0.53	0.87	0.76	2.15	4.53	10
3.3	0.26	0.27	1.74	0.39	2.39	6.13	60
3.4	0.52	0.53	1.74	0.76	3.02	4.21	10
4.1	0.28	0.50	0.80	0.30	1.38	6.77	50
4.2	0.56	1.00	0.80	0.60	1.96	5.74	10
4.3	0.84	1.50	0.80	0.90	2.54	4.24	0
4.4	0.28	0.50	1.60	0.30	2.18	5.91	0
4.5	0.56	1.00	1.60	0.60	2.76	4.85	0
4.6	0.84	1.50	1.60	0.90	3.34	7	100
5.1	0.34	0.51	0.78	0.20	1.32	5.47	0
5.2	0.69	1.02	0.78	0.40	1.87	5.50	10
5.3	1.03	1.53	0.78	0.60	2.41	4.35	0
5.4	0.34	0.53	1.57	0.20	2.11	5.16	0
5.5	0.69	1.02	1.57	0.40	2.66	5.71	40
5.6	1.03	1.53	1.57	0.60	3.2	4.86	0

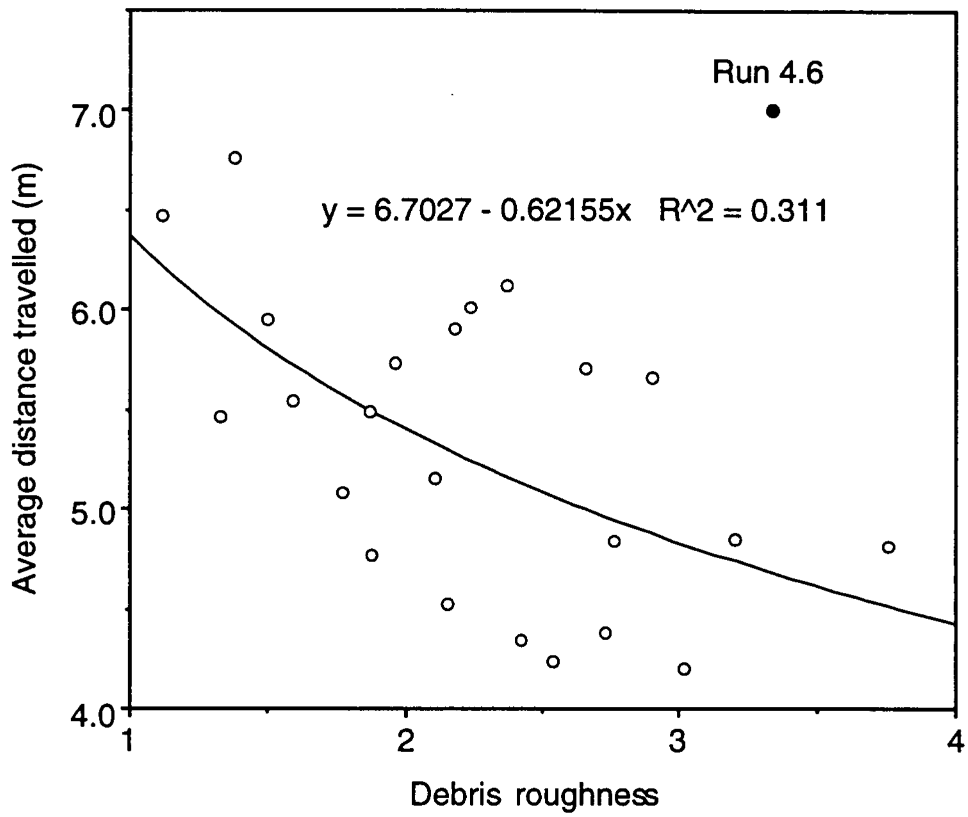

Figure 3.19. Average distance travelled versus debris roughess for all runs. Debris roughness is calculated as the sum of L_{log}/w_{av}, D_{log}/d_{av}, and L_{log}/R_c. The line of best fit is calculated without run 4.6.

Discussion

Previous studies of LWD movement indicate that stability increases and distance travelled decreases with increasing piece length. Our theoretical model and these experiments indicate that piece length does not significantly affect the probability of entrainment when $L_{log}/w_{av} \leq 0.5$. However, piece length does influence the distance pieces travel once in motion. Both the theoretical model and these experiments indicate that piece orientation, and the presence/absence of rootwads are far more important than piece length when determining piece stability.

There are several factors that can account for the difference between previous field studies on entrainment and our experiments. First, many previous studies occurred on small streams where $L_{log}/w_c > 1$, and roughness is high. Longer pieces will be more likely to have part of their length on the bank or lodged upstream of obstructions than shorter pieces, which causes them to be less mobile. We did not seek to model any of these conditions in our entrainment experiments, which may best model larger streams where the entire piece length may be on a relatively flat bar. Second, long pieces often enter the channel via blowdown or bank erosion (Van Sickle and Gregory, 1990) and therefore often tend to have rootwads, which these experiments show increase the entrainment threshold, regardless of orientation.

While for the most part, distance travelled decreased with increased debris roughness, run 4.6 had the second highest debris roughness, yet all of its pieces passed through the flume. Run 2.4 also had a higher percentage of its pieces pass through the flume relative to the other pieces in run 2 than our debris roughness model predicts. This is consistent with field observation made during the February, 1996 flood in the western Cascades, Oregon, when many large pieces (i. e. > 30 m long) were observed traveling down relatively narrow (i. e. < 30 m wide) channels (Grant, personal communication). We hypothesize that these pieces moved long distances due to the combination of high momentum and a high percentage of the channel area where $d_w > d_b$. Figure 3.20 is a plot

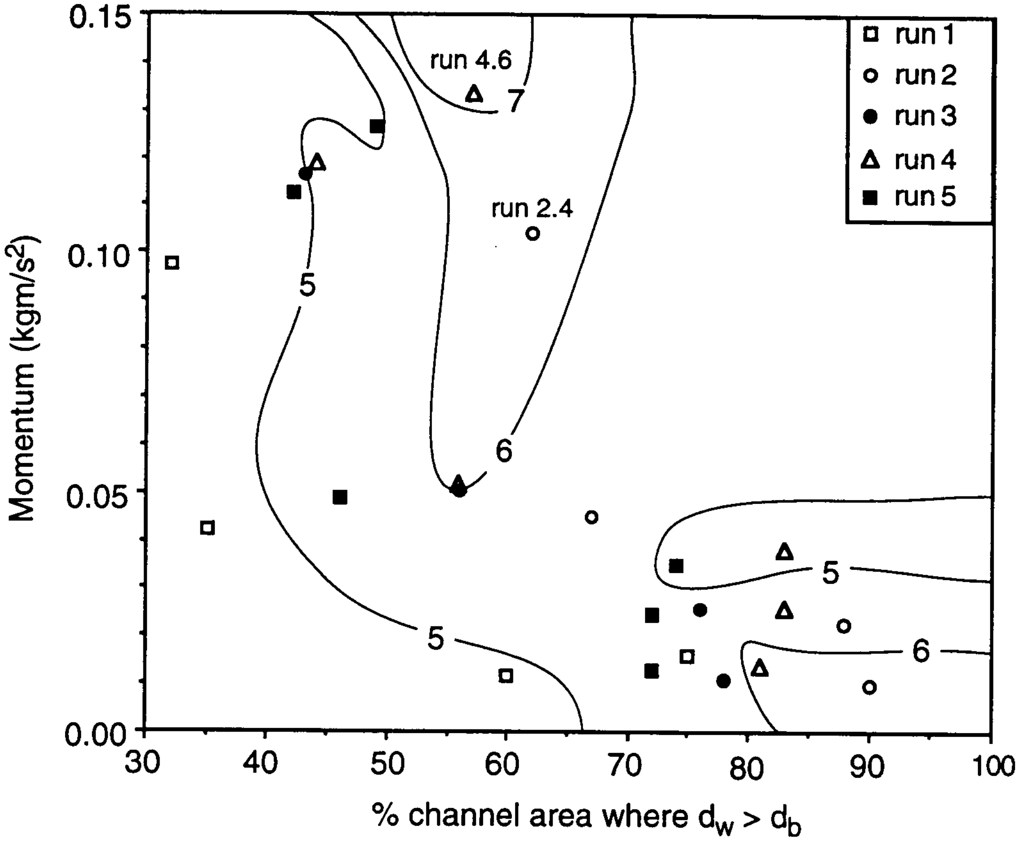

Figure 3.20. Contour map of mean distance travelled as a function of momentum and percent channel area where $d_w > d_b$. Contour interval = 1 m.

of the percent of the active channel area where $d_w > d_b$ versus the momentum of the piece (equal to the mass of the piece times the average velocity). The majority of runs have momentum below 0.06 kg-m/s, particularly those with a high percent of the channel area deeper than buoyant depth. The two runs where our debris roughness model did not accurately predict distance transported, runs 2.4 and 4.6, had high momentum, and over 50 % of their channel area with $d_w > d_b$. Run 4.6 had a well defined thalweg, with few shallow bars, so both velocity and % channel area where $d_w > d_b$ were high. 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.

We therefore propose that the movement of wood down a channel reflects the interaction of piece momentum, which acts to move the piece down the channel, and the debris roughness, which inhibits movement. In general, debris roughness increases with increasing piece size, but if pieces are traveling at the same velocity, momentum increases with piece size as well. If a channel has high debris roughness there are many potential locations where the wood can encounter bed or banks thereby losing momentum. However, if both L_{log}/w_c and L_{log}/R_c are high, but a large proportion of the channel area has $d_w > d_b$, the piece encounters fewer potential deposition sites, but the channel still has a relatively high debris roughness. Because there are few potential deposition sites, pieces with high momentum (large pieces) can continue to move past the obstruction, and possibly through the reach. Also, because pieces tend to orient parallel to flow, debris roughness is minimized in well-defined channels since piece length becomes less important. If a small portion of the channel area has $d_w > d_b$, momentum is constantly lost each time a piece encounters the bed, and piece velocity reduces so that stranding or grounding is likely.

We can extrapolate the results from the flume experiments to the field, by examining the depth, width, and sinuosity of streams. Figure 3.21 shows predicted retention as a function of channel depth, width, and sinuosity. Debris roughness will be

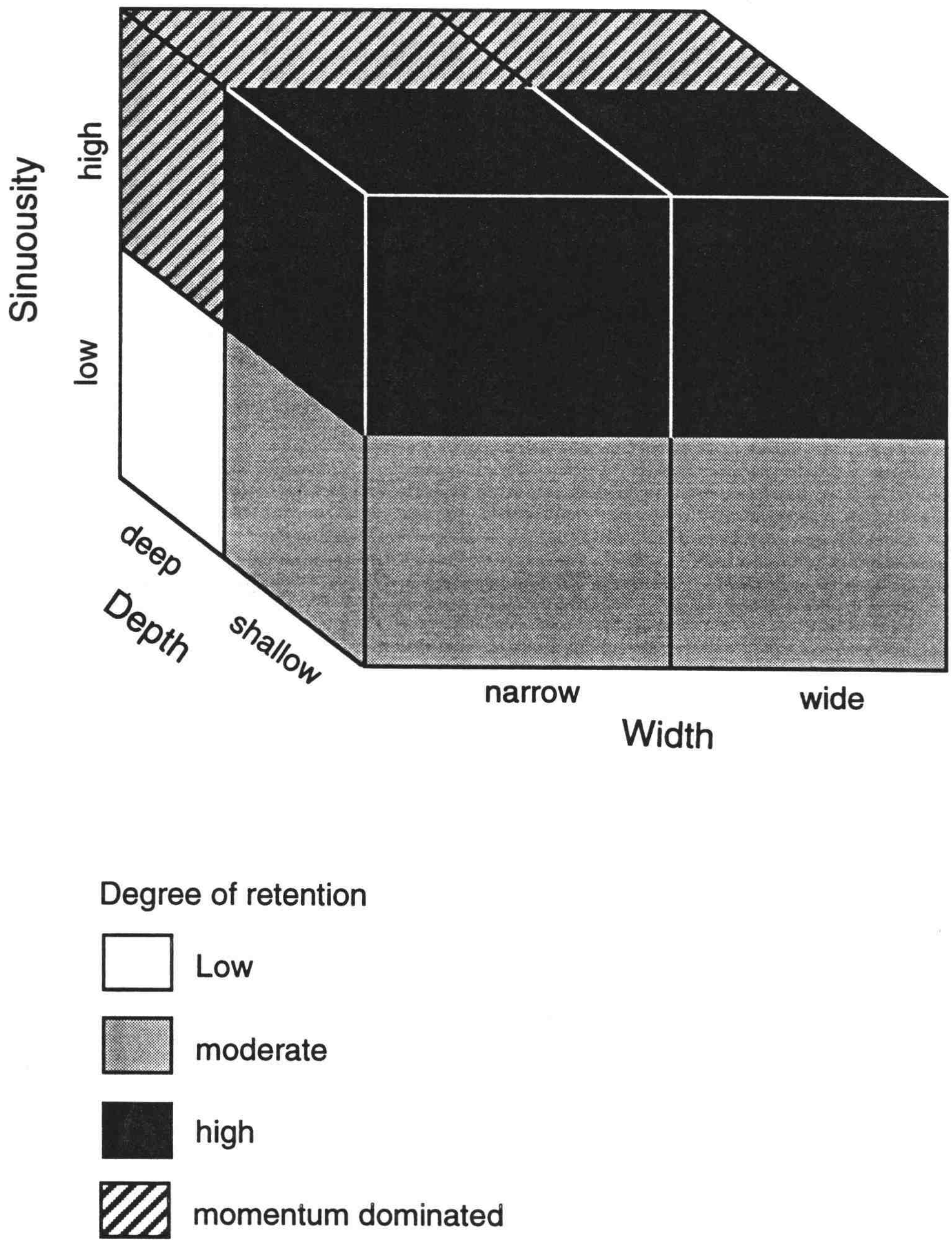

Figure 3.21. Schematic diagram of the degree of retention based on channel sinuousity, width, and depth. The hatched area represents morphologies where the debris roughness is moderate, but retention may be low due to high momentum.

low and momentum will dominate in deep channels, regardless of L_{log}/w_{av} or L_{log}/R_c. In shallow channels, debris roughness will either be moderate or high, and retention will be a function of the number of potential deposition sites. Wide, sinuous, shallow streams will have high debris roughness, because of the frequency of bars. Constrained reaches and bedrock streams (both of which tend to be deep) will tend not to retain pieces, in spite of their narrow width. Low- (<3rd) order channels tend to be dominated by obstructions, such as boulders and other logs, which will inhibit piece movement. In low-order channels L_{log}/w_{min} may be a more appropriate measure than L_{log}/w_{av}, where the minimum width is measured on either side of an obstruction. Since momentum will dominate deep channels we expect that constrained reaches and very large rivers (where both depth and width are high) will not retain wood. Wood may still deposit in large streams on the head of islands, if they exist, or upstream of obstructions such as bridges.

We feel that the comparison of momentum and portion of the channel area where $d_w > d_b$ explains why wide-sinuous channels retain wood while wood passes through narrow-straight channels (Nakamura and Swanson, 1994). Wide-sinuous reaches generally have low depth in unmodified channels. They also tend to be dominated by bars and mid-channel islands. Therefore L_{log}/R_c and D_{log}/d_w will be high. In combination, these factors contribute to a high debris roughness, promoting deposition. On the other hand, both narrow-straight and narrow-sinuous reaches tend to have low D_{log}/d_w with the proportion of the channel deeper than d_b high during large floods. The distribution of likely deposition locations is low, and large pieces can maintain high enough momentum to pass through the reach. High L_{log}/w_{av} in constrained reaches should not be a factor, because we have shown that pieces travel parallel to flow unless they encounter shallow bars, which are infrequent in constrained reaches during flood stage.

Conclusions

Our force balance model and these experiments show that the two most important factors in the entrainment of pieces are the piece orientation, and the presence/absence of rootwads. The data plotted into two groups where pieces without rootwads oriented at 0 degrees to flow, and pieces with rootwads were the most stable, and moved after their flotation threshold, and pieces without rootwads oriented at 45 and 90 degrees to flow were the least stable, and moved below their flotation threshold. Pieces with rootwads oriented parallel to flow were more stable than pieces with rootwads oriented at 45 and 90 degrees to flow. However, pieces with rootwads oriented at 45 and 90 degrees to flow pivoted towards 0 degrees and did not move far, indicating that the stability of pieces with rootwads oriented at 45 and 90 degrees is essentially the same as pieces oriented at 0 degrees. Although previously reported as the most important factor determining piece stability, both the experiments and force balance model show that piece length does not play a significant role in determining piece stability. Both the physical model and these experiments best model wood in large streams, where the depth is uniform across the cross-section.

We found that the distance pieces travel decreased as L_{log}/w_{av}, and L_{log}/R_c increased, but increased when both L_{log}/w_{av} and L_{log}/R_c are high. Distance travelled also decreased with increasing D_{log}/d_{av} within run 1. There was also a general trend of decreasing distance travelled with increasing debris roughness. Taken together, these results indicate that debris roughness may be able to predict distance travelled. Some pieces were transported further than our debris roughness model predicted, because they had high momentum. Momentum only plays an important role in channels where the portion of the active channel where $d_w > d_b$ is greater than approximately 50%. Wide, sinuous, and shallow channels promote the greatest deposition of wood, and wide, straight, and shallow channels retain the fewest pieces.

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Chapter 4: Conclusions

In these two papers we quantified some of the dynamics of woody debris in streams and discovered characteristics of wood movement that had not been previously observed. We have shown that wood dynamics can be studied using physical models and flume experiments, approaches that have been widely used in studying sediment dynamics, but have previously received little use in wood studies.

Our physically-based entrainment models appear to adequately predict entrainment the relative stability of pieces of various geometries and orientations. However, pieces tended to move at higher depths and velocities than we predicted because of increased resistance imparted on the piece by the relatively large grain size used. While field observations show that piece length is the primary control on the likelihood of transport, piece length did not affect our force balance equations or experimental results for pieces oriented at 45 or 90 degrees to flow. This indicates that some other factors other than the velocity and depth cause larger pieces to be more stable in the field. Most field studies occur on rather small streams where wood can be lodged upstream of boulders or vegetation, and pieces tend to have at least part of their length outside the active channel. Long pieces will be more likely to be lodged upstream of the channel and will have a larger portion of their channel length outside of the channel. They can also be suspended over the channel if the channel is steep sided and they are longer than channel width. Long pieces are not more stable than shorter pieces simply because they are larger, but because they are more likely to encounter obstruction or be suspended over the channel. Entrainment of pieces in larger streams, where pieces tend to be shorter than the channel width and large obstructions are not common, can be modeled more accurately using equations 3.4 and 3.5 than pieces in smaller channels.

We can use the fabric of wood deposits to determine their transport regime during transport. Using this method we can analyze areas that have been dominated by congested transport, and therefore predict where we expect congested transport to occur in the future. This will help us predict areas where hazards posed by woody debris are highest, and take preventative measures against them. Since transport regime increases with increasing Q_{log}/Q_w, and to a lesser degree increasing L_{log}/w_{av} and D_{log}/d_{av}, congestion will be reduced by decreasing any of these factors.

Our debris roughness model, analogous to hydraulic roughness, appears to be valid, but other factors, such as momentum may be more important than debris roughness for some channels. We expect that the debris roughness will be high in low-order streams, and they will be dominated by congested transport. Individual logs will move infrequently, because of frequent obstructions and small channel dimensions relative to piece size. Pieces will remain immobile until the input rate of logs is high, such as when a debris flow enters the channel, and a congested mass of logs entrains pieces laying in its path. Uncongested transport will occur throughout the channel network, but will be the sole transport type in higher-order channels where input rates are low and channel dimensions are large relative to piece size. The debris roughness of these channels varies with their depth, width, and sinuosity, and can be used to predict the distance traveled once the pieces are in motion. We expect that constrained reaches, which tend to be deep, will be dominated by momentum, and will transport pieces regardless of the width and sinuosity of the channel. Unconstrained reaches, which have frequent bars and multiple channels, will be locations of wood deposition, and the distance travelled will vary with their debris roughness.

Management of wood in streams has suffered from a paucity of data about wood dynamics. Most wood studies have been site-specific, and little is known about how wood movement changes throughout a channel network. We believe that the results of these studies can be used to make restoration more effective. Stability of pieces can be improved by using large diameter logs with rootwads, particularly if part of the piece lays outside of the channel. If there are obstructions such as boulders in streams, they can be used to help anchor pieces. The debris roughness model can be used to predict the most likely locations for wood in streams, and can help to reconstruct the distribution of wood in streams prior to removal. By placing wood in locations where deposition is most likely, other logs will deposit upstream of the introduced wood and stable jams should begin to form.

These experiments were preliminary investigations of some of the dynamics of woody debris in streams and there is room for further investigation. While we showed that the debris roughness model is a useful tool in determining the likely deposition of pieces, further flume experiments are needed to define the relative importance of each of the coefficients in equation 3.6. Similarly further experiments are needed to assess the thresholds between transport regime. Field analysis of both debris roughness and the deposits of transport regimes is also needed to verify the experiments. While we have probably raised more questions about wood transport than we have answered, it is clear that assessing wood dynamics requires not only analyzing the piece size distribution, but analysis of channel geometry and form as well.

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