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# Factors influencing wood mobilization in streams

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[1] Natural pieces of wood provide a variety of ecosystem functions in streams including habitat, organic matter retention, increased hyporheic exchange and transient storage, and enhanced hydraulic and geomorphic heterogeneity. Wood mobilization is a critical process in determining the residence time of wood. We documented the characteristics and locations of 865 natural wood pieces (>0.05 m in diameter for a portion >1 m in length) in nine streams along the north shore of Lake Superior in Minnesota. We determined the locations of the pieces again after an overbank stormflow event to determine the factors that influenced mobilization of stationary wood pieces in natural streams. Seven of 11 potential predictor variables were identified with multiple logistic regression as significant to mobilization: burial, effective depth, ratio of piece length to effective stream width (length ratio), bracing, rootwad presence, downstream force ratio, and draft ratio. The final model ($P < 0.001$, $r^2 = 0.39$) indicated that wood mobilization under natural conditions is a complex function of both mechanical factors (burial, length ratio, bracing, rootwad presence, draft ratio) and hydraulic factors (effective depth, downstream force ratio). If stable pieces are a goal for stream management then features such as partial burial, low effective depth, high length relative to channel width, bracing against other objects (e.g., stream banks, trees, rocks, or larger wood pieces), and rootwads are desirable. Using the model equation from this study, stewards of natural resources can better manage in-stream wood for the benefit of stream ecosystems.

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## 1. Introduction

[2] Natural pieces of wood enhance habitat conditions and promote key ecosystem functions in streams. Wood pieces provide stable substrate for invertebrates and biofilms, entrap leaves and other organic matter, afford overhead cover for fish, promote hyporheic exchange flow and transient storage, enhance hydraulic heterogeneity, and encourage pool formation and channel meandering [*Angermeier and Karr*, 1984; *Beechie and Sibley*, 1997; *Gregory et al.*, 2003; *Johnson et al.*, 2003; *Mutz and Rohde*, 2003; *Eggert and Wallace*, 2007; *Stofleth et al.*, 2008]. The frequency and character of wood inputs varies in space and time [*Latterell and Naiman*, 2007; *Golladay et al.*, 2007] and is strongly affected by riparian management [*Flebbe and Dolloff*, 1995; *Angradi et al.*, 2004; *Kreutzweiser et al.*, 2005; *Czarnomski et al.*, 2008].

[3] Many factors and processes control the transport of wood in streams. For example, a piece of wood may be mobilized and carried downstream by fluvial entrainment, entrapped in narrow or shallow sections of a stream, and ultimately deposited on the floodplain. Moving pieces of wood are entrapped more readily if they are long relative to the channel width and heavy, although entrapment may often simply occur wherever the piece is located when stormflows recede [*Merten et al.*, 2009]. Wood also gradually loses mass by decay processes and may become buried only to be exposed later by stream meandering [*Latterell and Naiman*, 2007]. In this paper we analyze wood mobilization, the process of a stationary piece of wood being set into motion in a stream.

[4] Wood mobilization is important for several reasons. From an ecological perspective, wood mobilization influences local stream functions. Traditionally, wood was considered "debris" and removed from many streams to increase hydraulic conveyance capacity, reduce flooding, and improve navigation [*Walter and Merritts*, 2008]. From a stream restoration perspective, it is valuable to know whether newly installed woody habitat will remain in place. Wood mobilization is analogous to incipient motion of sediment particles; both processes are also difficult to predict [*Braudrick and Grant*, 2000].

[5] Wood mobilization in natural streams has been investigated in a number of field studies [*Bilby*, 1984; *Lienkaemper and Swanson*, 1987; *Berg et al.*, 1998; *Jacobsen et al.*, 1999; *Warren and Kraft*, 2008; *Wohl and Goode*,

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2008]. The most frequently cited predictor of mobilization that has emerged from these studies is the ratio of the length of a wood piece to the bankfull width of the stream channel [*Gurnell et al.*, 2002; *Hassan et al.*, 2005]. This length ratio is related to the probability that the piece of wood becomes braced against stream banks, rocks, or riparian trees before traveling an appreciable distance.

[6] Wood mobilization has also been investigated in laboratory flumes. In a pioneering flume study, the most important factors for mobilization were the orientation of the piece of wood relative to flow (from parallel to perpendicular to flow) and the presence of rootwads [*Braudrick and Grant*, 2000]. In contrast to field studies, piece length did not influence mobilization [*Braudrick and Grant*, 2000]. Two reasons were suggested for the contrast with mobilization observed in natural channels. First, all pieces investigated were shorter than the channel width, making it impossible for a piece to resist mobilization by bracing against both banks. Second, the laboratory channel was of uniform depth and width and void of obstructions. A later flume experiment improved prediction of mobilization by including greater detail on the hydraulic conditions immediately surrounding each wood piece [*Bocchiola et al.*, 2006].

[7] Another study attempted to combine the detailed hydraulic predictions of flume studies with the realism of a field study and determined that mobilization was influenced by the ratio of piece diameter to water depth [*Haga et al.*, 2002]. However, that study had two major limitations. The 63 wood pieces were artificially introduced and were not representative of those found in natural streams; the pieces were cut shorter than the channel width, were similar in size, and had branches removed. Further, the hydraulic data were of low resolution; the 5.5 km study reach was divided into 24 sections, and hydraulic conditions were averaged for each section.

[8] In this paper we describe the conduct and results of a study in nine streams to determine the factors most influential on wood mobilization. The diversity of wood piece characteristics representative of natural streams, a variety of geomorphic stream conditions, and a fine resolution of hydraulic information were used in the study. In the analysis, we relate mobilization potential to mechanical factors and forces, which in turn are linked to geometry and density of the wood pieces, their position in the stream, and hydraulic stream parameters such as water velocity, depth, and width. We measured and tracked the movement of 865 wood pieces and measured stream levels and discharge on a 15 min time scale. We also simulated water surface profiles and stream depths at cross sections every 10 m. Field observations of wood mobilization were statistically tested against predictor variables to develop a predictive model of wood mobilization. We selected initial predictor variables based on a literature review of the forces acting on wood pieces in natural streams.

## 2. Forces Acting on Wood Pieces in a Stream and Potential Mobilization Predictors

[9] Any object in a stream will be mobilized when the total forces acting on it in the downstream direction exceed those in the upstream direction. The difficulty in predicting mobilization lies in identifying and quantifying all the forces acting on a given piece of wood, particularly in a field setting. Below we describe selected forces acting on single pieces of wood in natural streams.

### 2.1. Floatation

[10] The simplest case of wood mobilization is an individual piece lying on a stream bed and not interacting with other objects (e.g., stream banks, live vegetation, boulders, or other pieces of wood). Such a piece is held in place solely by gravity and friction with the stream bed. In a natural setting where flows are temporally dynamic, one must first determine whether movement is caused by floatation, when friction with the stream bed is eliminated. Floatation occurs when buoyancy ($F_B$) exceeds the weight ($F_W$). Buoyancy and weight are expressed by the relationships (1) and (2)

$$F_B = g\rho_w V_{sub} \tag{1}$$

and

$$F_W = g\rho_{log} V_{log}, \tag{2}$$

where $g$ is gravity, $\rho_w$ is the density of water, $V_{sub}$ is the submerged volume of the piece, $\rho_{log}$ is the density of the piece, and $V_{log}$ is the total volume of the piece. Calculating $V_{sub}$ requires information on the size, submerged depth, and spatial position of the piece [*Erdmann and Merten*, 2010; *Merten et al.*, 2009].

[11] When buoyancy exceeds weight for a piece of wood, the draft (Figure 1) is less than the water depth. The formula to determine the draft ($D$) of a cylindrical piece with radius ($r$) can be estimated from *Braudrick et al.* [1997] as

$$D = 2r\left(0.05 + 0.9\left(\rho_{log}/\rho_w\right)\right). \tag{3}$$

### 2.2. Interactions With the Stream Bed

[12] If floatation does not occur, a piece may still move by sliding along the stream bed if the force of friction ($F_F$) is insufficient to hold the piece in place. Friction is

$$F_F = (F_W - F_B) f_{bed} \cos a, \tag{4}$$

where $f_{bed}$ is the coefficient of friction on the stream bed and $\alpha$ is the stream slope or gradient. Besides sliding, a piece may also move by rolling [*Bocchiola et al.*, 2006], but the moment forces involved are beyond the scope of this study.

[13] Pieces of wood may be partially buried in the stream bed; some studies suggest that burial is the most important determinant of mobilization [*Berg et al.*, 1998; *Wohl and Goode*, 2008]. A partially buried piece requires a greater force to mobilize it compared to an exposed piece [*Brooks et al.*, 2006]. The opposite process also occurs in streams; buried pieces may become unburied by stream meandering [*Latterell and Naiman*, 2007] and thus subject to mobilization.

### 2.3. Interactions With the Flow

[14] A piece will slide when the hydrodynamic drag ($F_D$) exerted by the water is sufficient to overcome friction ($F_F$)

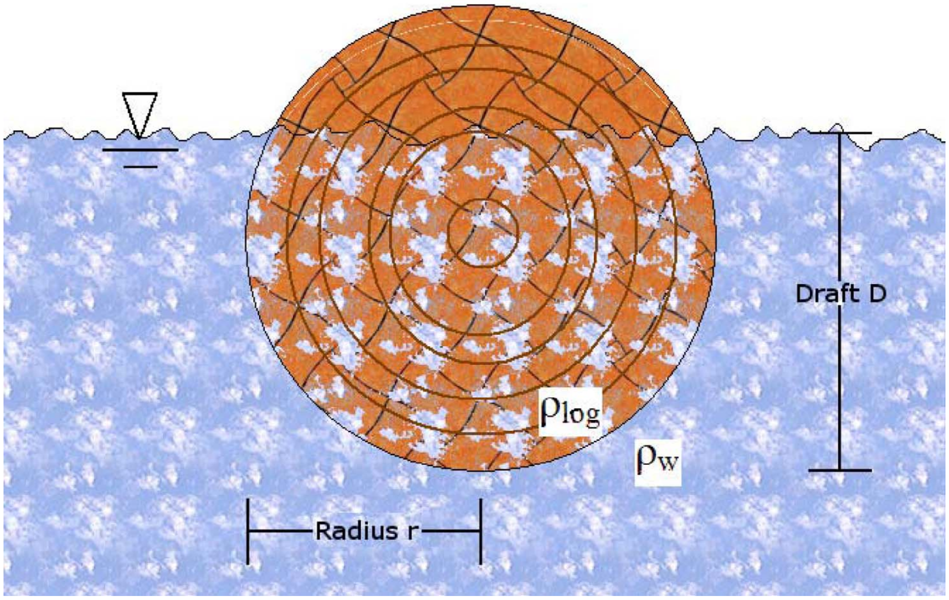

**Figure 1.** Draft of a floating piece of wood, shown in cross section. Draft ($D$) is a function of the density of the piece ($\rho_{log}$) and the water ($\rho_w$), and the radius of the piece ($r$).

with the stream bed. The hydrodynamic drag acting on a piece is approximated as

$$F_D \approx (U^2/2)\rho_w C_d A_N + (U^2/2)\rho_w C_f A_{SA} \cos^3\theta, \quad (5)$$

where $U$ is the mean water velocity, $C_d$ is the form drag coefficient, $A_N$ is the submerged area normal to flow, $C_f$ is the skin friction drag coefficient, $A_{SA}$ is the submerged surface area of the piece, and $\theta$ is the plan-view orientation of the piece relative to the flow (Figure 2). The submerged area normal to flow ($A_N$) is a complex function of the size, submerged depth, and spatial position of the piece [*Erdmann and Merten*, 2010; *Merten et al.*, 2009]. The total drag is the sum of form drag and skin friction drag (equation (5)). The submerged surface area ($A_{SA}$) of a piece can be approximated as

$$A_{SA} \approx \pi L d_{sub} \quad (6)$$

up to the maximum when $d_{sub} = 2r$, where $L$ is the length of the piece and $d_{sub}$ is the submerged depth of the piece.

[15] Form drag coefficients ($C_d$) are a function of the shape of the object, its position in the stream, and a Reynolds number defined as

$$Re = 2r\,U/\nu, \quad (7)$$

where $\nu$ is the kinematic viscosity. In a simple case where the stream bed, stream banks, and water surface are far away from the piece, they will have little effect on the drag coefficients. For that case, drag coefficients on many different shapes of bodies have been studied extensively and can be found in the published literature [e.g., *Hoerner*, 1965]. *Brooks et al.* [2006] reviewed the literature and selected a drag coefficient of 1.2 for wood in streams, whereas *Bocchiola et al.* [2006] used dowels in flumes to obtain a drag coefficient of 1.41. Natural pieces of wood likely have greater drag due to skin friction than the smooth dowels used by *Bocchiola et al.* [2006]; thus, we have included the skin friction component of equation (5) with a skin friction drag coefficient $C_f = 0.005$ [*Olson*, 1961].

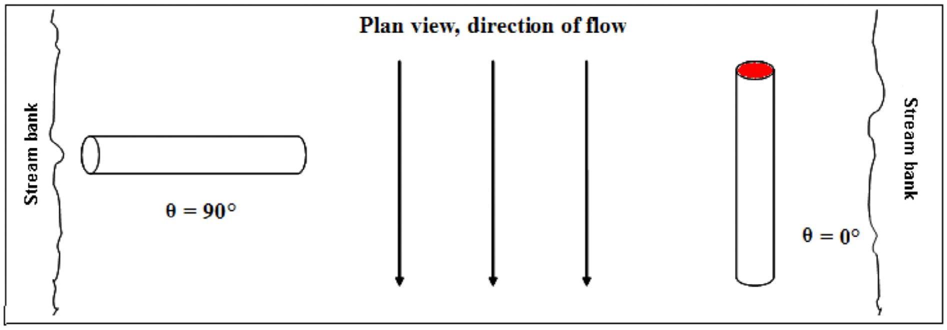

**Figure 2.** Plan view of channel with pieces of wood-oriented perpendicular to the flow ($\theta = \pi/2$ radians) and parallel to the flow ($\theta = 0$ radians).

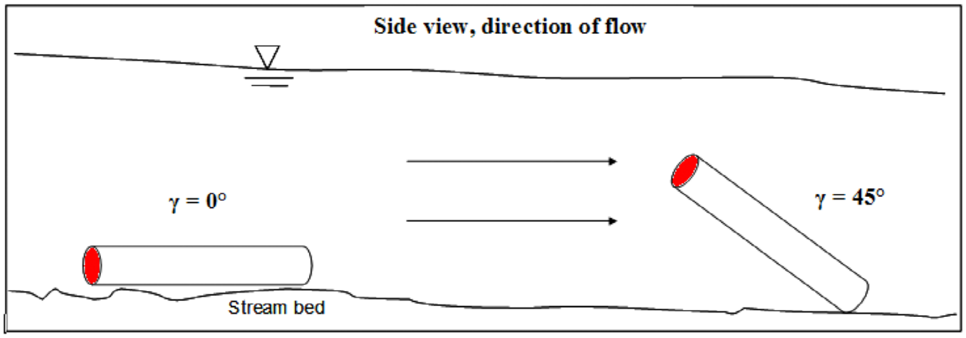

**Figure 3.** Side view of channel illustrating pieces of wood pitched parallel to the stream bed ($\gamma = 0$ radians) and at 45° to the stream bed ($\gamma = \pi/4$ radians).

[16] The flow around a piece may also produce differences in pressure that result in a vertical lift force. In an infinite fluid, the lift force ($F_L$) acting on a piece can be estimated as

$$F_L \approx U^2/2\ C_{lp}A_N \cos\theta + U^2/2\ C_{lg}A_N \sin\theta, \tag{8}$$

where $C_{lp}$ and $C_{lg}$ are the lift coefficients for pitch and gap lift. Pitch lift can be positive (upward) or negative (downward) depending on the pitch of the piece relative to the stream bed ($\gamma$, Figure 3); a piece with positive pitch has positive lift and a piece with negative pitch has negative lift. Pitch lift coefficients ($C_{lp}$) for objects of various shapes are given by *Hoerner* [1985]. The pitch lift coefficient for a cylinder is insensitive to the fineness ratio (i.e., diameter/length [*Hoerner*, 1985]), making a javelin a suitable surrogate for a piece of wood in terms of pitch lift. Pitch lift is greatest for pieces oriented parallel to the direction of flow ($\theta = 0$). For a javelin, the pitch lift coefficient can be estimated as

$$C_{lp} = \sin^2\ \gamma \cos\gamma. \tag{9}$$

Unlike pitch lift, gap lift ($C_{lg}$) is greatest for pieces oriented perpendicular to the flow ($\theta = \pi/2$) and always acts in a downward direction. Gap lift is a function of piece diameter and the gap between the piece and the stream bed and is caused by the Bernoulli effect [*Lei et al.*, 1999]. When water must pass through a constricted opening (the gap), the velocity increases and the pressure decreases; the decreased pressure under the piece causes a downward force. Gap lift coefficients can be estimated from *Lei et al.* [1999] as

$$C_{lg} \approx 0.0916(G/2r)^{-0.5911} \tag{10}$$

with a maximum value of $C_{lg} = 0.55$.

### 2.4. Role of Hydrology

[17] Stream hydrology is a major determinant of wood transport. Any piece of wood will be mobilized at a sufficient discharge, just as the largest boulders are mobilized during extreme floods [*Gordon et al.*, 2004]. Discharge depends on hydrologic factors including climate (mainly precipitation) and watershed characteristics such as topography, geology, soils, vegetation, and artificial or natural storage [*Gordon et al.*, 2004]. Under uniform flow conditions, the water level and mean velocity at a channel cross section can be related using Manning's equation [*Olson*, 1961]

$$U = Q/A_{\mathrm{wet}} = n^{-1}R^{2/3}a^{1/2}, \tag{11}$$

where $U$ is mean stream velocity, $Q$ is the discharge rate, $A_{\mathrm{wet}}$ is the wetted area, $n$ is Manning's roughness coefficient for the channel, and $R$ is the hydraulic radius (approximated by the water depth in a wide channel). Manning's roughness coefficient ($n$) is a function of the substrate, shape, and vegetation of a channel [*Arcement and Schneider*, 1989]. Channel roughness is also influenced by obstructions, generally rocks and wood, which can have more direct effects on mobilization.

### 2.5. Interactions With Obstructions

[18] In natural streams, pieces of wood are often braced against obstructions in the channel. Rocks, islands, or fallen trees can provide support and prevent the mobilization of a wood piece. To become mobilized, a braced piece must rise up and over a bracing object, requiring a net upward force. As with floatation of an unbraced piece, buoyancy plus hydrodynamic lift must be greater than the weight of the piece, but vertical friction ($F_V$) must also be overcome. Vertical friction acts between a braced piece and the bracing object and is related to the hydrodynamic drag ($F_D$), where

$$F_V = F_D f_{\mathrm{brace}} \cos\ \psi \tag{12}$$

and $f_{\mathrm{brace}}$ is the coefficient of friction of the bracing object and $\psi$ is the angle of the upstream face of the bracing object.

[19] Wood pieces may also be braced against stream banks and live vegetation. Particularly, during overbank flows, a piece may become braced against trees at the edge of the floodplain; a piece braced against trees is unlikely to be lifted over them. A piece may also become wedged between stream banks and require a substantial force to be mobilized. Moment forces may cause a piece to pivot off a bracing obstruction, but this type of motion is beyond the scope of this study.

### 2.6. Theoretical Predictors of Wood Mobilization

[20] On the basis of the preceding discussion, a number of theoretical variables emerge for predicting wood mobilization. Some relevant forces have been described above,

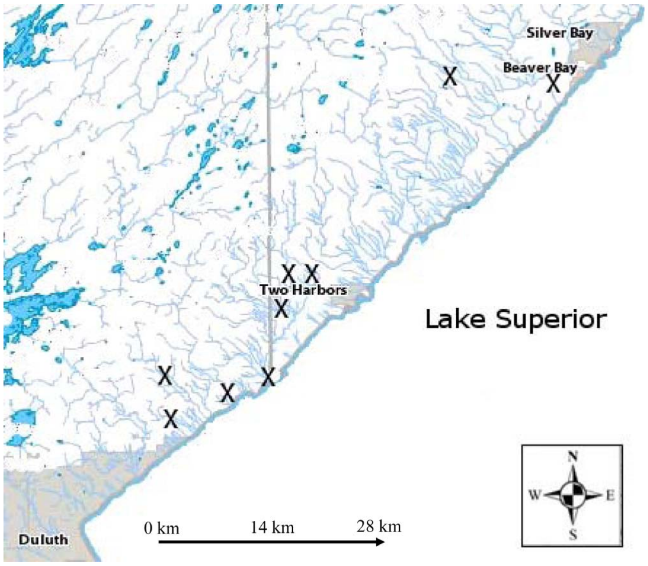

**Figure 4.** Study sites (X) along the north shore of Lake Superior in Minnesota.

specifically $F_B$, $F_W$, $F_F$, $F_D$, $F_L$, and $F_V$. These forces can be combined into ratios that are most likely to promote or resist mobilization. Examples are a vertical force ratio ($R_V$, equation (13)) and a downstream force ratio ($R_D$, equation 14)

$$R_V = (F_W + F_V)/(F_B + F_L) \tag{13}$$

$$R_D = F_F/F_D \tag{14}$$

The vertical force ratio ($R_V$) thus describes the relative force acting in a downward direction, whereas the downstream force ratio ($R_D$) describes the relative force acting in an upstream direction. If either ratio is <1, then mobilization is theoretically possible, and ratios closer to zero imply a greater likelihood of mobilization. Thus, we expect that mobilization is most likely for pieces where the buoyancy, lift, and hydrodynamic forces are high and the weight, vertical friction, and horizontal friction forces are low.

[21] Additional forces that can be expected to influence wood mobilization include the resisting force due to burial in the stream bed and the normal force exerted by bracing objects. Both forces are difficult to quantify under field conditions, however, and may be simplified as either present or absent (i.e., buried/unburied, braced/unbraced).

[22] Aside from forces, the probability of mobilization may also be related to other physical and positional attributes of a wood piece. These attributes make a piece more or less likely to be in contact with the stream bed, banks, or other obstructions. We predicted that five physical attributes would influence mobilization: the length ratio ($L^*$, ratio of piece length to the effective stream width), draft ratio ($D^*$, ratio of piece draft to mean depth in the channel), branching complexity, rootwad presence, and blockage (the percentage of the wetted channel cross-sectional area occupied by the piece). We also expected two positional attributes to influence mobilization. The lateral distance of the wood piece from the stream bank is important because pieces in the channel are more likely to be mobilized than those among floodplain trees, and effective depth is important because pieces on the channel bottom are more likely to be mobilized than those suspended above it. We next designed a field study, described below, to test our predictions.

## 3. Methods

### 3.1. Study Area and Streams

[23] The study area was in forested watersheds along the north shore of Lake Superior in Minnesota. High flows occur in area streams after spring snowmelt, but overbank stormflows are also common in summer or fall. We selected nine streams with continuous discharge data available (15 min intervals) for study (Figure 4). The study streams were the Beaver River, French River, Knife River, Little East Knife River, Little West Knife River, Sucker River, Talmadge Creek, Upper Knife River, and West Split Rock River. These nine streams represented a wide range of geomorphic conditions; stream beds were dominated by cobble and gravel and mean bankfull widths ranged from 3.4 to 24.4 m.

[24] We established a single study reach 250–800 m in length in each stream, for a total of 4190 m. Study reaches were longer for streams with less frequent wood pieces so that streams would have similar total numbers of pieces. We then divided each study reach into 10 m sections marked with wire flags, flagging tape, and GPS. In all instances, the particular 10 m section from which data were collected was noted. Data were collected from June to November 2007.

[25] Water levels in summer 2007 were low (Figure 5) due to extreme drought conditions (U.S. Department of Agriculture, USDA, Drought Monitor, 14 August 2007). However, storms from mid-September through mid-October produced heavy rainfall in the study area. Rainfall observers within 10 km of Lake Superior from Duluth to Silver Bay recorded a mean of 25.3 cm of rainfall (standard deviation = 2.3) from 15 September to 15 October 2007, compared to 19.6 cm for the entire period from 15 June to 15 August 2007 (Minnesota State Climatology Office). The rainfall caused a stormflow with a recurrence interval of 1.1 years at the Knife River, the only study stream with a long-term hydrologic record (per the St. Louis County Soil and Water Conservation District). Discharge at the Knife River increased from 0.11 $m^3/s$ in early September to a peak daily discharge of 41.6 $m^3/s$ on October 9. Although the hydrologic records were insufficient to estimate the recurrence intervals at other study streams, the relatively uniform rainfall in the study area suggests that the recurrence intervals at other study streams were comparable to the Knife River. Overbank flows were observed at all nine study streams during the stormflow event; during the peak discharges, wetted widths in the nine streams ranged from 3.4 to 90.7 m and mean cross-sectional water depths from 0.3 to 3.1 m.

### 3.2. Wood Data Collection

[26] In June through August of 2007, we located and marked all preexisting natural pieces of large wood (>0.1 m in diameter for a portion >1 m in length) in the study reaches. We also located marked a subset ($n \approx 20$) of smaller pieces (>0.05 m in diameter for a portion >1 m in length) in each study reach, for a total of 963 pieces. All pieces that lay

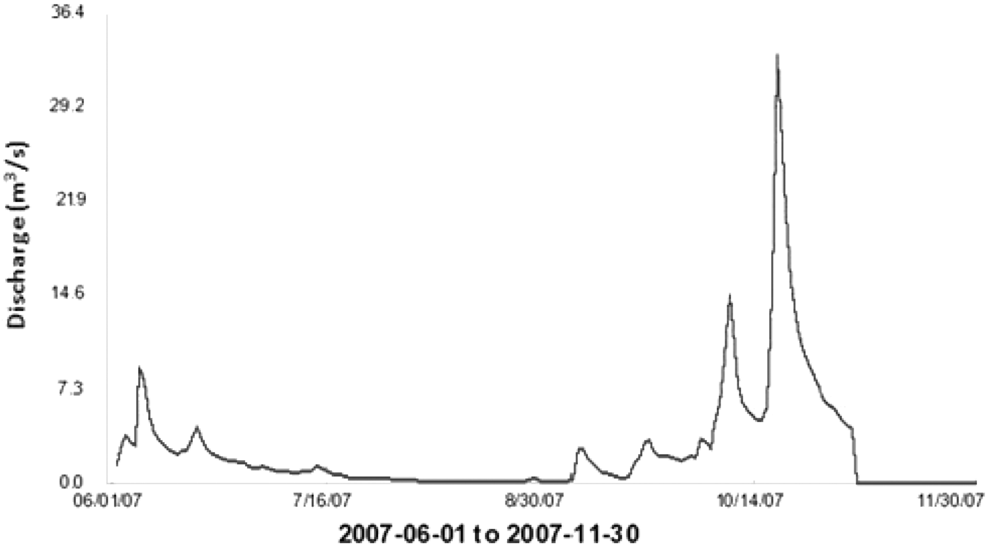

**Figure 5.** Hydrograph for the Poplar River from June to November 2007. Hydrographs for other study streams were similar. Data from Minnesota Pollution Control Agency.

within the channel or that had a portion over 0.05 m in diameter extending into the bankfull channel were assessed. We included pieces if they were entirely dead but still rooted or still alive but entirely uprooted. Each piece was marked with flagging tape and one ($n$ = 334) or three ($n$ = 629) individually numbered log tags. Log tags were plastic or metal and attached at the middle and near each end with long nails or wires, depending on the firmness of the piece. We again located all marked pieces in the study reaches in mid-October through November 2007, after floodwaters from the early October storm had receded.

[27] We measured total length (for the portion over 0.01 m in diameter) and diameter of each piece using a tree caliper at the ends and middle. We treated each piece as a cylinder for estimation of total volume, using the total length and mean diameter (i.e., the sum of both end diameters and twice the middle diameter all divided by four). The presence of rootwads was noted. We estimated the orientation of each piece as the horizontal angle relative to the flow ($\theta$, Figure 2) using categories of 0, $\pi/6$, $\pi/3$, and $\pi/2$ radians. We visually estimated the pitch of each piece relative to the stream bed ($\gamma$, Figure 3) using categories of 0, $\pi/6$, $\pi/4$, $\pi/3$, and $\pi/2$ radians; we also measured pitch on a subset of pieces ($n$ = 374) using a clinometer. Pieces where a clinometer was employed used the clinometer measurement; the remainder of the pieces used an estimate based on the relationship between visual estimates and clinometer measurements ($r^2 = 0.73$).

[28] We assessed the branching complexity for each piece as described by *Newbrey et al.* [2005], where higher branching complexity corresponds to a greater number of branches and twigs. Each piece was assigned to a decay class [*Robison and Beschta*, 1990] ranging from 1 (branches and bark present) to 5 (no branches or bark, irregular in shape). We determined the density of each piece using a sample obtained with an increment borer. It was noted if a piece was braced against other pieces, live trees, rocks, or the stream channel (including pieces that had a portion above the stream bed pinned under other pieces or rocks) or was buried. A piece of wood was considered buried if >5% of its cross-sectional area was embedded into the substrate or if either end was buried in the substrate (including pieces that were entirely dead but still rooted).

[29] We noted the location of the midpoint of each piece by measuring its longitudinal location within its 10 m section, the elevation relative to the existing water level, and the lateral distance from the nearest bank. We used the elevation of the midpoint of the piece relative to the existing water level in conjunction with continuous discharge data and the hydraulics models described below to determine the absolute elevation of each piece.

[30] We estimated the forces acting on each piece based on characteristics of the piece and local hydraulic conditions. We first calculated the buoyancy ($F_B$), weight ($F_W$), and friction against the stream bed ($F_F$) using equations (1), (2), and (4). We then calculated the hydrodynamic drag ($F_D$), lift force ($F_L$), and frictional force against braces ($F_V$) using equations (5), (8), and (12). We used a bed coefficient of friction $f_{bed} = 0.2$, the mean of values for sliding and rolling on gravel determined by *Bocchiola et al.* [2006], and a vertical coefficient of friction $f_{brace} = 0.2$ and $\psi = \pi/2$ radians.

### 3.3. Wood Mobilization Response Data

[31] We determined changes in the locations of wood pieces in fall 2007 by comparing the locations of tagged pieces that were initially marked in summer 2007 to their locations in October–November. Each piece generated a logistic data point: 0 if the piece remained within 10 m of its original longitudinal position or 1 if it moved downstream at least 10 m. By this definition, the response variable for mobilization addressed at the 10 m scale was whether pieces initially at rest remained at rest over the time frame of this study. Although pieces were not remeasured, only nine pieces were known to have broken (based on the position of the tags; the shorter portion of the piece was disregarded).

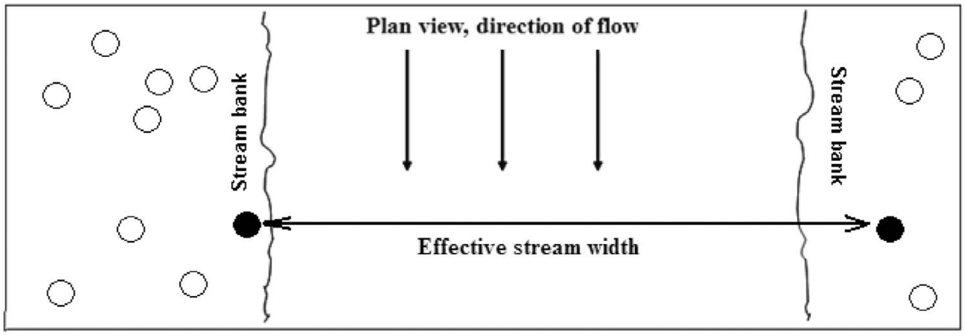

**Figure 6.** Plan view of stream channel illustrating lateral positions of trees (open circles) large enough (i.e., 2 cm diameter) to brace a floating piece of wood. Effective stream width was the lateral distance between the innermost trees (closed circles) for each 10 m section of stream or the actual wetted width, whichever was shorter.

### 3.4. Geomorphic Data

[32] We collected data on stream geomorphology from all study reaches in summer 2007. We used a survey laser and measuring tape to survey cross sections every 10 m, except at the two largest streams where 40 of 80 (Beaver River) or 12 of 50 (Knife River) 10 m sections were surveyed. Cross sections were referenced to one another using frequent turning points [*Harrelson et al.*, 1994]. We recorded elevations near inflection points along the cross section and calculated the bed slope for each reach as the slope between the lowermost points at the upstream and downstream ends of the reach. We noted the innermost lateral location of bank vegetation >0.02 m in stem diameter on both sides of each cross section and used it to estimate the effective stream width (Figure 6) available to transport wood. We estimated Manning's roughness coefficient by the methods of *Arcement and Schneider* [1989], using separate estimates for the stream channel and floodplain of each study reach.

### 3.5. Hydraulic Analysis

[33] We used the computer simulation model HEC-RAS 4.0 (http://www.hec.usace.army.mil/software/hec-ras/) to calculate hydraulic characteristics at each 10 m section during overbank stormflows in fall 2007; HEC-RAS is appropriate for studying stream characteristics at a 10 m resolution [*Brooks et al.*, 2006]. On the basis of the geomorphic survey data, HEC-RAS was used to estimate unit stream power, stage, mean water velocity, and energy grade slope [*Gordon et al.*, 2004] at each 10 m section at the peak discharge in fall 2007. The velocity estimates from the HEC-RAS models represent a cross-sectional average.

[34] To calibrate the hydraulic model for each study reach, we varied the initial value for channel roughness (between 0.02 and 0.07) to obtain the best fit between predicted water stages and observed stages during summer 2007. The $r^2$ values between predicted and observed water stages for the summer 2007 discharges ranged from 0.77 to 1.00, indicating good prediction of hydraulic characteristics.

### 3.6. Calculation of Wood Piece Variables Using Hydraulic Variables

[35] We used the peak discharge in each stream during overbank flows in fall 2007 to determine all hydraulic variables. The effective channel width was defined as the wetted width that was available to transport wood, taken as either the lateral distance between the innermost trees (Figure 6) or the modeled wetted width, whichever was less. We calculated the length ratio ($L^*$) for each piece as the piece length divided by the effective channel width in the initial 10 m section where the piece was located. We determined the absolute elevation of each piece by applying the measured difference between the piece elevation and the existing water level to the modeled stage. Using the absolute elevation for each piece, we determined the distance between the lowermost point on each piece and the water surface (i.e., the effective depth) for the fall overbank flows. The draft ratio ($D^*$) for each piece was calculated as the draft divided by the mean depth in the channel in the initial 10 m section. Blockage by each piece was estimated as $A_N/A_{wet}$ using the original orientation and pitch of the piece. We calculated the hydrodynamic drag acting upon each piece using equation (5). We used a form drag coefficient $C_d$ of 1.41 [*Bocchiola et al.*, 2006] and a skin friction drag coefficient $C_f$ of 0.005 [*Olson*, 1961]. We calculated the vertical force ratio ($R_V$) and downstream force ratio ($R_D$) for each piece using equations (13) and (14). On the basis of the observed distributions of $R_V$ and $R_D$, we set the maximum value for $R_V$ to 100 and set the maximum $R_D$ to 10, including cases where the denominator was zero (i.e., the piece was above the water level). The predictor variables did not account for flexing or breakage of pieces, mobilization by jarring contact from other pieces or sediment in transit, flexing, or movement of bracing obstructions themselves, mobilization via rolling or pivoting (as opposed to floatation or sliding), or human intervention.

### 3.7. Data Analysis

[36] We used multiple logistic regression [*Weisberg*, 1985] to model the mobilization response. Unlike multiple linear regression or discriminant function analysis, logistic regression analysis does not require normally distributed response variables, nor does it assume homogeneous variances for the response variable [*Weisberg*, 1985]. The binomial response variable for this study (mobilization) is well suited for logistic regression but not for multiple linear regression. In addition, the sample size of 963 pieces provided a suitable representation of possible cases. We developed a multiple

**Table 1.** Mean and Standard Deviation for Wood Piece Characteristics in Summer 2007 and Geomorphic and Hydraulic Stream Characteristics During Peak Discharges in Fall 2007

| | Units | Mean | |
|---|---|---|---|
| Buoyancy ($F_B$) | N | 12 | 30 |
| Weight ($F_W$) | N | 13 | 30 |
| Wood density ($\rho_{\log}$) | g/cm$^3$ | 0.75 | 0.31 |
| Piece length ($L$) | m | 3.8 | 3.0 |
| Diameter ($2r$) | m | 0.18 | 0.13 |
| Volume ($V_{\log}$) | m$^3$ | 0.18 | 0.49 |
| Pitch from stream bed ($\gamma$) | rad | 0.18 | 0.17 |
| Effective depth | m | 1.06 | 0.76 |
| Submerged volume ($V_{sub}$) | m$^3$ | 0.12 | 0.30 |
| Draft ($D$) | m | 0.12 | 0.10 |
| Friction on stream bed ($F_F$) | N | 0.7 | 2.8 |
| Piece surface area ($A_{SA}$) | m$^2$ | 2.2 | 3.0 |
| Hydrodynamic drag ($F_D$) | N | 573 | 963 |
| Orientation to flow direction ($\theta$) | rad | 0.73 | 0.49 |
| Area normal to flow ($A_N$) | m$^2$ | 0.34 | 0.47 |
| Lift ($F_L$) | N | 0.003 | 0.025 |
| Water velocity ($U$) | m/s | 1.5 | 0.5 |
| Vertical force ratio ($R_V$) | - | 17 | 49 |
| Downstream force ratio ($R_D$) | - | 1.1 | 3.2 |
| Length ratio ($L$*) | - | 0.47 | 0.50 |
| Draft ratio ($D$*) | - | 0.14 | 0.16 |
| Branching complexity | - | 12 | 39 |
| Blockage | - | 0.06 | 0.12 |
| Lateral distance from bankfull | m | 6.7 | 15.6 |
| Wetted width | m | 23 | 17 |
| Effective stream width | m | 12.2 | 8.0 |
| Energy grade slope | m/m | 0.011 | 0.011 |
| Unit stream power | N/m s | 138 | 137 |
| Mean depth in channel | m | 1.13 | 0.59 |

logistic regression model using the logistic mobilization data as the response variable. Each tagged piece represented one data point. We selected predictor variables for the full model that accounted for known mechanisms of wood transport: vertical force ratio ($R_V$), downstream force ratio ($R_D$), burial, bracing, ratio of piece length to effective channel width (length ratio, $L$*), ratio of piece draft to mean depth in the channel (the draft ratio, $D$*), branching complexity, rootwad presence, blockage, lateral distance from bankfull, and effective depth of the piece. We then chose the final model using the step Akaike information criterion AIC function of the statistical software R (available online) (http://www.r-project.org/) to determine the model with the fewest predictors that would each make a significant improvement to the AIC [*Weisberg*, 1985]. We examined the variance inflation factor (VIF) for all predictor variables in the final model to evaluate collinearity; predictors with VIF > 2 were culled. The final model produced a probability of mobilization for pieces under specific conditions; the goodness of fit was evaluated using Nagelkerke's $r^2$ [*Nagelkerke*, 1991], and variables were ranked by importance according to the absolute value of their Wald $z$ score.

## 4. Results

### 4.1. Range of Variables

[37] We tagged and measured 963 pieces of wood, but some were excluded from analyses. Two spanning logjams were present at the study reaches and were completely mobilized by the overbank event; wood pieces from either logjam ($n$ = 98) were omitted from analyses. Pieces in a logjam move via congested flow [*Braudrick et al.*, 1997; *Bocchiola et al.*, 2008] that represents a gross violation of the statistical assumption of independence. This study focused on uncongested flow, where mobilization of a piece is considered independent of other pieces.

[38] Wood pieces that were not in logjams ($n$ = 865) exhibited a range of characteristics (Table 1). For example, the mean piece length was 3.8 m with a standard deviation of 3.0 m, mean diameter was 0.18 m (0.13 m), and mean wood density was 0.75 g/cm$^3$ (0.31 g/cm$^3$). Many characteristics appeared to follow a $\chi^2$ distribution, which is acceptable because multiple logistic regression makes no assumptions about the distributions of predictor variables [*Weisberg*, 1985]. Pieces in decay classes 1–5 were 8%, 16%, 24%, 41%, and 11%, respectively, although branches and bark were likely removed by impacts by rock and ice more often than by decay.

[39] Geomorphic and hydraulic conditions also covered a wide range during peak flows in fall 2007, whether all data were combined (Table 1) or examined by stream (Table 2). The mean wetted width was 23 m (17 m), and the mean water depth in the channels was 1.13 m (0.59 m). The mean effective channel width was only 12.2 m (8.0 m), showing the importance of riparian trees in limiting available width. The mean water velocity in the channels was 1.5 m/s (0.5 m/s), and unit stream power in the channels averaged 138 N/m s (137 N/m s).

[40] Of the 865 wood pieces used in this study, 356 (41%) were mobilized during the study period. The mean length and diameter for mobilized pieces was 2.84 and 0.15 m,

**Table 2.** Mean and Standard Deviation for Geomorphic and Hydraulic Stream Characteristics for Each Study Site During Peak Discharges in Fall 2007[a]

| Stream | Mean Depth (m) | Water Velocity (m/s) | Power (N/m s) | Bed Slope (m/m) | Bankfull Width (m) | Peak Flow (m$^3$/s) |
|---|---|---|---|---|---|---|
| Beaver River | 1.66 *0.30* | 0.86 *0.32* | 15 *35* | 0.001 *0.002* | 16.0 *3.0* | 21.7 |
| French River | 0.74 *0.17* | 1.53 *0.34* | 119 *84* | 0.020 *0.010* | 11.3 *2.5* | 12.0 |
| Knife River | 1.51 *0.29* | 1.44 *0.22* | 137 *57* | 0.006 *0.003* | 24.4 *5.3* | 54.7 |
| Lt. East Knife | 1.48 *0.22* | 1.17 *0.42* | 78 *135* | 0.004 *0.015* | 3.4 *0.9* | 7 |
| Lt. West Knife | 0.53 *0.15* | 1.15 *0.33* | 40 *36* | 0.012 *0.013* | 3.7 *0.8* | 2.1 |
| Sucker River | 0.98 *0.13* | 1.84 *0.33* | 252 *169* | 0.016 *0.008* | 9.9 *2.2* | 17.5 |
| Talmadge Cr. | 0.78 *0.14* | 1.62 *0.25* | 247 *135* | 0.025 *0.035* | 5.3 *1.6* | 7.0 |
| Upper Knife | 0.84 *0.08* | 1.48 *0.25* | 93 *46* | 0.009 *0.003* | 6.6 *1.1* | 8.3 |
| W Split Rock | 2.48 *0.28* | 1.92 *0.45* | 153 *108* | 0.007 *0.002* | 6.9 *0.9* | 54.4 |

[a] Depth, velocity, and power values do not include water in the floodplain. Lt, Little. Values in italics are standard deviation.

**Table 3.** Variables Retained in the Final Model for Mobilization[a]

| | Coefficient | SE | Wald $z$ | $P$ Value | VIF |
|---|---|---|---|---|---|
| Intercept | 0.39 | 0.23 | 1.65 | 0.098 | |
| Burial | −2.64 | 0.35 | −7.67 | <0.001 | 1.09 |
| Effective depth | 0.86 | 0.14 | 6.27 | <0.001 | 1.27 |
| Length ratio | −1.52 | 0.26 | −5.80 | <0.001 | 1.18 |
| Bracing | −0.77 | 0.17 | −4.54 | <0.001 | 1.06 |
| Rootwad presence | −0.80 | 0.26 | −3.06 | 0.002 | 1.02 |
| Downstream force ratio | −0.09 | 0.04 | −2.59 | 0.010 | 1.12 |
| Draft ratio | −1.59 | 0.74 | −2.15 | 0.032 | 1.18 |

[a] $n$ = 865 pieces of wood (356 mobilized). Overall model $P < 0.001$ and Nagelkerke's $r^2 = 0.39$.

whereas the mean length and diameter for stable pieces was 4.53 and 0.19 m. Mean wood density was 0.75 and 0.76 g/cm$^3$ for mobilized and stable pieces.

## 4.2. Mobilization Model

[41] The final model for mobilization was highly significant ($P < 0.001$) and had seven predictor variables (Table 3). An additional variable (blockage) was present in the final model but was culled due to a high VIF (2.656). The seven remaining predictor variables were burial, effective depth, length ratio ($L$*), bracing, rootwad presence, downstream force ratio ($R_D$), and draft ratio ($D$*). Each predictor had a $P$ value < 0.05 and a VIF < 2, indicating that the variables were not collinear. Nagelkerke's $r^2$ for the final model was 0.39, corresponding to a Goodman-Kruskal $\gamma$ of 0.67 and Kendall's $\tau$-a of 0.32.

## 4.3. Model Sensitivity to Changes in Individual Predictors

[42] The probability of a positive response (i.e., mobilization) can be expressed for individual predictors using a logistic equation as

$$P_{\mathrm{mob}} = \exp(\beta_0 + \beta_1 x_1)/(1 + \exp(\beta_0 + \beta_1 x_1)), \qquad (15)$$

where $\beta_0$ was the intercept (e.g., 0.385 in Table 3), $\beta_1$ was the model coefficient for the variable of interest, $x_1$ was the value for the variable of interest, and all other variables were held constant. Using the model coefficient for burial (−2.643 in Table 3), equation (15) indicated that a piece that was not buried ($x_1$ = 0) had a 0.60 probability of being mobilized, whereas a piece that was buried ($x_1$ = 1) had a 0.09 probability of being mobilized. Taking the difference (0.09 − 0.60 = −0.51) showed that a piece that was buried was 51% less likely to be mobilized, assuming all other variables were held constant. Similarly, a piece that was braced was 19% less likely to be mobilized than an unbraced piece, and a piece with a rootwad was 20% less likely to be mobilized than one without. Increasing the effective depth of a piece by one standard deviation from 1.06 m (the mean value) to 1.82 m was associated with a 9% increase in the probability of mobilization (Figure 7). Increasing the length ratio ($L$*)

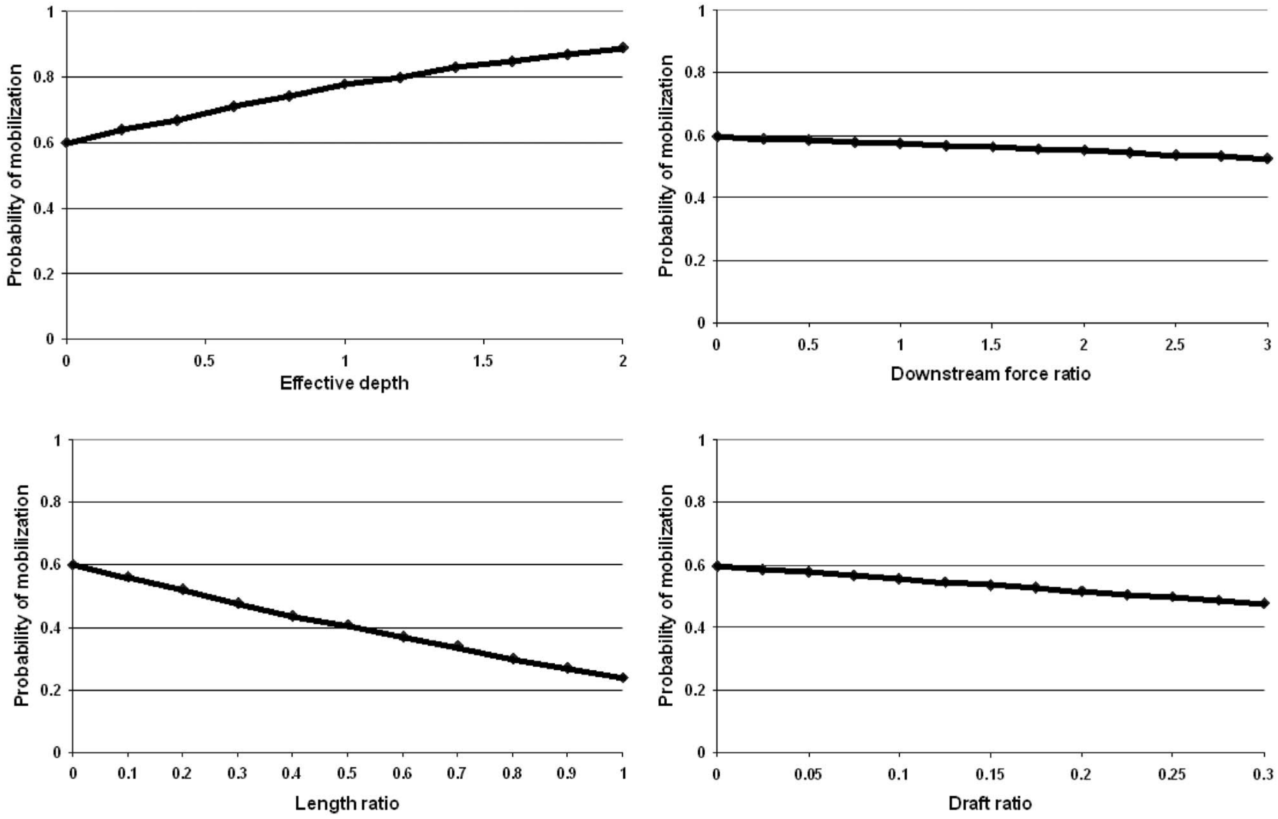

**Figure 7.** Expected probability of mobilization as a function of the effective depth, length ratio ($L$*), downstream force ratio ($R_D$), or draft ratio ($D$*).

by one standard deviation from 0.47 (the mean value) to 0.97 was associated with a 17% decrease in mobilization. Likewise, increasing the downstream force ratio or draft ratio by 1 standard deviation was associated with reductions of 7% or 6%.

### 4.4. Predicting Mobilization With the Full Model

[43] Expanding equation (15) to consider the sensitivity of model projections to the full set of predictor variables yields

$$P_{\mathrm{mob}} = \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_6 x_6 + \beta_7 x_7) / (1 + \exp(\beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots + \beta_6 x_6 + \beta_7 x_7)) \quad (16)$$

where $\beta_1 x_1 \ldots \beta_7 x_7$ correspond to coefficients and values for the seven predictor variables. Combining the prior examples, a piece of wood that was unburied, unbraced, and had no rootwad, effective depth of 1.82, length ratio of 0.47, downstream force ratio of 1.1, and draft ratio of 0.14 had $P_{\mathrm{mob}} = 0.71$. Conversely, a piece that was buried, braced, and had a rootwad, effective depth of 1.06, length ratio of 0.97, downstream force ratio of 4.3, and draft ratio of 0.30 had $P_{\mathrm{mob}} = 0.01$.

### 4.5. Categories for Bracing

[44] At the time of tagging in summer 2007, most pieces were not braced ($n = 581$). Of the 284 pieces that were braced, 104 were braced by other pieces of wood, 79 were braced by live trees, 73 were braced by rocks in the channel, and 28 were braced by the stream banks or channel itself. Of the pieces braced by wood, trees, rocks, and the channel, 40%, 24%, 63%, and 30% were mobilized.

## 5. Discussion

[45] We identified 11 variables through literature review and assessed them for their potential influence on mobilization of natural pieces of wood in streams. No known study has examined wood mobilization with such a comprehensive set of potential predictors. Seven of the variables contributed significantly to the prediction of mobilization, as ranked by the absolute value of their Wald $z$ score: burial, effective depth, length ratio ($L^*$), bracing, rootwad presence, downstream force ratio ($R_D$), and draft ratio ($D^*$). The overall model had a $P$ value $< 0.001$ and $r^2 = 0.39$ [*Nagelkerke*, 1991].

[46] Our study agrees with the statement that predicting wood transport is much more complex than sediment transport [*Braudrick and Grant*, 2000], even with a large field data set and seven significant predictors. It is noteworthy that our force ratios were relatively unimportant in predicting mobilization; a true account of forces in natural streams would quantify forces exerted by burial and bracing and include the hydraulic influence of branches and rootwads. Below we discuss each of the significant predictor variables, describe the characteristics of stable pieces, and make suggestions for future models of wood mobilization.

### 5.1. Controls of Mobilization

[47] Burial was easily most important variable in the final model for mobilization, based on the Wald $z$ score. Pieces that were partially buried were less likely to be mobilized. Burial and unburial can remove or return a substantial amount of wood to streams [*Latterell and Naiman*, 2007]. Although few studies have considered the effects of burial on mobilization, when burial is included in analyses, it is of primary importance [*Berg et al.*, 1998; *Wohl and Goode*, 2008]. Our study demonstrated the importance of burial to mobilization using a quantitative analysis and a large number (865) of wood pieces.

[48] The effective depth of the wood piece was the second most important variable in the final model for mobilization, with more-submerged pieces more likely to be mobilized. Effective depth may function as a composite descriptor of the various mobilizing forces acting on a piece (e.g., buoyancy, hydrodynamic drag, and lift). Effective depth also affects the likelihood that a piece will contact the stream bed before escaping a 10 m section. In a turbulent stream, a piece floating in deep water is less likely to contact the stream bed than the same piece floating in shallow water. Effective depth is affected by stream discharge, the importance of which was recognized in the pioneering work by *Bilby* [1984].

[49] The next important variable in the final model for mobilization was the length ratio ($L^*$). Pieces that were long relative to the effective channel width were less likely to be mobilized. At the 10 m scale, the length ratio may relate to the probability that a piece becomes braced before it can escape the 10 m section. Most previous studies have likewise found a negative relationship between length ratios and mobilization [*Bilby*, 1984; *Lienkaemper and Swanson*, 1987; *Berg et al.*, 1998; *Jacobsen et al.*, 1999; *Gurnell et al.*, 2002; *Hassan et al.*, 2005; *Warren and Kraft*, 2008, but see *Wohl and Goode*, 2008]. Finally, we used the effective channel width (i.e., the unobstructed wetted width available to transport wood) to determine our length ratio rather than bankfull width or wetted width.

[50] Bracing was also a significant predictor of mobilization; a piece that was braced was less likely to be mobilized. Thus, three of the variables predicting mobilization (burial, length ratio, and bracing) are in agreement with the qualitative results of the extensive field study by *Berg et al.* [1998], which did not assess the remainder of our variables. However, for reasons that are unclear, pieces braced by rocks showed the opposite effect and were more likely to be mobilized. It also bears noting that, of the pieces that were braced in summer 2007, the largest number was held by other pieces of wood, even after pieces in spanning logjams were culled from the data set. The frequency of wood pieces in a stream may provide a positive feedback by reducing mobilization of other pieces.

[51] Rootwad presence was associated with a lower probability of mobilization. A rootwad presents additional surface area that may become entangled with rocks, vegetation, or other pieces to prevent a piece from being mobilized. Rootwads tend to be sturdy; for example, if a rootwad becomes wedged between rocks, it may hold the entire piece against substantial hydrodynamic drag. Rootwads may also project downward and elevate a piece, reducing the submerged volume and thus the buoyancy and hydrodynamic drag [*Braudrick and Grant*, 2000].

[52] Pieces with higher downstream force ratio ($R_D$, meaning pieces with more friction on the stream bed relative

to hydrodynamic drag) were less likely to be mobilized. The downstream force ratio integrates the effects of piece density, volume, and submerged volume into friction and the effects of water velocity and submerged piece area into hydrodynamic drag. The downstream force ratio is lowest when buoyancy is greater than weight (meaning the piece floats and has no friction with the stream bed), and the water velocity is zero (meaning the piece is in slack water or is above the water level). The influence of downstream force ratio on mobilization was relatively minor after accounting for the five preceding variables.

[53] Draft ratio ($D^*$) was the least important predictor variable, although the Wald $z$ score was still significant ($P = 0.032$). Pieces with higher draft relative to the water depth were less likely to be mobilized. As for the length ratio, the draft ratio may affect the probability that a piece is halted (by friction with the stream bed in this case) before it can escape a 10 m section. Although prior research [*Braudrick and Grant*, 2001; *Haga et al.*, 2002] suggests that draft ratio may be important to entrapment, our analysis found that draft ratio plays a relatively minor role in mobilization.

[54] Four predictor variables were not included in the final model for mobilization: the vertical force ratio ($R_V$), blockage, branching complexity, and lateral distance from bankfull. The vertical force ratio may overlap with bracing; the vertical friction for pieces that were braced constituted 80% of total vertical forces (i.e., the sum of $F_B$, $F_W$, $F_L$, and $F_V$) on average. The unimportance of branching complexity supports the assertion that branches do not measurably increase the hydrodynamic drag acting on a piece [*Hygelund and Manga*, 2002]. The value for branching complexity is also highly influenced by the presence of small twigs [*Newbrey et al.*, 2005], which break off easily under duress. It bears noting, however, that the definition of mobilization used for this study (i.e., moved at least 10 m) is conservative. Finer-scale definitions of mobilization that include any measurable motion [*Bocchiola et al.*, 2006] may be more sensitive but less ecologically meaningful.

[55] Overall, the composition of the final model indicated that mobilization under natural conditions is a complex function of both mechanical factors (burial, length ratio, bracing, rootwad presence, draft ratio) and hydraulic factors (effective depth, downstream force ratio). Although our study included only a single year, the nine streams exhibited a wide range of geomorphic and hydraulic conditions. Thus, the results from this study are applicable to at least a similar range of conditions in other streams. Four of the final seven predictor variables take discharge into account (i.e., effective depth, length ratio, downstream force ratio, draft ratio), and the remainder have been identified as important in other settings [*Berg et al.*, 1998; *Braudrick and Grant*, 2000; *Wohl and Goode*, 2008].

### 5.2. Applications to Stream Management

[56] The model equation (16) can be used for management of wood in streams. If a management goal is to have stable wood, pieces can be partially buried, long relative to the channel width, braced against other objects (e.g., stream banks, standing trees, rocks, or larger pieces), have rootwads, and have high draft relative to the water depth. Pieces can also have higher downstream force ratios by having higher density (increasing weight, decreasing buoyancy, and thereby increasing friction with the stream bed) and by being located in slow-moving water or above the waterline (thus minimizing the effective depth).

[57] Although pieces located above the waterline are less likely to be mobilized, they also provide fewer ecological functions to a stream. In particular, pieces that are not submerged do not provide stable substrate for biofilms and aquatic invertebrates, enhance hydraulic heterogeneity, promote hyporheic recharge or transient storage, encourage pool formation and channel meandering, or entrap leaves and other organic matter. However, wood that is within stream channels but above the waterline can still provide overhead cover for fish and is valuable for riparian species such as frogs, turtles, snakes, and waterfowl.

[58] We suggest several possibilities for improving the statistical strength of the mobilization model. First, the resolution of hydraulic information could be increased, with velocity and water level measured in the area immediately around each piece [*Bocchiola et al.*, 2006]. The moment forces controlling pivoting and rolling could also be calculated. Such detailed data are difficult to obtain in a field setting, however, and the effort must be weighed against other considerations such as investigating a broad range of conditions. Second, the amount of sturdy branches on each piece could be measured in some other way. For example, a branching ratio could be determined for each piece as the combined length of large branches (>0.05 m in diameter, excluding the main bole of the piece) divided by the length of the main bole. Third, data could be collected to estimate the forces acting on a partially buried piece, using methods described by *Brooks et al.* [2006].

[59] Further research is needed to better understand the processes that remove wood from streams. For example, the process of in-stream decay is known to depend on the tree species [*Diez et al.*, 2002] and water chemistry [*Gulis et al.*, 2004] but has received relatively little study [*Hassan et al.*, 2005]. Similarly, the processes by which wood becomes buried and unburied in streams merit further study [*Hassan et al.*, 2005; *Latterell and Naiman*, 2007]. Perhaps the most important area for study is the sociological reasons for intentional wood removal by humans [*Gregory and Davis*, 1993; *Piegay et al.*, 2005; *Chin et al.*, 2008; *Wyzga et al.*, 2009; *Merten and Decker-Fritz*, 2010].

## 6. Conclusion

[60] In this study we collected an extensive data set to study wood mobilization in streams. This study can serve as a template for models of wood mobilization that use a wide range of piece characteristics and geomorphic stream conditions representative of natural conditions and use an appropriate resolution for hydraulic information. We have identified 7 factors out of 11 tested that influence wood mobilization in streams and developed a model that includes all the significant predictors. Using the relationships developed in this study, stewards of natural resources can better manage in-stream wood for the benefit of stream ecosystems.

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