A Theoretical Model for the Initiation of Large Woody Debris Movement in Caspar Creek, CA
FINAL

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1. Introduction

Over the last twenty five years, our understanding of the geomorphic and ecological role of large woody debris (LWD) has altered our view of wood in streams. Where managers were pulling LWD out of the channel in the 1970's, they are now adding wood to channels to improve their aquatic habitat. The pace of placing the wood in channels, however, is greater than our increases in understanding of LWD dynamics. Therefore, our ability to predict the stability of LWD is somewhat limited. In particular, there are no guidelines that can be used to assess how wood stability differs according to channel type (e.g., small channels versus large channels). Movement of logs can pose several potential problems, particularly if there are structures such as culverts, bridges, or houses downstream that could be affected by moving logs. This is a particularly sensitive issue if the logs have been added to the stream for restoration purposes, rather than entered the stream naturally. Because of this uncertainty, logs added to restore stream habitat are often cabled to the bank, or not added at all where their downstream movement could be potentially harmful. A better understanding of log dynamics will help to make restoration projects more effective in two ways. First, logs could be added that were likely to be stable at a given flow. Also, understanding log dynamics would help make wood budgets more accurate.

There are two components to understanding the LWD added to or naturally occurring in the channel, the first is defining the thresholds for log movement and the second is predicting how far logs will travel once in motion. In this study, we seek to address the thresholds for log movement for wood added to Caspar Creek in the Jackson Demonstration State Forest in Mendocino County, CA. A full understanding of LWD dynamics requires understanding both components.

This study is based on work by Braudrick and Grant (2000), who examined the thresholds for LWD movement for logs with and without rootwads using force balance models and flume experiments. In their models and experiments, they assumed that the entire length of the log was in the stream. Consequently, they argued that their model was more appropriate for larger streams, where logs are not perched on terraces. Their results showed that if log length is less than channel width, piece length did not significantly affect wood movement if the log did not have a rootwad, which contradicted the results of many field studies. They hypothesized that piece length was more important in small channels where much of the piece length would lie outside of the stream. LWD that is able to alter the channel bed and provide habitat for aquatic organisms, however, is often much longer than channel width, and often large portions of logs are located outside the bankfull channel width. In addition, most streams where LWD is being used to improve aquatic habitat are smaller, where wood can be stabilized by anchoring it on the bank.

The models of Braudrick and Grant (2000) and the modified models we present here are simplifications of natural systems, and are useful as a first-order guide for log stability rather as a definitive rule for thresholds of wood movement. Several components of natural channels are not included in the models presented here, including mobility of the channel bed, irregularities in the shape of the wood and the bed, non-uniform flow, and roughness elements on the bank (e.g., trees, boulders, and other logs). The models are still very useful, however, because we know very little about LWD dynamics relative to our understanding of the dynamics of inorganic sediment transport. Simple models can therefore be used to identify the relative importance of different parameters. As part of a program to promote research on state forests, the California Department of Forestry and Fire Protection (CDF) contracted Stillwater Sciences to modify and test models of wood movement. We chose to conduct this study on a portion of Caspar Creek where wood had recently been added to the channel.

2. Site Description

This study was conducted in Caspar Creek in the Jackson Demonstration State Forest near Mendocino, CA (Figure 1). The study area extends from the confluence of the north and south forks of Caspar Creek downstream approximately 1 km. In the study reach, Caspar Creek has an average bankfull width of 10 m and an average slope of 0.7 percent. In the study area, Caspar Creek has a pool-riffle channel morphology with fine gravel, sand, and silt substrates. Where the valley width is narrow coast redwood (*Sequoia sempervirens*) and Douglas-fir (*Pseudotsuga menzesii*) are the predominant riparian trees. In areas where the valley floor widens, alders (*Alnus spp.*) tend to be the dominant riparian trees. The valley slopes in the study area are forested with second- and third-growth redwood.

Most of the LWD in the study reach was added to Caspar Creek in 1999 in a joint project between CDF and the California Department of Fish and Game. Prior to the log addition project, there was little LWD in the channel in Caspar Creek (William Baxter, personal communication), although there was no documented removal of LWD in the study reach (JDSF Map Atlas 1999). Most of the added logs were coast redwoods, but some alders and Douglas-fir were also placed in the channel. Almost all of the pieces had at least one end on the bank, and many were placed orthogonal to flow (rather than parallel to flow) in order to maximize habitat created by the logs. The logs were placed both as individuals and in small jams. None of the pieces were cabled because one of the goals of the study was to let the LWD and the bed interact naturally. The redwoods were generally second-growth and had diameters ranging from 0.3 to 0.75 m.

The USDA Forest Service Redwood Sciences Laboratory and CDF have been conducting a long-term study on the North and South forks of Caspar Creek, upstream of our study area to examine some of the effects of logging practices on streams. As part of their studies they have long-term flow records in both tributaries upstream of our study site (Figure 1). The annual peak flows from 1963–2002 are shown in Figure 2. The maximum discharge for the North Fork gauge was 304 cfs which occurred in both 1966 and 1974. The maximum discharge for the South Fork gauge occurred in 1974 and was 296 cfs. Discharge has not exceeded bankfull discharge at either gauge since the logs have been added to the channel (Figure 2). The added logs have caused some alteration to the bed prior to our initial survey in 2001 (William Baxter, personal communication).

3. Theoretical Background

3.1 Braudrick and Grant's (2000) model for in-channel logs without rootwads

Braudrick and Grant (2000) used a force balance model to predict thresholds for wood transport in streams. Similar models have been used to describe the initiation of sediment transport by water and wind. In their analysis, they assumed that the log was lying in a uniform flow field with a smooth immobile bed. They further assumed that the logs were right circular cylinders of constant density. Logs can move by rolling, sliding, or pivoting, but in order to simplify their calculation, they assumed that logs moved by sliding. In their model, they assumed that all forces were body forces acting at the center of mass. The logs moved when the downstream components of the force balance model, gravitational force and drag force, are balanced with the upstream component of the force balance model, the frictional force[1]. To simplify the model, we have made several assumptions regarding the physical characteristics of the wood and channel.

We will not go through Braudrick and Grant's (2000) derivation in detail in this manuscript but rather will present only the equations used in our analysis. Their force balance model for a log without a rootwad, entirely in the channel is:

$$\left(g\rho_{log} L_{log} \frac{\pi D_{log}^{2}}{4} - g\rho_w L_{log} A_{sub} \right)(\mu_{bed}\mathrm{Cos}\alpha - \mathrm{Sin}\alpha) = \frac{U^2}{2}\rho_w C_d \left(L_{log} d_w \mathrm{Sin}\theta + A_{sub}\mathrm{Cos}\theta\right) \qquad (1)$$

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, α is the bed angle in the flow-parallel plane, g is gravity, θ is the angle of the log relative to flow (where the log is parallel to flow when θ=0), C_d is the drag force acting on the log, μ_{bed} is the coefficient of friction between the log and the bed, U is the water velocity, and A_{sub} is the submerged area of the log perpendicular to piece length exposed to drag (Figure 3). A_{sub} is equal to:

$$A_{sub} = \left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right)\right)\right)\frac{D_{log}^{2}}{8} \qquad (2)$$

3.2 Braudrick and Grant's (2000) model for in-channel logs with rootwads

Using the same assumptions, Braudrick and Grant (2000) found that the force balance acting on a cylindrical log with a rootwad is:

$$\left(g\rho_{log}\left(L_{log}\frac{\pi D_{log}^{2}}{4} + V_{rw}\right) - g\rho_w (V_1 + V_2)\right)(\mu_{bed}\mathrm{Cos}\alpha - \mathrm{Sin}\alpha) = \frac{U^2}{2}\rho_w C_d \left((A_1 + A_2)\mathrm{Sin}\theta + A_3\mathrm{Cos}\theta\right) \qquad (3)$$

where V_1 is the submerged volume of bole, V_2 is the submerged volume of the rootwad, V_{rw} is the volume of the rootwad, A_1 is the submerged area of the bole, A_2 is the submerged area of the rootwad, perpendicular to piece length, and A_3 is the submerged area of the rootwad perpendicular to piece length (Figure 4). V_1 is equal to:

[1] These forces are described in detail in Braudrick and Grant (2000) and are not discussed here.

$$V_1 = \pi\left(\frac{d_w - r}{\tan\gamma_{rw}}\right)r^2 \tag{4}$$

where γ_{rw} is:

$$\gamma_{rw} = \frac{D_{rw} - D_{log}}{2L_{log}} \tag{5}$$

If the water depth is less than the diameter of the log, V_1 becomes:

$$V_1 = \frac{2}{3\tan\gamma_{rw}}\left(r^2 - (d_w - r)^2\right)^{\frac{3}{2}} + r^2\left(\frac{d_w - r}{\tan\gamma_{rw}}\right)\left(\sin^{-1}\left(\frac{(d_w - r)}{r}\right) + \frac{\pi}{2}\right)$$

$$+\frac{1}{2}r^2\left(\frac{d_w - r}{\tan\gamma_{rw}}\right)\mathrm{Sin}\left(2\sin^{-1}\left(\frac{(d_w - r)}{r}\right)\right) \tag{6}$$

If the depth is greater than the diameter, the submerged area of the log, A_1 is equal to:

$$A_1 = \frac{(d_w - r)}{\tan\gamma_{rw}}r \tag{7}$$

If the water depth is less than the diameter of the log, A_1 becomes:

$$A_1 = \frac{1}{2\tan\gamma_{rw}}\left((d_w - r)^2 - r^2\right) + \frac{d_w - r}{\tan\gamma_{rw}}(d_w - 2r) \tag{8}$$

A_3, the submerged area of the rootwad is equal to:

$$A_3 = \left(2\mathrm{Cos}^{-1}\left(1 - \frac{2d_w}{D_{rw}}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{rw}}\right)\right)\right)\frac{{D_{rw}}^2}{8} \tag{9}$$

3.3 The force balance of a log with one end outside the bankfull channel

For this study, we adapted Braudrick and Grant's (2000) equation to work in Caspar Creek. We altered their equations to accommodate pieces that have part of their length resting outside of the bankfull channel. The initiation of movement occurs when the overall forces on the log add up to zero:

$$F_{friction} - F_{gravity} - F_{drag} = 0 \tag{10}$$

which can be rewritten as:

$$F_{friction} - F_{gravity} = F_{drag} \tag{11}$$

The resulting force balance equation is:

$$\left(g\rho_{log} L_{log} \frac{\pi D_{log}{}^2}{4} - g\rho_w V_{sub} \right)\left(\mu_{bed}\cos\alpha - \sin\alpha\right) = \frac{U^2}{2}\rho_w C_d \left(A_{sub1}\sin\theta + A_{sub2}\cos\theta\right) \tag{12}$$

Where V_{sub} is the submerged volume of the log, A_{sub1} is the submerged area of the log parallel to piece length, A_{sub2} is the submerged area of the log perpendicular to piece length, and all other variables are as defined previously (Figure 5). V_{sub}, A_{sub1}, and A_{sub2} always have positive values.

If the water depth is greater than the piece diameter, V_{sub}, the submerged volume of the log is equal to:

$$V_{sub} = 2\int_{-r}^{d_w - r}\int_0^{\sqrt{r^2 - y^2}}\int_0^{my+b} dz\,dx\,dy \tag{13}$$

Where x, y, and z are the coordinate axes. If the water depth is greater than the piece diameter, equation 13 becomes:

$$V_{sub} = \frac{\pi D_{log}^2}{4} b \tag{14}$$

Where b is the submerged length of the log defined in equations 17 and 18.

If the water depth is less than the diameter of the log, V_{sub} becomes:

$$V_{sub} = \frac{2}{3\tan\gamma}\left[r^2 - (d_w - r)^2\right]^{\frac{3}{2}} + r^2\left(\frac{d_w - r}{\tan\gamma}\right)\left(\sin^{-1}\left(\frac{d_w - r}{r}\right) + \frac{\pi}{2}\right)$$

$$+\frac{1}{2}r^2\left(\frac{d_w - r}{\mathrm{Tan}(\gamma)}\right)\mathrm{Sin}\left(2\mathrm{Sin}^{-1}\left(\frac{(d_w - r)}{r}\right)\right) \qquad (15)$$

Where:

$$\gamma = \sin^{-1}\left(\frac{h_{bank}}{L_{bank}}\right) \qquad (16)$$

where h_{bank} is the height of the bank the log is perched from and L_{bank} is the length of the log inside the channel (Figure 5). b is equal to:

$$b = \frac{d_w - r}{\tan(\gamma)} \qquad (17)$$

m is equal to:

$$m = -\gamma \qquad (18)$$

If the water depth is greater than the log diameter A_{sub1} is equal to:

$$A_{sub1} = bD_{log} \qquad (19)$$

If the water depth is less than the log diameter A_{sub1} becomes:

$$A_{sub1} = \frac{d_w{}^2 - 2d_w r}{2\tan\gamma} + \frac{d_w - r}{\tan\gamma}(d_w - 2r) \qquad (20)$$

A_{sub2} is the area of the log perpendicular to flow (Figure 5). If the water depth is greater than the log diameter, A_{sub2} is equal to:

$$A_{sub2} = \frac{\pi D_{log}{}^2}{4} \qquad (21)$$

if the water depth is less than the log diameter, A_{sub2} becomes:

$$A_{sub2} = \left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right)\right)\right)\frac{D_{log}{}^2}{8} \qquad (22)$$

Buoyant and drag forces would be lower for logs with one end outside of the bankfull channel than pieces entirely in the bankfull channel, because less of the log is exposed to flow. We therefore expect that logs that are partially outside of the bankfull channel will move at higher discharges than logs that are entirely in the channel (if the logs are the same size).

Pieces that are suspended on both ends were treated as in-channel pieces that did not interact with flow until the discharge was greater than bankfull. The model for suspended pieces is similar to Equation 1, except that depth is replaced by depth greater than bankfull and is not presented in detail here.

3.4 Parameters used in the model

Several of the parameters used in the model have been investigated by other researchers or could be assumed from known relationships. Hygelund and Manga (in press) found that the drag coefficient (C_d) did not vary with piece angle (as assumed in Braudrick and Grant 2000), and depended more on the ratio of the piece diameter to flow depth. They found if the diameter was greater than 0.3 times the depth, which is generally the case on Caspar Creek, C_d did not vary significantly and was approximately 2.1. Ishikawa (1989) found that the critical bed angle[2] for wood on a fine sand bed was 25 degrees, which corresponds to μ_{bed} equal to 0.47. We assumed that ρ_w was assumed to be equal to 1,000 kg/m^3. Manning's equation was used to calculate velocity. Because the LWD provides a great deal of roughness to the channel, n was assumed to be 0.08, a relatively high value.

Rather than measuring the piece density for each log, it was estimated based on the species and the decay class using values from the US Forest Products Library (1976). Because density can vary greatly within an individual log, we believed it would be sufficient to use empirically-derived densities. All other parameters were measured in the field (as described in Section 4, below).

Several physical parameters that are important for wood transport were not included in the model in order to maintain its simplicity. We assumed that the channel is smooth without any riparian vegetation. LWD can commonly deposit against riparian trees, which can help to anchor the wood. In addition, we treat every log as an individual, and did not try to model interaction between groups of logs.

In order to use the models to predict LWD motion in Caspar Creek, we assumed that:

- all logs are right circular cylinders as shown in Figures 3-5, with a diameter equal to the average of the three diameter measurements taken in the field;
- the logs are lying in a uniform flow field and Manning's equation can be used to assess relationships between depth and velocity;
- unless otherwise noted in the field, the height of the banks on which logs were suspended was equal to the bankfull height off the channel bed; and

[2] The critical angle is the angle at which wood slides on a planar bed.

- the average water depth of the cross section as measured in the field can be substituted for d_w in the above equations.

4. Methods

4.1 LWD characteristics

Over a ten-day period in October/November 2001, we tagged 46 logs over an approximately 1-km long reach in Caspar Creek, CA in the Jackson Demonstration State Forest. Each log was photographed, marked with two metal tags (generally one on each end), and the tags were surveyed with a total station to document their position relative to local benchmarks. Logs in a wide range of sizes were selected for surveying in order to observe a variety of potential responses and to ensure that surveyed logs were representative of the range of LWD in the study reach.

We measured the following log characteristics for input into the model, and also to explain results that diverged from modeled predictions:

- piece length (L_{log})
- piece length in the wetted channel
- piece length in the bankfull channel (L_{bf})
- piece length suspended over the channel
- piece diameter in three locations (D_{log})
- piece and flow orientation, which can be used to derive the piece angle relative to flow (θ)
- rootwad length
- rootwad diameter (D_{rw})
- whether or not the piece was part of a jam
- location characteristics (e.g., lodged against a tree, location within a jam, etc.)
- species
- decay class (after Harmon et al. 1986)

All data were entered on data sheets in the field, transferred to a Microsoft Access database and analyzed for quality assurance and quality control.

In November 2002, we returned to the study reach to document the movement of tagged LWD. All recovered pieces were resurveyed with a total station. The original location of missing pieces was searched thoroughly to verify that the piece had moved. Piece characteristics were compared with characteristics from the previous year, and any changes were measured. Piece movement was measured by calculating the distance the midpoint between the two tags moved between the 2001 and 2002 surveys. To describe which model to use, logs were characterized as being in one of four general locations:

- in-channel, calculated using Equation 1 (if the entire length of the log was in the bankfull channel);
- in-channel with rootwad, calculated using Equation 3 (if the entire length of the log was in the bankfull channel with a rootwad,);
- suspended from one end, calculated using Equation 12 (one end of the log was out of the bankfull channel and one end of the log was in the channel); and
- suspended, calculated using Equation 1 where depth greater than bankfull is substituted for depth (both ends of the log were outside of the bankfull channel, and the log was suspended over the channel).

4.2 Channel characteristics

Channel characteristics were surveyed using a total station in fall 2001 to provided slope and cross section data for input to the model. We surveyed the thalweg profile (noting substrate composition) and 16 representative cross sections. Cross sections were chosen to be representative of a reach, and a new cross section was surveyed when it was determined that the morphology had changed sufficiently to require a new cross section. The appropriate cross section was noted for each log. For each cross section, we noted the bankfull indicators, low-water surface, and thalweg. Channel characteristics were not resurveyed in fall 2002 because it beyond the scope of this study, but there was evidence that the channel bed had changed somewhat since the initial surveys. These changes were not accounted for in the transport model.

The bankfull width and depth of each cross section, as well as the mean, minimum, and maximum are listed in Table 1. The results for cross sections 8 and 10 have been excluded since those cross sections were used to define local variations and did not cover the entire channel width. Bankfull widths in the study reach ranged from 6.8 m to 15.2 m, and averaged 10.0 m. The reach had a mean average depth of 0.5 m, with a minimum average depth of 0.2 m and a maximum of 1.0 m.

Table 1. Dimensions of cross sections surveyed in fall 2001.

Cross Section	Bankfull Width (m)	Average Depth (m)
1	7.1	0.7
2	9.1	0.5
3	14.6	0.4
4	10.9	0.2
5	9.2	0.7
6	15.2	0.5
7	9.3	0.5
9	9.7	1.0
11	7.5	0.4
12	12.7	0.3
13	6.8	0.7
14	8.4	0.3
15	9.4	0.5
16	10.6	0.6
Mean	*10.0*	*0.5*
Minimum	*6.8*	*0.2*
Maximum	*15.2*	*1.0*

4.3 Discharge

In 2002, the maximum discharge at the South Fork and North Fork Caspar Creek gauges was 99.5 cfs (2.82 cms) and 98.6 cfs (2.79 cms), respectively (Figure 6). Based on flood frequency analysis of annual peak flows using flow data from 1963–2002, these flows would be expected to occur at both gauges every 1.5 years. Because the stage recorder we installed at the upstream area of the study area did not function properly, we used data from the South Fork Caspar Creek and North Fork Caspar Creek gauges, respectively. We scaled the drainage area at the gauges (508 hectares and 424 hectares at the South Fork gauge and North Fork gauge, respectively) by the drainage area of the two creeks at their confluence (435 hectares and 992 hectares, respectively). Based on this methodology, the combined maximum discharge using the records from the two gauges was 294 cfs (8.34 cms). While this assumes that the flood peaks are coincident, we believe that it can be used as an indicator of discharge at the study site. The discharge at each gauge and the area-adjusted discharge for water year 2002 (through April) are shown in Figure 6 (Data courtesy of USDA Forest Service Redwood Sciences Laboratory).

Because flows capable of moving LWD mostly occurred early in the season and over the Christmas holiday (Figure 6), we were unable to measure velocity during peak flows directly in the field, and instead estimated it with Manning's equation.

5. Results

5.1 Log movement

Surveyed logs ranged in length from 0.8 m to 37.8 m and in diameter from 0.11 m to 1.15 m. The mean length and diameter of surveyed pieces was 11.1 m and 0.37 m, respectively (Table 2). Twenty one of the 46 logs were in-channel logs, three of which had rootwads, 22 logs were suspended from one bank, and 3 of the logs were suspended over the channel from both banks (Table 2). We did not analyze suspended logs with rootwads separately from suspended logs with rootwads, because the rootwads did not control the elevation of the logs off the bed (e.g., the logs were elevated by the bank and not the rootwad).

Because most of the added logs were either large Douglas-firs or redwoods and had at least one end on the bank, and because in-channel logs tended to be naturally recruited and smaller, pieces that had one end on the bank tended to be much longer than pieces that were entirely in the channel (Table 2).

Table 2. Physical characteristics of logs by position.

Log Position	Number of pieces	Mean length (m)	Mean diameter (m)
In-channel	18	5.0	0.29
In-channel, with rootwad	3	5.9	0.31
Suspended from one bank	22	15.3	0.43
Suspended from both banks	3	22.1	0.40
total	*46*	*11.1*	*0.37*

Of the 46 tagged pieces, 28 moved during water year 2002 (Table 3). Most pieces did not move far, but rather rotated into a more stable position. This was particularly true for logs suspended from one bank. This minor adjustment of log location occurred in part because the pieces were added to the stream recently and had not experienced flows with a magnitude greater than a 1.5-

year recurrence interval. Because pieces were only tagged in two places, and the tags could easily end up on the bottom of logs against the bed, recovering pieces that moved long distances was very difficult.

Table 3. Movement of surveyed logs following winter 2001 flows.

Log Position	Number of pieces	Number of pieces that moved	Percent of pieces that moved	Mean distance traveled (m)
In-channel	18	16	89%	8.5*
In-channel, with rootwad	3	3	100%	1.9
Suspended from one bank	22	8	36%	2.1
Suspended from both banks	3	1	33%	2.0
total	*46*	*28*	*59%*	*5.3*

*6 in-channel pieces moved but were not recovered, and are therefore not included in this calculation.

In this study, pieces with their length entirely in the channel were more likely to move than pieces that had part of their length on the bank. Eight of the 22 pieces that were suspended from the bank moved, whereas 14 of the 16 pieces that had their entire length in the channel moved (Table 3). This is at least partially because the pieces suspended from one bank tended to be longer and have a larger diameter than pieces that were entirely within the bankfull channel. Also, movement thresholds for pieces of equal size would occur at a higher discharge for logs with part of their length outside of the channel. We were unable to find six of the in-channel pieces that moved, but we searched their original locations thoroughly to verify that they had moved downstream. The in-channel logs without rootwads tended to move farther than either the suspended logs or the logs with rootwads (Table 3).

Of the 28 logs that moved, 9 had piece lengths greater than the bankfull width of the channel. This is shown in Figure 7 which depicts log length divided by channel width (L_{log}/w_c) plotted against distance transported. A value of L_{log}/w_c equal to 1 occurs when the piece length is greater than channel width. For graphical purposes only, we assumed logs that were not found during the resurveys moved 20 m. Most of the logs that were not found during the resurveys were relatively small. Similar to logs that were shorter than bankfull width, only 3 of the logs where L_{log} was greater than w_c moved more than 5 m downstream.

The portion of logs in jams that moved was approximately the same as the portion of individuals that moved (Table 4). This indicates that movement was not significantly altered by the presence of a jam, although most of the distances moved were small, reflecting minor adjustments of log position.

Table 4. The relationship between log movement and whether logs were in jams or individuals.

	Total number	Number that moved	Percent that moved
Logs in jams	15	9	60%
Individual logs	31	18	58%
total	*46*	*27*	*59%*

5.2 Application of the model

Because of difficulties translating discharge from cross section to cross section, we used the bankfull flow indicators on the cross section as a surrogate for stage. As described above, the maximum discharge during WY 2002 had a 1.5-year recurrence interval at the South Fork Caspar Creek and North Fork Caspar Creek gauges. These flows correspond to bankfull recurrence interval, and therefore bankfull flow may be a relatively close assumption. We also did not see evidence that the flow had overtopped the channel banks in 2002. In order to calculate velocity, we assumed that Manning's n was 0.08, a relatively high value that seemed appropriate for Caspar Creek. We tested the sensitivity of the results to Manning's n, as discussed below. We had hoped to measure velocity and stage during a peak flow, but we were unable to be at the field site during high flows. We also assumed that logs moved during the annual peak discharge, although it is possible that their initial motion occurred at a lower discharge.

In order to calculate the force acting on a given log, the data for each log used in the equations in Sections 3.1–3.3 were exported from our database to an Excel spreadsheet. Data from the channel surveys were added to the spreadsheet, including depth and velocity calculated at bankfull discharge for each cross section. The logs were then divided by their appropriate model (e.g., in-channel versus suspended from one bank) and the overall force balance on the log was calculated. The results from these calculations are given below.

A summary of predicted and actual movement for each log location is shown in Table 5. In general, the model was relatively successful at predicting movement, particularly for in-channel logs. Tables 5–8 show the overall force acting on the logs at bankfull flow for each modeled log location. We have also included information on log length and diameter because many studies have examined log transport in terms of piece length and diameter. The force was calculated by subtracting the right-hand side of Equation 12 from the left-hand side (setting the Equation equal to zero as in Equation 10). The model predicts that the piece will remain in place if the force is greater than zero, and be transported if the force is less than zero. Because log movement was a function of log position we have examined each position separately.

Table 5. Model predictions of in-channel logs examined during this experiment.

Log Number	Position	Species	L_{log}/w_{bf}	D_{log}/d_{bf}	Force (kgm/s^2)	Predicted to move?	Did it move?
3	in-channel	redwood	0.4	0.4	-2387	yes	yes
6	in-channel	Douglas-fir	0.6	0.8	-9488	yes	yes
16	in-channel	alder	0.1	0.2	-1105	yes	yes
17	in-channel	alder	0.1	0.3	-891	yes	yes
18	in-channel	alder	0.1	0.3	-1067	yes	yes
19	in-channel	alder	0.2	0.3	-1857	yes	yes
21	in-channel	redwood	1.2	1.1	-6645	yes	yes
26	in-channel	redwood	0.5	1.2	-11448	yes	yes
29	in-channel	alder	0.3	0.3	-973	yes	yes
33	in-channel	alder	0.3	0.4	-1998	yes	no
34	in-channel	alder	0.2	0.5	-1687	yes	no
37	in-channel	redwood	2.6	1.9	-4006	yes	yes
38	in-channel	alder	0.6	2.0	-1440	yes	yes
39	in-channel	alder	0.5	0.3	-2661	yes	yes
40	in-channel	alder	0.1	0.4	-756	yes	yes
41	in-channel	alder	0.2	0.3	-1536	yes	yes
8	in-channel (elevated)	Douglas-fir	0.2	1.1	-1212	yes	yes
11	in-channel (elevated)	alder	0.8	0.6	-3914	yes	yes

Our model predicted that all in-channel logs would move regardless of whether or not they had a rootwad (Tables 5 and 6). Of the 18 in-channel logs without rootwads, 16 moved, and all three of the logs with rootwads moved as predicted. The largest in-channel log, Log 37, (with a value of log length divided by bankfull width [L_{log}/w_{bf}] = 2.6) moved downstream approximately 20 m. The two in-channel logs that were predicted to move but remained in place (Logs 33 and 34) were next to each other and part of a small jam. One of these logs (Log 34) was submerged and partially buried by sediment during our resurveys. If we revise the model prediction for this log by assuming its density is greater than that of water (which would occur if it was submerged and became waterlogged), the model predicts that the log would remain in place.

Table 6. Model predictions of in-channel logs with rootwads examined during this experiment.

Log number	Position	Species	L_{log}/w_{bf}	D_{log}/d_{bf}	Force (kgm/s^2)	Predicted to move?	Did it move?
4	rootwad	redwood	0.4	1.0	-2114	yes	yes
28	rootwad	alder	1.4	0.5	-1365	yes	yes
7	rootwad	alder	0.3	0.6	-280	yes	yes

While the in-channel model did a good job of predicting movement, the model for logs with one end suspended out of the channel was not as successful. This is partially because conditions on the bank are much more complex than conditions in the channel and a simplified model might not replicate bank conditions as well as in-channel conditions. Also, slight deviations in the velocity, channel bed slope, or coefficient of friction from the average values used in the model could alter the model predictions. Equation 12 predicted that eight logs would move when flow reached bankfull stage. Six of these logs did move, and two logs moved that were predicted to remain in place (Table 7).

Log 24 remained in place when Equation 12 predicted it would move. This log was lodged against the opposite bank and was partially buried by sediment, so the force balance equations do not accurately represent actual conditions in the stream. Two logs (Logs 31 and 45) moved that were predicted to remain in place. Both logs rotated about 20 cm downstream despite the model's prediction that they would not move. Our model, however, does not take rotation into account. These logs were nearly parallel to flow, and more of the log could have been in the flow than we expected.

Table 7. Model predictions of logs suspended from one bank examined during this experiment.

Log Number	Position	Species	L_{log}/w_{bf}	D_{log}/d_{bf}	Force (kgm/s^2)	Predicted to move?	Did it move?
1	suspended from one bank	redwood	2.5	0.4	895	no	no
2	suspended from one bank	redwood	1.9	0.7	609	no	no
5	suspended from one bank	Douglas-fir	1.7	1.1	3349	no	no
10	suspended from one bank	alder	1.7	0.9	225	no	no
13	suspended from one bank	redwood	1.3	0.8	1311	no	no
14	suspended from one bank	redwood	0.3	1.4	-2944	yes	yes
20	suspended from one bank	redwood	1.8	1.1	2900	no	no
22	suspended from one bank	redwood	2.0	0.7	-836	yes	yes
23	suspended from one bank	redwood	1.1	0.4	-115	yes	yes
24	suspended from one bank	alder	1.3	0.3	-180	yes	no
27	suspended from one bank	redwood	1.4	1.0	279	no	yes
30	suspended from one bank	redwood	2.1	2.0	7100	no	no
31	suspended from one bank	alder	0.9	0.9	-2	yes	yes
32	suspended from one bank	redwood	1.3	1.6	949	no	no
35	suspended from one bank	redwood	3.4	0.4	1530	no	no
36	suspended from one bank	redwood	2.2	0.7	-969	yes	no
42	suspended from one bank	redwood	2.3	0.8	3417	no	no
43	suspended from one bank	redwood	0.7	0.7	-296	yes	yes
44	suspended from one bank	Douglas-fir	1.5	0.7	1164	no	no
45	suspended from one bank	Douglas-fir	1.6	0.5	1345	no	yes
46	suspended from one bank	redwood	1.5	1.1	1733	no	no
25	suspended from one bank	Alder	1.7	0.5	-1442	yes	yes

Table 8 shows the force acting on logs suspended over the channel. Movement was not predicted for any of these logs, because they were suspended above the bankfull channel, and therefore they were just above the water surface during the peak discharge. One of the logs did move, however, presumably because it broke in half.

Table 8. Model predictions of suspended logs examined during this experiment.

Log Number	Position	Species	L_{log}/w_{bf}	D_{log}/d_{bf}	Force (kgm/s^2)	Predicted to move?	Did it move?
9	suspended	redwood	1.5	2.8	3922	no	no
12	suspended	Douglas-fir	1.3	0.4	1279	no	yes*
15	suspended	redwood	2.5	0.7	6861	no	no

*log broke in half, allowing it to move

We did a sensitivity analysis of the model results to changes in Manning's roughness coefficient (n), which was selected as 0.08. Decreasing n will increase velocity and the drag force, making piece movement more likely, while increasing n will make piece movement less likely. The force balance was recalculated for Manning's n equal to 0.05 and 0.10. For n equal to 0.05, the model predictions were the same, except for Log 32 which was not predicted to move when n was equal to 0.08, but was predicted to move when n was equal to 0.05. Similarly, changing n to 0.10 did not change the stability predictions described above, except for Log 31 which was predicted to move for when n was equal to 0.08, but was not predicted to move when n was equal to 0.10. As stated above, Log 31 was very close to the movement threshold when n was equal to 0.08, and slight deviations in channel morphology or slope could account for its observed stability. We therefore believe that a Manning's n of 0.08 is an appropriate assumption for our study reach.

6. Discussion and management recommendations

In-channel logs would be expected to move at bankfull flows if the log diameter is less than bankfull depth, because the buoyant forces would be sufficient to cause flotation. If one end of the log is outside of the channel, the buoyant force is decreased and log stability increases relative to logs entirely in the bankfull channel. Previous studies have found that logs longer than bankfull width (which tend to be at least partially outside of the bankfull channel) tend to remain in place while logs shorter than bankfull width tend to be mobile (Nakamura and Swanson 1994, Lienkaemper and Swanson 1987). We were therefore surprised by the amount of movement that we saw in this study. Much of this movement can be attributed to the recent placement of the logs in the stream. This is partially because WY 2002 had the highest peak discharge since the logs were placed, and they had not adjusted themselves to be stable at that discharge.

There are several factors that affect log stability that were not examined in the models or in this study. In particular, riparian vegetation, boulders, and other logs can help to stabilize wood preventing it from moving downstream. While these factors are not accounted for in our modeled predictions, they are undoubtedly important and should be considered when log stability is being assessed. In addition, this model and other models developed by Braudrick and Grant (2000) assumed that the bed was static, when in fact the bed likely moves before many of the logs. Movement of the bed may cause logs to destabilize and may be a very important component of LWD dynamics.

While almost half of our tagged pieces moved, very few of the pieces moved substantial distances downstream. It is clear that understanding the likelihood of wood deposition given log and channel characteristics is as important as knowing the thresholds for movement. Many researchers have examined the distances logs travel based on channel characteristics (e.g., Abbe and Montgomery 1996, Braudrick and Grant 2001, Nakamura and Swanson 1994, and Haga et al. 2002). The area of Caspar Creek where LWD has been added would be a perfect place to test these models of wood movement.

While these studies show that the model for logs with part of their length suspended outside of the channel has promise, flume experiments and further field studies are necessary to validate the model. Flume experiments would allow us to test the model more fully for a variety of channel configurations, log sizes, and hydrographs. Flumes have been used successfully in attempts to describe wood dynamics (Braudrick and Grant 2001, Braudrick and Grant 2000, and Braudrick et al. 1997) and to examine scour from logs (Beschta 1983), and would be an appropriate tool to further examine the models developed as part of this project. In addition, since discharge was relatively low during WY 2002, we cannot assess the success of models at higher flows. Tracking movement of these logs in the future would provide more data on the stability of logs under even higher discharges.

Based on the results of this study, we have learned several things about log movement in general and about Caspar Creek, specifically that have implications for how LWD is managed in streams.

- While many logs moved, most logs did not move very far, indicating that understanding the controls on deposition of moving logs may be as important as understanding mobility thresholds.
- Because in-channel logs move more readily than logs with part of their length outside of the channel, we recommend that any logs added to the stream have part of their length outside of the bankfull channel, particularly if piece stability is one of the goals of the study.
- Our results indicate that piece length does not affect mobility thresholds of logs entirely in the bankfull channel. Piece length may affect the distance transported, however, but distance transported was not investigated during this study.
- Rotation thresholds, rather than sliding thresholds, may be more important for logs with one end outside of the bankfull channel.

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Appendix A: Step-by-step example of application of the wood transport model

In order to describe the application of the model, the following section gives a step-by-step example of the measured and calculated input parameters used in the modeling. The equations used in this appendix are taken from the main report and a full description of their parameters. For this example, we will examine logs 20 and 22 (shown in figures A-1 and A-2, respectively). Both logs were suspended from one bank, and were located in the same reach. The force balance on these logs is given by equation 12 in the main document and is shown below in equation A1:

$$\left(g\rho_{log}L_{log}\frac{\pi D_{log}{}^{2}}{4}-g\rho_{w}V_{sub}\right)(\mu_{bed}\cos\alpha-\sin\alpha)=\frac{U^{2}}{2}\rho_{w}C_{d}\left(A_{sub1}\sin\theta+A_{sub2}\cos\theta\right) \tag{A1}$$

where all variables are as defined in the main report and tables A-1 and A-2. Equation A1 can be rewritten as:

$$F_{friction}-F_{gravity}-F_{drag}=0 \tag{A2}$$

or:

$$\left(g\rho_{log}L_{log}\frac{\pi D_{log}{}^{2}}{4}-g\rho_{w}V_{sub}\right)(\mu_{bed}\cos\alpha-\sin\alpha)-\frac{U^{2}}{2}\rho_{w}C_{d}\left(A_{sub1}\sin\theta+A_{sub2}\cos\theta\right)=0 \tag{A3}$$

The initiation of motion would occur when equation A3 is equal to zero. The log will move if the left-hand side of equation A3 is less than zero, and remain in place if the left-hand side is greater than zero.

Table A-1 shows the log characteristics as measured in the field.

Table A-1. Parameters used in the model for logs 20 and 22.

Parameter	Symbol	Log 20	Log 22
piece length (m)	L_{log}	16.8	19
length inside bankfull channel (m)	L_{bank}	8.75	12.9
mean diameter (m)	D_{log}	0.527	0.343
log radius (m)	r	0.26	0.17
flow orientation (degrees)	–	216	222
log orientation (degrees)	–	306	104
orientation relative to flow (degrees)	–	-90	118
orientation relative to flow (radians)	θ	-1.57	2.06
species	–	Redwood	Redwood
decay code	–	1	1
wood density (kg/m^3)	ρ_{log}	449	449
water density (kg/m^3)	ρ_w	1000	1000
gravitational acceleration (m/s^2)	g	9.81	9.81
Cross section	-	7	7
slope	α	0.0050	0.0050
Coefficient of friction	μ_{bed}	0.4	0.4
Drag coefficient	C_d	2.1	2.1
Bank height (m)	h_{bank}	1.08	0.61
Manning's roughness coefficient	n	0.08	0.08
Average flow depth* (m)	d_w*	0.51	0.62
Hydraulic radius* (m)	–	0.48	0.48
velocity* (m/s)	U	0.55	0.55

*at bankfull discharge

Both logs were located in the reach described by cross section 7 (Figure A-3). The bank height for both logs was determined in the field, and differs because log 22 was suspended from a notch in the left bank rather than from the top of the bank. Bankfull indicators were evaluated in the field, and because the cross section was somewhat incised, do not correspond to the bank height shown on the cross section.

Bankfull velocity and discharge were calculated using Manning's equation.

There are three unknowns in equation A3, V_{sub}, A_{sub1}, and A_{sub2}.

Because for log 20 $d_{av} < D_{log}$, we will use equations (15), (21), and (23) from the main report to calculate V_{sub}, A_{sub1}, and A_{sub2}, respectively. V_{sub} is equal to:

$$V_{sub} = \frac{2}{3\tan\gamma}\left[r^2 - (d_w - r)^2\right]^{\frac{3}{2}} + r^2\left(\frac{d_w - r}{\tan\gamma}\right)\left(\sin^{-1}\left(\frac{d_w - r}{r}\right) + \frac{\pi}{2}\right)$$

$$+\frac{1}{2}r^2\left(\frac{d_w - r}{\mathrm{Tan}(\gamma)}\right)\mathrm{Sin}\left(2\mathrm{Sin}^{-1}\left(\frac{(d_w - r)}{r}\right)\right) \qquad \text{(A4)}$$

where all variables are as defined in the main report.

Similarly, because the log diameter is greater than the depth, A_{sub1} and A_{sub2} are equal to:

$$A_{sub1} = \frac{d_w^{\,2} - 2d_w r}{2\tan\gamma} + \frac{d_w - r}{\tan\gamma}(d_w - 2r) \tag{A5}$$

and

$$A_{sub2} = \left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right) - \sin\left(2\cos^{-1}\left(1 - \frac{2d_w}{D_{log}}\right)\right)\right)\frac{D_{log}^{\,2}}{8} \tag{A6}$$

For log 22, the depth is greater than the log diameter, so V_{sub}, A_{sub1}, and A_{sub2} are equal to:

$$V_{sub} = \frac{b\pi D_{log}^2}{4} = \frac{\pi D_{log}^2(d_w - r)}{4\tan\gamma} \tag{A7}$$

$$A_{sub1} = D_{log} b = \frac{D_{log}(d_w - r)}{\tan\gamma} \tag{A8}$$

$$A_{sub2} = \frac{\pi D_{log}^{\,2}}{4} \tag{A9}$$

In equations A4 and A5 γ is equal to:

$$\gamma = \sin^{-1}\left(\frac{h_{bank}}{L_{bank}}\right) \tag{A10}$$

where h_{bank} is the height of the bank the log is perched from and L_{bank} is the length of the log inside the bankfull channel (Figure 5). Finally, b is equal to:

$$b = \frac{d_w - r}{\tan(\gamma)} \tag{A11}$$

Table A-2 shows the values of γ, $V_{sub,}$ A_{sub1}, and A_{sub2} for logs 20 and 22. These values were calculated by substituting data from Table A-1 into equations A4–A10.

Table A-2. Calculated parameters used in equation A3

Parameter	Log 20	Log 22
γ (radians)	0.1237	0.0474
V_{sub} (m^3)	0.426	0.877
A_{sub1} (m^2)	0.070	3.253
A_{sub2} (m^2)	0.216	0.0926

We can now calculate the overall force acting on each of the logs during a bankfull event by plugging the values from Tables A-1 and A-2 into equation A3. The resulting force acting on logs 20 and 22 during bankfull flow would be 2900 Newtons and -836 Newtons, respectively. The model would therefore predict that log 20 would remain in place and log 22 would move. In these cases, the model accurately predicted log stability.

Appendix B: list of variables

Variable	Description
A_1	the submerged area of the bole, A_2 is, perpendicular to piece length
A_2	the submerged area of the rootwad
A_3	the submerged area of the rootwad perpendicular to piece length
A_{sub1}	the submerged area of the log parallel to piece length
A_{sub2}	the submerged area of the log perpendicular to piece length
A_{sub}	submerged area of the log perpendicular to piece length for logs entirely in the channel
b	see equations 16 and 17
C_d	drag coefficient
d_{av}	average depth
d_{bf}	bankfull depth
d_w	water depth
D_{log}	log diameter
g	gravitational acceleration
h_{bank}	bank height
L_{log}	piece length
L_{bank}	length inside bankfull channel
m	see equation 19
n	Manning's roughness coefficient
r	log radius
U	velocity
V_1	the submerged volume of bole
V_2	the submerged volume of the rootwad
V_{rw}	the volume of the rootwad
V_{sub}	submerged log volume for a log with one end outside the bankfull channel
w_{bf}	bankfull width
x	x coordinate
y	y coordinate
z	z coordinate
α	slope
γ	gamma (see equation 16)
γ_{rw}	gamma for logs with rootwads (see equation 5)
μ_{bed}	coefficient of friction
ρ_{log}	wood density (kg/m^3)
ρ_w	water density (kg/m^3)
θ	orientation relative to flow (radians)