Modeling inputs of large woody debris to streams from falling trees

JOHN VAN SICKLE and STANLEY V. GREGORY

Department of Fisheries and Wildlife, Oregon State University, Corvallis, OR 97333, U.S.A.

Received November 9, 1989
Accepted April 25, 1990


A probabilistic model predicts means and variances of the total number and volume of large woody debris pieces falling into a reach per unit time. The estimates of debris input are based on the density (trees/area), tree size, and location, total input rates, as well as frequency distributions of piece size and orientation in the channel. Model predictions are compared with data from an old-growth coniferous stand for which LWD delivery rates and standing stocks have been independently estimated. In addition, we use the model to explore the relationship between LWD loading and the width of riparian management zones left uncut during timber harvests.

Introduction

Large woody debris (LWD) in streams helps to structure fish habitat (Bisson et al. 1987), trap sediment (Swanson and Lienkaemer 1978), and shape channels (Swanson et al. 1976). In recent years, data on the amounts, sizes, and locations of LWD (pieces >0.1 m diameter and >1.5 m long) in stream channels have accumulated rapidly and have been related to stream and adjacent forest stand characteristics (Harmon et al. 1986). However, it is extremely difficult to estimate rates of LWD delivery to channels from this in situ data; the observed LWD in a channel usually has accumulated over centuries from highly episodic and infrequent delivery events. Decay and transport of LWD further obscure the relationship between in situ LWD and the rates and processes of its delivery. Monitoring of input events has yielded some rate estimates (Lienkaemer and Swanson 1987), but the short time span (<15 years) and spatial limitations of these studies do not give a reliable quantitative picture of LWD delivery.

Effective management of riparian forests requires accurate estimates of current and future LWD input rates that result from various silvicultural strategies in riparian zones. Recognizing this need, Rainville et al. (1985) produced probabilistic estimates of the number of trees per decade falling into stream channels for three western coniferous habitat types. When coupled with a dynamic model of stand growth and management, their model provides long-term projections of LWD loading into streams. Robison and Beschta (1990) and McDade et al. (1990) have employed assumptions similar to those of Rainville et al. (1985) to compute the probability that falling trees of a given height and distance from the stream land in the channel.

We present a generalized model for estimating the amount of LWD delivered to streams from stands of mixed tree heights and species composition. The model allows for stand density and tree-fall probability to vary with distance from the stream bank and for nonrandom directions of tree fall. Model equations are derived from probability theory and geometry and include estimates of means and variances of total input rates, as well as frequency distributions of piece size and orientation in the channel. Model predictions are compared with data from an old-growth coniferous stand for which LWD delivery rates and standing stocks have been independently estimated. In addition, we use the model to explore the relationship between LWD loading and the width of riparian management zones left uncut during timber harvests.

Background and assumptions

Sources of LWD

The wood model assumes that LWD inputs consist of whole trees falling into the stream channel from an adjacent hillside or floodplain. LWD that has been transported into a reach from upstream is not included here. In addition to trees falling near the stream, LWD may be delivered from branches or crowns broken off standing trees (Harmon et al. 1986), but this source also is not included here.
A survey of LWD in 39 first- to third-order channels in Pacific Northwest coniferous forests showed that logs were more numerous than branches and tree tops; these logs constituted more than 70% of the total wood volume (McDade 1987)

From this survey, McDade et al. (1990) report that 33 to 52% of surveyed LWD pieces in streams had moved downslope from their point of origin median distances of 4.6 to 7 m, depending on slope steepness. However, more than 70% of those pieces originated at distances from the channel that were less than one-half the stand height (McDade et al. 1990). This suggests that while sliding or rolling can result in significant downslope movement of logs, it may not deliver a substantial number of new pieces to the channel that otherwise would not reach the channel as they fell. Thus, we did not include the complex process of downslope movement in the model.

Finally, deliveries of LWD by debris torrents and avalanches are beyond the scope of this model because of their extreme unpredictability in size and time of occurrence.

Riparian forest stands
In the model, total LWD inputs over a time period \( t_i, t_{i+1} \) are estimated from the stand density (trees/area) and height and species distributions of trees near the stream, measured at time \( t_i \). Thus, the model can project long-term debris inputs when coupled with any dynamic stand growth model that projects these stand variables at times \( t_i, i = 1, 2, \ldots \)

In addition to time variation, riparian stand density \( D \) is assumed to vary with respect to tree species, tree height \( h \), and distance \( z \) from the channel (Fig. 1). Apart from these modes of variation, density is assumed constant and trees are distributed uniformly in the stand.

Probability of tree fall
We defined \( P_F \) to be the probability of one tree falling during the time interval \( t_i, t_{i+1} \). In the model, \( P_F \) is allowed to vary with tree species, height, and distance from the channel; for example, bank cutting will lead to higher \( P_F \) values within the first few meters adjacent to mobile channels.

Most LWD from trees adjacent to a channel reach is probably delivered to that reach when live trees are felled by windthrow, bank cutting, or flooding. For example, high wind events are a major contributor of LWD to streams in Pacific Northwest forests (Lienkaemper and Swanson 1987; Franklin et al. 1987). In particular, windthrow is the primary cause of failure in riparian buffer strips left after timber harvest (Steinblums et al. 1984).

If long-term records exist, frequency analyses of wind or flood events can be combined with estimates of riparian trees' resistance to disturbance to estimate \( P_F \). Correlations between observed rates of riparian blowdown and characteristics of the stand and site (Steinblums et al. 1984; Andrus and Froelich 1990) provide one approach to estimating riparian-stand resistance.

Riparian trees are subject to catastrophic mortalities related to other agents such as fire or insect pest outbreaks, as well as continuous, low-level mortality from competition (Harmon et al. 1986; Franklin et al. 1987). In these cases, however, dead trees are often left standing, and LWD input to streams occurs after some period of decay (Harmon et al. 1986), thus complicating estimation of \( P_F \).

Very few direct estimates of LWD inputs to streams have been made, and estimates of tree-fall rates are equally rare. Instead, nearly all LWD production rates in forests have been determined by equating LWD inputs of both standing and fallen trees to total observed tree mortality (Harmon et al. 1986). Until field studies begin to focus on riparian tree fall in addition to tree death, stand mortality rates will have to serve as crude approximations of \( P_F \) or of any other measure of LWD production rate suitable for streams.

Direction of tree fall
A probabilistic model for the direction of tree fall is specified by defining \( f(a) \) as the probability density function (pdf) for the angle \( a \) of fall, with \( a = 0^\circ \) pointing upstream (Fig. 1). Thus

\[
\int_c^d f(a) \, da = P[\text{fall within the arc } (c, d)]
\]

and

\[
\int_0^{360} f(a) \, da = 1
\]

Future studies may yield a theoretical \( f(a) \) based on detailed mechanisms of tree fall; here, we suggest two density functions that adequately describe the simplest expected patterns of tree fall.

The uniform distribution (\( f(a) = 1/360, 0^\circ < a < 360^\circ \)) models a completely random direction of tree fall. Random fall would be expected in flat or gently sloped riparian forests where trees do not lean strongly toward the channel and mortality agents such as windthrow do not have a preferred direction.

Often, however, trees immediately adjacent to the stream will tend to fall towards the channel because of bank undercutting or a greater development of branches on the more open, stream-facing canopy. On steep slopes, rooting asymmetry and downslope tree lean may result in towards-channel falling. Defining \( f(a) \) as a normal distribution with a mean of 90° gives a convenient model for tree fall towards the channel. If, for example, the standard deviation is 15°, then 95% of trees are assumed to fall within the arc of 60° to 120°. A normal \( f(a) \) with a larger standard deviation describes cases between the extremes of channel-directed and random tree fall, but in this case \( f(a) \) may need to be trun-
cated and renormalized to satisfy
\[ \int_0^{360} f(a) \, da = 1 \]

A normal distribution with a different mean could apply when hillslope gradient and (or) prevailing strong wind conditions favor falling directions not perpendicular to the channel.

**Model structure and derivations**

**Riparian zones**

The model riparian zone is assumed to have length \( L \) and to border a stream reach of fixed bankfull channel width \( W \) (Fig. 1; Table 1 summarizes important model variables). For computational purposes, the riparian stand is partitioned into discrete tree height classes and discrete intervals of distance to the channel. Each distance interval \((z_{k-1}, z_k]\) marks off a strip of width \( \Delta z_k = z_k - z_{k-1} \) and length \( L \), parallel to the stream (Fig. 1). Stand densities and fall probabilities are allowed to vary among species, distance intervals, and height classes. The model zone is assumed to extend away from the stream only to a distance \( z_N \), which is equal to the height of the tallest trees in the stand. The zone length \( L \) is arbitrary; however, all stand characteristics in the zone are assumed to be constant within each species, distance interval, and height class.

Total LWD input is the sum of contributions from all distance classes, height classes, and species in the zone. Different stands can be specified for the left and right sides of the channel, or one can assume that the stand is identical on both sides and double the inputs from the single-sided zone to get total inputs.

LWD input from one tree is assumed to be that segment of the tree bole \((b_1, b_2)\) that intersects the channel boundaries (Fig. 1). At present we assume that the bole does not break when it falls, although this process may well influence LWD size distributions. However, the commonly observed breakage of tree crowns is implicitly modeled by defining \( h \) as the effective height of a tree, which may exclude the uppermost few meters of its bole (Robison and Beschta 1990).

The basic tree-fall geometry of Fig. 1 is not altered on steep slopes, since \( z \) is defined as the distance directly downslope to the channel. However, trees falling across V-notched channels often bridge the stream above the active channel, providing LWD input only after the bridging bole breaks and falls into the stream. Since the present model makes no explicit provision for slope steepness, it treats the segment suspended directly above and between the stream banks as an input.

**LWD inputs: number of trees**

The number of trees falling into the stream during \((t_i, t_{i+1})\) from an arbitrary class \((\text{species} \times \text{height} \times \text{distance})\) is estimated from the stand density \( D \), fall probability \( P_F \), and fall direction pdf, \( f(a) \), for that class at time \( t_i \). Along one side of the channel, the number of standing trees in the class is given by \( N = D \Delta z \), with \( N \) rounded off to the nearest integer.

If trees fall independently of one another, then the number of falling trees \((N_F)\) during the period is a binomial random variable with theoretical mean and variance (denoted by \( E(\ ) \) and \( \text{var}(\ ) \), respectively) given by

\[ E(N F) = N P F = D \Delta z L P F \]

\[ \text{var}(N F) = N P F (1 - P F) \]

Next, let \( P_S \) be the probability that a falling tree will land in the stream, in the sense of intersecting a stream bank. We assume that the tree bole does not break, so the full effective tree height \( h \) is available to enter the stream. An entry occurs if the tree falls at any angle within the circular arc \((a_S, 180 - a_S)\), where \( a_S = \sin^{-1}(z/h) \) (Fig. 1). The probability of entering the channel is then

\[ P_S = \int_{a_S}^{180 - a_S} f(a) \, da \]

For example, in the case of random fall direction, the above integration yields (cf. Robison and Beschta 1990; McDade et al. 1990)

\[ P_S = \cos^{-1}(z/h)/180 \]

The probability of one tree falling and then entering the channel is \( P_F P_S \). Thus, for the whole class, the number input \((N_i)\) during \((t_i, t_{i+1})\) is also binomially distributed, again assuming independence. Its mean and variance are

\[ E(N_i) = N P_F P_S \]

\[ \text{var}(N_i) = N P_F P_S (1 - P_F P_S) \]

**LWD inputs: wood volume and piece length**

Volume inputs are estimated by determining the wood volume of tree bole segments that enter the stream. For a tree falling at angle \( a \), the bole segment that intersects the channel (Fig. 1) is defined by \( b_1 = z \sin(a) \) and \( b_2 = (z + W)/\sin(a) \). If the bole is too short to span the channel, then \( b_2 = h \). The length of the segment in the stream is \( b_2 - b_1 \).

For simplicity, tree boles are assumed to be conical in shape. Diameter at breast height (dbh) and tree height \( h \) are

---

**Table 1. Notation and definitions of selected model variables**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>Angle of tree fall, relative to channel axis (Fig. 1)</td>
</tr>
<tr>
<td>( a_S )</td>
<td>Angle of fall at which tree top contacts nearest channel boundary (Fig. 1)</td>
</tr>
<tr>
<td>( D )</td>
<td>Riparian stand density (trees/area)</td>
</tr>
<tr>
<td>( f(a) )</td>
<td>Probability density of tree-fall angles</td>
</tr>
<tr>
<td>( h )</td>
<td>Effective tree height (Fig. 1)</td>
</tr>
<tr>
<td>( L )</td>
<td>Length of stream reach and model riparian zone</td>
</tr>
<tr>
<td>( N )</td>
<td>Number of standing trees in one (species ( \times ) height ( \times ) distance) class at time ( t_i )</td>
</tr>
<tr>
<td>( N_F )</td>
<td>Number of trees (out of ( N ) ) falling during ((t_i, t_{i+1}))</td>
</tr>
<tr>
<td>( N_L )</td>
<td>Number of falling trees (out of ( N_F ) ) delivered to stream</td>
</tr>
<tr>
<td>( N_T )</td>
<td>Total number of trees from all (species ( \times ) height ( \times ) distance) classes in model zone delivered to stream during ((t_i, t_{i+1}))</td>
</tr>
<tr>
<td>( P_F )</td>
<td>Probability of a given tree falling during ((t_i, t_{i+1}))</td>
</tr>
<tr>
<td>( P_S )</td>
<td>Probability of a falling tree being delivered to stream</td>
</tr>
<tr>
<td>( V )</td>
<td>Volume of that segment of a fallen bole that is in the stream (Fig. 1)</td>
</tr>
<tr>
<td>( V_I )</td>
<td>Total volume of bole segments delivered to stream from one (species ( \times ) height ( \times ) distance) class during ((t_i, t_{i+1}))</td>
</tr>
<tr>
<td>( z )</td>
<td>Perpendicular, downslope distance from standing tree to nearest channel boundary (Fig. 1)</td>
</tr>
</tbody>
</table>

---

[1] \( E(N_F) = NP_F = D \Delta z L P_F \)

[2] \( P_S = \int_{a_S}^{180 - a_S} f(a) \, da \)

[3] \( P_S = \cos^{-1}(z/h)/180 \)

[4] \( E(N_i) = NP_F P_S \)

[5] \( \text{var}(N_i) = NP_F P_S (1 - P_F P_S) \)
related by the species-specific regressions of Dale et al. (1986). Diameters of the tree segment at \( b_1 \) and \( b_2 \) are calculated from dbh and \( h \) by a similar-triangle argument, and the volume \( V \) of the bole segment \( (b_1, b_2) \) is the difference between the conical volume above \( b_1 \) and the conical volume above \( b_2 \).

With \( h \) and \( z \) held constant, \( V \) is a random variable, depending on the angle at which the tree falls. The mean and variance of \( V \) are

\[
E(V) = \int_{a_0}^{180-a_0} V(a)f(a) \, da
\]

\[
\text{var}(V) = E(V^2) - E^2(V)
\]

Now define \( V_1 \) to be the total volume input for all of the \( N_F \) falling trees in one class (species \( \times \) height \( \times \) distance). Then \( V_1 \) is the sum of a random number \( N_F \) of independent, random \( V \) values, and its mean and variance are given by standard formulae (Rice 1988).

\[
E(V_1) = E(N_F) \cdot E(V)
\]

\[
\text{var}(V_1) = [E^2(V) \cdot \text{var}(N_F)] + [E(N_F) \cdot \text{var}(V)]
\]

**Total LWD inputs**

Means and variances of \( N_F, N_I, \) and \( V_I \) are summed over all classes to give the mean and variance of total number and volume inputs from the entire model riparian zone. The summing of variances to yield a total variance assumes independence among all classes.

In particular, the total number of trees \( (N_T) \) input to the stream from the model zone has the mean value

\[
E(N_T) = (DLP_Fh)
\]

where the sum extends across all classes (species \( \times \) height \( \times \) distance) in the zone. Equation 7 with \( P_S \) replaced by \( E(V) \) gives mean total volume input.

**Distributions of piece size and orientation**

Based on eqs. 2 and 4, trees in a class (species \( \times \) height \( \times \) distance) that fall in the angle interval \((a, a + \Delta a)\) and enter the stream make a relative contribution \( (C) \) to the expected total number, where \( C = N_F P_F f(a) \Delta a \). This contribution is associated with LWD pieces having length \( b_2 - b_1 \), volume \( V(a) \), and orientation in the range \((a, a + \Delta a)\). Values of \( C \) are set to \( 0 \) for contributions that do not exceed the minimum diameter and length for LWD. Sums of \( C \) values across all classes and angle intervals, for fixed intervals of piece length and volume, give predicted frequency distributions for these variables. Similarly, a predicted distribution of piece orientations is determined by summing \( C \) values across all classes for each angle interval \((a, a + \Delta a)\).

**Spatial aggregation of inputs**

The large spatial variation in tree mortality between riparian stands (Harmon et al. 1986) suggests that LWD inputs from a single model riparian zone will not be representative at larger scales. However, the means and variances (assuming independence) of number and volume can be summed over any number of adjacent riparian zones along a stream to estimate total LWD inputs for a channel network. As inputs from an increasing number of adjacent zones are aggregated, the estimate of total number input becomes relatively more accurate in the sense that its coefficient of variation (CV) decreases. This result holds true regardless of heterogeneity among riparian stands along the stream network.

To see this, notice from eq. 4 that for any class in a model riparian zone, \( \text{var}(N_I) = E(N_I)(1 - P_F P_S) < E(N_I) \). Let \( N_X \) be the total number input from several adjacent riparian zones, so that \( N_X = \sum N_I \), where the sum extends over the set of adjacent zones and all classes within each zone. The inequality stated above implies that the coefficient of variation for \( N_X \) satisfies

\[
\text{CV} = \frac{\text{var}(N_X)}{E(N_X)} = \sqrt{\sum \text{var}(N_I)/E(N_I)} \leq 1/\sqrt{E(N_X)}
\]

In short, as \( E(N_T) \) increases because of spatial aggregation, CV decreases and a greater relative accuracy is achieved for estimates of \( N_X \).

**LWD inputs vs. stand characteristics and channel size**

The general relationship between riparian stand parameters and input rate is revealed by considering a model riparian zone in which all trees are of fixed height \( h \) and fall directly towards the channel. In this case, eq. 7 reduces to \( E(N_T) = (DLP_F h) \) (Appendix). That is, the mean total number of trees delivered to the channel is directly proportional to stand density, fall probability, and tree height. For example, an increase of 5% in any one of these stand parameters will produce a 5% increase in \( E(N_T) \). Similar effects will be seen in stands of mixed species, densities, and tree heights. The value of \( E(N_T) \) for a stand with random tree-fall direction is about one-third of the value predicted if trees instead fall directly towards the channel (Appendix).

The effect of channel width on LWD inputs helps explain some patterns that have been observed in field surveys of in situ LWD. Assuming constant riparian stand characteristics, our model predicts that total volume input, per unit area of the channel, decreases as \( W \) increases; for streams wider than one tree height, the total input from riparian trees remains constant as \( W \) increases, giving a hyperbolic decline in input per unit area. This pattern is consistent with the decrease of in situ LWD with increasing \( W \) that is noted by Harmon et al. (1986) in their survey of 83 channel reaches throughout North America. However, Harmon et al. (1986) point out that much of the decrease in resident LWD with increasing \( W \) is also due to the ability of larger streams to transport LWD downstream.

The relative importance of transport and input in determining amounts of in situ LWD may be clarified by considering LWD amounts per unit channel length, rather than area. For example, Bilby and Ward (1989) found an approximately exponential decline in resident LWD pieces, per unit length, with increasing \( W \) in old-growth coniferous watersheds. But our model equations show how \( E(N_T) \) is independent of \( W \); identical riparian stands along a small stream and a larger river contribute the same number of LWD pieces, per unit channel length, to both systems. Thus, the model supports Bilby and Ward’s (1989) conclusion that the decline in resident LWD was due to transport in the larger streams, rather than to changing LWD inputs.

**LWD input from an old-growth coniferous stand**

**Site description and methods**

We applied the model to data from a stand of 400- to 500-year-old Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco), western hemlock (Tsuga heterophylla (Raf.) Sarg.), and western red cedar (Thuja plicata Donn ex D. Don) trees
along a section of Mack Creek, a third-order stream (mean bankfull width = 12 m, gradient = 13%) in the H.J. Andrews Experimental Forest on the western slope of Oregon’s Cascade Mountains.

A 332-m reach of Mack Creek was mapped in 1975 to illustrate the distribution of individual logs and LWD accumulations in the channel (Lienkaemper and Swanson 1987). Since that time, inputs of new LWD pieces have been recorded annually. Beginning in 1981, the mapping was extended to include an additional 268 m of stream through the old-growth stand, in which all LWD pieces in the channel were individually tagged to monitor future movement; the dimensions and orientation of each piece were recorded. Individual pieces were assigned to one of three classes: (i) unmoved, i.e., in original fall location; (ii) moved, i.e., transported from original fall location; and (iii) unknown origin. The classification was based upon piece position relative to the channel banks and to other debris, the presence of an attached rootwad and rootwad cavity, and falling scars. For example, pieces partially on the bank in locations that preclude floating (e.g., wedged laterally between standing trees) were assigned to category 1. Category 3 pieces were excluded from further analyses.

The total density in 1979 of a 2-ha stand straddling a 100-m section of the reach described earlier was 257 trees/ha. Stem diameter maps for the three dominant species (85% of all trees) in the stand were converted to height distributions (Fig. 2); the remaining trees were nearly all western yew (*Taxus brevifolia* Nutt.) less than 10 m in height, which were assumed to make no significant LWD contribution. Assuming a conical bole, all three species have diameters below the LWD minimum diameter within the topmost approximately 5 m. Effective height distributions for use in the model were thus derived from Fig. 2 by subtracting 5 m from all heights. Stand density and tree-fall probability were assumed constant with respect to distance from the channel.

An initial estimate of $P_F = 0.017$ per decade, with a 95% confidence interval of (0.008, 0.040), was obtained by equating $P_F$ to the fractional mortality observed in the stand. Eight out of 516 trees died during the period 1979–1988; unfortunately, no records were kept of how many of these trees also fell during this period. LWD inputs were then predicted at several fall probabilities ranging from 0.017 per decade up to 0.2 per decade. Tree fall direction was assumed to be random.

**Results and discussion**

**Total number and volume of LWD pieces**

Predicted mean total number and volume of LWD inputs from both sides of the channel increased linearly with increasing tree-fall probability (Fig. 3). The large standard deviations reflect the uncertainty due to random tree-fall occurrence and direction, over the length of model riparian zone (100 m) and time period (10 years) that were assumed in the model. These standard deviations help explain the large variation observed among estimates of instream LWD volumes by Harmon *et al.* (1986, Table 6) for similar stands, each of which were based on sampling only 100–300 m of stream reach.

Observed inputs (Fig. 3) are based on the period 1976–1984; during that time, 10 trees fell into the 332-m reach, contributing 39.9 m$^3$ of LWD (Lienkaemper and Swanson 1987). The mean predicted number and the observed number coincide at a fall probability of about 0.13 per decade, which is about 7.5 times the observed mortality rate in the stand and about twice the overall mortality rate estimated.
for this type of forest (Franklin et al. 1987). For $P_F = 0.13$, the observed total input volume is greater than the predicted mean, but is still within 2 standard deviations of that mean.

If the trees along Mack Creek are assumed to fall directly downslope rather than in a random direction, then the mean predicted number delivered is increased by a factor of 3 (Appendix). Equivalently, assuming downslope falling, the mean predicted and observed numbers coincide at $P_F = 0.13/3 = 0.4$, which agrees with the upper 95% confidence limit for the observed stand mortality. Since Swanson and Lienkaemper (1987) recorded only those falling trees in the riparian zone that hit the stream, we do not have direct estimates of $P_L$ or $P_S$ for Mack Creek. However, the orientation of observed pieces in the channel (see below) suggests random, rather than downslope, falling. Differences between predicted and observed numbers and volumes highlight the episodic nature of LWD loading dynamics; two-thirds of the observed total volume input during the 9-year period was contributed by a single large tree.

**Piece orientation and size distributions**

From the 600-m reach of Mack Creek, length and volume were determined for those segments of 816 debris pieces either intersecting or suspended above the bankfull channel; 277 of these pieces were classified as unmoved. Piece orientation with respect to the channel axis was determined for 172 pieces that were anchored on at least one stream bank.

Assuming random fall direction, the theoretical pdf of piece orientations is $g(a) = \sin(a)$, for $0^\circ < a < 180^\circ$ (Appendix). This distribution was not significantly different ($p > 0.05$) from the observed distribution of unmoved pieces ($\chi^2 = 11.0$, df = 8, Fig. 4), suggesting that the model assumption of random fall direction is reasonable for the Mack Creek stand.

The model predicted a distribution of LWD piece lengths that is dominated by 15- to 20-m pieces, nearly all of which span the 15-m model channel (Fig. 5). However, 80% of all observed pieces are <5 m long. We believe that the discrepancy is due to fragmentation of tree boles, a process not yet incorporated in the model. In particular, the dominance of unmoved LWD by pieces <5 m suggests that most bole fragmentation occurred as falling trees shattered on impact.

The observed size-frequency distributions of unmoved and moved pieces are significantly different ($\chi^2 = 52.6$, df = 3, pooling all pieces >15 m). In the 0–5 m length class, moved pieces had a greater relative abundance than did unmoved pieces, and unmoved pieces were relatively more abundant in all larger size classes, reflecting the greater mobility of small LWD pieces.

As with piece lengths, the observed volumes of unmoved pieces were generally greater than volumes of moved pieces (Fig. 6); the two observed cumulative distributions are significantly different (Komolgorov-Smirnovo two-sample test). The model distribution was significantly different from the observed distribution of moved pieces, but not significantly different from the unmoved distribution (Komolgorov-Smirnov one-sample tests). The model underpredicts the contribution of small pieces and predicts a noticeably larger contribution from the 8–16 m$^3$ class than was observed; this class contains the 15–20 m pieces discussed earlier.

In summary, bole fragmentation was the likely cause of the significant discrepancies between observed and predicted LWD size distributions. Furthermore, the difference between observed and predicted total number, based on random fall direction, suggests that tree-fall probability in a
percent of total volume

Percent of input from uncut stand

Volume/piece (m³)

RMZ width (m)

Number, mixed
Volume, mixed
Number, uniform
Volume, uniform

Fig. 6. Predicted vs. observed volumes of LWD pieces in Mack Creek.

riparian stand may be considerably greater than can be inferred from mortality rates alone in nonriparian stands.

LWD inputs from riparian management zones

The LWD model provides comparisons of input rates that result from various riparian zone management strategies. For example, assume that a stand is clear-cut for $z > z_B$ so that all trees in the distance interval $(0, z_B)$ are left standing as a riparian management zone (RMZ) of width $z_B$. What is the potential LWD input from RMZs of varying widths, relative to the input from the stand prior to harvest?

We used the model to estimate these relative inputs for data from a mixed-height riparian stand along the Siuslaw River (width = 15 m) in Oregon's Coast Range. The stand consists of 41% hardwoods > 20 m tall (mostly red alder, *Alnus rubra* (Bong.) Carr., 32% hardwoods between 20 and 30 m tall, 17% conifers < 30 m tall, and 10% conifers between 30 and 65 m tall. Within these ranges, tree heights were assumed to be uniformly distributed.

We also estimated relative inputs for RMZs in a hypothetical uniform-height stand of 50-m mature conifers (cf. McDade *et al.* 1990). In all cases, we assumed that stand density was constant with respect to distance from the channel, $P_F$ was constant for all trees, and tree-fall direction was random.

For both the mixed-height and uniform stands, the relative mean wood volume delivered to the stream was greater than the relative number of pieces delivered, at any RMZ width (Fig. 7). Trees entering the channel from a short distance contribute longer pieces with greater diameters, and thus greater volume, than do trees entering from a greater distance. The relative number (volume) delivered from the mixed-height stand is greater than the relative number (volume) from the uniform stand at any $z_B$, because the mixed-height stand is dominated by trees much shorter than 50 m. This demonstrates the importance of considering stand composition and not just channel size in designing RMZs.

The distance to channel relationships between number and volume inputs and between short and tall stands (Fig. 7) are implied by the model whenever stand density and $P_F$ do not vary over $z$. A third distance relationship implied by the model is that trees far from the channel (but within one tree height) make relatively smaller number and volume contributions to streams when fall direction is random, as compared with towards-channel falling. With a random fall direction, $P_S$ decreases with increasing distance from the channel [3], but $P_S = 1$ for trees falling towards the channel from any distance less than one tree height (Appendix). In addition, with random fall direction, trees near the stream that fall almost parallel to the channel may contribute large LWD volumes. Thus, RMZ designs may need to consider the effects of slope steepness on tree-fall direction, in addition to its effects on channel shading (Steinblums *et al.* 1984).

Summary and conclusions

Our general probabilistic model estimates woody debris delivery to streams from falling trees. Since predicted inputs are aggregated with respect to the distances, heights, and species of LWD source trees, the model can be applied to heterogeneous riparian stands at spatial scales ranging from a single tree to an entire stream network. Model estimates can be made for any time interval during which stand characteristics remain relatively constant. As a result, the model
can easily be coupled to a model of stand dynamics for long-term projections of debris delivery. The model's spatial and temporal flexibility facilitate its use as a component of geographic information systems of forest resources, making it a valuable tool for forest planning.

Predicted total inputs of woody debris were similar to observed inputs in Mack Creek, within the uncertainties surrounding tree-fall probabilities in riparian stands and the random, highly variable nature of the input process. Predicted distributions of woody debris piece volume and orientation were similar to those observed for unmoved pieces in Mack Creek. However the observed and predicted distributions of piece length differed markedly, because the model lacks a function for the breakage of falling trees. A complete accounting, over time, for the amounts and size distributions of all LWD pieces in most stream channels must also include redistribution of debris due to streamflow.

The predicted relationships between RMZ width and relative LWD inputs rates demonstrate one of several potential uses for the model in riparian zone management. The model can also explore the effects of other variables in RMZ design, such as the proportion and size of trees harvested within the zone. In addition, managers may wish to compare alternative RMZ designs in field tests. Here again, the model should be useful. The model's predictions of LWD input means and variances can help determine the time horizon and total length of channel over which an RMZ design should be monitored, in order to obtain statistically sound estimates of LWD inputs against a background of high spatial and temporal variation.

The streamside management applications of the model discussed here have assumed a static riparian stand. In the future, the LWD model coupled to a stand dynamics model will give land managers a tool to explore the long-term consequences of management alternatives for patterns of woody debris inputs into streams and floodplains.

Acknowledgements

This research was supported by the Long-Term Ecological Research program of the National Science Foundation (BSR-8514325), Research Work Units 4202 and 4356 of the Pacific Northwest Research Station, USDA Forest Service, and the Coastal Oregon Productivity Enhancement Program. We thank Jim Sedell for the use of unpublished stand data and Linda Ashkenas for technical assistance. Bob Beschta, Gordon Grant, Joe Means, and two anonymous reviewers provided valuable comments on the manuscript. Finally, we thank Art Mckee, Tom Spies, Jim Sedell, and Fred Swanson for helpful discussions.


Appendix

Let z be a continuous variable, so that sums over distance classes are replaced by integrals. Assume D and Pλ are constant over z. Fall angles are in radians rather than degrees. We prove two results for fixed h.

Result 1: relative inputs from random and directed fall

If trees of height h fall directly towards the channel, then 
\[ P_S = 1 \] 
in the distance interval (0, h). By analogy with eq. 7, the total number input \( N_d \) has a mean of 
\[ E(N_d) = \int_0^h DLP_F dz = DLP_F h. \]

On the other hand, 
\[ P_S(z) = \cos^{-1}(z/h)/\pi \]
for a random direction of tree fall [eq. 3]. In this case, the total number input \( N_r \) from (0, h) has a mean of 
\[ E(N_r) = DLP_F \int_0^h P_S(z) dz = DLP_F h/\pi. \]

The ratio of the two is 
\[ E(N_r)/E(N_d) = 1/\pi \approx 1/3. \] That is, about one-third of randomly falling trees, within one tree-height of the channel, will enter the channel.
Result 2: piece orientation in the channel for random fall direction

The pdf \( g(a) \) describes the orientation of only those fallen trees that enter the channel. Thus, it can be written as a conditional pdf, \( g(a|S) \), where \( S \) is the event of an entry to the stream, and calculated from Bayes' theorem (Papoulis 1965)

\[
[A1] \quad g(a|S) = \frac{P(S|a) \cdot f(a)}{\int_0^{2\pi} P(S|a) \cdot f(a) \cdot da}
\]

In this equation, \( f(a) \) is the fall angle pdf, and \( P(S|a) \) is the probability of entering the stream, for all trees that fall at the angle \( a \). The probability of entering the stream also depends on \( z \), so \( P(S|a) \) must be written as

\[
[A2] \quad P(S|a) = \int_0^h P(S|a,z) \cdot c(z) \cdot dz
\]

Here, \( c(z) \) is the pdf for the \( z \)-position of falling trees, in the interval \((0,h)\); since \( D \) and \( P_F \) are assumed constant over \( z \), \( c(z) = 1/h \). The probability \( P(S|a,z) \) is conditional on \( a \) and \( z \), and Fig. 1 implies that

\[
[A3] \quad P(S|a,z) = \begin{cases} 1, & \text{for } z < h \sin(a) \\ 0, & \text{elsewhere} \end{cases}
\]

Substitution of eq. A3 and \( c(z) = 1/h \) into eq. A2 yields

\[
P(S|a) = \begin{cases} \sin(a), & \text{for } 0 < a < \pi \\ 0, & \text{elsewhere} \end{cases}
\]

Finally, this probability is inserted into eq. A1, along with \( f(a) = 1/(2\pi) \) for a random fall direction, to yield

\[
g(a) = g(a|S) = \begin{cases} \sin(a), & \text{for } 0 < a < \pi \\ 0, & \text{elsewhere} \end{cases}
\]

The pdf \( g(a) \) and the ratio of inputs between random and directed tree fall are independent of \( h \) and species, so they also hold true for total LWD inputs from any model riparian zone.