Modeling inputs of large woody debris to streams from falling trees

JOHN VAN SICKLE[1] 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

VAN SICKLE, J., and GREGORY, S. V. 1990. Modeling inputs of large woody debris to streams from falling trees. Can. J. For. Res. **20**: 1593–1601.

A probabilistic model predicts means and variances of the total number and volume of large woody debris pieces falling into a stream reach per unit time. The estimates of debris input are based on the density (trees/area), tree size distribution, and tree-fall probability of the riparian stand adjacent to the reach. Distributions of volume, length, and orientation of delivered debris pieces are also predicted. The model is applied to an old-growth coniferous stand in Oregon's Cascade Mountains. Observed debris inputs from the riparian stand exceeded the inputs predicted from tree mortality rates typical of similar nonriparian stands. Debris pieces observed in the stream were generally shorter, with less volume per piece, than those predicted by the model, probably because of bole breakage during tree fall. As a second application, predicted debris inputs from riparian management zones of various widths are compared with the input expected from an unharvested stand.

VAN SICKLE, J., et GREGORY, S. V. 1990. Modeling inputs of large woody debris to streams from falling trees. Can. J. For. Res. **20** : 1593–1601.

Un modèle probabiliste prédit les moyennes et les variances du nombre total et du volume des gros morceaux de débris ligneux qui tombent dans un ruisseau par unité de temps. Les apports estimés de débris sont basés sur la densité (nombre d'arbres par unité de surface), la distribution de la taille des arbres et la probabilité de chute des arbres du peuplement riparien adjacent au ruisseau. Le modèle prédit aussi la distribution du volume et de la longueur des morceaux de débris et leur orientation. Il est appliqué à un peuplement résineux mature des Cascades en Orégon. Les apports observés de débris provenant du peuplement riparien dépassaient les apports prédits à partir des taux de mortalité de peuplements semblables mais non ripariens. Les morceaux de débris observés dans le ruisseau étaient généralement plus courts et avaient un volume inférieur à ce qui était prédit par le modèle, probablement à cause du bris de la tige lors de la chute des arbres. Comme deuxième application, les apports de débris prédits, suite à l'aménagement de zones ripariennes de différentes largeurs, sont comparés aux apports attendus dans le cas d'un peuplement inexploité.
[Traduit par la revue]

Introduction

Large woody debris (LWD) in streams helps to structure fish habitat (Bisson *et al.* 1987), trap sediment (Swanson and Lienkaemper 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 (Lienkaemper 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 hillslope 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.

[1]Author to whom all correspondence should be addressed.

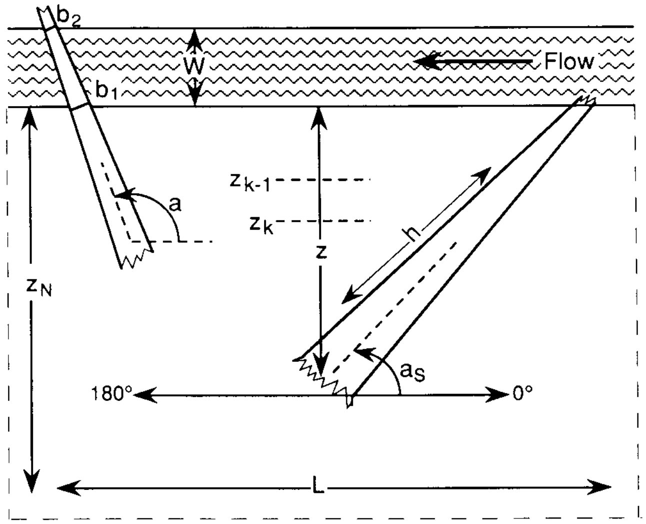

FIG. 1. Model riparian zone with fallen trees, along a stream channel of width W. See Table 1 and text for variable definitions.

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 same 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 $a = 0°$ 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 ($f(a) = 1/360$, $0° < a < 360°$) 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 truncated and renormalized to satisfy

$$\int_0^{360} f(a)\,\mathrm{d}a = 1$$

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 (species × height × 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 $N = D\Delta z_k L$, 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 $\mathrm{var}(\ )$, respectively) given by

TABLE 1. Notation and definitions of selected model variables

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

[1] $$E(N_F) = NP_F = D\Delta z_k L P_F$$
$$\mathrm{var}(N_F) = NP_F(1 - P_F)$$

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

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

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

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

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

[4] $$E(N_I) = NP_F P_S$$
$$\mathrm{var}(N_I) = NP_F P_S(1 - P_F P_S)$$

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 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

$$[5] \quad E(V) = \int_{a_S}^{180-a_S} V(a)f(a)\,da$$

$$\mathrm{var}(V) = E(V^2) - E^2(V)$$

Now define V_I to be the total volume input for all of the N_F falling trees in one class (species × height × distance). Then V_I 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)

$$[6] \quad E(V_I) = E(N_F) \cdot E(V)$$

$$\mathrm{var}(V_I) = [E^2(V) \cdot \mathrm{var}(N_F)] + [E(N_F) \cdot \mathrm{var}(V)]$$

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

$$[7] \quad E(N_T) = \sum D\Delta z_k L P_F P_S$$

where the sum extends across all classes (species × height × 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 × height × 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 $C = NP_F f(a)\Delta a$. 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, $\mathrm{var}(N_I) = E(N_I)(1 - P_F P_S) < E(N_I)$. Let N_X be the total number input from several adjacent riparian zones, so that $N_X = \Sigma N_I$, 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

$$\mathrm{CV} = \mathrm{var}(N_X)/E(N_X)$$

$$= \sqrt{\sum \mathrm{var}(N_I)} / \sum E(N_I) \le 1/\sqrt{E(N_X)}$$

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 treefall 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 consant 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

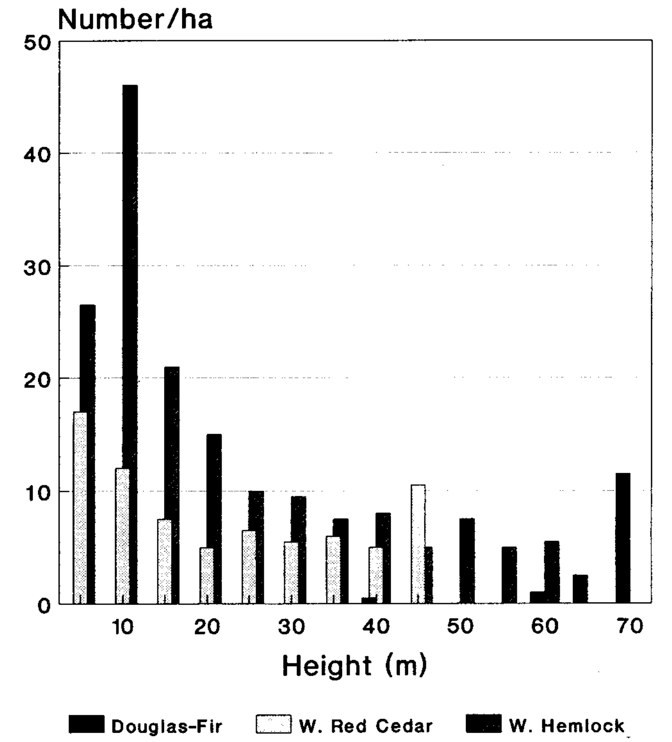

FIG. 2. Stand densities (trees/ha) of dominant species in Mack Creek riparian zone.

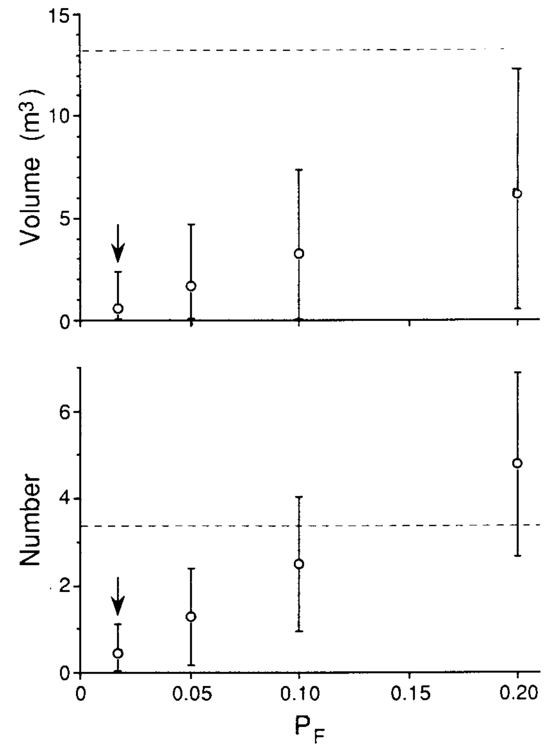

FIG. 3. Predicted LWD input rates (mean ± SD, per decade, per 100 m channel) to Mack Creek vs. tree-fall probability, P_F (per decade). Arrows indicate P_F estimated from stand mortality, and horizontal lines indicate observed input rates.

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

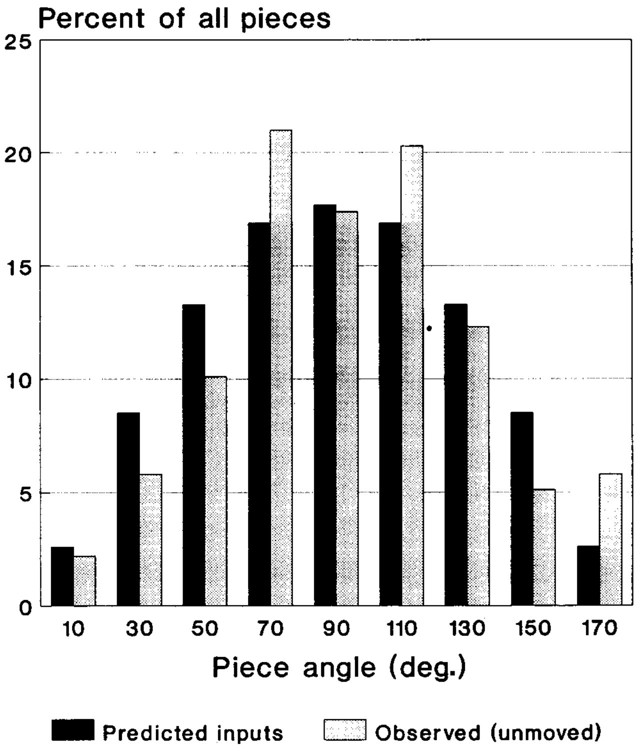

FIG. 4. Predicted vs. observed orientations of LWD pieces in Mack Creek.

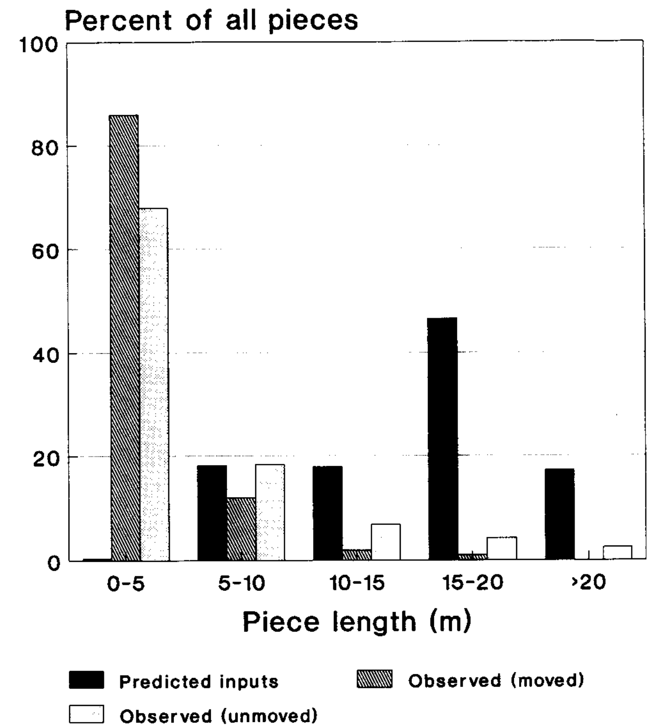

FIG. 5. Predicted vs. observed lengths of LWD pieces in Mack Creek.

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_F 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 $0° < a < 180°$ (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–Smirnov 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

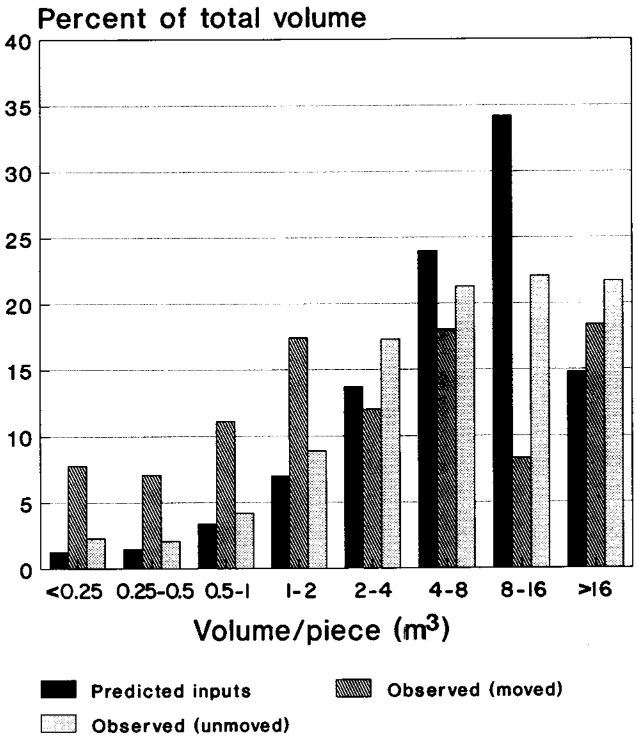

FIG. 6. Predicted vs. observed volumes of LWD pieces in Mack Creek.

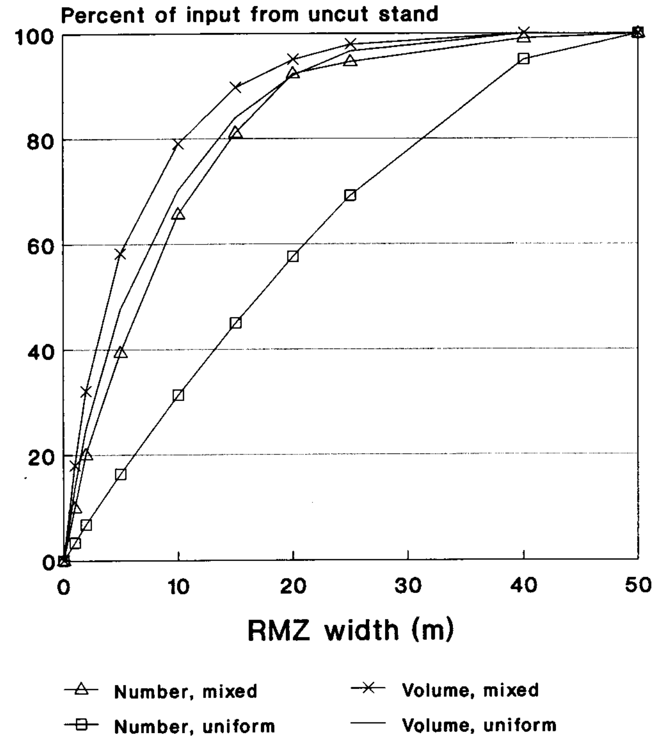

FIG. 7. Relative LWD inputs from riparian management zones (RMZ) of varying width, for mixed-height and uniform-height (h = 50 m) stands.

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 flexibilty 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.

ANDRUS, C.W., and FROELICH, H.A. 1990. Wind damage within streamside buffers and its effect on accelerated sedimentation in coastal Oregon streams. N. Am. J. Fish. Manage. In press.

BILBY, R.E., and WARD, J.W. 1989. Changes in characteristics and function of woody debris with increasing size of streams in Western Washington. Trans. Am. Fish. Soc. **118**: 368–378.

BISSON, P.A., BILBY, R.E., BRYANT, M.D., DOLLOFF, C.A., GRETTE, G.B., HOUSE, R.A., MURPHY, M.L., KOSKI, K.V., and SEDELL, J.R. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. *In* Streamside management: forestry and fishery interactions. *Edited by* E.O. Salo and T.W. Cundy. Institute of Forest Resources, University of Washington, Seattle. Contrib. No. 57. pp. 143–190.

DALE, V.H., HEMSTROM, M., and FRANKLIN, J. 1986. Modeling the long-term effects of disturbances on forest succession, Olympic Peninsula, Washington. Can. J. For. Res. **16**: 56–67.

FRANKLIN, J.F., SHUGART, H.H., and HARMON, M.E. 1987. Tree death as an ecological process. BioScience, **37**: 550–556.

HARMON, M.E., FRANKLIN, J.F., SWANSON, F.J., SOLLINS, P., GREGORY, S.V., LATTIN, J.D., ANDERSON, N.H., CLINE, S.P., AUMEN, N.G., SEDELL, J.R., LIENKAEMPER, G.W., CROMACK, K., JR., and CUMMINS, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133–302.

LIENKAEMPER, G.W., and SWANSON, F.J. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Can. J. For. Res. **17**: 150–156.

MCDADE, H. 1987. The source area for coarse woody debris in small streams in Western Oregon and Washington. MS thesis, Oregon State University, Corvallis.

MCDADE, M.H., SWANSON, F.J., MCKEE, W.A., FRANKLIN, J.F., and VAN SICKLE, J. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Can. J. For. Res. **20**: 326–330.

PAPOULIS, A. 1965. Probability, random variables, and stochastic processes. McGraw-Hill, New York.

RAINVILLE, R.P., RAINVILLE, S.C., and LIDER, E.L. 1986. Riparian silvicultural strategies for fish habitat emphasis. *In* Proceedings of the 1985 Technical Session of the Wildlife and Fish Ecology Working Group, Society of American Foresters National Convention, July 1985, Fort Collins, CO. Society of American Foresters, Bethesda, MD. SAF86-07. pp. 23–33.

RICE, J.A. 1988. Mathematical statistics and data analysis. Wadsworth & Brooks/Cole, Pacific Grove, CA.

ROBISON, E.G., and BESCHTA, R.L. 1990. Identifying trees in riparian areas that can provide coarse woody debris to streams. For. Sci. In press.

STEINBLUMS, I.J., FROELICH, H.A., and LYONS, J.K. 1984. Designing stable buffer strips for stream protection. J. For. **82**: 49–52.

SWANSON, F.J., and LIENKAEMPER, G.W. 1978. Physical consequences of large organic debris in Pacific Northwest streams. USDA For. Serv. Gen. Tech. Rep. PNW-69.

SWANSON, F.J., LIENKAEMPER, G.W., and SEDELL, J.R. 1976. History, physical effects, and management implications of large organic debris in western Oregon streams. USDA For. Serv. Gen. Tech. Rep. PNW-56.

Appendix

Let z be a continuous variable, so that sums over distance classes are replaced by integrals. Assume D and P_F 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 $E(N_r)/E(N_d) = 1/\pi \cong 1/3$. 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)

$$[\text{A1}] \quad g(a|S) = P(S|a) \cdot f(a) \;/\; [\int_0^{2\pi} P(S|a) \cdot f(a) \cdot \mathrm{d}a]$$

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

$$[\text{A2}] \quad P(S|a) = \int_0^h P(S|a,z) \cdot c(z) \cdot \mathrm{d}z$$

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

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

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.