Estimating Large Woody Debris Recruitment from Adjacent Riparian Areas

by

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Abstract

Large woody debris recruitment to streams from adjacent riparian forests influences stream channel morphology, sediment routing, and fish habitat. A mathematical model was developed to 1) determine whether the trees in a stand adjacent to a stream, upon falling, would provide large woody debris of a specified size to the stream and 2) determine the volume of trees, upon falling, that reach a stream over a specific time period. The model considered stand and topographic parameters such as tree size, tree form, distance from the stream, hill slope gradient, stream gradient, stream width, riparian buffer width, and basal area of the stand. The likelihood that a tree of a specified size will reach the channel is the probability the tree will fall in a given direction evaluated at 1 degree azimuths from 0 to 360 degrees multiplied by the probability it is tall enough to reach the stream. Volume estimates were calculated by multiplying estimated tree volumes by the joint probabilities.

A test riparian polygon comprised of Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) was selected to illustrate how the model predicts large woody debris recruitment of both key pieces and volume to an adjacent stream. Estimating large woody debris recruitment to streams from adjacent riparian stands over several decades may be useful in determining effectiveness of various configurations of riparian buffers and provide assistance in the prediction of the future quality of aquatic and terrestrial habitats in riparian zones. This model provides one way to estimate where large wood is coming from within a riparian leave area and could be useful in determining necessary widths for riparian areas that are intended to provide large woody debris recruitment over time.

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Estimating Large Woody Debris Recruitment to Streams from Adjacent Riparian Areas

Large downed trees are a functionally important component of forest streams in the Pacific Northwest (Swanson et al. 1976; Harmon et al. 1986; Bisson et al. 1987; Naiman et al. 1992; Maser and Sedell 1994). Large woody debris influences channel morphology by altering the longitudinal profile, reducing the local gradient, and influencing pool formation (Bisson et al. 1987; Andrus et al. 1988). Downstream routing of sediment and organic matter is influenced by the storage of this material behind large wood (Bestcha 1979; Bilby 1981; Maser and Sedell 1994). Large woody debris also affects the formation and distribution of habitat for fishes and other aquatic biota (Swanson et al. 1982; Bisson et al. 1987). Once large wood enters a stream, it may be deposited immediately in the channel or along the margins or it may be transported down the channel and deposited considerable distances from the source during storm flows and soil mass movements (Swanston 1991).

Large woody debris loadings in many forested streams have been reduced due to a variety of past and present management activities. Historical timber harvesting practices on some public and private lands have left inadequate long-term sources of wood. In areas where riparian buffers were established, partial harvesting and salvage logging have reduced their ability to contribute large woody debris to streams (FEMAT 1993). The general absence of riparian buffers on intermittent streams has reduced the amount of wood these streams can deliver to permanently flowing streams (Naiman el al. 1992). Cleanup activities from the 1950's through 1970's removed large woody debris from Pacific Northwest streams in an effort to enhance anadromous fish passage and protect bridges and culverts from damage during floods (Narver 1971; Bisson and Sedell 1984). Earlier activities such as splash-damming, which was used in the Pacific Northwest as late as the 1950's in some locations, removed large amounts of wood from streams (Sedell and Luchessa 1982; Maser and Sedell 1994).

Forest managers are currently attempting to retain, or even increase large woody debris in streams. To ensure a continual supply of large woody debris in forested streams, many states and federal agencies in the Pacific Northwest have adopted forest practice rules that call for setting aside standing live trees within riparian areas or no-harvest riparian buffers for future large woody debris recruitment (Adams et al. 1988; USDA Forest Service and USDI Bureau of Land Management 1994). The possibility that these buffers may not provide large woody debris of sufficient size and in sufficient quantities to streams over a long period of time suggests that a method to determine the source area of large woody debris in streams would be useful in designing effective riparian buffers.

One way to estimate large woody debris source areas would be to sample large woody debris in streams and determined its origin. McDade (1987) sampled 39 streams bordered by old-growth forests in the Cascade and Coast Ranges of Oregon and Washington. She found that the distribution of source areas was similar in these streams; approximately 10 percent of the total number of debris pieces originated within 3 ft. of the channel and 90 percent originated within 100 ft. in 29 of the 39 streams (Figure 1).

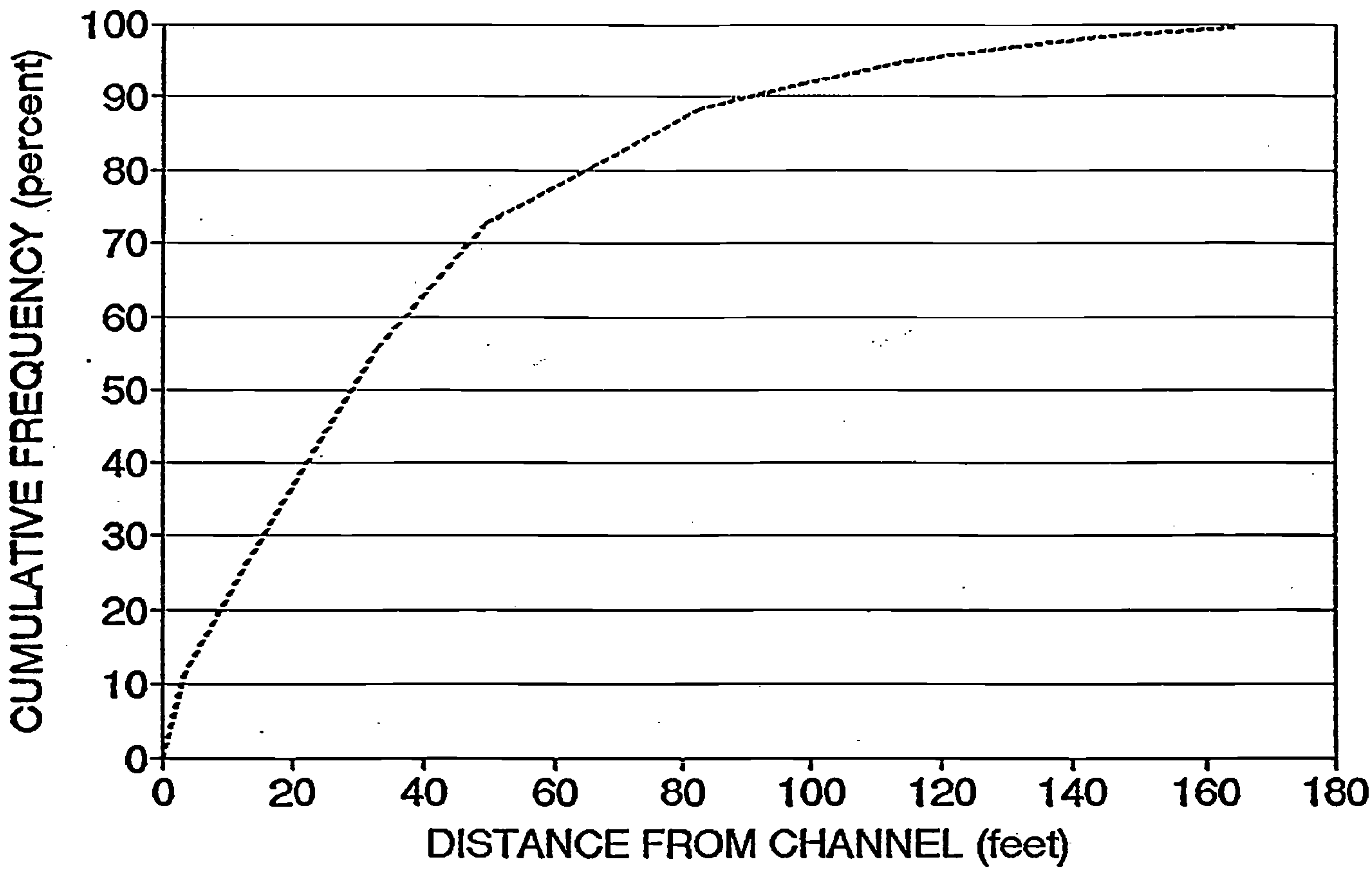


Figure 1. Source area for coarse woody debris in small streams in western Oregon and Washington (Adapted from McDade 1987).

Another way to estimate large woody debris source areas is to develop a physical model which estimates the amount and size of large woody debris that will likely be supplied to the stream channel over time given known stand conditions and riparian management guidelines. The purpose of this paper is to develop a mathematical model to 1) determine whether the trees in the stand adjacent to the stream, upon falling, will provide large woody debris of a specified size to the stream and 2) determine the volume of the trees, upon falling, that reach a stream channel over a specific time period.

Model Development

General Assumptions

Several assumptions were required to develop the following equations and methodology. First, for each time period and for any given riparian polygon adjacent to a stream, the number of trees, their diameter at breast height (DBH), and their location on the hill slope in relation to the stream were assumed to be known. Growth and mortality models were used to predict tree sizes over time and estimate the number of trees, by diameter class, that will fall in a specified time period. Stream width, width of riparian buffer, basal area of the stand, site index, average slope of the riparian area (the slope perpendicular to the elevation contour lines), and stream gradient are also assumed to be known prior to using this model.

Second, the chance of a tree falling downhill (towards the stream) was assumed to increase with increasing slope. No literature was found that determined the direction of tree fall near a stream or on a hill slope. Several factors may influence the direction of tree fall near streams. Prevailing wind direction may be associated with the direction of tree fall, although the interaction of wind pattern and topography is complex and not easily modeled (Steinblums et al. 1984). Soil creep, stream bank erosion, or other instability associated with the higher soil moisture near streams might cause a tendency for trees to fall towards streams. Increased light availability near the stream channel may cause greater growth and biomass of trees towards streams causing trees to lean towards streams. Analyses of downed timber on 17-70 percent hill slopes in the Oregon Cascades (Beschta, unpublished data) indicated that the probability of a tree falling down slope was often greater than 75 percent. For tree fall in riparian zones, this model assumes that the probability of trees falling toward the stream increases exponentially with increasing slope.

Third, the model evaluates the potential of trees of given sizes and locations to provide debris at the time of evaluation. Channel adjustments over long time periods, particularly for streams flowing through floodplains, may move a stream closer to or farther from a tree, thus altering the ability of a tree to contribute large woody debris to a stream channel. Channel adjustments are not incorporated into this model.

Fourth, the model assumes that the entire tree bole will fall to the ground. Subsequent log movement from rolling or sliding and breakage were not considered.

Fifth, this model does not evaluate the contribution of large wood to streams from landslides or debris flows. While those contributions may be significant in steep headwater streams, an assessment of their inputs was beyond the scope of this study.

Determining Probability

If a tree is assumed to have an equal probability of falling in any direction, the possible surface area that could be impacted by the tree can be represented by the area of a circle whose radius is equal to the total tree height (H_t) (Figure 2) (Robison and Beschta 1990). The upper portion of the crown does not normally have wood of a sufficient size to influence channel hydraulics, stream morphology, and fish habitat. Large woody debris that influences stream channels ("key pieces") is usually considered to be pieces of wood or tree boles that exceed a certain diameter and height (Bisson et al. 1987). Thus, an "effective tree height" (H_e), which is the height to a minimum diameter and length necessary to qualify as a key piece, would be more appropriate for assessing the potential tree fall area (Figure 2) (Robison and Bestcha 1990). The effective tree height can be adjusted based on management considerations. For example, when estimating the volume contribution of large woody debris to a stream channel, the minimum diameter and length could be reduced. In general, the probability of a tree falling into a stream is primarily a function of its height and its distance from the stream.

Assuming equal probability of falling in any direction for terrain with zero percent slope, the probability of a tree falling at any one degree increment around the circle is equal to 1/360. Thus, the chances of a tree on flat ground falling toward the stream are equal to 50 percent (180/360). However, as slope increases, the chance of a tree falling down slope (toward the stream) is assumed to increase.

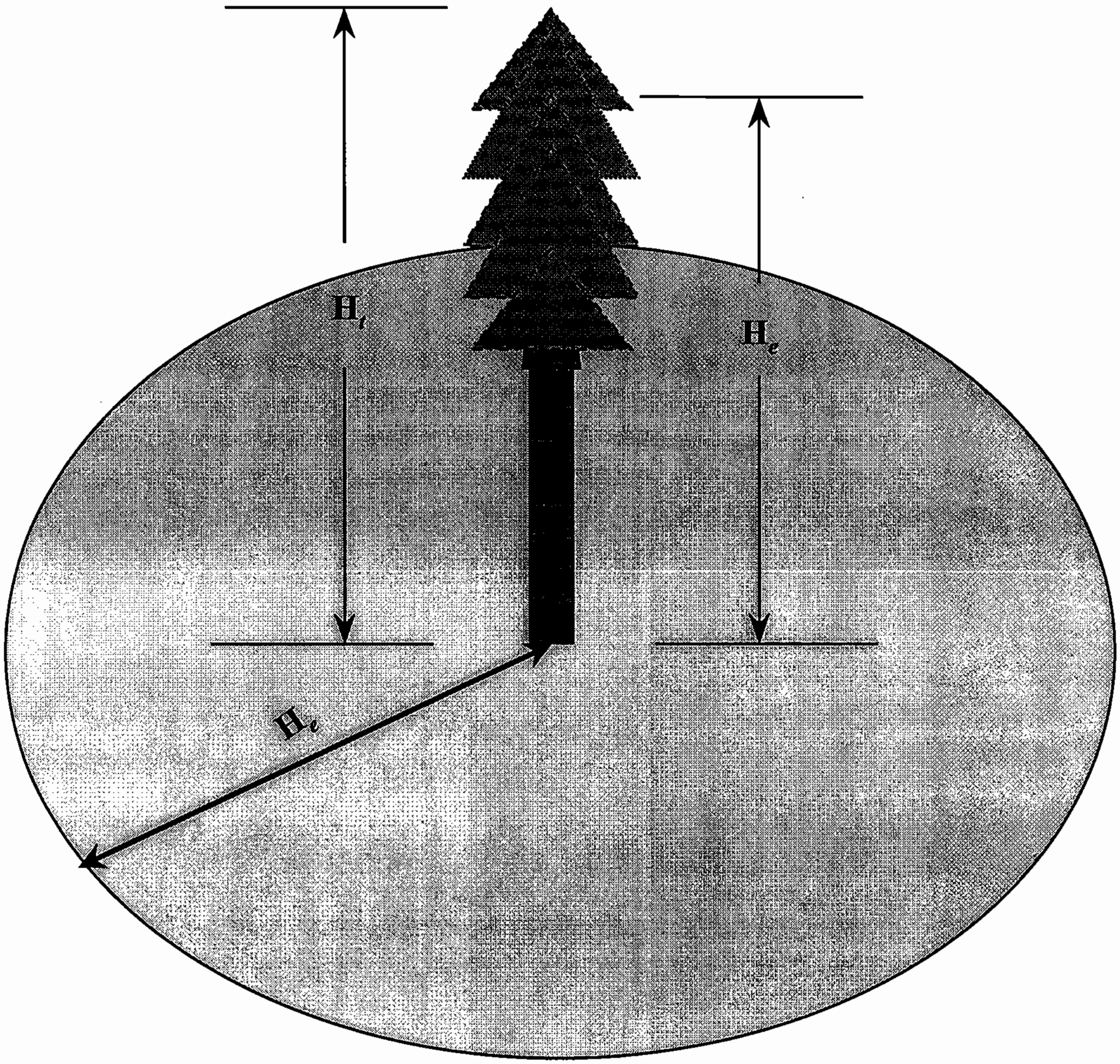
Average slope perpendicular to the contour lines (α, rate of greatest fall) and stream gradient (s) in a riparian polygon are assumed to be known in this model. Slope perpendicular to the stream is calculated in the model using the following relationship[1]:

$$\beta = \sqrt{\alpha^2 - s^2} \tag{1}$$

where

β = slope perpendicular to stream channel (ft./ft.)
α = average slope perpendicular to contour lines (ft./ft.)
s = stream gradient (ft./ft.)

[1] Derivation of this relationship was performed by Dr. Thomas Dick, Mathematics Department, Oregon State University, Corvallis, Oregon. Details and complete derivation are available from the authors.



H_t = Total Height
H_e = Effective Height

Figure 2: The potential tree fall area showing total tree height (H_t), effective tree height (H_e), and possible surface area impacted (shaded) by the effective height (H_e) (Adapted from Robison and Beschta 1990).

Using Beschta's unpublished data, we hypothesized a relationship between the probability of large woody debris falling towards the stream channel (P_{down}) and the ground slope perpendicular to the stream (β). This relationship is provided by Equation 2 and illustrated in Figure 3.

$$P_{down} = 1 - \frac{0.5}{10^{k\beta}} \qquad (2)$$

where

$k = 1.4375$, curve shape factor
$\beta =$ slope perpendicular to stream channel (ft./ft.)

The probability of a fallen tree reaching a stream is affected by its distance from the stream, the height of the tree, and the ground slope. These conditions are evaluated by 1) estimating the probability of a tree falling in a given direction and 2) calculating whether the tree would reach the stream in that direction.

On flat ground (zero percent slope), assuming a random direction of fall, a probability surface is represented by a circle of radius $1/\sqrt{\pi}$. This probability surface is referred to as the probability circle. The probability of a tree falling randomly within any arc defined by $d\theta$ is equal to portion of the area of the probability circle defined by $d\theta$ (Figure 4) or:

$$dP = \frac{d\theta}{360}\pi R^2 \qquad (3)$$

where

$\theta =$ azimuth that defines direction of tree fall (degrees)
$d\theta =$ angle that defines the arc for tree fall (degrees)
dP = probability of tree falling in the direction of θ
R = radius of the probability circle

The sum of all subarea probabilities is equal to one.

The likelihood that a tree will actually reach the stream is the probability the tree will fall in a given direction multiplied by the probability it is tall enough to reach the stream if it fell in that direction. Since we know the height of the tree and its distance from the stream, we can calculate for each direction of fall whether the tree will reach the stream, given that it does fall. The tree is assigned a probability of 1 if it will reach the stream and 0 if it will not. Thus, the probability of a falling tree reaching the stream is the sum of the joint probabilities evaluated over $\theta = 0$ to 360 degrees.

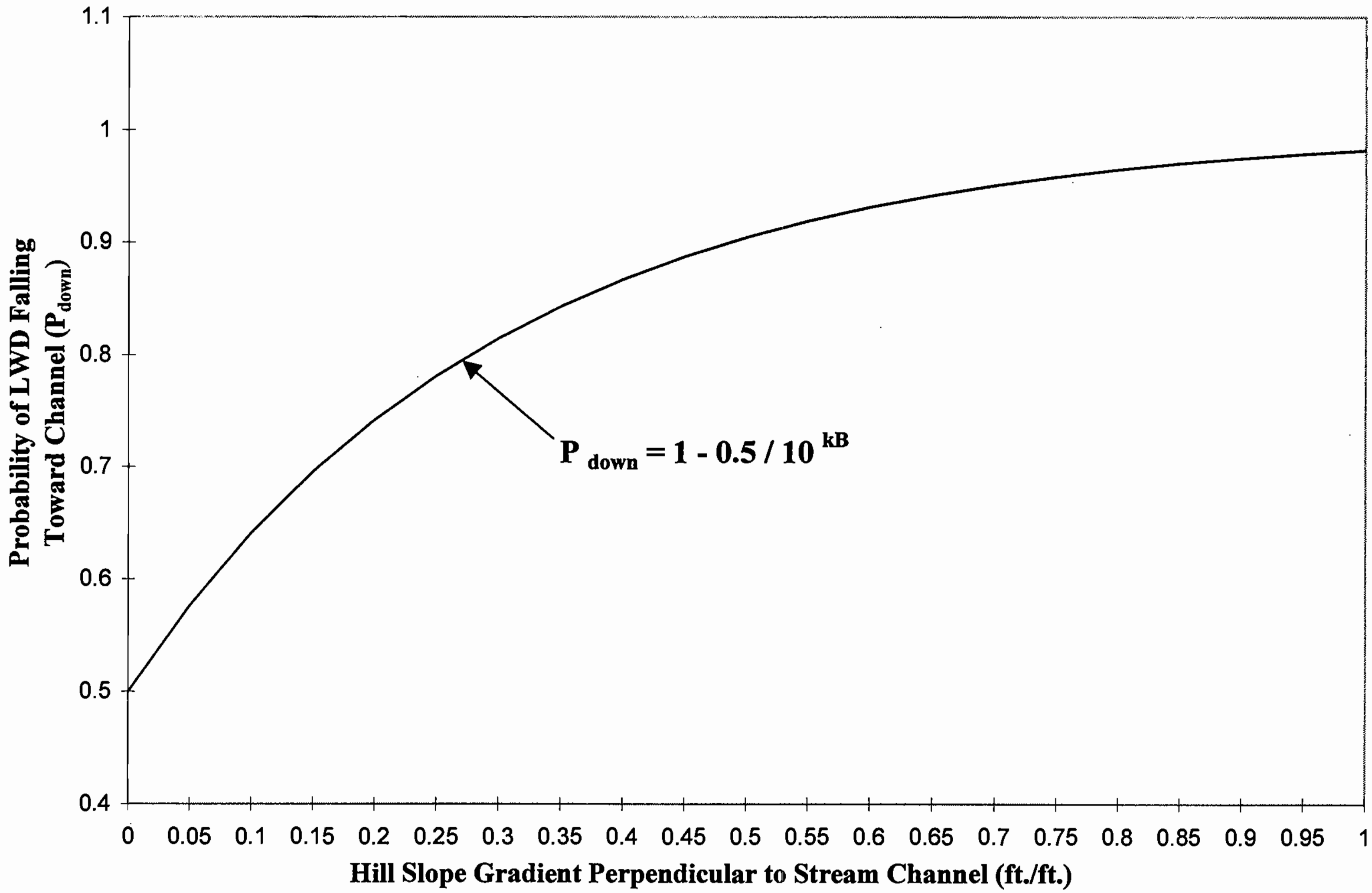
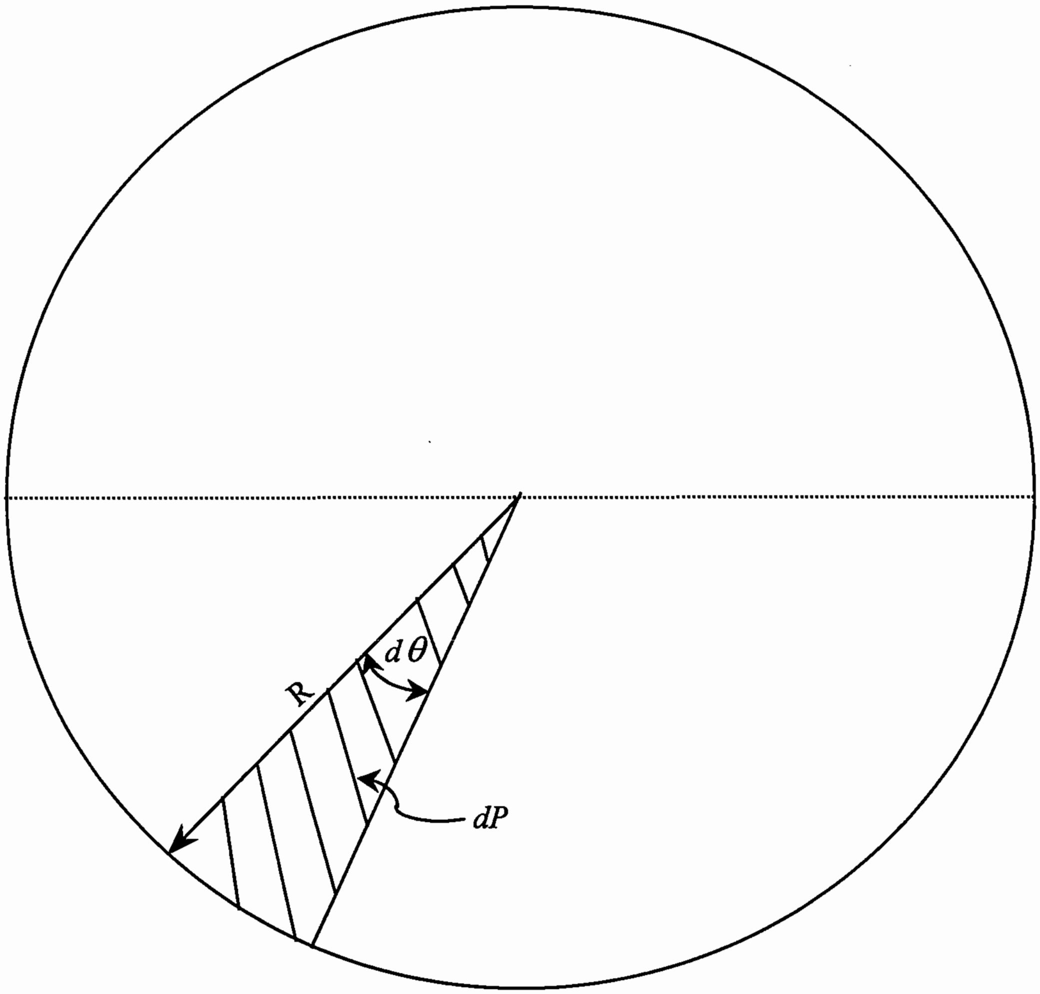


Figure 3. Relationship between hill slope gradient perpendicular to the stream and the probability of large woody debris falling toward the channel using Equation 2.



$$dP = \frac{d\theta}{360}\pi R^2$$

Figure 4: Tree fall probability circle with a radius of $R = \frac{1}{\sqrt{\pi}}$ for flat ground (0% slope).

As previously indicated, for ground slopes which are not zero, an increased tendency for trees to fall downhill towards a stream channel is assumed (Figure 3). However, the procedure for estimating the probability of a tree reaching the stream channel if it fell was further modified to generalize it for slopes which are not flat. Instead of assuming the tree is in the center of a circle of radius $1/\sqrt{\pi}$, we move the position of the tree from the center of the probability circle to a position on the chord of the circle where the area of the circle below the chord corresponds to the probability of the tree falling downhill (Equation 2). The sum of the probabilities of a tree falling in any direction is still equal to one, but the probability of the tree falling downhill is now greater (Figure 5) as slope increases. The probability of tree fall is spatially distributed by assuming that the probability density is now proportional to the distance from the offset tree location to the edge of the circle (Figure 6). The distance from the offset location to the arc of the circle is referred to as the effective radius, R_e. The effective radius is greatest at $\theta = 90$ degrees (directly downhill) and is a minimum at $\theta = 270$ degrees (directly uphill). To estimate the probability of tree fall in a given direction considering slope effects, the effective radius is substituted for the radius ($1/\sqrt{\pi}$) in the previous calculation to obtain the following probability equation:

$$dP = \frac{d\theta}{360}\pi R_e^{\,2} \tag{4}$$

where

θ = azimuth that defines direction of tree fall (degrees)
$d\theta$ = angle that defines the arc for tree fall (degrees)
dP = probability of tree falling in the direction $d\theta$
R_e = radius of the probability circle

For zero-slope with $R_e = 1/\sqrt{\pi}$, the generalized procedure reduces to the zero-slope estimate provided earlier. For slopes greater than zero percent, the effective radius is calculated using a numerical technique (see Appendix).

While probability surfaces other than circles (i.e. elliptical and rectangular) were considered for the non-zero slope case, the circle was retained because it required fewer parameters to describe. If empirical data were available for a particular area that showed that tree fall probability was better represented by a shape other than a circle, the probability surface could be changed within the model to represent those conditions.

In addition to estimating the probability of a tree bole reaching the stream, an estimate of the tree volume and size of the bole is also undertaken. These attributes are determined in a similar way to the previous conditional probability where a binary variable was used to indicate whether a tree would reach the stream or not, given that the tree fell in a specific direction.

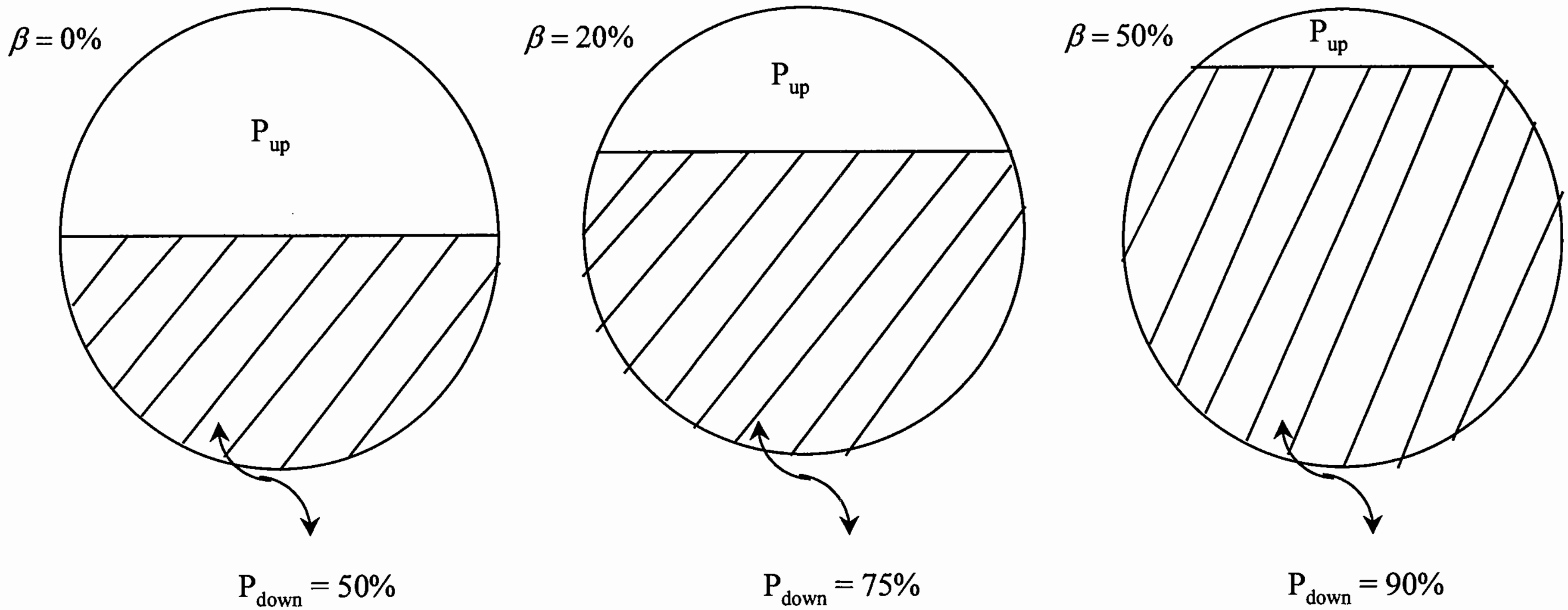


Figure 5: Example probability densities for different hill slope gradients (β). P_{down} determined from Equation 2.

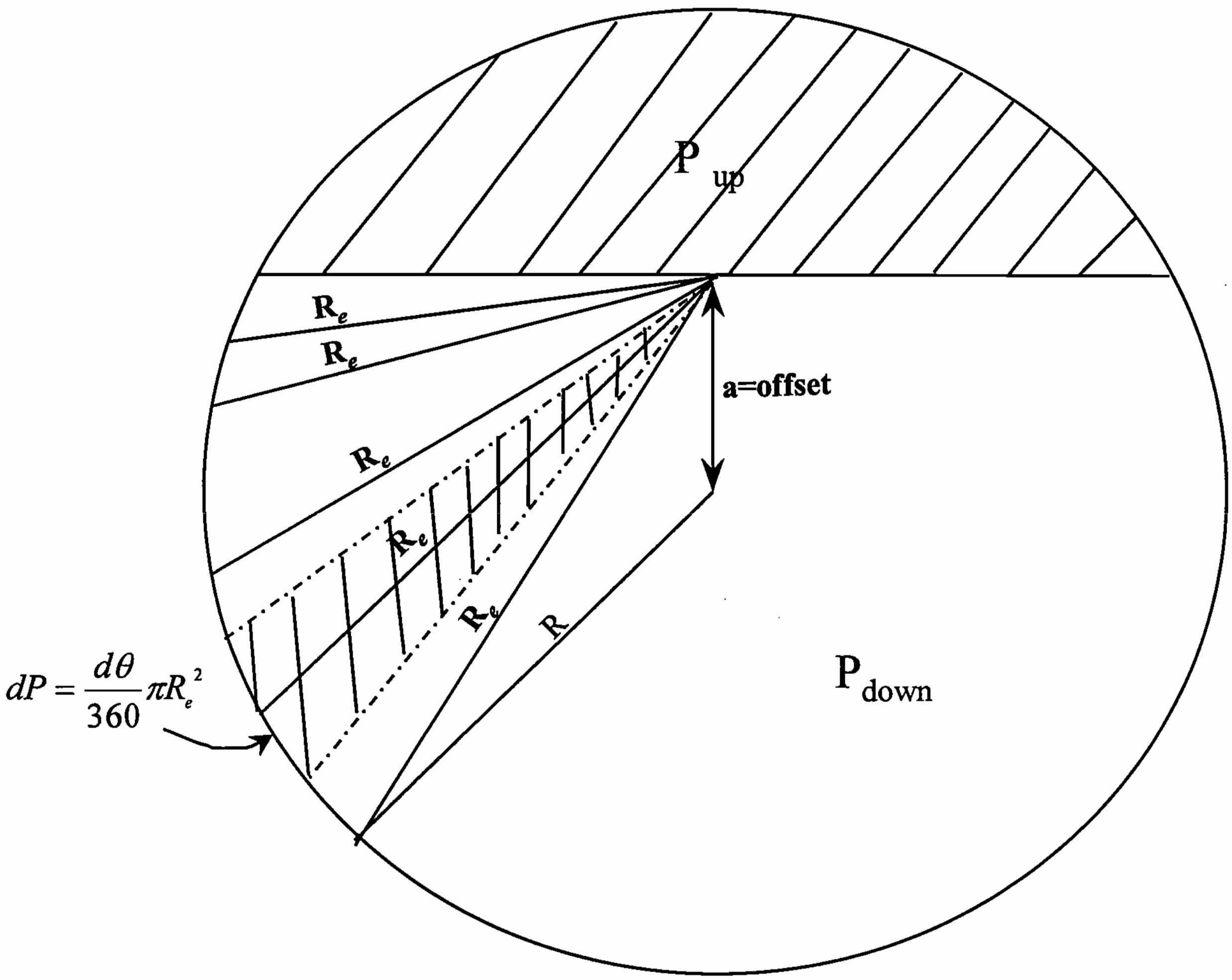


Figure 6: Determination of effective radius at each $d\theta$ and the probability that a given tree will fall at each $d\theta$.

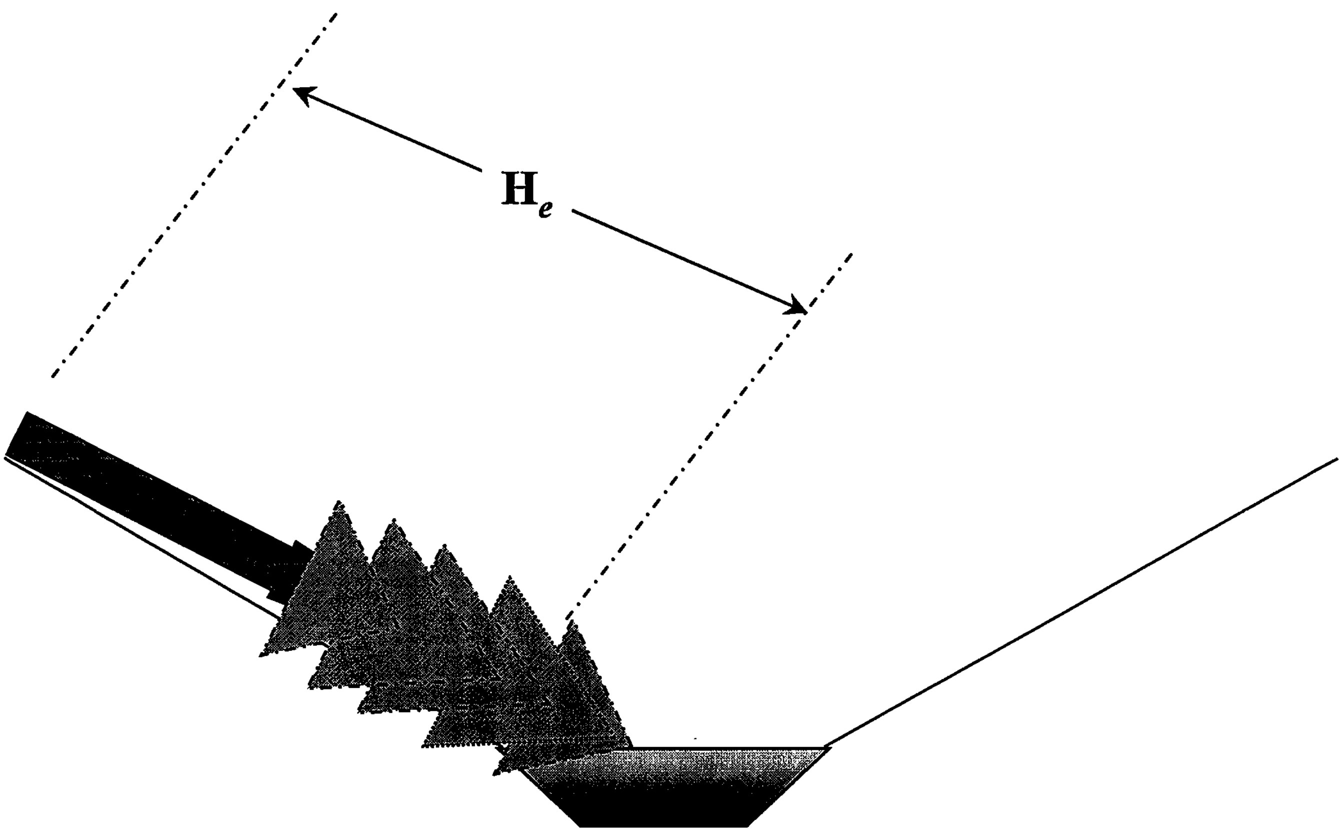


Figure 7: Schematic view illustrating effective height (H_e) of key piece intersecting stream channel.

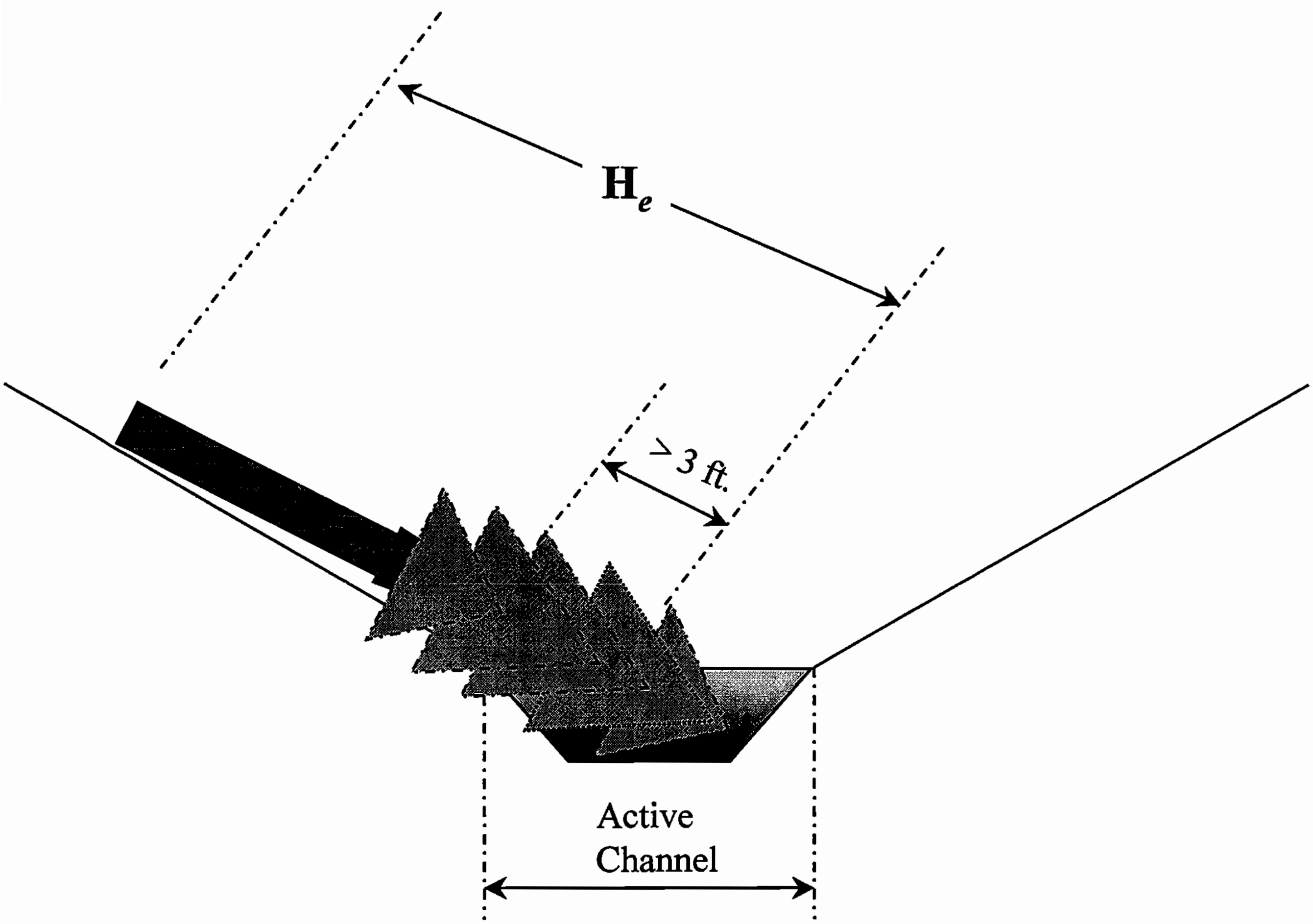


Figure 8: Schematic view illustrating tree intersecting active channel. Volume is calculated in the active channel and the whole tree if greater than 3 ft. of the effective height (H_e) falls within the active channel.

where

H_e = effective tree height (ft.)
H_t = total tree height (ft.)
d = top diameter (in.)
DBH = diameter at breast height, including outside bark (in.)
b_1 and b_2 = coefficients that vary with tree species (Table 2)
$\lambda = 1\text{-exp}(-b_1/b_2)$

These taper equations are based on data from second-growth forests in California and thus provide only rough estimates for trees from other regions or relatively large trees.

Table 2. Arithmetic values for coefficients for taper equations (Biging 1984).

	Coefficients	
Tree Species	b_1	b_2
Ponderosa pine	1.016215	0.332529
Douglas-fir	1.027763	0.333721
White fir	1.093343	0.364280
Sugar pine	1.067508	0.411978
Incense-cedar	1.077913	0.482610

To determine the effective tree height necessary to comprise a key piece, the height to a 24 inch diameter for a given tree was calculated using Equation 7 with d = 24 inches. If this calculated height was greater than 16.5 ft. (half of the key piece length) then the effective tree height necessary to make a key piece was the height to a 24-inch diameter plus 16.5 ft. as long as this calculated effective height was less than the total tree height. Otherwise, the tree was determined not to be of sufficient size to make a key piece. This method ensures that when the effective height of a fallen tree intersects a stream channel, it qualifies as a key piece (Figure 9). To determine the effective tree height for the volume prediction, the height to a 6 inch top was calculated using Equation 7 with d = 6 inches.

Input Requirements

A riparian area is divided into polygons based on similarities in vegetation, topography, stream class, and stream gradient. For each polygon in the model, the riparian area was divided into 20 ft. strips parallel to the stream. However, the first two 20 ft. strips were further divided into 2 ft. increments in order to obtain a more accurate estimate of fall probabilities relative to the stream since most large woody debris that falls into streams is expected to originate from tree fall within this zone.

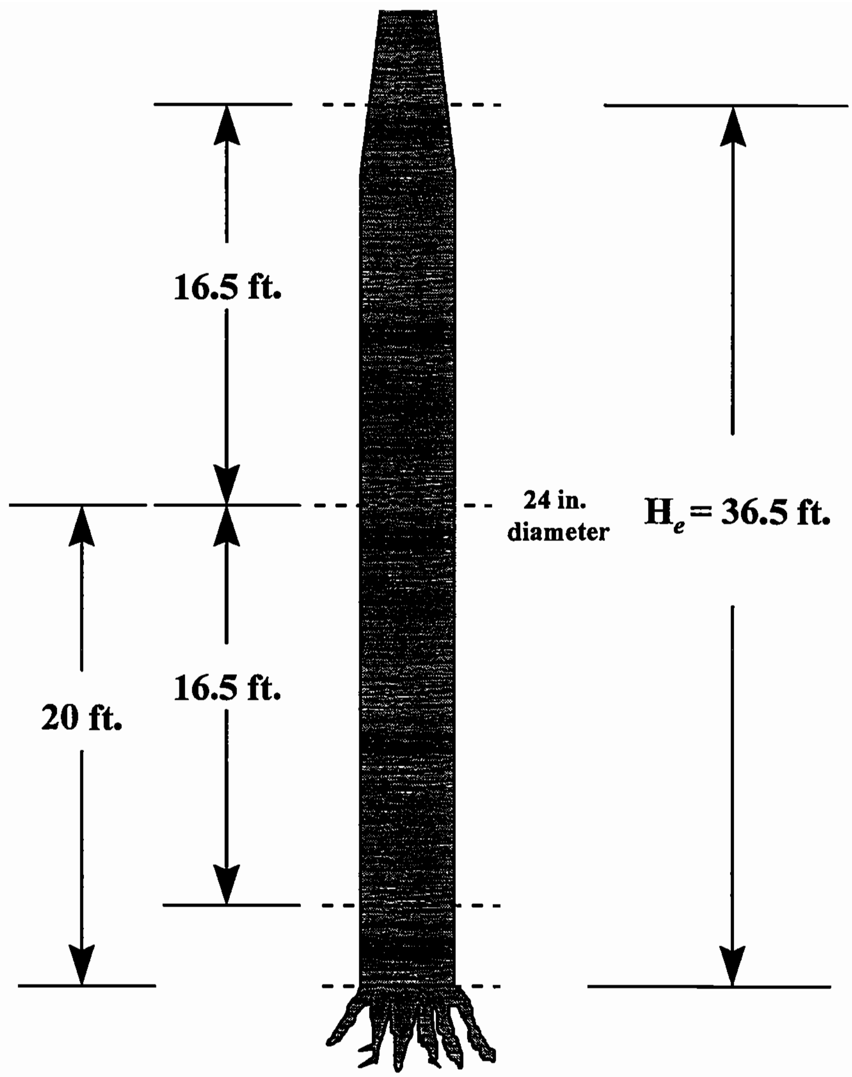


Figure 9: Method of calculating effective height (H_e) for key piece determination.

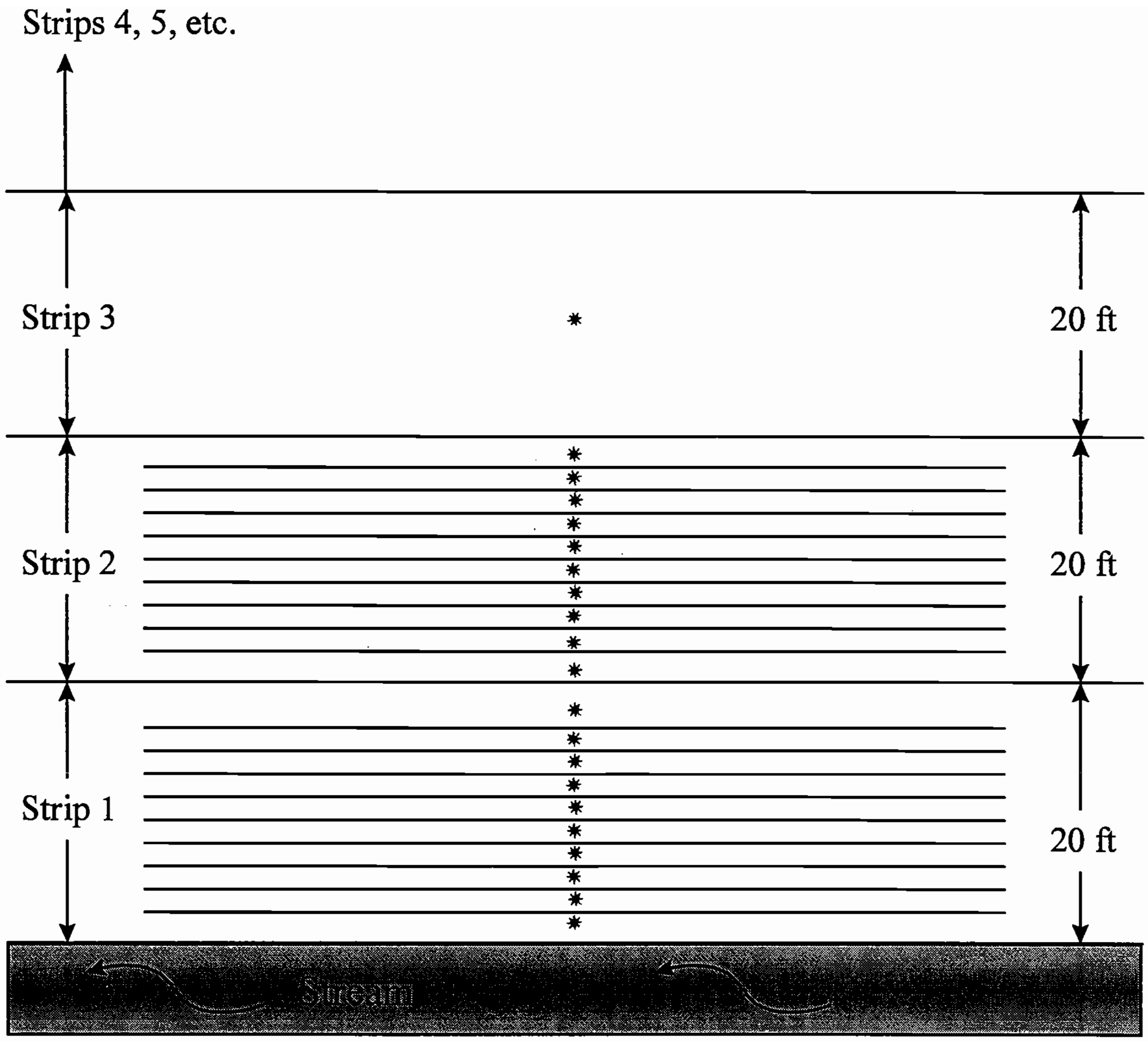
Trees that fall during any given time period were assumed to be located at the center of these 2 ft. increments. For the remaining strips to the outer edge of the riparian zone, the trees that would fall in each 20 ft. strip were assumed to be located in the center of the strip (Figure 10).

For each polygon and each time period, data needs include site index, stand basal area, stream width, average slope of riparian area, stream gradient, and trees per strip that will fall during a time period for each of the 21 diameter classes.

Computations

Total heights and effective heights are calculated for trees in each of the diameter classes that will fall within a time period for each of the strips. Trees expected to die in a given time period are "felled" at one degree increments ($d\theta$) around the probability circle (0 to 360 degrees). Slope distance to the stream is calculated, taking into account stream gradient.

If the effective height of a key piece was less than the total tree height, then the effective height was compared to the slope distance from that tree to the stream. If the effective height exceeded the slope distance, it was counted as a key piece. The trees per strip in that diameter class were then multiplied by the probability of the tree falling within that incremental angle ($d\theta/360\pi R_e^2$) to determine the key piece contribution of that increment. All of the increments that contribute key pieces are summed for a given strip to predict the portion of a key piece that the strip can be expected to provide in the given time period.



∗ - Assumed Tree Location

Figure 10: Assumed location of trees within 20 ft. riparian strips. Trees assumed to be located at center of 2 ft. strips for first 40 ft. from streams. Trees located at center of 20 ft. strips from a distance of 40 ft. to outer edge of riparian zone.

For the volume calculation, the effective height to a 6-inch top was compared to the slope distance to the stream. If this effective height exceeded the slope distance by 3 ft. or more, the volume of the entire tree from the root wad to the effective height and the volume of the portion of the tree that intersected the active channel width were calculated. Volume was calculated using the integration of Biging's (1984) taper equations for mixed conifer species in northern California:

$$V = \int_a^b 0.00545\, d^2(h)\, dh$$

$$= K_1 H(b' - a')$$

$$+ K_2 H\left[-\frac{3}{\lambda^3}\right]\left[q\ln(q) - q - q^2\ln(q) + \frac{q^2}{2} + \frac{q^3}{3}\ln(q) - \frac{q^3}{9}\right]_{a''}^{b''}$$

$$+ K_3 H\left[-\frac{3}{\lambda^3}\right]\left[\frac{q^3\ln^2(q)}{3} - q^2\ln^2(q) + q\ln^2(q) - \frac{2}{9}q^3\ln(q)\right.$$

$$\left. + q^2\ln(q) - 2q\ln(q) + \frac{2}{27}q^3 - \frac{q^2}{2} + 2q\right]_{a''}^{b''} \qquad (8)$$

where

H = total height (ft.)
b = height to top point in the upper stem (ft.)
a = height to some base point (not necessarily the stump) (ft.)
h = height to some point in the stem between a and b (ft.)
$\lambda = 1\text{-}\exp(-b_1/b_2)$
$q = 1-\lambda(h/H)^{1/3}$
$K_1 = 0.00545 b_1^2 \mathrm{DBH}^2$
$K_2 = 0.00545(2b_1b_2)\mathrm{DBH}^2$
$K_3 = 0.00545 b_2^2 \mathrm{DBH}^2$
$a' = a/H$
$b' = b/H$
$a'' = 1-\lambda(a')^{1/3}$
$b'' = 1-\lambda(b')^{1/3}$
$d = \mathrm{DBH}\{b_1 + b_2\ln[1-\lambda(h/H)^{1/3}]\}$
DBH = diameter at breast height outside bark (in.)
ln = natural logarithm

The trees per strip in a diameter class were then multiplied by the volume and the probability of the tree falling within that incremental angle ($d\theta/360\pi R_e^2$) to determine the volume contribution of that increment. All of the increments that contribute volume to a stream are summed for a given strip to predict the volume that the strip can be expected to provide in the given time period.

Model Output

Computations for key pieces and volume are repeated for all of the 21 diameter classes in each of the strips for each polygon for the number of time periods defined by the user. For each riparian polygon, the model yields 1) the total number of key pieces that enter the stream channel, 2) the volume of large woody debris segments that intersect the active channel width, and 3) the volume of the entire trees that fall within the active stream channel for each of the strips for each time period. The results can be further segregated by diameter class, if necessary.

Applications

Designing Riparian Buffers

Designing an effective riparian buffer that will provide adequate recruitment of large woody debris over time requires a method to estimate where on the hill slope the large wood is likely to come from. This model can assist in making these estimates and in comparing the effects of different physical variables of a riparian zone such as hill slope gradient, tree species, tree sizes and locations, as well as, making comparisons between different management regimes within riparian areas. To illustrate how this model could be used to estimate large woody debris recruitment to a stream, a test riparian polygon was evaluated with the model.

Initial Conditions

The test riparian polygon was a Douglas-fir type with a basal area of 374 $ft.^2$/acre and a site index of 107. The stream width adjacent to the riparian polygon was 9.8 ft. The trees per 20 ft. strip that were estimated to fall in a decade, diameter class, and strip were held constant (.03 trees in each diameter class per 20 ft. strip) in order to evaluate the effects of increasing hill slope gradient on large woody debris recruitment. Recruitment of key pieces, volume in the active channel, and whole tree volume reaching the active channel were evaluated at 10 percent slope increments for 0 percent to 70 percent hill slope gradients perpendicular to the stream channel. Total tree heights and effective tree heights for key piece and volume determinations are shown in Table 3.

Table 3. Height calculations for test riparian polygon based on sample trees in a strip.

Diameter at Breast Height (inches)	Total Height (feet)	Effective Height (He) for Key Piece Determination (feet)	Effective Height (He) for Volume Determinations (feet)
13	103	0	64
15	112	0	79
17	121	0	91
19	129	0	102
21	137	0	112
23	144	0	121
25	150	0	129
27	157	0	136
29	163	34	143
31	168	46	150
33	173	58	156
35	179	71	162
37	183	83	167
39	188	94	173
41	192	104	178
43	197	114	182
45	201	123	187
47	205	132	191
49	209	140	195
51	212	147	200
53	216	154	203

Results and Discussion

The results of the model represent large woody debris recruitment for one side of the stream. If stand conditions are the same on the other side of the stream, the key piece and volume results can be doubled. Large woody debris recruitment for the test riparian polygon was only examined for a single decade. Growth and mortality models could be used to supply the input requirements for the model to examine large woody debris recruitment over several decades.

The results of the model simulations for key pieces showed that the number of key pieces reaching the channel increased with increasing slope until the hill slope gradient perpendicular to the stream reached 50 percent (Figure 11). Even though the probability of trees falling down hill continues increasing with increasing slope, the number of key pieces reaching the channel does

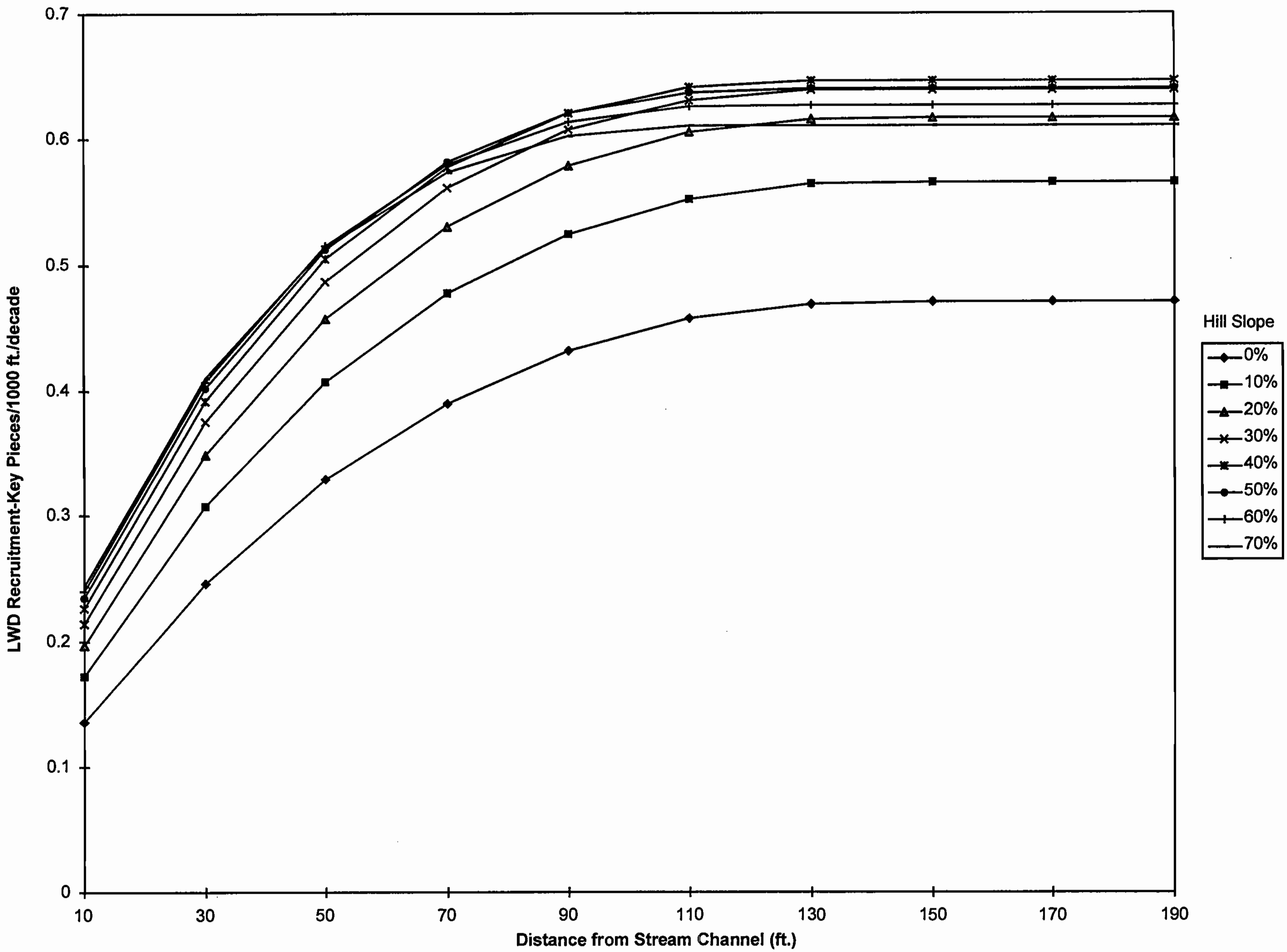


Figure 11. Large woody debris recruitment of key pieces.

not increase because the distance from the stream channel at the higher slopes is increasing at a faster rate. The contribution of key pieces to the stream channel decreases as the distance from the channel increases, with approximately 52 to 67 percent of the number of key pieces coming from the first two 20 ft. strips, respectively. For all the hill slope gradients, the contribution to key piece recruitment is negligible at distances of approximately 130 ft. or more from the stream channel.

The volume of the large woody debris in the active channel also increased with increasing hill slope gradient perpendicular to the stream (Figure 12). Approximately 63 to 77 percent of the volume of large woody debris recruited to the active channel comes from the first two 20 ft. strips, respectively. For all hill slope gradients, recruitment of large woody debris volume to the active channel similarly become negligible at distances of approximately 130 ft. or more from the stream channel.

The volume of the whole trees reaching the active channel increased with increasing slope until the hill slope gradient perpendicular to the stream reached 50 percent (Figure 13). As mentioned previously, even though the probability of trees falling down hill continues increasing with increasing slope, the volume of whole trees decreases because the distance from the stream channel at the higher slopes is increasing at a faster rate. The whole tree volume contribution of large woody debris to the stream channel is more evenly distributed between the strips than was key pieces or active channel volume, with approximately 33 to 46 percent coming from the first two 20 ft. strips, respectively. For all hill slope gradients, whole tree volume recruitment of large woody debris to the active channel becomes negligible at distances of approximately 170 ft or more from the stream channel.

It is interesting to note that the results from our test riparian polygon corresponded closely to the empirical results of McDade's (1987) study (Figure 14). McDade showed that 75 percent of the debris pieces in her streams originated within 50 ft. of the channel. The stand conditions for McDade's study areas are not known. The test riparian polygon was a uniform stand with the same number of trees in each diameter class falling in a decade. The model results showed that between 70 to 84 percent of the key pieces originated within 50 ft. of the stream channel depending on slope (0 to 70 percent). Side slope steepness in McDade's study ranged from 8 to 40 degrees (14 to 84 percent). In addition, Murphy et al. (1987) reported that 90 percent of the large woody debris from riparian forests originated from within 50 ft. of the stream channel in southeast Alaska and Van Sickle and Gregory's (1990) model predicted 83 percent of the large woody debris originated from within 50 ft. of the stream channel.

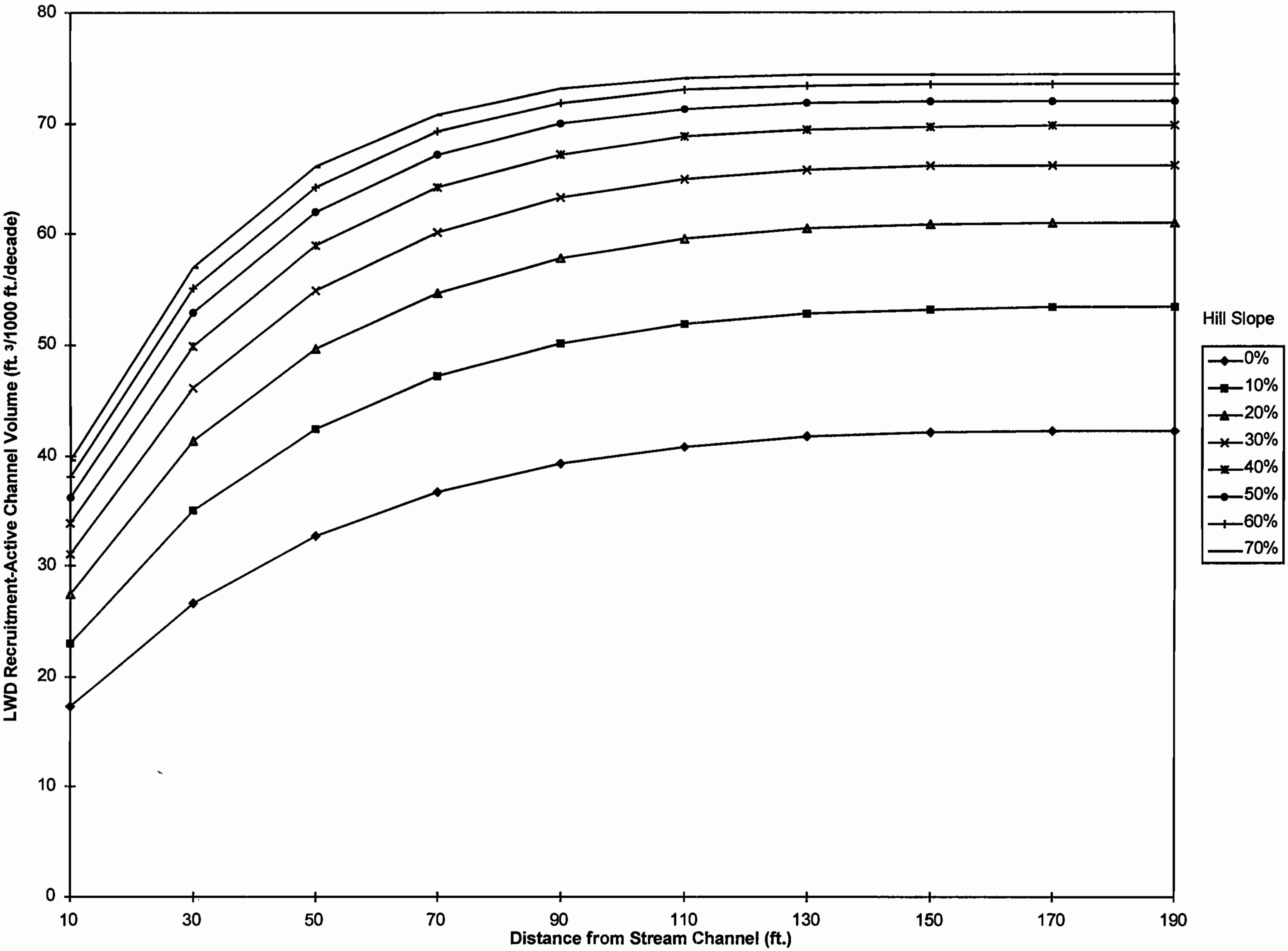


Figure 12. Large woody debris recruitment in the active channel.

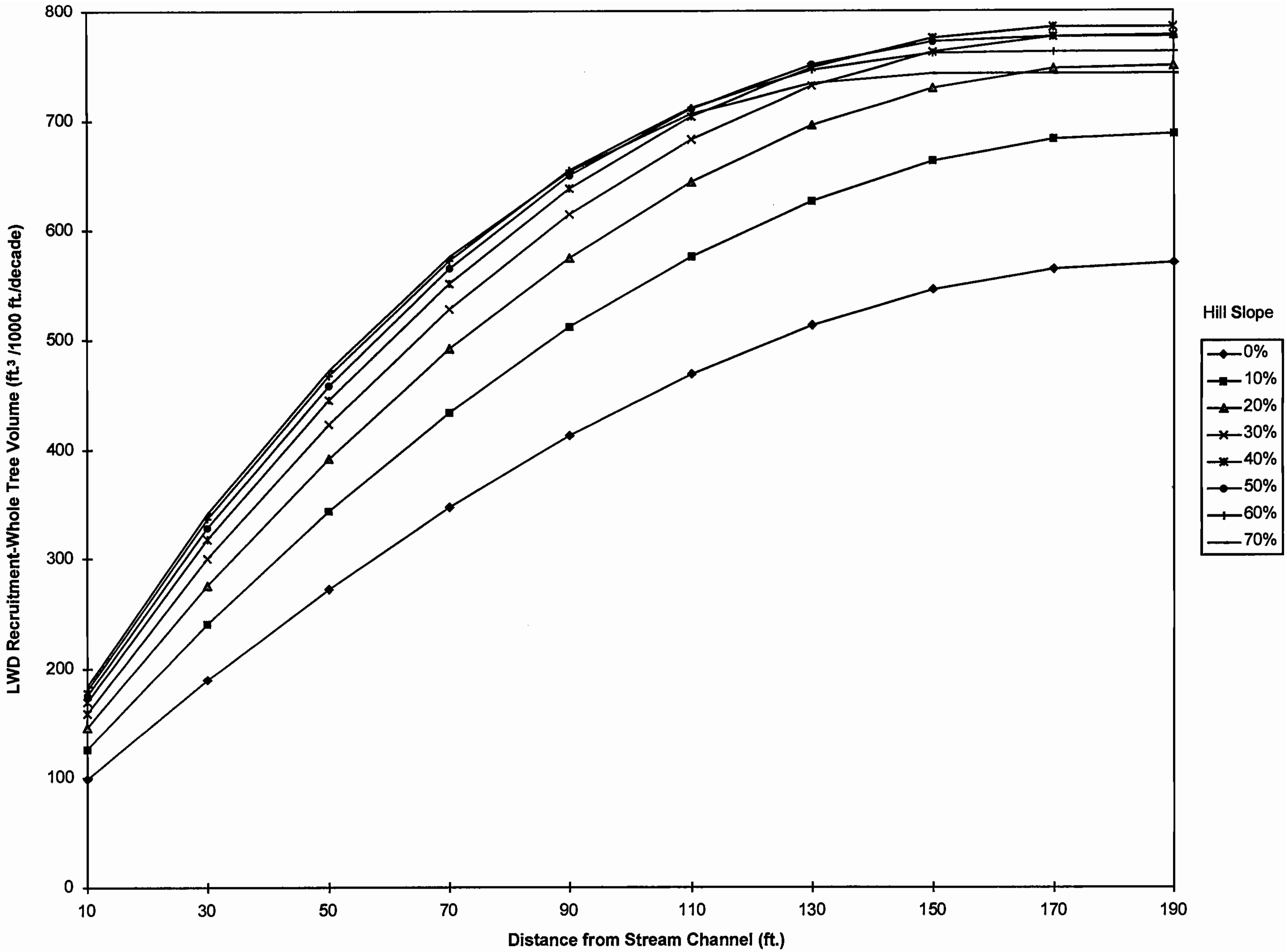


Figure 13. Large woody debris recruitment of whole tree reaching the stream channel.

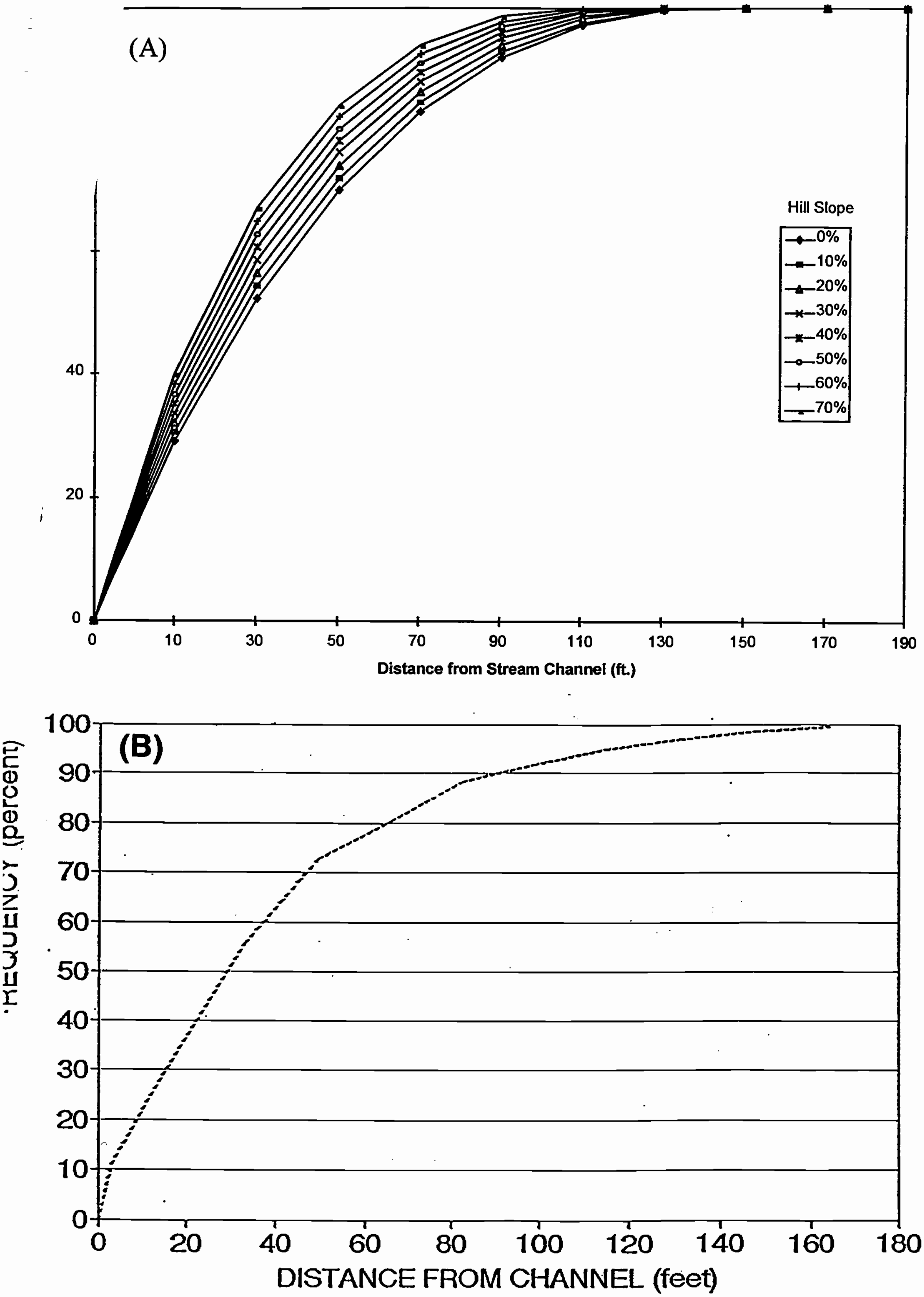


Figure 14. Comparison between test riparian polygon and McDade. (A) Modelled large woody debris recruitment (this study) relative to (B) that measured by McDade (1987).

Conclusions

Estimating large woody debris recruitment to streams from adjacent riparian stands may be useful in determining effectiveness of various configurations of riparian buffers. It may also provide an estimate of the future quality of aquatic and terrestrial habitats in riparian zones. This model provides one way to estimate where within a riparian leave area large wood is coming from and could be useful in determining necessary widths for riparian areas to provide large woody debris recruitment over time. Where stand conditions near the stream are not uniform, this method provides explicit recognition of the stand conditions through the tree list at various distances from the stream. Forest managers could also use this model to determine the distance necessary to plant tree species for future recruitment of large woody debris as part of restoration efforts.

With further development, this model could also be integrated into forest planning on a landscape scale in one of several ways. In the simplest way, individual stream sections could be identified and average slope and stand conditions along each side of the stream modeled using the methods described in this paper. The large woody debris recruitment from each side of each stream segment could then be estimated over time. In a more sophisticated approach, the methods here could be combined with a digital terrain model. The digital terrain model would provide a more complex representation of the ground slope. While the common 30 meter pixel digital terrain models provide rough information on local slope conditions, one to three meter pixel information will be available in the near future although dense tree cover will be a continuing problem. In broken topography, tree fall could be combined with tree breakage relationships using the physical properties of trees, direction of fall, and slope to estimate ground impact in order to improve the estimate of what portion of the tree might be available for wood recruitment.

Additional information is needed to refine the probability surface. This paper has used limited tree fall data and the assumption of a circular probability surface to incorporate the effects of ground slope. As additional data becomes available, other probability surface shapes may be more appropriate. Additional explanatory variables such as local storm wind direction may be important. If so, future developments may permit the incorporation of local storm wind direction to modify the probability surface using a digital terrain model and local weather data.

This paper has provided a methodology to estimate large woody debris recruitment from adjacent riparian areas. Much additional empirical information and theoretical work remains to be done.

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Appendix

Numerical Technique for Calculating Effective Radius (R_e)

Angle θ is the direction of tree fall and is known. All angles mentioned in this technique are in radian measurement. The probability surface was considered to be a circle of radius $1/\sqrt{\pi}$. The area of the circle above the offset tree location (Figure 1) represents the proportion of the trees that will fall uphill and is calculated by:

$$P_{up} = 1 - P_{down} \tag{1}$$

Using a geometric relationship for the area of the circle bounded by the arc and the chord of the circle (P_{up}) (Chow 1959), we then solved for α iteratively and then calculated *m*. This was accomplished by comparing the known area (P_{up}) to the results of the following relationship for different α's.

$$Area = \frac{1}{8}(\alpha - \sin\alpha)(2R)^2 \tag{2}$$

Once α had been determined, *m* was calculated from the following relationship:

$$m = (1 - \cos\frac{\alpha}{2})R \tag{3}$$

Once *m* had been determined, ten trigonometric relationships were used (Figure 2) to determine R_e as follows:

$$a = R - m \tag{4}$$

$$\beta = 90\frac{\pi}{180} - \theta \tag{5}$$

$$b = a\sin\beta \tag{6}$$

$$c = b\tan\beta \tag{7}$$

$$e = \sqrt{R^2 - b^2} \tag{8}$$

$$f = e - c \tag{9}$$

$$g = f \cos\theta \tag{10}$$

$$h = \sqrt{b^2 + c^2} \tag{11}$$

$$\sin\phi = [\frac{(h+g)}{R}] \tag{12}$$

$$R_e = \frac{R\sin\phi}{\sin\beta} \tag{13}$$

A separate R_e was calculated for each 1 degree increment around the probability circle. R_e was then used to calculate the probability of tree fall in a given direction.

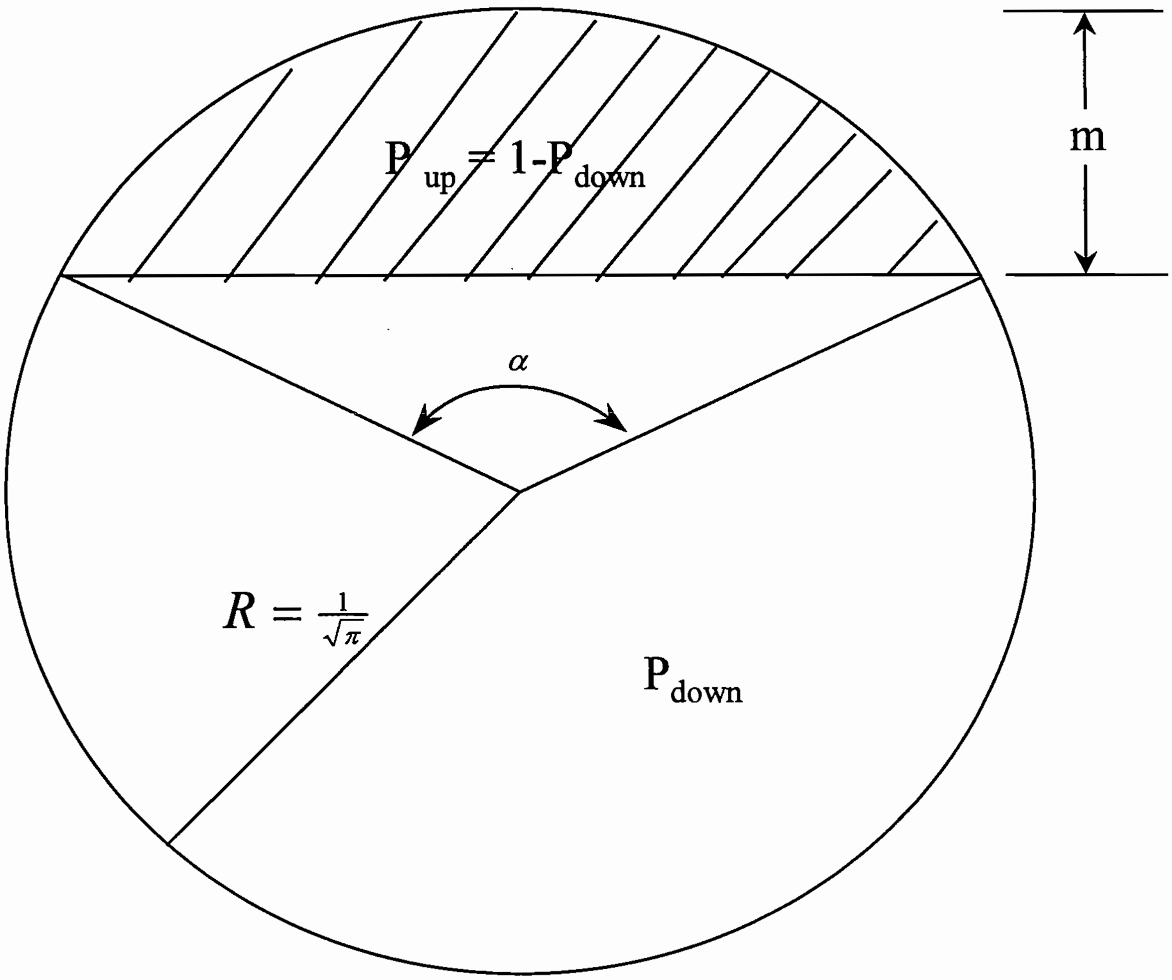

Figure 1: Tree fall probability circle.

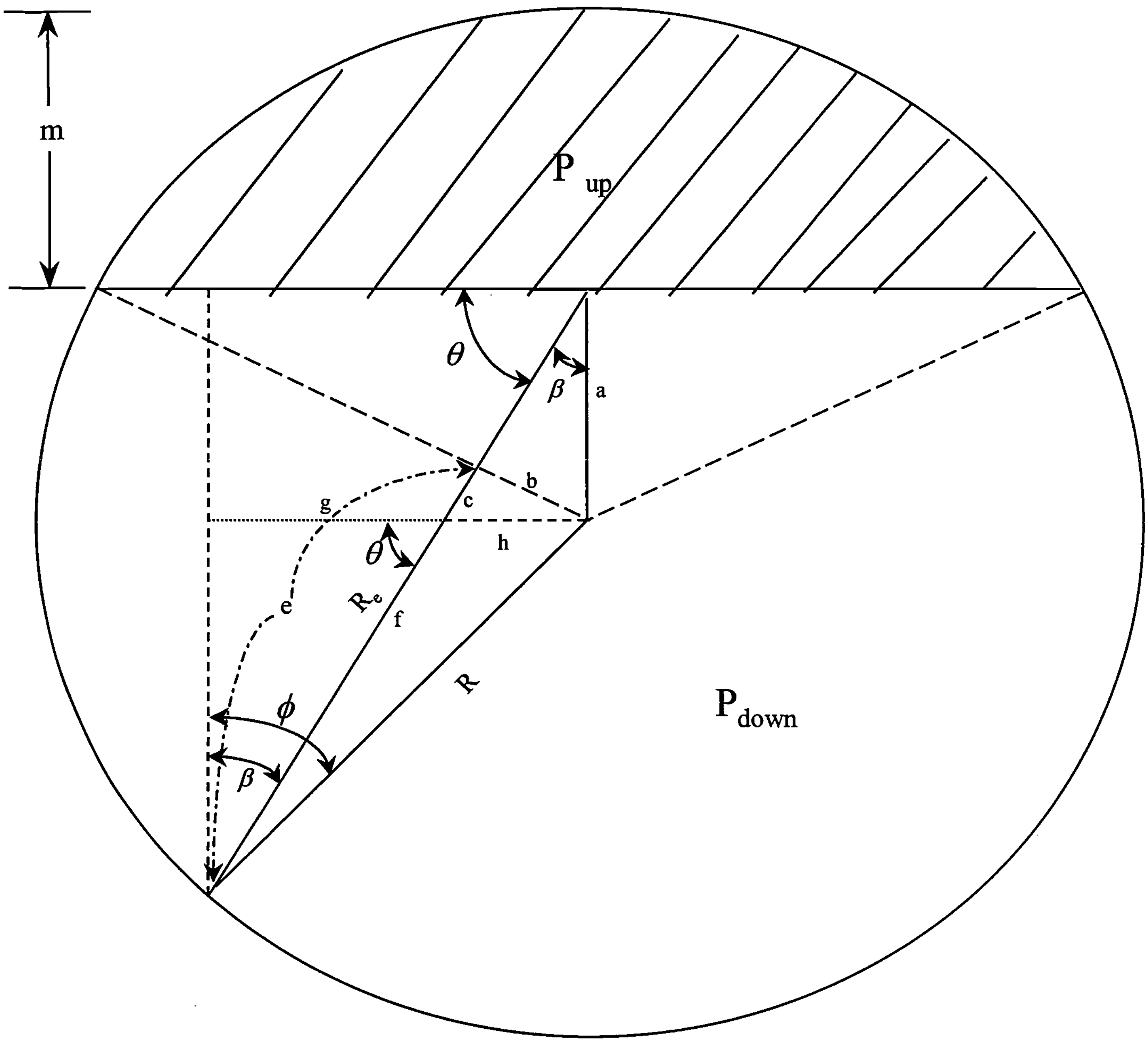

Figure 2: Determining effective radii (R_e) along the probability circle.