An Individual Tree Simulation Model for Estimating Expected Values of Potentially Available Large Woody Debris (LWD) (DRAFT)

A report prepared by

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Abstract

An individual tree based simulation model for estimating expected values of potentially available functional large woody debris (AFLWD) was developed. Potentially available LWD was defined as woody debris that could be recruited into a stream, from the standing live trees in an adjacent forest, if the trees were to fall. The simulation model was derived using the basic geometry of tree fall and stream intersection and the assumption that standing live trees in forests adjacent to streams are the source of instream LWD, through mortality, bank erosion, windthrow, among other input processes. Given the fixed locations of trees at any point in time, estimates of potential LWD availability may be more relevant from a regulatory perspective than direct estimates of LWD recruitment, transport, and decay within a stream.

Expected AFLWD values were estimated for 120 year old riparian forests in western Washington (USA) using data from 179 sample plots representing Douglas-fir (*Pseudotsuga menziesii*) dominated stands at elevations less than 2500 ft. Minimum dimensions of LWD logs that function within a stream channel, providing bank stability, forming pools, etc., were assumed to vary with stream size, with larger streams requiring larger functional LWD logs than smaller streams. A size distribution of the estimated AFLWD values was obtained by using five nominal stream size classes having bank-full widths from 5.0 ft to 75.0 ft and associated minimum functional LWD log dimensions.

Values were computed for volume (ft^3ac^{-1}) and number of pieces ($n\ ac^{-1}$) for a 170 ft wide, one acre buffer on one side of a stream representing 256.2 ft of stream reach. Stream intersection probabilities within the model were derived by assuming a uniform distribution for tree fall directions, that trees within a forest stand adjacent to a stream were uniformly distributed, and that LWD logs were produced by perpendicular tree fall toward the adjacent stream. Perpendicular tree fall directions were used so that the maximum effective buffer width, the buffer width containing the trees most likely to contribute to instream LWD, could be estimated.

Mean expected AFLWD volume (piece) values ranging from 592.6 ft^3ac^{-1} (1.7 pieces ac^{-1}) for the largest stream class to a value of 1435.7 ft^3ac^{-1} (17.9 pieces ac^{-1}) for the smallest stream class were predicted by the model. The model also predicted that approximately 50% of the AFLWD volume (pieces) would occur within 11.1 ± 7.3 ft (12.6 ± 10.2 ft) of the stream for the largest stream class and within approximately 24.2 ± 4.2 ft (34.7 ± 9.3 ft) of the stream for the smallest stream class. Approximately 90% of the AFLWD volume (pieces) was predicted to occur within 41.5 ± 20.3 ft (46.4 ± 25.5 ft) of the stream for the largest stream class and within 69.3 ± 10.6 ft (92.8 ± 18.0 ft) of the stream for the smallest stream class.

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Acknowledgements

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Chapter 1

Introduction

An understanding of the roles played by forests that are adjacent to streams has become an important component of forest management in the Pacific Northwest and in Washington State (FFR, 1999, Ehlert and Mader, 2000, Fairweather, 2001). These roles include, but are not limited to, bank stability, shade, habitat for wildlife, and the production of large woody debris (LWD). The presence of LWD in a stream influences the channel morphology, the frequency, size, and structure of pools, the rates and locations of sediment deposition, as well as providing suitable habitat for fish (Bilby and Ward, 1989, McDade et al., 1990, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Welty et al., 2002). The ability of a forest adjacent to a stream to produce LWD that may be recruited into the stream channel over time has become of particular importance in Washington State since the passage of its new forest practices rules for riparian areas (FFR, 1999, WFPB, 2001).

Given the importance of instream LWD to stream function, and its role in the creation of potential fish habitat, a number of models have been developed to estimate expected LWD contributions to a stream from the adjacent forests, as well as providing estimates of some of the characteristics, e.g., size, of LWD logs that may be produced (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Cross, 2002, Welty et al., 2002). The LWD estimation models may be divided into two general types: LWD recruitment models (Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) and LWD availability models (Robison and Beschta, 1990, Cross, 2002). Both types of models estimate the *potential* for LWD production from forests adjacent to a streams, as neither approach can predict the actual amount of LWD that a particular riparian forest will produce, nor can they predict the actual amount of instream LWD at a particular location and point in time.

The LWD recruitment models estimate expected amounts of LWD that *has potentially been recruited* into a stream channel from the adjacent forests (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). The objective of LWD recruitment models is to identify the potential amount of LWD that is likely to actually enter a stream from trees that fall in the adjacent forest and other sources of LWD input, e.g., transport from upstream, at any point in time, or the overall recruitment rate (Robison and Beschta, 1990, Van Sickle and Gregory, 1990). The recruitment rate, which may vary over time and can include terms for LWD loss due to transport or decay, is then integrated over time to obtain an estimate of the amount of LWD potentially recruited into a stream channel from the adjacent forest, and other sources, during the time period of interest (Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002).

The LWD availability models, on the other hand, estimate expected amounts of LWD that *could potentially be available for recruitment* into a stream channel from the adjacent forest (Robison and Beschta, 1990, Cross, 2002). The objective of an LWD availability model is to identify the potential amount of LWD that is likely to be available to enter a stream at the current time based on the stock of standing live trees in the adjacent forest. Trees that have already fallen have either contributed to instream LWD or not by the current time, and are assumed to not influence the potential amount of available LWD. Standing dead trees or snags may potentially contribute to instream LWD if they fall and intersect a stream but their influence is expected to be small, as they are typically smaller trees, relative to the surrounding forest, and they occur at lower densities, relative to the standing live trees.

The LWD recruitment models and LWD availability models are closely related, being essentially opposite sides of the same coin, with LWD recruitment models being past-looking and cumulative, while LWD availability models are future-looking and instantaneous. The LWD availability models approach the problem from the perspective of the *source* of instream LWD, while the LWD recruitment models take the perspective of a *sink* or final disposition of fallen trees that intersect a stream. When LWD is actually recruited into a stream channel, the LWD must have come from the pool of potentially available LWD in the forests adjacent to the streams within a watershed, i.e., the standing live or recently dead trees that fell and intersected a stream. Given sufficiently good estimates of tree fall rates, fall directions, and LWD recruitment rates, estimates from an LWD availability model could be used to determine estimates of LWD recruitment into a stream channel.

Three factors directly impact the production of instream LWD, and, hence, models that are developed to estimate it: 1) the probability of tree fall and stream intersection, 2) the distribution of tree sizes within a riparian area, and 3) the locations of the individual trees in a riparian area relative to a stream. A fourth factor, whether a model aggregates based on area or trees, is also important, and affects the spatial resolution obtainable by a particuloar model. Each of these factors is discussed in turn, with brief descriptions of how they have been addressed in existing LWD recruitment and availability models, highlighting some of their potential limitations. Finally, a need for greater detail and flexibility in LWD models is identified, and a simulation based modeling alternative is proposed as a framework for model development and use to overcome some of the limitations of existing models while providing a high level of detail and flexibility.

1.1 Tree fall and stream intersection

The determination of the probability of a tree falling and intersecting a stream so that a piece of instream LWD is produced is the most fundamental component of any LWD recruitment or availability model. A number of factors may affect the probability that a tree would fall and intersect a stream to produce LWD including, but not limited to, the distance of a tree from a stream, the height of a tree, the taper of a tree or its diameter, the slope of the stream bank, the wind direction and speed, bank erosion, mortality rates, soil characteristics, and edge effects (McDade et al., 1990, Van Sickle and Gregory, 1990, Welty et al., 2002). These factors are not necessarily independent of one another, and they may interact in a complex manner.

The LWD recruitment models typically model the tree fall and stream intersection probabilities directly by assuming the existence of a tree fall rate, and then combining this rate with a probability of stream intersection model to obtain estimated values for potential instream LWD (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). Large uncertainties, however, are present in the rates of tree fall for riparian forests, given the many possible physical causes of tree fall (Beechie et al., 2000, Welty et al., 2002). The LWD recruitment models typically simplify the problem by assuming that mortality is the sole source of instream LWD, that tree fall rates are directly related to rates of stand mortality, and that tree fall rates are independent of the probability of stream intersection, (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). In making these assumptions, that fact that mortality is only one possible cause of tree fall and recruitment is acknowledged, but other sources of recruitment are generally not included. The large uncertainties that exist for tree fall rates and the reliance on stand mortality alone as the source of potentially recruitable LWD may limit the applicability of the current generation of tree based LWD recruitment models that make these assumptions.

Other LWD recruitment models include a broader range processes for LWD recruitment into a stream, e.g., bank erosion, scouring, etc., as well as complex LWD bugeting schemes, but directly accounting for the myriad of processes and factors that affect the amount and distribution of LWD within streams or watersheds and their interactions is a daunting task, and while technically feasible, a paucity of data are available for the development and validation of these complex models (Benda et al., 2003, Benda and Sias, 2003, Gregory et al., 2003, Hassan et al., 2005). Further, current levels of LWD have high variability and rates for the gain and loss of instream LWD have significant uncertainty associated with them, in particular input rates of LWD to streams and decay and transport of LWD already in a stream (Benda et al., 2003, Benda and Sias, 2003, Gregory et al., 2003, Hassan et al., 2005). Finally, large LWD input events caused by floods, landslides, or wind storms, for example, occur sporadically at irregular times, and are therefore difficult to predict, both in terms of timing and magnitude (Acker et al., 2003, Benda et al., 2003, Benda and Sias, 2003, Gregory et al., 2003, Hassan et al., 2005). These types of LWD recruitment models, therefore, may have a high degree of uncertainty incorporated into their formulations, which may limit their applicability, particularly in a regulatory context.

The LWD availability models, however, typically use only a probability of stream intersection model with the standing stock of live trees, and possibly snags, to estimate the LWD that could potentially be available for recruitment into a stream (Robison and Beschta, 1990, Cross, 2002). The LWD availability models, therefore, do not require assumptions for a tree fall rate, transport of LWD witihin a stream, decomposition and breakage, etc., and they automatically account for mortality and ingrowth by considering the standing live trees at a particular point in time as an estimate of the source of future LWD logs that could potentially contribute to instream LWD. An LWD availability model may, then, provide a simpler basis for model development, with the potential of having a lower level of uncertainty in its formulation, making these types of models more relevant within a regulatory context.

The uncertainty associated with the amount of LWD that is actually recruited into a stream at a particular location and point in time is the same for either type of model. The possibility for lower overall uncertainty from LWD availabiltiy models relates only to model formulation and interpretation of model outputs, and stems from the fact that LWD avilability models include fewer processes and their associated uncertainties than LWD recruitment models.

The probability of stream intersection has been modeled similarly for both LWD recruitment and availability models. Probabilities of stream intersection have been assumed to depend on a distribution of tree fall directions, the size (height) of a tree, and its perpendicular or slope distance from a stream, and the slope of the stream bank (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Cross, 2002). The physical geometry of the tree location relative to the stream and the tree size have been used to identify a range of tree fall directions that would result in a stream intersection, independent of other factors, if it were to fall. The range of stream intersecting tree fall directions has then been used with a distribution of tree fall directions to compute a probability of stream intersection. A uniform distribution of tree fall directions has typically been assumed (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Cross, 2002), but is not necessary.

The primary limitations in computing probabilities of stream intersection in the current generation of tree-based LWD recruitment and availability models are the assumptions that trees fall independently of one another and a lack of factors such as stand density, which could impact the stream intersection probability through both tree size and tree location. Van Sickle and Gregory (1990) have provided a more general formulation of the stream intersection problem that could be used with empirically determined tree fall direction distributions, but it also does not directly account for other factors, in particular stand density, in determining stream intersection probabilities, emphasizing fall direction while assuming that trees fall independently of one another. An LWD availability or recruitment model that extends the stream intersection probability to a more general representation could provide additional flexibility and better agreement with actual stream intersection probabilities.

1.2 Tree size distribution

Tree size affects the production of instream LWD: larger trees may produce larger pieces of LWD, depending on their distance from a stream. This is particularly relevant for the production of functional LWD, for which the number of LWD pieces and the size of LWD logs varies by stream size (Bilby and Ward, 1989, 1991, Beechie and Sibley, 1997, Beechie et al., 2000, Welty et al., 2002). The frequency of LWD logs providing for stream functions, e.g., pool creation, is lower for larger streams than for smaller streams, and the dimensions of the functional LWD logs are also greater for the larger streams (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Welty et al., 2002). Assumptions relating to the distribution of tree sizes in forested riparian areas, then, directly affect the amount of potential LWD estimated using a particular recruitment or availability model.

LWD recruitment models and LWD availability models both require some assumptions about the distributions of tree sizes. Tree height is the size attribute having the most influence on the production of LWD, through the stream intersection probability, so size distributions have most frequently been stated in terms of height distributions. Tree heights have been assumed to be equal for all trees (McDade et al., 1990, Cross, 2002), or to be uniformly distributed through one or more ranges (Van Sickle and Gregory, 1990). Tree size distributions have also been based on tree diameters (Robison and Beschta, 1990).

The size distribution assumptions were made to simplify the computations necessary when deriving the formulas used to estimate potential LWD for a forested riparian area. The assumption of a uniform distribution for tree size, or a mixture of uniform distributions, may not reflect the variability of the actual tree size distributions that are known to occur, e.g., bell shaped, skewed, or multimodal distributions. The assumption of a uniform distribution of tree heights may, therefore, be too restrictive. An LWD availability or recruitment model having no height, or tree size, distribution restrictions would be preferable, and should be feasible to produce.

1.3 Tree location relative to a stream

The location of a tree relative to a stream, given by its perpendicular or slope distance from the stream, also significantly affects the potential production of instream LWD: large trees may produce large pieces of LWD if they are close to the stream, or they may produce no LWD or small pieces of LWD if they are located far from the stream. Again, this is particularly relevant for the production of functional LWD for which the number of LWD pieces and the size of LWD logs varies by stream size (Bilby and Ward, 1989, 1991, Beechie and Sibley, 1997, Beechie et al., 2000, Welty et al., 2002).

LWD recruitment models and LWD availability models both require assumptions about the distribution of tree distances from a stream. This distribution has typically been assumed to be uniform within the riparian area of interest (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Cross, 2002, Welty et al., 2002). Although the same distribution was assumed for perpendicular or slope tree distances from a stream in all cases, the manner in which it was used differed among the models. The majority of models (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) used the uniform distribution assumption to compute, and integrate, the potential LWD production as a continuous value throughout a riparian buffer of fixed width. Cross (2002), on the other hand, used this assumption to identify the midpoint of a fixed width buffer as the average location of the trees when computing potential LWD production.

While the assumption of a uniform distribution may not be unwarranted, using it in a continuous manner to compute potential LWD production fails to recognize the discrete nature of trees and their locations relative to a stream, and the effects of the discrete tree locations on the production of LWD in an actual riparian forest. Similarly, the use of a single distance from a stream, or several distances, for tree placement to compute potential LWD production over simplifies the relationships between tree location relative to a stream and potential LWD production in an actual riparian forest. Further, the use of a small number of tree distances or zones may not be wholly justified by the assumption of a uniform distribution, particularly given the discrete nature of tree locations. The locations of individual trees relative to a stream, even if trees are distributed uniformly, has a significant impact on the potential for production of LWD. An LWD availability or recruitment model capable of using independent distances from a stream for each tree in a riparian area, recognizing the discreteness of the trees as well as their locations, is therefore desirable.

1.4 Individual tree or aggregated

Models that estimate the potential production of LWD may use the locations and sizes of individual trees within a riparian area, but they have more commonly been based on *a priori* aggregations within the riparian area. Two types of aggregation have generally been used: tree aggregation and area aggregation, and they are frequently combined. Tree aggregation uses a single tree, or an average tree, to represent multiple trees for some specified area (Cross, 2002), and area aggregation assumes uniform properties, e.g., probability of stream intersection or tree height, within a particular region, or set of regions, (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002). In the following discussion, the cited models were identified with the aggregation type that best represented their underlying structures, but all of the models had some aspects of both forms of aggregation, for example, the model of Van Sickle and Gregory (1990) aggregates both by area and tree, dividing a riparian area into strips of varying widths parallel to a stream and by tree height classes for different tree species.

Aggregated LWD models may not provide sufficient resolution for all applications, or they may require an inordinately large number of divisions, relative to the number of trees in a riparian area, if, for example, a high spatial resolution was desired for a riparian buffer. Suppose a resolution of 3.3 ft is desired for both the perpendicular distance from a stream and tree height in a riparian forest containing ten tree species, for a 170 ft wide one acre buffer, assuming a maximum tree height of 164 ft. The model of Van Sickle and Gregory (1990) would require $10 \times 170/3.3 \times 164/3.3 = 25601$ individual distance$\times$height$\times$species cells, a number that is likely to greatly exceed the number of trees present that could potentially contribute LWD to the adjacent stream. Decreasing the spatial resolution by a factor of two, to a 6.6 ft resolution, reduces the number of cells dramatically, to 6400, which may still be quite large relative to the number of trees that could potentially contribute LWD to the stream. Increasing the spatial sizes of the cells, reducing their resolution, may require averaging over relatively large areas, discounting the actual locations of the individual trees that could contribute LWD to a stream channel by distributing their contributions over the area represented by a cell.

Further, the locations of individual trees relative to a stream in a managed riparian buffer are important from regulatory, biological, and economic perspectives. Trees in managed riparian buffers will most likely be located to provide maximum benefit to an adjacent stream, to achieve regulatory compliance, or to minimize management costs, particularly for landowners who may, for simplicity, remove some or all of a riparian buffer area from active management. Models representing potential LWD production that account for the individual tree locations relative to a stream rather than using tree or area based aggregation may, therefore, be preferable, from regulatory, biological, and computational perspectives: each tree would represent itself, providing its own contribution to LWD, allowing for localized clumping or other discrete distributional characteristics, and computational effort becomes proportional to the number of trees large enough to potentially contribute to LWD rather than the number of cells in an arbitrary spatial grid.

1.5 A simulation based model for LWD availability

As the factors affecting the development of models for estimating the potential production of instream LWD were discussed, a number of potential limitations to existing approaches were identified. An individual tree based simulation model for LWD availability may provide a means to eliminate or reduce the impacts of many of the identified model limitations. Such a model would take as input a tree list describing the sizes, species, and numbers of trees in a forested riparian stand adjacent to a stream and produce an estimate of the potential for LWD production or, preferably, an estimate of a distribution of potential LWD values. This approach is consistent with the use of individual tree based forest growth simulators, which typically use tree lists to represent forest stands (Belcher et al., 1982, Donnelly, 1997, Hann et al., 1997). The potential LWD production for a managed or unmanaged riparian buffer area represented by a tree list, or a sequence of actual or projected tree lists, could then be estimated directly from each tree list using the following basic simulation algorithm.

1. Randomly place each tree represented by the tree list relative to a stream within a well defined riparian buffer area using some distribution of tree distances from a stream. This may be a theoretical distribution, such as the uniform distribution, or an empirically derived distribution, if available.

2. Determine the probability of stream intersection for each tree using a distribution of tree fall directions, the tree sizes, and their random locations relative to the stream.

3. Compute the potential LWD contribution for each tree. This may include computing the dimensions or volume of the potential LWD pieces. This step may also include a simulation component, for example to determine whether a tree produces multiple LWD pieces or a single piece.

4. Combine the LWD contributions from the individual trees to obtain the total potential LWD contribution for the riparian area.

5. Repeat steps 1 through 4 a number of times to compute a statistical summary, which could include the mean and standard deviation or an estimate of a potential LWD distribution, to obtain estimates of the desired potential LWD contribution.

By modeling LWD availability much of the uncertainty introduced into the potential LWD recruitment models by their use of tree fall rates and stand mortality alone to specify the potential production of instream LWD, or the usee of complex budgeting schemes, may be reduced. By using the tree list directly, the need to assume a tree height, or size, distribution has also been eliminated, the heights, or sizes, of the trees in the tree list are simply used. By randomly placing each tree relative to a stream the discreteness of the trees is recognized, allowing their actual locations to influence their potential LWD contributions to a stream. Placing each tree relative to a stream also helps to resolve a number of issues related to aggregation, particularly the averaging of potential LWD production over large regions.

A simulation model for potential LWD production may be specified by identifying a tree fall direction distribution for computing stream intersection probabilities which may be used to derive a distribution of stream intersecting tree fall directions, a distribution of the distances of trees from a stream, and a model for determining the potential LWD contribution from each tree in a tree list. Variability in the values of potentially available LWD may then be estimated directly through the simulation processs, requiring no additional distributional assumptions. Using an LWD availability model within the simulation model makes effective use of available data by directly using the individual trees from available tree lists and by permitting the distributions for tree fall direction and the distances of trees from a stream to be directly specified and used. As additional information about the production of instream LWD becomes available, assumptions about the tree fall direction or tree distances from a stream may be modified by changing their respective distributions.

In the next chapter, a general framework for specifying a simulation model to estimate potential LWD production is described. The model is an LWD availability model, but the framework could be readily modified for an LWD recruitment model. Following the description of the general simulation framework in Chapter 2, the simulation model is applied to estimate mean expected values for potentially available LWD volume and piece count for unmanaged, 120 year old Douglas-fir (*Pseudotsuga menziesii*) dominated riparian areas in western Washington. The general model was specialized to this application by specifying the requisite distributions and procedures used to compute the potential LWD contribution from each tree. The application, the distributions used, the computational procedures, and the data are described in Chapter 3, followed by results of the simulations in Chapter 4. A brief discussion of the performance of the simulation model is provided in Chapter 5, followed by some concluding remarks.

Chapter 2

Methods

Given the myriad of factors influencing the probability of a tree falling and intersecting a stream to produce a large woody debris log, it would be difficult, if not impossible, to account for them all. The possible physical causes for tree fall and the probabilities of their occurrence were, therefore, not directly addressed in the development of the LWD simulation model. Instead, all standing, live trees within a riparian forest were considered to be capable of potentially contributing LWD to a stream, weighted by an estimate of their probability of intersecting the stream *if* they were to fall. The model, therefore, is a potential LWD availability model, providing estimates of the amount of LWD that *could* potentially be available for recruitment into a stream. The model does *not* estimate the amount of LWD that *has* been recruited into a stream or that *would* be recruited into a stream.

A simulation framework was selected for the LWD availability model since the same forest structure, as represented by the numbers and sizes of trees in a riparian area, could produce a variety of LWD amounts and LWD log sizes, depending on the locations of the individual trees relative to a stream. In the LWD availability simulation model, the distributional aspects of the primary physical factors influencing the production of LWD were emphasized: the probability of stream intersection for each tree, the location of each tree relative to a stream, and the presence of trees of differing sizes in a riparian area. The distributional characteristics of the model may be easily modified by changing the shapes of the distributions associated with the various simulation based aspects of the model.

The LWD availability simulation model as developed has six components: 1) a submodel for generating potential stream intersecting logs, computing their sizes and volumes, and identifying potential LWD logs and potential functional LWD logs for different nominal stream sizes; 2) a submodel specifying the probability of stream intersection; 3) a submodel for the distribution of tree fall directions relative to a stream; 4) a submodel for the distribution of the perpendicular or slope distances of trees from a stream; 5) procedures for computing expected values for potentailly available LWD volume and piece count using the computed stream intersection probabilities; and 6) a simulation procedure that was used to obtain estimates of the expected potentially available LWD volume and piece count, and approximations to the distributions of these riparian forest attributes. The specific objectives for the model are defined next in Section 2.1, followed by definitions and notation in Section 2.2, and then by descriptions of the LWD simulation model components in Section 2.3 through Section 2.8.

2.1 LWD availability model objectives

The primary objectives for the potential LWD availability simulation model were to provide a first order approximation to the LWD log generation processes for forests adjacent to streams. Specifically, estimates of both total and functional log volumes and piece counts, as well as estimates of their respective distributions, that were in qualitative agreement with trends and values from available empirical studies (Bilby and Ward, 1989, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Fox, 2001) for different stream sizes and forest structures. Quantitative agreement with empirically obtained LWD volume and piece count values, while also important, was a secondary objective, as it could be improved through refinements to the basic simulation model.

The total number of potential LWD pieces and the total LWD volume produced by forests adjacent to streams were assumed to be independent of stream size across a landscape or within a sufficiently large region (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990). This assumption does not imply that LWD production is identical for all forest structures and all stream sizes; LWD piece count and volume values clearly depend on the structural characteristics of a particular forest relative to a stream, e.g., the stand density, the tree size distribution, and the distances of the trees from a stream, or more simply whether the forest may be considered to be in a particular structural class such as old-growth, second growth, or a younger managed forest. Instead, the assumption implies that the distribution of potential LWD piece count or volume values that may be produced by a particular forest structure does not vary as a function of stream size. For example, old growth riparian forests having similar characteristics within a particular region would be expected to have similar potential to produce LWD for recruitment into a stream. Potentially available total LWD piece count and volume values will be referred to using the acronym ALWD.

The number of functional LWD pieces and the sizes of functional LWD logs are known to vary by stream size (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Fox, 2001, Welty et al., 2002). The frequency of LWD logs providing stream function, e.g., pool creation or bank stability, is lower for larger streams than for smaller streams, and the functional LWD logs are also larger for the larger streams (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Fox, 2001, Welty et al., 2002). This implies that the total number of LWD logs produced by a forest adjacent to a stream is greater than the number of LWD logs that function within a stream, and that the average size of LWD logs produced by a forest adjacent to a stream is smaller than the average size of functional LWD logs within that stream. Given the dependence of functional LWD on stream size, a potentially available functional LWD log for a particular stream size was assumed to be an ALWD log that was large enough to function within a stream for a particular stream bank full width, that is, an ALWD log that exceeded some minimum log diameter and log length, or volume requirement (Beechie et al., 2000, Welty et al., 2002). Potentially available functional LWD piece count and volume values computed using minimum log sizes to identify functional LWD logs for different stream size classes will be referred to using the acronym AFLWD.

2.2 Definitions and notation

The fundamental concepts and basic notation used to specify the LWD simulation model are now defined. For a tree in a forested area adjacent to a stream, let D^{dbh} be its diameter at breast height (DBH), H be its total height, and d be its perpendicular or slope distance from a stream, measured from the center of the base of the tree at ground level. The tree DBH value was assumed to be positive, $D^{\text{dbh}} > 0$, since trees having heights less than breast height contribute little, if any, LWD to a stream. This implies that total tree height must be at least breast height, $H \geq 4.5$ ft. The perpendicular or slope distance of a tree to a stream was assumed to be nonnegative, $d \geq 0$, that is trees do not grow wholly within a stream, but may have up to half of their diameter at ground level located within the bank full width of a stream channel.

Let f_{taper} be a taper function giving the diameter D of a tree at any height h above the ground for a tree having a DBH of D^{dbh} and a total height H, where $D = f_{\text{taper}}(h; D^{\text{dbh}}, H)$ and $0 \leq h \leq H$. The taper function f_{taper} was assumed to be continuous and monotonically decreasing in the interval $[0, H]$, with $f_{\text{taper}}(H; D^{\text{dbh}}, H) = 0$. The inverse taper function f_{taper}^{-1}, then, exists, and gives the height above the ground h at which a diameter D occurs, $h = f_{\text{taper}}^{-1}(D; D^{\text{dbh}}, H)$. The volume V of a log from the bole of a tree having a DBH of D^{dbh} and a height H between heights h_1 and h_2 with $0 \leq h_1 \leq h_2 \leq H$ is given by Equation 2.1, where $k = \frac{\pi}{4 \cdot 144} = 0.005454$.

$$V(h_1, h_2; D^{\text{dbh}}, H) = k \int_{h_1}^{h_2} \left[f_{\text{taper}}(h; D^{\text{dbh}}, H) \right]^2 dh \tag{2.1}$$

The *effective height* of a tree, H^{eff}, was defined to be the height from the ground to a point on the tree where a minimum upper stem diameter, or effective LWD diameter, $D^{\text{eff}} \geq 0$, was reached (Robison and Beschta, 1990, Van Sickle and Gregory, 1990). If the minimum effective diameter is zero, $D^{\text{eff}} = 0$, then the effective height is equal to the total tree height, $H^{\text{eff}} = H$. If the base diameter of the tree, the diameter at the ground or $h = 0$, is less than the minimum effective LWD diameter, $f_{\text{taper}}(0; D^{\text{dbh}}, H) \leq D^{\text{eff}}$, then the effective height of the tree was defined to be zero, $H^{\text{eff}} = 0$. The effective height for a tree was obtained using the inverse taper equation as in Equation 2.2.

$$H^{\text{eff}} = \begin{cases} f_{\text{taper}}^{-1}(D^{\text{eff}}; D^{\text{dbh}}, H), & \text{if } f_{\text{taper}}(0; D^{\text{dbh}}, H) > D^{\text{eff}} \\ 0 & \text{otherwise} \end{cases} \tag{2.2}$$

The use of a nonzero effective LWD diameter D^{eff} and the consequent effective height reduces the influence of the tops of trees when computing estimates of instream LWD. Very small pieces produced by the tops of trees intersecting a stream could substantially increase estimates of the number of instream LWD pieces while having little impact on the volume, or quality, of instream LWD. To avoid this situation the effective LWD diameter and effective height were used to constrain the portion of a tree bole that could be considered as contributing to instream LWD.

The *potential stream intersection region* for a tree having an effective height H^{eff}, located a perpendicular or slope distance d from a stream, where $d < H^{\text{eff}}$, was defined as the set of tree fall directions θ that could lead to a stream intersection, independent of any particular distribution of fall directions. To identify a potential stream intersection region, a tree was assumed to be able to fall in any direction, giving a range of possible fall directions from zero to 360 degrees or 2π radians. The perpendicular fall direction toward a stream was defined as $\theta = 0$, giving fall directions $\theta \in [-180, 180]$ degrees, or $\theta \in [-\pi, \pi]$ radians, where positive fall directions are interpreted as upstream and negative fall directions as down stream.

A potential stream intersection region is shown in Figure 2.1. The circle centered at the tree, having a radius H^{eff}, identifies the region where the tree could fall, given the assumption that trees may fall in any direction. The potential stream intersection region is then delineated by the upstream and downstream radii, as indicated in the figure, where the outer end of the radius perpendicular to the stream would just touch the stream boundary when rotated upstream and downstream. These are the limiting radii for the potential stream intersection region and define the range of tree fall directions, $\theta \in (-\alpha, \alpha)$, that could produce a stream intersection if the tree were to fall. The angle α, measured from the perpendicular direction toward the stream, $\theta = 0$, to the upstream limiting radius, is the *limiting stream intersection fall direction.* Trees whose effective heights are less than their perpendicular distances from a stream, $H^{\text{eff}} < d$, are assigned limiting stream intersection fall directions of zero, $\alpha = 0$. The formula used to compute α is given in

Equation 2.3.

$$\alpha = \alpha(d, H^{\text{eff}}) = \begin{cases} \arccos\left(\frac{d}{H^{\text{eff}}}\right), & \text{if } d < H^{\text{eff}} \\ 0 & \text{otherwise} \end{cases} \tag{2.3}$$

The value of α obviously depends on the effective tree height H^{eff} and the perpendicular distance from the stream d. Three trees with their potential stream intersection regions indicated are shown in Figure 2.2. For this figure an effective diameter of zero, $D^{\text{eff}} = 0$, was used, making the effective height equal to the total height of the tree. The three trees and their respective potential stream intersection regions demonstrate that the size of the potential stream intersection region varies based on both the distance from the stream and the tree height. Tree 2 has a much larger potential stream intersection region than Tree 1, since it is much closer to the stream, and Tree 3 has no potential stream intersection region since its effective height is less than its distance from the stream, making it impossible for it to fall and intersect with the stream.

The impact of the effective LWD diameter D^{eff} on the effective height H^{eff} and the potential stream intersection region of a tree adjacent to a stream is shown in Figure 2.3. The figure shows the potential stream intersection regions for three identical trees, located at the same distance from an adjacent stream, for effective LWD diameters of $D^{\text{eff}} = 0$ inches, $D^{\text{eff}} = 4$ inches, and $D^{\text{eff}} = 8$ inches, from left to right. As the effective LWD diameter increases the effective height decreases, and the potential stream intersection region narrows and contracts toward the tree. In this example, the leftmost and center trees could fall and intersect the stream, their effective heights are greater than their distances to the stream, but the rightmost tree could not, as its effective height is less than its distance to the stream.

2.3 Log types, dimensions, and volume

The determination of the size of a log produced by a tree that has fallen and intersected a stream requires a fixed point of reference relative to both the tree and the stream. The point of near bank stream intersection provides such a point of reference and was used to derive the formulas for computing the dimensions and volume of that segment of a bole of a tree that was to be considered as a stream intersecting log. Stream intersecting logs were determined in three steps. First, identify the height on the tree bole where the point of stream intersection would occur, if the tree were to fall and intersect a stream. Next, identify the portion of a stream intersecting log resting on the stream bank that is to be included. Finally, determine the formulas used to compute the dimensions and volume of the stream intersecting log.

The height on the bole of a tree where the point of stream intersection on the near bank would occur, H^{inter}, depends on the direction of tree fall θ, where $\theta \in (-\alpha, \alpha)$, for a tree that is close enough to fall and intersect a stream, i.e., a tree having $d < H^{\text{eff}}$, see Figure 2.1. The relationship given in Equation 2.4 defines the stream intersecting height for such trees.

$$H^{\text{inter}} = \frac{d}{\cos(\theta)} \tag{2.4}$$

If a tree were to fall perpendicular to a stream, $\theta = 0$, then the height where the near bank stream intersection would occur is simply the perpendicular distance to the stream, $H^{\text{inter}} = d$, but as θ increases or decreases away from zero, $\cos(\theta)$ decreases, and the height where the near bank stream intersection occurs would increase. For $\theta = \alpha$, the stream intersection height equals the effective height of the tree, and no stream intersecting log is produced. In the event that a tree was located very close to a stream, $d \approx 0$, and a fall angle was parallel, or nearly parallel, to the stream, $\theta \approx \frac{\pi}{2}$, then the stream intersecting height was assumed to be zero, $H^{\text{inter}} = 0$. In that situation, the entire bole of the tree from its base to its effective height was considered to be a stream intersecting log.

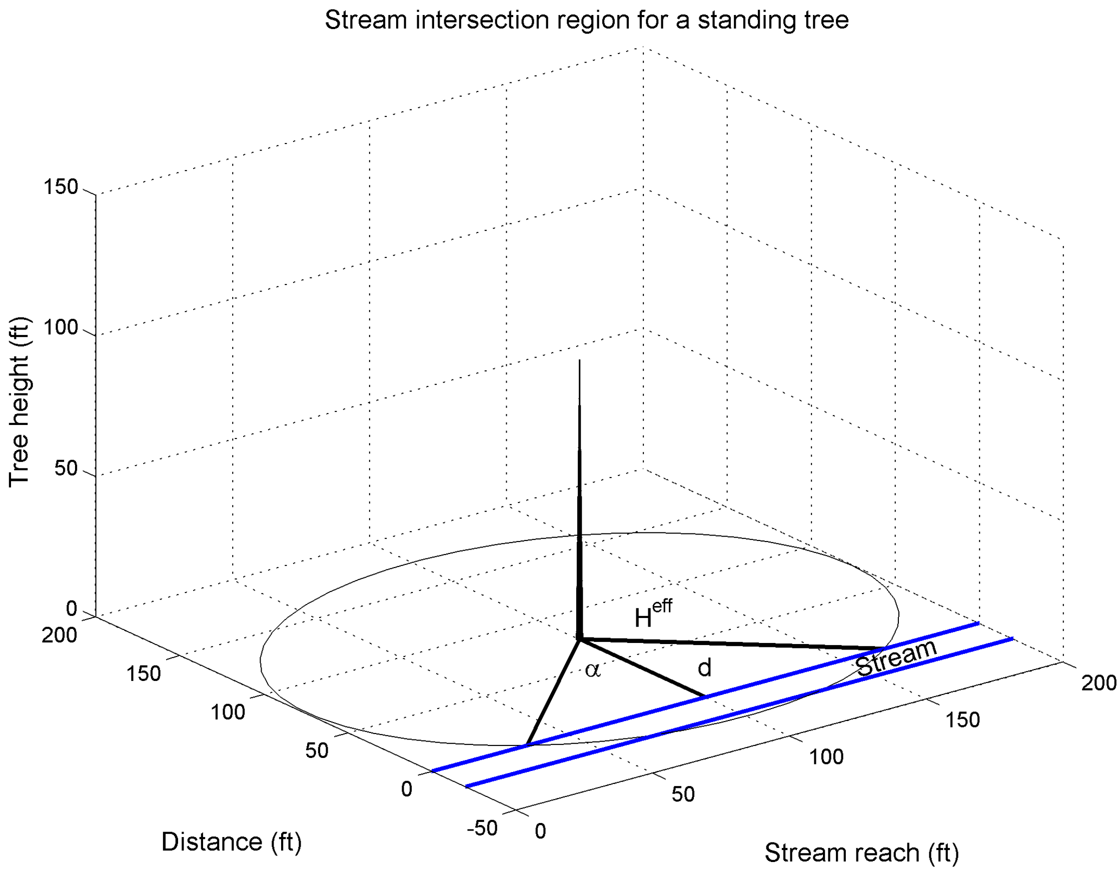

Figure 2.1: Diagram showing the potential stream intersection region assuming an arbitrary tree fall direction. The potential stream intersection region is delineated by the portion of the circle having a radius equal to the effective tree height H^{eff}, centered at the tree, between the two radial lines marking the range of stream intersecting fall directions.

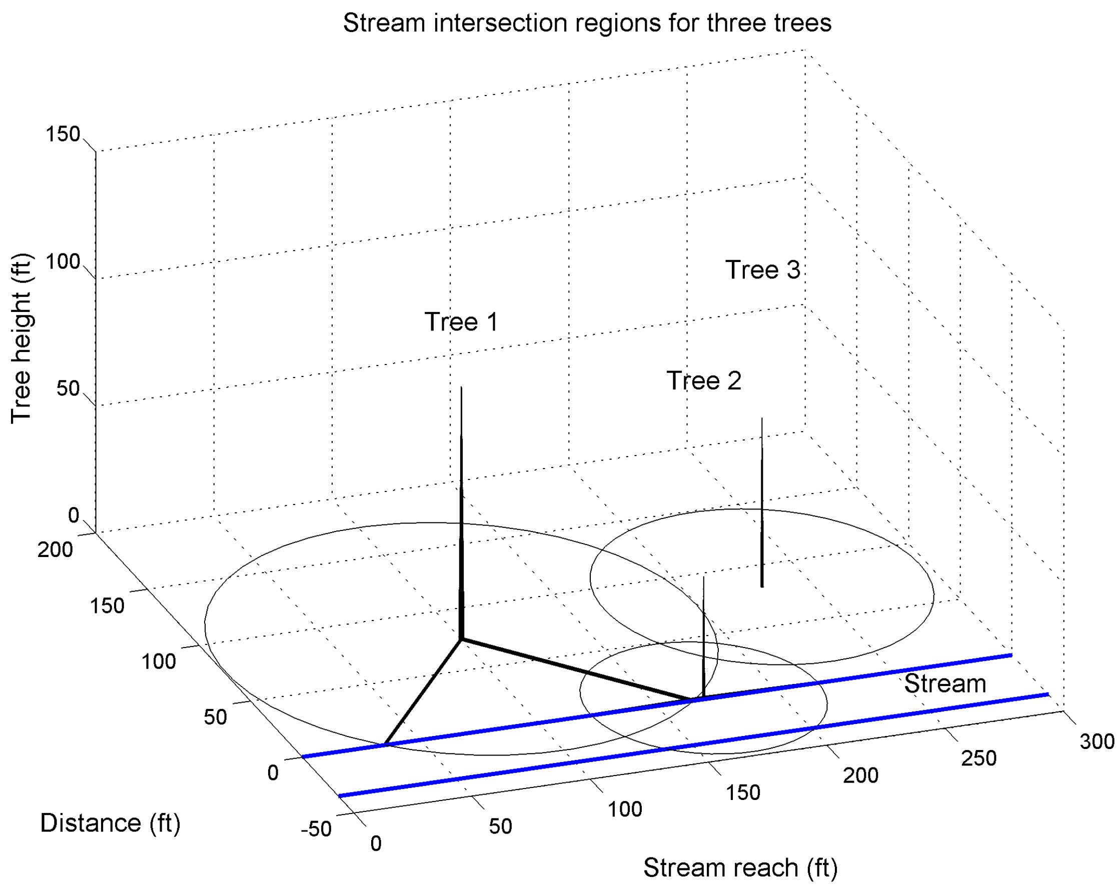

Figure 2.2: Three trees are shown with their stream intersection regions. The distance of a tree from a stream and the effective tree height both influence the potential stream intersection region. Tree 1 and Tree 2 could fall and possibly intersect the stream, but Tree 3 will not: its effective height is less than its distance to the stream.

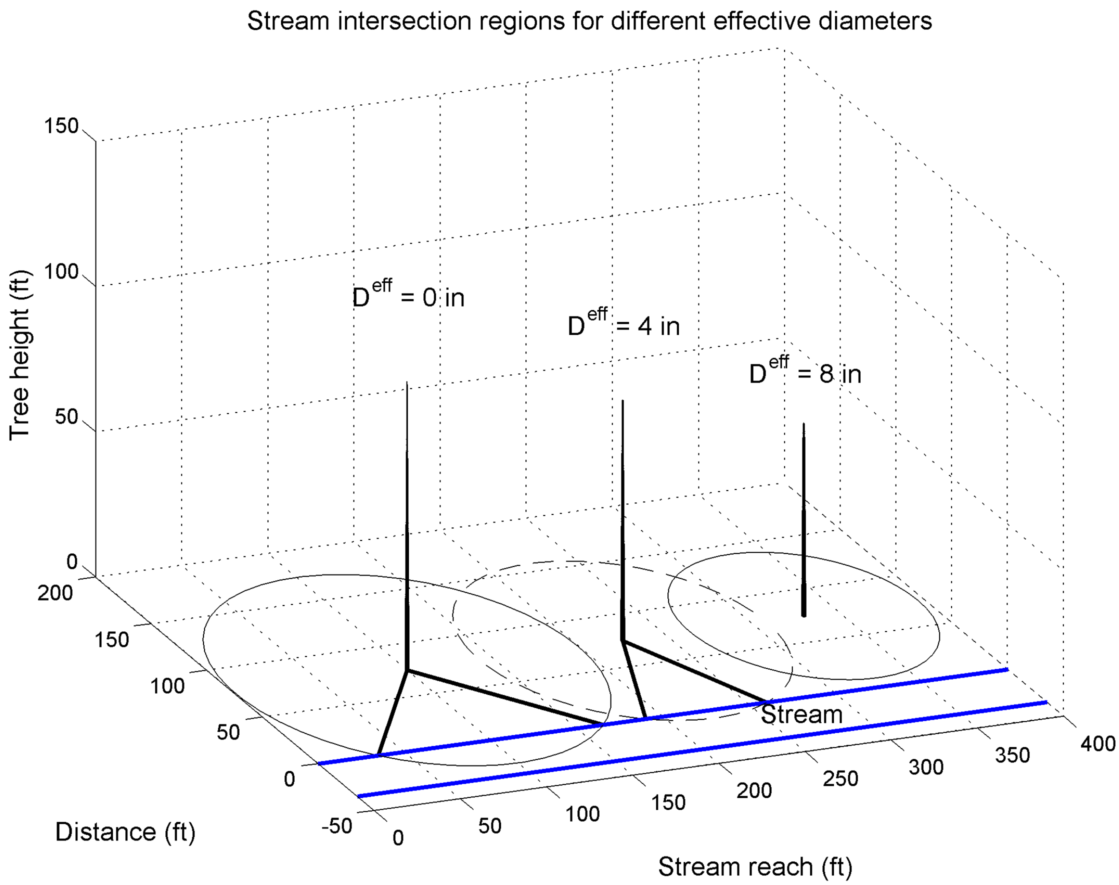

Figure 2.3: Stream intersection regions for effective LWD diameters of $D^{\text{eff}} = 0$ inches, $D^{\text{eff}} = 4$ inches, and $D^{\text{eff}} = 8$ inches, from left to right, for identical trees located the same distance from a stream. The leftmost and center trees could fall and intersect the stream, their effective heights are greater than their distances to the stream, but the rightmost tree could not, as its effective height is less than its distance to the stream.

The stability of instream LWD is an important factor for habitat creation, pool formation, and siltation (Bilby and Ward, 1989, 1991, Beechie et al., 2000). Given this importance, a portion of a tree that is on the stream bank may contribute to the size of a stream intersecting log (Welty et al., 2002), since the part of the log that is on the bank will provide the majority of the stability for a log. Let $H^{\text{offset}} \geq 0$ be the length of the portion of a stream intersecting log that rests on the stream bank, measured from the point of near bank stream intersection H^{inter} toward the base of the tree. The height where the base of the stream intersecting log begins is then given by Equation 2.5, with the diameter at the base of the log given by Equation 2.6.

$$H^{\text{base}} = \begin{cases} H^{\text{inter}} - H^{\text{offset}}, & \text{if } H^{\text{inter}} > H^{\text{offset}} \\ 0 & \text{otherwise} \end{cases} \tag{2.5}$$

$$D^{\text{base}} = f_{\text{taper}}(H^{\text{base}}; D^{\text{dbh}}, H) \tag{2.6}$$

The value of H^{offset} was assumed to be fixed for all trees and all stream sizes. This assumption may be somewhat restrictive, since, for example, a greater portion of the bole on the bank would most likely be necessary to provide stability in larger streams, for a stream intersecting log of fixed size. Consistency in the definition of a stream intersecting log across stream sizes was imposed for simplicity, and is consistent with the assumption that the production of LWD is independent of stream size. Effects of stream size and other factors on LWD were assumed to be incorporated through the definition of functional LWD.

The dimensions of a stream intersecting log were then defined by the base diameter of the log and its length, as given in Equation 2.7 and Equation 2.8, respectively, with the volume of the stream intersecting log given by Equation 2.9.

$$D^{\text{si}} = D^{\text{base}} \tag{2.7}$$

$$L^{\text{si}} = H^{\text{eff}} - H^{\text{base}} \tag{2.8}$$

$$V^{\text{si}} = V(H^{\text{base}}, H^{\text{eff}}; D^{\text{dbh}}, H) \tag{2.9}$$

The relationships among a standing live tree, its effective height and potential stream intersection region, based on an effective diameter of $D^{\text{eff}} = 4$ inches, a perpendicular tree fall, and the resulting stream intersecting log for $H^{\text{offset}} = 0$, are presented as a schematic diagram in Figure 2.4. Only the bole of a tree, without breakage, is considered as potentially contributing to AFLWD volume or piece count.

A *potential stream intersecting log* was defined to be the portion of the bole of a standing, live tree that could intersect a stream, *if* the tree were to fall in such a way as to intersect with a stream. The dimensions and volume of a potential stream intersecting log were defined as specified by Equation 2.4 through Equation 2.9.

A *potential LWD log* was defined to be a potential stream intersecting log whose base diameter and length simultaneously met or exceeded minimum base diameter and length values, $D^{\text{lwd}}_{\text{min}} > 0$ and $L^{\text{lwd}}_{\text{min}} > 0$, respectively, required of LWD logs. Potential stream intersecting logs not meeting the minimum size requirements were assumed to not contribute to ALWD, and their log dimensions and volumes were assigned values of zero. The formulas used to identify potential LWD logs and to specify their base diameters, lengths, and volumes are presented in Equation 2.10, Equation 2.11, and Equation 2.12, respectively.

$$D^{\text{lwd}} = \begin{cases} D^{\text{si}}, & \text{if } D^{\text{si}} \geq D^{\text{lwd}}_{\text{min}} \text{ and } L^{\text{si}} \geq L^{\text{lwd}}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{2.10}$$

$$L^{\text{lwd}} = \begin{cases} L^{\text{si}}, & \text{if } D^{\text{si}} \geq D^{\text{lwd}}_{\text{min}} \text{ and } L^{\text{si}} \geq L^{\text{lwd}}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{2.11}$$

$$V^{\text{lwd}} = \begin{cases} V^{\text{si}}, & \text{if } D^{\text{si}} \geq D^{\text{lwd}}_{\text{min}} \text{ and } L^{\text{si}} \geq L^{\text{lwd}}_{\text{min}} \\ 0 & \text{otherwise} \end{cases} \tag{2.12}$$

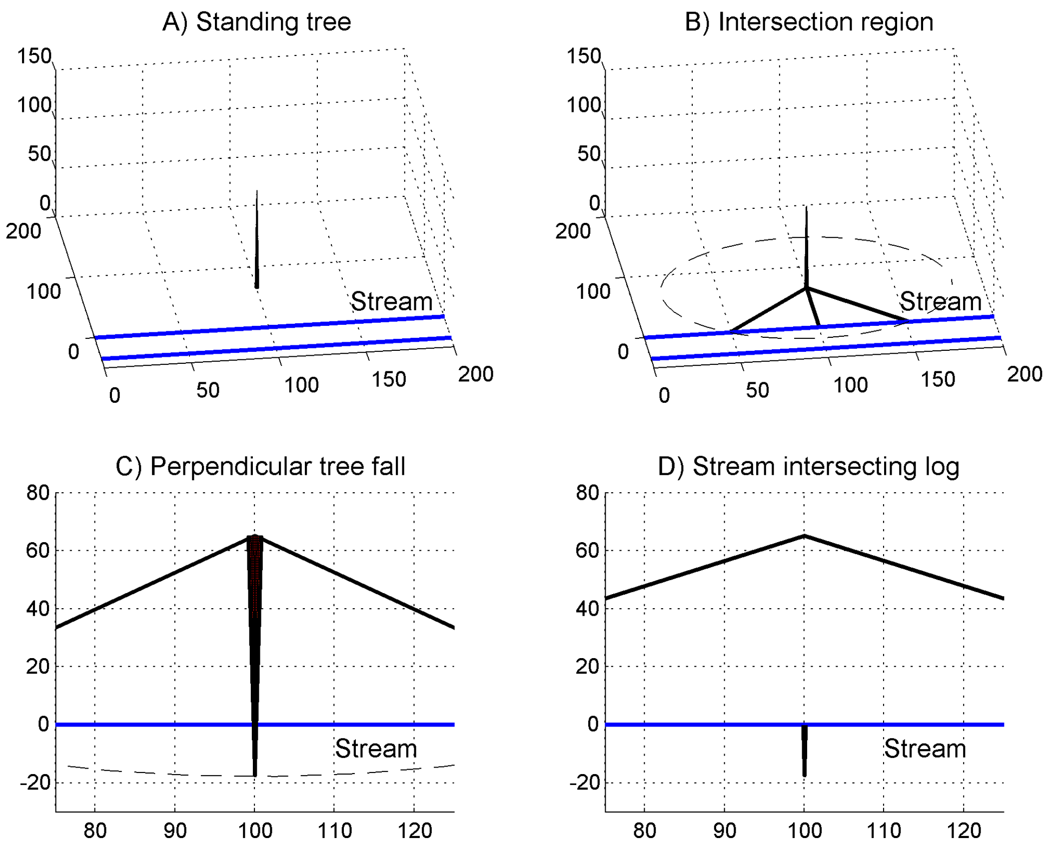

Figure 2.4: Schematic diagram showing a stream intersecting log that could have been produced by a falling tree. A) Standing tree: only the bole counts as LWD. B) The effective height and potential stream intersection region, $D^{\text{eff}} = 4$ inches. C) The tree falls perpendicularly and intersects a stream. D) The portion of the bole from the base height to the effective height is a stream intersecting log.

Values that have been used for $D_{\text{min}}^{\text{lwd}}$ and $L_{\text{min}}^{\text{lwd}}$ in the Pacific Northwest are 4 inches and 6.6 ft, respectively (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Fox, 2001, Welty et al., 2002).

A *potential functional LWD log* for a stream size class j, $j = 1, 2, \ldots, J$, where J is the number of stream size classes, was defined to be a potential LWD log whose base diameter and length simultaneously met or exceeded minimum base diameter and length values required of functional LWD logs for a stream size class, $D_{\text{min}}^{\text{lwd},j}$ and $L_{\text{min}}^{\text{lwd},j}$, respectively, with $D_{\text{min}}^{\text{lwd},j} \geq D_{\text{min}}^{\text{lwd}}$ and $L_{\text{min}}^{\text{lwd},j} \geq L_{\text{min}}^{\text{lwd}}$. Potential LWD logs not meeting the minimum size requirements to be considered as functional for a particular stream size class were assumed to not contribute to AFLWD for that stream size class, and their log dimensions and volumes were assigned values of zero. The formulas used to identify potential functional LWD logs and to specify their base diameters, lengths, and volumes are presented in Equation 2.13, Equation 2.14, and Equation 2.15, respectively.

$$D^{\text{lwd},j} = \begin{cases} D^{\text{lwd}}, & \text{if } D^{\text{lwd}} \geq D_{\text{min}}^{\text{lwd},j} \text{ and } L^{\text{lwd}} \geq L_{\text{min}}^{\text{lwd},j} \\ 0 & \text{otherwise} \end{cases} \tag{2.13}$$

$$L^{\text{lwd},j} = \begin{cases} L^{\text{lwd}}, & \text{if } D^{\text{lwd}} \geq D_{\text{min}}^{\text{lwd},j} \text{ and } L^{\text{lwd}} \geq L_{\text{min}}^{\text{lwd},j} \\ 0 & \text{otherwise} \end{cases} \tag{2.14}$$

$$V^{\text{lwd},j} = \begin{cases} V^{\text{lwd}}, & \text{if } D^{\text{lwd}} \geq D_{\text{min}}^{\text{lwd},j} \text{ and } L^{\text{lwd}} \geq L_{\text{min}}^{\text{lwd},j} \\ 0 & \text{otherwise} \end{cases} \tag{2.15}$$

Values for the minimum functional log diameter $D_{\text{min}}^{\text{lwd},j}$ and the minimum functional log length $L_{\text{min}}^{\text{lwd},j}$ used in the Pacific Northwest for a particular stream size class j have, for example, been obtained from equations developed to describe minimum pool forming log diameters (Beechie and Sibley, 1997, Beechie et al., 2000).

The definitions for a potential stream intersecting log, a potential LWD log, and a potential functional LWD log are nested, implying that the volume and number of potential stream intersecting logs are greater than or equal to the volume and number of potential LWD logs, which, in turn, are greater than or equal to the volume and number of potential functional LWD logs for a particular stream size class in a riparian forest. The definitions of functional logs for different stream sizes are also nested, so that the volume and number of pieces for larger streams is less than or equal to the volume and number of pieces for smaller streams. By using these definitions the basic building blocks of instream LWD have been modeled: the potential stream intersecting logs, are filtered to obtain the subset of stream intersecting logs that may be considered as LWD, and the potential LWD logs are then filtered again to obtain the potential functional LWD for a specified stream size. The nesting of log types and the process for identifying the different log types also mimics the context within which samples of instream LWD have been collected in empirical studies and their interpretation (Bilby and Ward, 1989, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Fox, 2001).

2.4 Stream intersection probability

The *stream intersection probability* was defined as the probability that a standing live tree in a forest adjacent to a stream could intersect the adjacent stream, *if* it were to fall. The stream intersection probability for a tree is clearly a fundamental characteristic, if not the most fundamental characteristic, of the processes related to the production of LWD in streams. If a tree in a forest adjacent to a stream falls, regardless of the physical cause or causes of its fall, it will either intersect the adjacent stream or it will not, depending on the local physical environment of the tree, the initial fall direction of the tree, the size of the tree, in particular its height, and the distance of the tree from the stream.

The local physical environment of a tree may strongly influence the probability of stream intersection.

For example, a tree having other trees located between it and a stream will have a lower probability of stream intersection than a tree having no intervening trees between it and a stream: the tree may fall and hit other trees which could deflect it away from the stream, or the tree could become hung up in the branches of an intervening tree. A falling tree that hits other trees could also increase their probability of intersecting a stream. The external environment may also influence the probability of stream intersection. For example, prevailing winds directed perpendicular to a stream could increase the likelihood of trees falling towards a stream on one bank, increasing their probability of stream intersection, while decreasing the likelihood of trees falling towards a stream on the other bank, thereby decreasing their probability of stream intersection. Erosion of the stream bank directly adjacent to a stream could also increase the probability that trees close to the stream could fall into it. The importance of the stream intersection probability to the generation of LWD made its inclusion as a fundamental component of the LWD availability model essential.

Accounting for all of the factors that could possibly influence the stream intersection probability for a tree adjacent to a stream is a daunting, if not impossible, task. A simplified description of the stream intersection probability that takes into account its most important characteristics is, therefore, necessary. A regional distribution of tree fall directions for standing live trees in riparian forests, averaged over the local physical environments of the individual trees across the region, provides one type of useful simplification. Averaging over the local physical environments of all riparian trees across a region permits the use of a small number of factors known to directly influencing the stream intersection probability for a tree when defining the regional distribution of tree fall directions.

A three parameter representation of the regional distribution of tree fall directions was chosen for the theoretical development of the LWD availability model to account for effects of the tree fall direction, the size of a falling tree as indicated by its effective height, and the distance of a tree from an adjacent stream on the probability of stream intersection. Potential stream intersection probabilities for standing live trees in a riparian forest may, then, be derived from the regional fall direction distribution by restricting it to only those parameter values that could potentially produce a stream intersection if a tree were to fall, i.e., conditioning on the stream intersecting fall directions.

Let $f_{\text{fall}}(\theta, d, H^{\text{eff}})$ be a continuous probability density function (PDF) defining a regional distribution of potential fall directions for standing live trees in riparian forested areas, where θ is the fall direction for a tree, d is the perpendicular or slope distance of a tree from a stream, and H^{eff} is the effective height of a tree as defined in Equation 2.2. The PDF $f_{\text{fall}}(\theta, d, H^{\text{eff}})$, then, gives the likelihood that a tree having an effective height of H^{eff}, located a distance d from a stream would fall in the direction θ. Define $S^{\cap}$ to be the set of all parameter values $(\theta, d, H^{\text{eff}})$ such that a tree having an effective height of H^{eff}, located a distance d from a stream, and falling in the direction θ could intersect a stream, if it were to fall. The set $S^{\cap}$ is the subset of the domain of the PDF $f_{\text{fall}}(\theta, d, H^{\text{eff}})$ for which a stream intersection is possible. The likelihood of stream intersection may then be defined as in Equation 2.16.

$$f_{\text{intersect}}(\theta, d, H^{\text{eff}}) = \begin{cases} f_{\text{fall}}(\theta, d, H^{\text{eff}}), & \text{if } (\theta, d, H^{\text{eff}}) \in S^{\cap} \\ 0 & \text{otherwise} \end{cases} \tag{2.16}$$

The function $f_{\text{intersect}}$ gives the likelihood that a tree of effective height H^{eff}, located a perpendicular distance d from a stream, and falling in a direction θ, relative to the perpendicular line between the tree and the stream, would intersect the stream if it were to fall. The stream intersection probability p_0 for a particular tree having an effective height of H_0^{eff} located a distance d_0 from a stream is given by Equation 2.17.

$$p_0 = \int_{-\pi}^{\pi} f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}}) d\theta \tag{2.17}$$

If there is only one stream, Equation 2.18 may be used, where the limiting stream intersection fall directions

$\pm\alpha$, as depicted in Figure 2.1, were obtained using Equation 2.3.

$$p_0 = \int_{-\alpha}^{\alpha} f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}})d\theta \tag{2.18}$$

2.5 Stream intersecting fall direction distribution

The distribution of stream intersecting fall directions for each tree in a riparian forest was assumed to depend on tree size and the perpendicular or slope distance of a tree from a stream through the regional distribution of tree fall directions given by the PDF $f_{\text{fall}}(\theta, d, H^{\text{eff}})$ and the function $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$. For example, trees having perpendicular distances from a stream exceeding their effective height, $d > H^{\text{eff}}$, cannot fall and intersect a stream, and $f_{\text{intersect}}(\theta, d, H^{\text{eff}}) = 0$ for all fall directions θ, whereas trees having perpendicular distances from a stream that are smaller than their effective heights, $d < H^{\text{eff}}$, cannot intersect a stream if they fall away from it.

The distribution of possible stream intersecting fall directions for a particular tree having an effective height H_0^{eff} that is a distance d_0 from a stream is given by the conditional stream intersecting fall direction distribution $f_{S^\cap}(\theta; d_0, H_0^{\text{eff}})$, defined by Equation 2.19,

$$f_{S^\cap}(\theta; d_0, H_0^{\text{eff}}) = f_{S^\cap}(\theta | d = d_0, H^{\text{eff}} = H_0^{\text{eff}}) = \frac{f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}})}{f_{d,H^{\text{eff}}}(d_0, H_0^{\text{eff}})} \tag{2.19}$$

for $f_{d,H^{\text{eff}}}(d_0, H_0^{\text{eff}}) > 0$, where $f_{d,H^{\text{eff}}}$ is the marginal probability function for distance from a stream d and effective tree height H^{eff}, as defined in Equation 2.20.

$$f_{d,H^{\text{eff}}}(d, H^{\text{eff}}) = \int_{-\pi}^{\pi} f_{\text{intersect}}(\theta, d, H^{\text{eff}})d\theta \tag{2.20}$$

For a particular tree having an effective height H_0^{eff} that is a distance d_0 from a stream, the marginal probability density function $f_{d,H^{\text{eff}}}(d, H^{\text{eff}})$ is simply the probability of stream intersection p_0, and the conditional stream intersecting fall direction distribution is then given by Equation 2.21.

$$f_{S^\cap}(\theta; d_0, H_0^{\text{eff}}) = \begin{cases} \frac{1}{p_0} f_{\text{intersect}}(\theta, d_0, H_0^{\text{eff}}) & \text{if } p_0 > 0 \\ 0 & \text{otherwise} \end{cases} \tag{2.21}$$

The conditional distribution of stream intersecting fall directions is simply the likelihood of stream intersection $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$ scaled by the probability of stream intersection for the particular tree p_0 so that the conditional distribution integrates to one, making $f_{S^\cap}$ a PDF.

A hypothetical stream intersecting fall direction distribution, scaled by a multiple of 30 to be visible on the axes, is given in Figure 2.5. For this example, trees are much more likely to intersect the stream if they fall toward the stream, since the fall direction distribution peaks for the perpendicular tree fall direction, $\theta = 0$, and then tapers off to zero as θ increases or decreases. The stream intersecting fall directions need not be greater than zero for all fall directions θ within the potential stream intersection region defined by the interval$[-\alpha, \alpha]$, as indicated in the figure. For example, intervening trees may make some potential stream intersecting fall directions less likely, and a lack of intervening trees may make some potential stream intersecting fall directions more likely. The conditional stream intersecting fall direction captures these variations as they are represented by the PDF for the stream intersection probabilities. Further, the distribution of stream intersecting fall directions for a particular tree may be zero everywhere, if physical conditions, as represented in the PDF $f_{\text{fall}}(\theta, d, H^{\text{eff}})$, are such that the tree cannot intersect the stream, e.g., due to topography or a very high stand density between the tree and the stream, but it is large enough and close enough to the stream to have a nonempty potential stream intersection region.

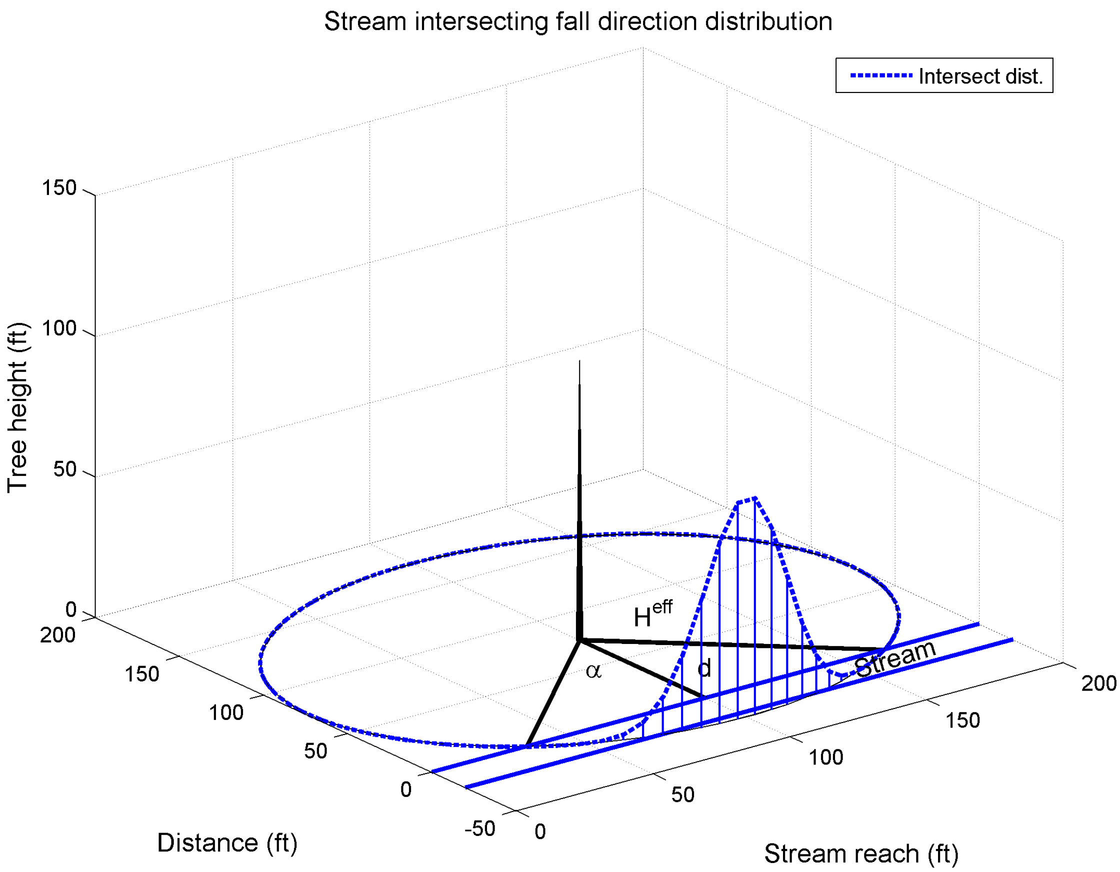

Figure 2.5: Diagram showing the potential stream intersection region with an hypothetical tree fall direction distribution.

2.6 Distribution of tree distances from a stream

The location of a tree relative to a stream is a critical factor in determining whether or not the tree may contribute to the potentially available LWD. This is clearly demonstrated by the three trees in Figure 2.2 and by the dependence of the potential stream intersection region on the distance to the stream d in Equation 2.3 and the stream intersection probability in Equation 2.17. Given the importance of tree location to the potential production of LWD, the distance of a tree to its adjacent stream must be included as a component in a model for LWD production.

A regional distribution for the perpendicular or slope distances of trees in riparian forests relative to an adjacent stream was assumed. This distribution exists, but is not known. Let $f_{\text{distance}}(d)$ be the PDF for the regional distribution of the perpendicular or slope distances of trees from their adjacent streams for $d \geq 0$. The PDF $f_{\text{distance}}(d)$ simply specifies the likelihood of finding a tree a distance d from a stream. The regional distribution of perpendicular or slope distances may be thought of as a mixture distribution, $f(d) = \sum_{i=1}^{N_S} \alpha_i f_i(d)$, where N_S is the number of tree species found in the riparian areas of a region, and where $f_i(d)$ represents the probability density function for the perpendicular or slope distance to a stream for tree species i, with weights α_i giving the relative influence of each species specific PDF $f_i(d)$ on the mixture distribution (Silverman, 1986, Duda and Hart, 1973).

If f_{distance} is used for multiple tree species or species groupings, e.g., coniferous species and hardwood species, then stream size may also be a factor that should be included. For example, forests adjacent to small streams may be indistinguishable from upland or nonriparian forests in terms of species composition and tree location, but forests adjacent to large streams may have a greater proportion of hardwood species closer to the stream (Fox, 2003). This effect may be taken into account by adding two additional parameters for stream size and species, e.g., bank-full width, W^{bf} and S, to the PDF, to obtain a three-dimensional distribution $f_{\text{distance}}(d, W^{\text{bf}}, S)$.

The shape of the distribution $f_{\text{distance}}(d)$ whether or not it takes tree species and stream size into account, may span a range from distributions that are skewed away from a stream, having more trees nearer to the stream than further away from it, to distributions that are skewed toward a stream, having fewer trees nearer to the stream than further away from it. A uniform distribution for $f_{\text{distance}}(d)$ may also occur and would indicate a lack of preference for tree location relative to a stream. If data for the perpendicular or slope distances of trees from a stream are available they may be used to obtain an estimate of the distribution f_{distance}, either by calibrating an appropriate theoretical distribution by estimating its parameters, or by creating an empirical approximation to the distribution.

2.7 Computing expected values for LWD

The expected value $E(x)$ for a discrete random variable x is defined in Equation 2.22, where p_i is the probability of occurrence for the value x_i and N is the number of possible values for x (Bickel and Docksum, 1977, Mood and Graybill, 1963, Mardia et al., 1979). Expected ALWD and AFLWD piece count or volume values for a forested riparian area may be computed by matching the components of the expected value equation, p_i, x_i, and N, to their respective ALWD or AFLWD counterparts for piece count and volume, and then substituting them into the expected value formula.

$$E(x) = \sum_{i=1}^{N} p_i \, x_i, \tag{2.22}$$

Let $T = \{T_1, T_2, \ldots, T_{N_T}\}$, be a tree list containing N_T standing, live trees representing a forested riparian area. Each tree T_i is assumed to be represented as a 5-dimensional vector $T_i = [N_i, D_i^{\text{dbh}}, H_i, S_i, d_i]^T$, where ^{T} indicates the transpose of a vector, and N_i is the number of live trees per acre (TPA) represented by tree i, D_i^{dbh} and H_i, are the DBH and height measurements, respectively, for tree i, S_i indicates the species of tree i, and d_i is the average distance from a stream for the N_i trees represented by tree i, or simply the distance of tree i from a stream if $N_i \leq 1$. The number of trees contained in the riparian area represented by the tree list T is $\sum_{i=1}^{N_T} N_i$. These values provide the minimal set of measurements necessary to estimate expected values for ALWD and AFLWD from individual trees.

To compute expected values for the potentially available LWD piece count and volume over the riparian area represented by the tree list T, the number of TPA represented by each tree, N_i, the dimensions of the potential LWD log for each tree D_i^{lwd} and D_i^{lwd}, the volume of the potential LWD log produced by each tree, V_i^{lwd}, and the stream intersection probability, p_i for each tree are needed. The TPA values were readily available from the tree list T, the dimensions and volumes for potential LWD logs were obtained using the procedures defined in Section 2.3, and the stream intersection probabilities were obtained using the procedures defined in Section 2.4.

The formulas used to compute expected values for ALWD or AFLWD were based on those for potential LWD logs and their dimensions, as defined by Equation 2.10 through Equation 2.12. The indicator function, defined in Equation 2.23, was used to identify potential LWD logs or potential functional LWD logs that contributed to the expected values, based on the appropriate minimum LWD log dimensions. The indicator function simply returns a value of one if its first argument is greater than or equal to its second argument and a value of zero otherwise. When used in the expected value summations, the indicator function restricts the piece count and volume contributions to potential LWD logs for ALWD, and to potential functional LWD logs meeting the size requirements for a particular stream class for AFLWD. Use of the indicator function simplified the presentation of the formulas used to compute the expected values, making the formula for the piece counts particularly convenient.

$$I(x,y) = \begin{cases} 1 & \text{if } x \geq y \\ 0 & \text{otherwise} \end{cases} \tag{2.23}$$

Equations for computing expected values for LWD piece count and volume are presented for arbitrary values of $N_i > 0$, the number of TPA represented by tree T_i. If $N_i > 1$, the distance from the stream d_i was assumed to represent the average perpendicular or slope distance to the adjacent stream for all of the trees represented, and if $N_i \leq 1$, then d_i is simply the perpendicular or slope distance from the tree to the adjacent stream. This situation is representative of data obtained from a typical forest inventory where one or more samples were collected to estimate per acre characteristics for a stand, or of output from a typical growth and yield model. If $N_i = 1$ for all trees, $i = 1, 2, \ldots, N_T$, then d_i is, again, simply the distance from the tree to the adjacent stream. This situation would be representative of a complete inventory of all trees within a riparian area.

2.7.1 Computing expected values for ALWD

All potential LWD logs contribute to the expected values for potentially available LWD piece counts and volumes. Potential LWD logs have base diameters that are least $D^{\min}$ inches and lengths that are at least $L^{\min}$ ft. Stream intersecting logs that were not large enough to be potential LWD logs were excluded from the computed expected values since their dimensions and volume were assigned values of zero, and hence could not meet the minimum log dimensions necessary to be considered LWD. The expected value for potentially available LWD volume was computed by using Equation 2.24, and the expected value for the number of potentially available LWD pieces was computed similarly, as in Equation 2.25.

$$E(\text{ALWD}^V) = \sum_{i=1}^{N_T} p_i \cdot V_i^{\text{lwd}} \cdot N_i \cdot I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd}}) \cdot I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd}}) \quad (2.24)$$

$$E(\text{ALWD}^N) = \sum_{i=1}^{N_T} p_i \cdot N_i \cdot I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd}}) \cdot I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd}}) \quad (2.25)$$

2.7.2 Computing expected values for AFLWD

Potential LWD logs were considered to be potential functional LWD logs for a particular stream size class if the potential LWD logs had base diameters and lengths that were simultaneously greater than minimum functional LWD log dimensions specified for that stream class (Beechie et al., 2000, Welty et al., 2002). Let J be the number of stream size classes and define $D_{\text{min}}^{\text{lwd},j} \geq D_{\text{min}}^{\text{lwd}}$ and $L_{\text{min}}^{\text{lwd},j} \geq L_{\text{min}}^{\text{lwd}}$ to be the minimum base diameter and length, respectively, for a functional LWD log for stream class j. Potential LWD logs that do not simultaneously meet both the minimum diameter and length requirements are excluded in the expected value computations by using the product of the two indicator functions, $I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd},j})$ for the potential functional LWD log base diameter and $I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd},j})$ for the potential functional LWD log length. Expected values for potentially available functional LWD volume and piece count for stream class j were computed using Equation 2.26 and Equation 2.27.

$$E(\text{AFLWD}_j^V) = \sum_{i=1}^{N_T} p_i \cdot V_i^{\text{lwd}} \cdot N_i \cdot I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd},j}) \cdot I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd},j}) \quad (2.26)$$

$$E(\text{AFLWD}_j^N) = \sum_{i=1}^{N_T} p_i \cdot N_i \cdot I(D_i^{\text{lwd}}, D_{\text{min}}^{\text{lwd},j}) \cdot I(L_i^{\text{lwd}}, L_{\text{min}}^{\text{lwd},j}) \quad (2.27)$$

2.8 Putting it together: The simulation model

Let T be a tree list $T = \{T_1, T_2, \ldots, T_{N_T}\}$ containing N_T standing live trees, representing a forested riparian area, where $T_i = [N_i, D_i^{\text{dbh}}, H_i, S_i, d_i]^T$, and N_i is the number of live TPA represented by tree i, D_i^{dbh} and H_i, are the DBH and height measurements, respectively, for tree i, S_i indicates the species of tree i, and d_i is the average distance from a stream for the N_i trees represented by tree i, or simply the distance of tree i from a stream if $N_i \leq 1$. Expected values for the potentially available LWD volume or piece count computed for the riparian area represented by the tree list T, however, would be specific to the particular tree list and the distances of its trees from a stream. The expected values would, therefore, provide only a small part of the information regarding the potential for a riparian forest stand having a structure defined by the size and density characteristics of the trees in the tree list T to produce LWD. Estimates of expected piece count and volume distributions as well as estimates of their variability were desired to obtain a better understanding of the potential for a particular tree list representing the structure of a riparian forest to produce LWD.

A simulation model that randomly generates tree locations and tree fall directions for the trees in a tree list T was implemented to characterize the distribution and variability of the expected ALWD and AFLWD piece count and volume values by randomly varying the tree locations and tree fall directions for the trees in the tree list T. Random tree locations in the simulation model were derived from the distribution f_{distance}, giving the perpendicular or slope distance of a tree from a stream, and tree fall directions were derived from the distribution of conditional stream intersecting tree fall directions $f_{S^{\cap}}(\theta; d, H^{\text{eff}})$, which in turn was dependent upon the stream intersection probability distribution $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$.

The simulation model description uses a function $G = G(T)$ that returns the expected value, or a vector of expected values, for a particular tree list T, and N_S a number of simulation trials to be performed. For the simulation model the vector representing each tree $T_i = [N_i, D_i^{\text{dbh}}, H_i, S_i]^T$ was augmented to produce a tree list T_s containing tree vectors T_{is}, for $s = 1, 2, \ldots, N_S$, that included a randomly generated perpendicular or slope distance from a stream for each tree d_{is}, the effective height H_{is}^{eff}, the tree fall direction θ_{is}, the stream intersection probability p_{is}, and the dimensions and volume of the potential LWD logs produced by each tree D_{is}^{lwd}, L_{is}^{lwd}, and V_{is}^{lwd} for each simulation trial, yielding augmented tree vectors

$$T_{is} = [N_i, D_i^{\text{dbh}}, H_i, S_i, d_{is}, H_{is}^{\text{eff}}, \theta_{is}, p_{is}, D_{is}^{\text{lwd}}, L_{is}^{\text{lwd}}, V_{is}^{\text{lwd}}]^T.$$

The expected value, or values, computed by the function $G(T)$ may include the ALWD or AFLWD volume or piece counts obtained by using the appropriate formulas from Section 2.7, or other characteristics, such as cumulative LWD profiles perpendicular to a stream which approximates the distribution of source distances for instream LWD. Using the notation just described, the algorithm used in the LWD simulation model is defined by the following steps.

1. Randomly generate perpendicular or slope distances from a stream d_{is} from the distribution f_{distance} for each tree T_i in the tree list T for simulation trial s.

2. Compute the effective tree height H_{is}^{eff} and the limiting stream intersection fall directions $\alpha_{is} = \alpha(d_{is}, H_{is}^{\text{eff}})$ for each tree T_i in the tree list T using Equation 2.2 and Equation 2.3, respectively. This defines the potential stream intersection region for each tree for simulation trial s.

3. Compute the stream intersection probability p_{is} using Equation 2.17 for each tree T_i in the tree list T for simulation trial s.

4. Using the distribution $f_{S^{\cap}}(\theta; d_{is}, H_{is}^{\text{eff}})$, generate stream intersecting tree fall directions θ_{is} for each tree T_i in the tree list T for simulation trial s. The fall directions may be random or fixed at some particular angle, e.g., perpendicular to a stream or $\theta_{is} = 0$.

5. Compute the dimensions, D_{is}^{lwd} and L_{is}^{lwd}, and volume, V_{is}^{lwd}, of the potential LWD log produced by each tree T_i using d_{is}, p_{is}, and θ_{is}, for each tree T_i in the tree list T for simulation trial s. Only trees that could produce a potential LWD log have nonzero values for D_{is}^{lwd}, L_{is}^{lwd} and V_{is}^{lwd}, all other trees have $D_{is}^{\text{lwd}} = 0$, $L_{is}^{\text{lwd}} = 0$ and $V_{is}^{\text{lwd}} = 0$.

6. Create the augmented tree list T_s by combining the tree vectors T_i in the tree list T to produce the tree vectors T_{is} for simulation trial s.

7. Compute the desired expected value, or vector, $G_s = G(T_s)$, from the augmented tree list T_s, for simulation trial s.

8. Repeat steps 1 through 7 for $s = 1, 2, \ldots, N_S$ to obtain a set of estimates G_s, for the desired expected value or vector.

9. Compute the desired statistical summary using the expected values or vectors G_s. The statistical summary could consist of the mean and standard deviation for scalar values of G_s, the mean and covariance matrix for vectors G_s, an estimate of the distribution of the values of G_s, or some other relevant summary.

Chapter 3

Application

The simulation model described in Chapter 2 was used to compute regional estimates of the expected values for AFLWD volume and piece count, as well as estimates of their distributions, for riparian areas of western Washington State. The expected values for the AFLWD volume and piece count were computed for productive, Douglas-fir dominated, 120 year old, unmanaged forests for several stream size classes. Estimates of AFLWD volume and piece count accumulation profiles perpendicular to a stream were also computed to determine the most likely source distances from a stream for potential LWD recruitment.

The primary objective of this application of the AFLWD model was to assess the qualitative performance of the individual tree simulation procedures, recognizing that refinements to the model could be made at a later time as information about the tree fall direction distribution, the distribution of distances to a stream, log sizes and breakage became available to improve the quantitative accuracy of the model. The specific objectives were to keep the model simple, to obtain results that were consistent with the trends for LWD that have been reported in the literature (Bilby and Ward, 1989, McDade et al., 1990, Van Sickle and Gregory, 1990, Bilby and Ward, 1991, Fox, 2001), and to maintain compatibility with other published LWD models (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) to facilitate a comparison of results.

A complete specification of the LWD simulation model, as used for this assessment, is given in Section 3.1, where the size of the riparian area, the requisite distributions, and the minimum dimensions for functional LWD logs are defined. The procedures used to test the LWD simulation model follow in Section 3.2, and include a description of the methods used to compute the mean expected values and the accumulation profiles for AFLWD volume and piece count perpendicular to a stream. Finally the data used in the simulations to estimate the AFLWD volume and piece count values are described in Section 3.3.

3.1 Specifying the LWD simulation model

To use the AFLWD simulation model, the riparian area and the distributions for the stream intersection probability, the tree fall directions, and the distances of trees from a stream need to be specified. The taper equation, or equations, used to compute the dimensions and volumes of potential stream intersecting logs and potential LWD logs also need to be specified, as do the stream sizes and the minimum sizes for LWD and functional LWD logs. These aspects of the LWD simulation model, as well as additional assumptions, are specified in Section 3.1.1 through Section 3.1.8.

3.1.1 Riparian area

The riparian area of interest for the LWD simulations was assumed to be a one acre riparian buffer located immediately adjacent to a stream on one side . The riparian buffer was assumed to have a width of 170 ft, measured perpendicular to the stream, and a stream reach of 256.2 ft, measured along the bank of the stream. The value of 170 ft for the buffer width was chosen based on the total width of a riparian buffer that would be required under the Forests and Fish Rules of Washington State (FFR, 1999) for productive Douglas-fir (*Pseudotsuga menziesii*) sites, those in site class II and III (King, 1966).

3.1.2 Stream intersection probability

A probability of stream intersection for a tree T_i located a distance d_i from a stream, having an effective height H_i^{eff}, and falling in direction θ was obtained by making several simplifying assumptions. The simplifying assumptions employed were consistent with those used to develop other LWD production models (McDade et al., 1990, Robison and Beschta, 1990, Van Sickle and Gregory, 1990, Welty et al., 2002). First, trees were assumed to fall and potentially intersect with an adjacent stream independently of one another. Second, the probability of stream intersection was assumed to depend only on the tree fall direction θ. Tree location and size were assumed to influence the probability of stream intersection only through the geometry identifying the potential stream intersection region. Third, only one stream was present in the riparian areas being simulated.

The distribution of tree fall directions $f_{\text{fall}}(\theta)$ was assumed to be a uniform distribution in the interval $[-\pi, \pi)$ (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) giving the distribution defined by Equation 3.1.

$$f_{\text{fall}}(\theta) = \frac{1}{2\pi} \tag{3.1}$$

The likelihood of stream intersection was then defined by Equation 3.2,

$$f_{\text{intersect}}(\theta) = \begin{cases} f_{\text{fall}}(\theta), & \text{if } \theta \in (-\alpha, \alpha) \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

where $S^{\cap} = (-\alpha, \alpha)$, is the potential stream intersection region. The stream intersection probability p_i was, then, computed as in Equation 3.3.

$$p_i = \int_{-\alpha}^{\alpha} f_{\text{fall}}(\theta) d\theta = \int_{-\alpha}^{\alpha} \frac{1}{2\pi} d\theta = \frac{2\alpha}{2\pi} = \frac{\alpha}{\pi} \tag{3.3}$$

Recalling that $\alpha = \alpha(d_i, H_i^{\text{eff}})$ is the limiting stream intersection fall direction for a tree of effective height H_i^{eff} located a distance d_i from a stream, the formula for α from Equation 2.3 is substituted into Equation 3.3 to obtain the formula in Equation 3.4 for computing a stream intersection probability.

$$p_i = \begin{cases} \frac{1}{\pi} \arccos\left(\frac{d_i}{H_i^{\text{eff}}}\right), & \text{if } d_i < H_i^{\text{eff}} \\ 0 & \text{otherwise} \end{cases} \tag{3.4}$$

Assuming that the stream intersection probabilities depend only on θ and that the fall directions were uniformly distributed is equivalent to assuming that trees fall independently of one another. The uniform distribution of tree fall directions implies that only the geometry of tree location and tree size influence the stream intersection probability. The local physical environment of the tree, including other trees that may be present, therefore, has no influence and trees intersect with a stream independently of one another.

3.1.3 Distribution of stream intersecting tree fall directions

The conditional distribution of stream intersecting tree fall directions $f_{S^\cap}(\theta; d_i, H_i^{\text{eff}})$ for a tree having an effective height of H_i^{eff} located a distance d_i from a stream takes a particularly simple form in this situation. Recalling that

$$f_{S^\cap}(\theta) = \begin{cases} \frac{1}{p_i} f_{\text{intersect}}(\theta) & \text{if } p_i > 0 \\ 0 & \text{otherwise} \end{cases}$$

the conditional distribution of stream intersecting fall directions θ given a uniform distribution of tree fall directions is then given in Equation 3.5 for $\alpha > 0$ and fall directions $\theta \in (-\alpha, \alpha)$.

$$f_{S^\cap}(\theta) = \frac{\pi}{\alpha} \cdot f_{\text{intersect}}(\theta) = \frac{\pi}{\alpha} \cdot \frac{1}{2\pi} = \frac{1}{2\alpha} \tag{3.5}$$

Recall that $\alpha = 0$ only if a tree could not fall and intersect with an adjacent stream, and that values computed for α using Equation 2.3 were positive if a steam intersection could occur due to the symmetry of the potential stream intersection region. Potential stream intersecting fall directions are, therefore, uniformly distributed in the interval $(-\alpha, \alpha)$.

3.1.4 Distribution of tree distances to a stream

The shape of the regional distribution of perpendicular or slope distances from a stream, $f_{\text{distance}}(d)$, is not known, and it may vary with stream size and tree species. The possible distribution shapes are bracketed by distributions that are skewed toward the stream, having the majority of trees located further from the stream, and by distributions that are skewed away from the stream, having the majority of trees located nearer to the stream. Given the uncertainty about the shape of this distribution, a uniform distribution within the range of the riparian buffer width was assumed, that is, distances from a tree to a stream were assumed to be distributed as $U(0, 170)$ random variables. This assumption has also been used by others (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002), and its use here facilitates comparisons to their results.

3.1.5 Stream widths and minimum functional LWD log sizes

Stream size classes were identified by using the average bank-full width along a reach of stream (Bilby and Ward, 1989, 1991, Fox, 2001, Welty et al., 2002). Let J be the number of stream size classes, and define W_j^{bf} to be the bank-full width for stream size class j, where $j = 1, 2, \ldots, J$. Associated with each stream size class was a stream size class code c_j and minimum LWD log dimensions, diameter and length, $D_{\text{min}}^{\text{lwd},j}$ and $L_{\text{min}}^{\text{lwd},j}$, respectively, that were necessary for a log to be considered a functional LWD log for that stream class. Values for the minimum functional LWD log dimensions are presented in Table 3.1 for the five stream classes used with the simulation model to estimate regional AFLWD values. The minimum dimensions of functional LWD logs for stream class E equal the typical minimum dimensions for LWD logs that have been used in the Pacific Northwest (Bilby and Ward, 1989, 1991, Fox, 2001, Welty et al., 2002), and were, therefore, used to define ALWD.

The AFLWD volume and piece count values for the different stream classes provide a size breakdown for the AFLWD logs. The AFLWD volume and piece count values for stream class A, representing the largest streams, tally the largest AFLWD logs, with values for stream class B tallying all AFLWD logs for both A and B streams, etc., until all potential LWD logs are tallied for stream class E to obtain ALWD.

Table 3.1: Minimum functional LWD log base diameters and lengths for five stream size classes. Minimum functional LWD base diameters were based on (Beechie and Sibley, 1997, Beechie et al., 2000) and minimum functional LWD lengths were based on (Fox, 2001) with adjustments.

Stream size class j	Stream class code c_j	Bank-full width (ft) W_j^{bf}	Minimum LWD base diam. (in) $D_{\text{min}}^{\text{lwd},j}$	Minimum LWD length (ft) $L_{\text{min}}^{\text{lwd},j}$
1	A	75.0	25.6	44.0
2	B	30.0	10.3	24.5
3	C	15.0	5.3	15.0
4	D	7.5	4.0	7.5
5	E	5.0	4.0	6.6

3.1.6 Log sizes, volume, and tree taper

A taper equation is necessary to obtain the base diameter, length, and volume of a potential stream intersecting log, D^{si}, L^{si} and V^{si}, respectively, from which the dimensions and volume of potential LWD logs were derived. For simplicity, the assumption that the bole shape for all tree species could be represented by a single taper equation was made. Taper equations for each species could have been used, and will be added to the model at some future date. A single taper equation was deemed sufficient at this time to demonstrate the simulation aspects of the model. Douglas-fir dominated riparian forests were of primary interest, so a taper equation for Douglas-fir was chosen from those available in the literature.

The taper equation used to define the bole shape for all trees was a variable exponent taper equation for the inside bark diameter, D^{ib}, of Douglas-fir (Kozak, 1988, 1998). The outer bark diameters, D^{ob}, was used to derive log dimensions and volumes, and were obtained by multiplying the inside bark diameter D^{ib} obtained from the taper equation by $1/r_{\text{ib/ob}}$ where $r_{\text{ib/ob}}$ is the ratio of the inside bark diameter to the outside bark diameter. A value of $r_{\text{ib/ob}} = 0.91$ was used (Goudie, 1993), which is consistent with the value of 0.9 that was used in (Welty et al., 2002), published after this work began. The formula for the inside bark diameter is defined by the taper equation given in Equation 3.6 and Equation 3.7,

$$D^{\text{ib}} = f_{\text{taper}}^{\text{ib}}(h; D^{\text{dbh}}, H) = a_0 (D^{\text{dbh}})^{a_1} a_2^{D^{\text{dbh}}} X^E, \tag{3.6}$$

with

$$E = b_1 z^2 + b_2 \ln(z + 0.001) + b_3 \sqrt{z} + b_4 e^z + b_5 \frac{D^{\text{dbh}}}{H} \tag{3.7}$$

and where a_0, a_1, a_2 and b_1, b_2, b_3, b_4, b_5 are regression coefficients; D^{dbh} is the outside bark diameter of a tree at breast height or the DBH, measured 4.5 ft above the ground; H is total tree height; z is relative tree height h/H for a height h above the ground, $0 \leq h \leq H$; $X = [1 - \sqrt{z}]/(1 - \sqrt{p})$, and p is a relative height constraint guaranteeing that $X = 1$ when $z = p$, providing a point where the exponent does not influence the inside bark diameter. Outside bark diameters were then obtained using Equation 3.8.

$$D^{\text{ob}} = f_{\text{taper}}^{\text{ob}}(h; D^{\text{dbh}}, H) = \frac{D^{\text{ib}}}{r_{\text{ib/ob}}} = \frac{f_{\text{taper}}^{\text{ib}}(h; D^{\text{dbh}}, H)}{r_{\text{ib/ob}}} \tag{3.8}$$

Values for the regression coefficients in the taper equation are given in Table 3.2. The description of the Douglas-fir taper equation and the notation used were based on those in Kozak (1988).

The volumes of potential stream intersecting logs were computed in three steps using the outside bark diameters obtained from Equation 3.8. First a cumulative volume profile based on the outside bark diameters

Table 3.2: Regression coefficients for the variable exponent Douglas-fir taper equation taken from Kozak (1988).

Coefficient	Value	Coefficient	Value
a_0	1.02453	b_1	0.95086
a_1	0.88809	b_2	-0.18090
a_2	1.00035	b_3	0.61407
		b_4	-0.35106
		b_5	0.05686

was computed for each tree from the ground to the top of the tree. Second, cumulative volumes V^{base} and V^{eff} were obtained by linear interpolation of the cumulative volume profile for the tree heights H^{base}, the height where the log begins, and H^{eff}, the effective height of the tree. The difference between the two volumes was then computed to get an estimate of the volume of the potential stream intersecting log, $V^{\text{si}} = V^{\text{eff}} - V^{\text{base}}$.

Cumulative volume profiles for each tree were approximated using volume values computed for segments of the bole representing approximately 0.5 ft of tree height using Smalian's formula (Husch et al., 1993). The cumulative volume profile for a tree having a DBH D^{dbh} and a total height H was computed in the following way. Let $N_V = 2 \cdot \text{Int}(H + 1)$ be the number of volume segments used to compute the cumulative volume profile, where $\text{Int}(x)$ returns the nearest integer to x, and let $\delta = H/N_V$ be the height of a volume segment. Define $h_i = i * \delta$, $i = 0, 1, 2, \ldots, N_V$ to be the heights delineating the N_V segments on the tree bole whose volumes are desired, and $D_i = f^{\text{ob}}_{\text{taper}}(h_i; D^{\text{dbh}}, H)$ as their corresponding outside bark diameters. Volumes for the bole segments v_i, $i = 1, 2, \ldots, N_V$, were then computed using Equation 3.9, with $k = \frac{\pi}{4 \cdot 144} = 0.005454$.

$$v_i = k \left(\frac{D_{i-1}^2 + D_i^2}{2} \right) \delta \tag{3.9}$$

Finally, the cumulative volume profile values V_i were obtained using Equation 3.10 by summing the appropriate segment volumes.

$$V_i = \sum_{j=1}^{i} v_i \tag{3.10}$$

The stream intersecting log size and volume computations for this application assumed that that all trees fell perpendicular to the adjacent stream, $\theta = 0$, for simplicity. This assumption produced conservative values, that is, values that were larger than expected, for the ALWD and AFLWD volumes and piece counts, given the other assumptions. Computing the expected ALWD and AFLWD values in this way provided approximate upper bounds for the expected potentially available LWD values that could be obtained.

3.1.7 Computing expected values

When computing the expected LWD values in the simulations, a representation that was as close as possible to an actual riparian acre populated with real trees was desired. To accomplish this, each tree represented in a tree list was to be represented by exactly one tree in the simulations, rather than using a riparian acre populated with statistical trees possibly representing multiple trees within the acre. The intent was to represent a physically realizable, rather than a theoretical average, forested riparian area where each tree in the simulation was accounted for separately. To accomplish this, when computing the expected values for the potentially available functional LWD volume and pieces with Equation 2.26 and Equation 2.27, respectively, trees in an original tree list representing more than one tree per acre, indicated by having a TPA value greater then one, $N_i > 1$, needed to be replicated by expanding the number of trees in the tree list, to account for each tree independently, prior to randomly placing the trees and computing the expected AFLWD values. The resulting expanded tree list T containing N_T trees, each representing exactly one tree within a simulated riparian area, having TPA values between zero and one, $0 < N_i \leq 1$. The procedure used to expand a tree list to obtain a tree list where each tree represented exactly one tree is described next.

A tree list $T' = \{T'_1, T'_2, \ldots, T'_{N'_T}\}$ containing $N_{T'}$ trees having TPA values N'_i was expanded into a tree list $T = \{T_1, T_2, \ldots, T_{N_T}\}$ containing N_T trees, where $N_T \geq N_{T'}$, and each tree T_i represented exactly one tree within the simulated riparian area using the following tree list expansion algorithm. For each tree T'_i in T', let $N^{\text{Int}} = \lfloor N'_i \rfloor$, where $\lfloor x \rfloor$ returns the largest integer less than or equal to x. If N^{Int} and N'_i were equal, then N'_i represented a whole number of trees, so add N^{Int} copies of tree T'_i to the tree list T, assigning a value of one to the TPA value for each of the replicated trees. If $N^{\text{Int}} < N'_i$, then there was a fractional tree represented, so add $N^{\text{Int}} + 1$ copies of tree T'_i to the tree list T, assigning a value of one to the TPA values for the first N^{Int} of the replicated trees and a TPA value of $N'_i - N^{\text{Int}}$ to the last replicated tree. The number of trees contained in the tree list T is $N_T = \sum_{i=1}^{N_{T'}} \lceil N'_i \rceil$, where $\lceil x \rceil$ returns the smallest integer greater than or equal to x. The number of trees represented by the expanded tree list T is equal to the number of trees represented by the original tree list T', that is $\sum_{i=1}^{N_T} N_i = \sum_{i=1}^{N_{T'}} N'_i$, which includes all trees having fractional TPA values.

3.1.8 Additional LWD simulation model assumptions

No explicit assumptions about the distribution of trees along a reach of stream have yet been made. In the general model the influence on the stream intersection probability of tree location and, implicitly, the distribution of trees along a stream reach, was represented by the function $f_{\text{intersect}}(\theta, d, H^{\text{eff}})$. The assumption that the stream intersection probability depended only on the tree fall direction, which was assumed to be uniformly distributed, takes into account only the perpendicular or slope distance from a stream and the effective tree height, and does not incorporate any information related to the distribution of trees along a reach of stream. The distribution of trees along a reach of stream was therefore assumed to be uniform. A number of additional simplifying assumptions have also been made, and they appear in the following list.

1. All trees were assumed to have a single bole.
2. The tree bole does not break.
3. Only the bole of a tree contributes to available LWD volume or piece count. No LWD volume and pieces from tree branches were included. See Figure 2.4 A through D.
4. The ground surface adjacent to a stream is flat.
5. The bank of a stream may be represented by a straight line.
6. Only standing live trees may contribute to ALWD and AFLWD pieces or volume. Trees that have died or already fallen are not included.
7. Movement of fallen logs down a slope was not included.
8. Only the forest directly adjacent to a stream was considered. Since the intent of the model was to consider the source of LWD and not instream LWD, log transport in the stream was not included.

3.2 Estimating regional AFLWD values

The AFLWD simulation model was used to estimate regional mean AFLWD volume and piece count values for five stream size classes, described in Section 3.1.5. For each stream size class mean expected values and mean accumulation profiles perpendicular to a stream, source distance curves, were computed for AFLWD as described in Section 3.2.1 and Section 3.2.2, respectively. Mean expected values for AFLWD and mean cumulative profiles for AFLWD were computed from the same information for each tree list and simulation trial. Potentially available LWD ALWD, values were assumed to be equal to the corresponding AFLWD values for the smallest stream size considered, stream class E.

The following notation is used to specify the procedures for computing the mean values and mean cumulative profiles for AFLWD. Let N_{TL} be the number of tree lists T_l used to characterize the region of interest. Each tree list contains N_{T_l} trees, $T_l = \{T_{l1}, T_{l2}, \ldots, T_{lN_{T_l}}\}$. Each tree in a tree list T_l was represented by a vector $T_{li} = [N_{li}, D_{li}^{\mathrm{dbh}}, H_{li}, S_{li}]^T$ containing the number of TPA represented by the tree, N_{li}, the DBH of the tree, D_{li}^{dbh}, the height of the tree, H_{li}, and the tree species, S_{li}. The TPA values for the trees in the tree lists T_l were assumed to have values less than or equal to one, $0 < N_{li} \leq 1$, so that each tree in the tree list represented exactly one tree in the riparian area being simulated. Such a tree list could be obtained from the tree list expansion algorithm described in Section 3.1.7 or some other means.

3.2.1 Computing regional mean AFLWD values

For each available tree list T_l, $l = 1, 2, \ldots, N_{TL}$, the AFLWD simulation model described in Section 2.8 was used with $N_S = 100$ simulation trials to obtain mean values and standard deviations for the expected AFLWD values for each of the J stream classes listed in Section 3.1.5. For each simulation trial s, $s = 1, 2, \ldots, N_S$, and tree list T_l, an augmented tree list T_{ls}, containing trees

$$T_{lsi} = [N_{li}, D_{li}^{\mathrm{dbh}}, H_{li}, S_{li}, d_{lsi}, H_{lsi}^{\mathrm{eff}}, \theta_{lsi}, p_{lsi}, D_{lsi}^{\mathrm{lwd}}, L_{lsi}^{\mathrm{lwd}}, V_{lsi}^{\mathrm{lwd}}]^T$$

was generated and used to compute the expected AFLWD volume or piece count values or AFLWD cumulative profiles perpendicular to a stream.

Expected values for the AFLWD volume and piece count were computed for each of the J stream size classes using the augmented tree lists generated for the N_S simulation trials and the functions $G_{ljs} = G(T_{ls}, D_j^{\min}, L_j^{\min})$ in Equation 3.11 or Equation 3.12, respectively.

$$G_{ljs} = G(T_{ls}, D_{\min}^{\mathrm{lwd},j}, L_{\min}^{\mathrm{lwd},j}) = \sum_{i=1}^{N_T} p_{lsi} \cdot V_{lsi}^{\mathrm{lwd}} \cdot N_{lsi} \cdot I(D_{lsi}^{\mathrm{lwd}}, D_{\min}^{\mathrm{lwd},j}) \cdot I(L_{lsi}^{\mathrm{lwd}}, L_{\min}^{\mathrm{lwd},j}) \tag{3.11}$$

$$G_{ljs} = G(T_{ls}, D_{\min}^{\mathrm{lwd},j}, L_{\min}^{\mathrm{lwd},j}) = \sum_{i=1}^{N_T} p_{lsi} \cdot N_{lsi} \cdot I(D_{lsi}^{\mathrm{lwd}}, D_{\min}^{\mathrm{lwd},j}) \cdot I(L_{lsi}^{\mathrm{lwd}}, L_{\min}^{\mathrm{lwd},j}) \tag{3.12}$$

Estimates of the means, $\bar{G}_{lj}$, and standard deviations, SD_{lj}, of the expected AFLWD values were then computed for each tree list T_l and stream class j, from the N_S volume or piece count expected values G_{ljs}, using Equation 3.13 and Equation 3.14, respectively.

$$\bar{G}_{lj} = \frac{1}{N_S} \sum_{s=1}^{N_S} G_{ljs} \tag{3.13}$$

$$\mathrm{SD}_{lj} = \sqrt{\frac{1}{N_S - 1}\sum_{s=1}^{N_S}\left(G_{ljs} - \bar{G}_{lj}\right)^2} \tag{3.14}$$

Finally, the regional mean $\bar{G}_j$ and standard deviation SD_j of the expected AFLWD volume and piece count values for each stream class j were obtained by averaging the mean values $\bar{G}_{lj}$ for each available tree list T_l and stream class, using Equation 3.15 and Equation 3.16, respectively.

$$\bar{G}_j = \frac{1}{N_{TL}}\sum_{l=1}^{N_{TL}}\bar{G}_{lj} \tag{3.15}$$

$$\mathrm{SD}_j = \sqrt{\frac{1}{N_{TL} - 1}\sum_{l=1}^{N_{TL}}\left(\bar{G}_{lj} - \bar{G}_j\right)^2} \tag{3.16}$$

Approximate distributions for the regional AFLWD volume and piece count values were also obtained using the mean values for each tree list and stream class, $\bar{G}_{lj}$, and by using the expected AFLWD values from the N_S independent simulation trials G_{ljs} for each tree list.

3.2.2 Computing regional mean AFLWD cumulative profiles

Mean values and standard deviations for cumulative AFLWD profiles perpendicular to a stream were computed for each of the J stream size classes using the augmented tree lists generated for the N_S simulation trials. The cumulative AFLWD profiles have two components: a vector of distances from a stream and a corresponding vector of expected cumulative AFLWD volume or piece count values. To compute mean values from the individual profiles a consistent set of distances from a stream was necessary for all tree lists and simulation trials. An evaluation interval of $\delta = 2$ ft was thought to be sufficient to capture trends in the cumulative AFLWD profiles over the 170 ft buffer width. Values for the cumulative AFLWD profiles were therefore computed at distances from the stream $d_k = (k-1)\delta$, $k = 1, 2, \ldots, K$, with $K = 86$ intervals, and $d_1 = 0$ ft and $d_K = 170$ ft.

For each stream class j the cumulative AFLWD profiles G_{ljs} were computed using the augmented tree lists T_{ls} for each of the N_S simulation trials using the following algorithm to define the function $G(T_{ls}, D_{\mathrm{min}}^{\mathrm{lwd},j}, L_{\mathrm{min}}^{\mathrm{lwd},j})$. Each profile was defined using the distances d_k and the vector of corresponding cumulative volume or piece count values $G_{ljs} = [G_{ljs1}, G_{ljs2}, \ldots, G_{ljsK}]^T$.

1. Sort the distances of the trees from a stream d_{lsi}, the number of TPA represented by each tree Nli, the stream intersection probabilities p_{lsi}, and the LWD log dimensions D_{lsi}^{lwd} and L_{lsi}^{lwd}, and the LWD log volumes V_{lsi}^{lwd} by distance from the stream to obtain d_i^{sort}, N_i^{sort}, p_i^{sort}, D_i^{sort}, L_i^{sort} and V_i^{sort}, $i = 1, 2, \ldots, N_{T_l}$.

2. Compute expected cumulative LWD volume, EV_i^{cum}, and piece count, EN_i^{cum} values for each stream class j and each sorted distance d_i^{sort} using Equation 3.17 or Equation 3.18, respectively.

$$EV_{ji}^{\mathrm{cum}} = \sum_{k=1}^{i} p_k^{\mathrm{sort}} \cdot V_k^{\mathrm{sort}} \cdot N_k^{\mathrm{sort}} \cdot I(D_k^{\mathrm{sort}}, D_{\mathrm{min}}^{\mathrm{lwd},j}) \cdot I(L_k^{\mathrm{sort}}, L_{\mathrm{min}}^{\mathrm{lwd},j}) \tag{3.17}$$

$$EN_{ji}^{\mathrm{cum}} = \sum_{k=1}^{i} p_k^{\mathrm{sort}} \cdot N_k^{\mathrm{sort}} \cdot I(D_k^{\mathrm{sort}}, D_{\mathrm{min}}^{\mathrm{lwd},j}) \cdot I(L_k^{\mathrm{sort}}, L_{\mathrm{min}}^{\mathrm{lwd},j}) \tag{3.18}$$

3. Linearly interpolate the cumulative LWD volume or piece count profiles defined by the sorted tree distance from a stream d_i^{sort} and EV_{ji}^{cum} or EN_{ji}^{cum}, respectively, at the distances d_k, $k = 1, 2, \ldots K$ to obtain EV_{jk}^{cum} or EN_{jk}^{cum} for each stream class j.

4. Assign the interpolated cumulative volume or piece count values to G_{ljs} using Equation 3.19 or Equation 3.20, respectively.

$$G_{ljs} = [EV_{j1}^{\mathrm{cum}}, EV_{j2}^{\mathrm{cum}}, \ldots, EV_{jK}^{\mathrm{cum}}]^T \tag{3.19}$$

$$G_{ljs} = [EN_{j1}^{\mathrm{cum}}, EN_{j2}^{\mathrm{cum}}, \ldots, EN_{jK}^{\mathrm{cum}}]^T \tag{3.20}$$

Given the interpolated cumulative profiles, estimates of mean AFLWD profiles,

$$\bar{G}_{lj} = [\bar{G}_{lj1}, \bar{G}_{lj2}, \ldots, \bar{G}_{ljK}]^T,$$

and standard deviations,

$$\mathrm{SD}_{lj} = [\mathrm{SD}_{lj1}, \mathrm{SD}_{lj2}, \ldots, \mathrm{SD}_{ljK}]^T,$$

were computed for each stream class j, tree list T_l, and distance d_k using the N_S volume or piece count profiles G_{ljs}, as defined by Equation 3.21 and Equation 3.22, respectively.

$$\bar{G}_{ljk} = \frac{1}{N_S} \sum_{s=1}^{N_S} G_{ljsk} \tag{3.21}$$

$$\mathrm{SD}_{ljk} = \sqrt{\frac{1}{N_S - 1} \sum_{s=1}^{N_S} \left(G_{ljsk} - \bar{G}_{ljk}\right)^2} \tag{3.22}$$

The mean cumulative AFLWD profiles for each stream class j and tree list T_l, $\bar{G}_{lj}$, were then summarized to obtain estimates of regional AFLWD accumulation characteristics. Mean cumulative expected AFLWD profiles $\bar{G}_j = [\bar{G}_{j1}, \bar{G}_{j2}, \ldots, \bar{G}_{jK}]^T$, and standard deviations, $\mathrm{SD}_j = [\mathrm{SD}_{j1}, \mathrm{SD}_{j2}, \ldots, \mathrm{SD}_{jK}]^T$ were computed for each stream class j using the mean AFLWD profile values $\bar{G}_{ljk}$ for each stream class j, and the tree lists T_l, at the distances d_k, with Equation 3.23 and Equation 3.24, respectively. The regional mean profile values were computed on a percentage basis.

$$\bar{G}_{jk} = 100\% \frac{1}{N_{TL}} \sum_{l=1}^{N_{TL}} \frac{\bar{G}_{ljk}}{\bar{G}_{ljK}} \tag{3.23}$$

$$\mathrm{SD}_{jk} = 100\% \sqrt{\frac{1}{N_{TL} - 1} \sum_{l=1}^{N_{TL}} \left(\frac{\bar{G}_{ljk}}{\bar{G}_{ljK}} - \bar{G}_{jk}\right)^2} \tag{3.24}$$

The mean distance from a stream required to achieve a particular level of AFLWD volume or piece count accumulation for different stream sizes was of particular interest. This statistic may be useful in determining effective buffer widths for streams. These distances may only be obtained for stream classes j and tree lists T_l for which the AFLWD volume and piece count were nonzero. Let N_{TL}^j be the number of tree lists having nonzero AFLWD volume and piece count values for stream class j, and let $l = 1, 2 \ldots, N_{TL}^j$ be an index for those tree lists. Let P be the percentage of the cumulative AFLWD for which a mean distance is desired, and let $k_{\min}$ be the index where the minimum value of the quantity given in Equation 3.25 occurs for stream class j and the mean AFLWD volume or piece count cumulative profile $\bar{G}_{lj}$ for each tree list.

$$k_{\min} = \min_{k=1,2,\ldots,K} \left| 100\% \frac{\bar{G}_{ljk}}{\bar{G}_{ljK}} - P \right| \tag{3.25}$$

The value of $k_{\min}$ gives the index where the simulated mean cumulative AFLWD volume or piece count percentage is closest to the desired accumulation percentage. Next, assign the distance d_{lj}^P the value $d_{k_{\min}}$, $d_{lj}^P = d_{k_{\min}}$. Approximate means and standard deviations of the distances from the stream where P percent of the AFLWD volume or piece count occurred for stream class j were then computed using Equation 3.26 and Equation 3.27, respectively.

$$\bar{d}_j^P = \frac{1}{N_{TL}^j} \sum_{l=1}^{N_{TL}^j} d_{lj}^P \tag{3.26}$$

$$\mathrm{SD}_j^P = \sqrt{\frac{1}{N_{TL}^j - 1} \sum_{l=1}^{N_{TL}^j} \left(d_{lj}^P - \bar{d}_j^P\right)^2} \tag{3.27}$$

If there were multiple minimum values, the smallest of the index values was assigned to $k_{\min}$. This situation could occur if P falls exactly between two percent accumulation values, or if $P = 100\%$ and 100% of the cumulative volume or piece count occurs for a value of k that is less than K. Means and standard deviations for distances from the stream were computed for each stream class j using AFLWD accumulation percentages P of 50%, 80%, 85%, 90%, 95%, 99%, and 100%.

3.3 Data

Estimates of regional averages for potentially available LWD volumes and piece counts were desired for productive Douglas-fir dominated, 120 year old, unmanaged riparian forests in western Washington State. The reference data set selection was motivated by the approach established in the Forests and Fish Rules (FFR), the Washington Forest Practices Rules governing riparian forest management in Washington that were adopted in 2001 (WFPB, 2001).

The FFR were based in large part on the Forests and Fish Report (FFR, 1999) and two scientific reviews of the FFR report (Ehlert and Mader, 2000, Fairweather, 2001). In particular, the FFR established the paradigm of using a quantitative description of riparian forest stand structure at a specified age, called a Desired Future Condition (DFC), to evaluate riparian forest management regimes (FFR, 1999, WFPB, 2001). The quantitative description of the desired riparian forest structures was obtained using a sample derived primarily from public data sources. Following this paradigm, a reference data set of forest stands that was considered to be representative of unmanaged riparian forest conditions in western Washington was desired.

When searching for publicly available data sources for unmanaged riparian stands a dearth of data were discovered for western Washington State. The data that did exist were primarily from the Pacific Northwest Forest Research Station Forest Inventory and Analysis (PNWFIA) program and the Continuous Vegetation Survey (CVS) program of the Pacific Northwest Region (R6, Region 6). While data from these sources were nominally from riparian stands there were several potential issues with regard to their use. First, few of the sample plots from either the PNWFIA data or the CVS data were located directly adjacent to a stream. A maximum distance from a stream that defines a riparian zone would, therefore, be required to select plots that were close enough to the stream to be considered riparian forest. Second, distances to the nearest stream were only available at a subplot level for the PNWFIA data, which used aa two level hierarchical sampling strategy. The plot level data identified by the riparian subplots within the PNWFIA data produced a sample size that was too small to be effective, while using the subplots directly produced an acceptable sample size, but required scaling the tree expansion factors to obtain per acre values. While scaling the subplot values was not expected to introduce a bias, it would increase the observed variability. While these issues were not insurmountable, an alternative approach was taken to identify a reference data set for the simulations.

Gross forest structure was assumed to be determined by the number and sizes of the trees and snags, and coarse woody debris within a forest stand, with finer levels of detail obtained by including tree species information if necessary. The number and sizes of the trees present in a well defined area adjacent to a stream should be sufficient to obtain a good estimate for the production of LWD. The gross forest structures within riparian stand adjacent to small streams should be similar to those in an upland, or nonriparian, stand dominated by the same species, particularly if the stream is not large enough to create a significant gap in the canopy.

Given this assumption, the range in forest structures for riparian stands with small streams would be well represented by the range in structures for upland or nonriparian stands, and estimates of AFLWD derived from the upland stands would provide estimates of AFLWD values consistent with those that would be obtained from riparian stands. For larger streams, the ability of an adjacent forest to produce LWD is generally thought to be independent of stream size (Bilby and Ward, 1989, 1991, Beechie et al., 2000, Welty et al., 2002); the effect of stream size relates to the sizes of LWD logs that are considered functional, e.g., pool forming logs (Beechie and Sibley, 1997), or logs providing other stream functions (Bilby and Ward, 1989, 1991). The use of upland, or nonriparian, forest structures for larger streams should, therefore, also be acceptable. Finally, there is some evidence indicating that differences between upland and riparian forests dominated by the same species may be small (Macdonald et al., 2004), lending further support to the use of upland stands to estimate LWD characteristics for riparian stands. When selecting data to define the reference condition for the simulations, no distinctions were made between data from upland and riparian stands.

Forest inventory data from version 1.4 of the integrated database (IDB) produced by the Pacific Northwest Forest Research Station Forest Inventory and Analysis program of the U.S. Forest Service (Hiserote and Waddell, 2004) were used to define the reference condition and provide tree lists for the AFLWD simulations. The IDB contains inventory data for California, Oregon, and Washington collected by the Forest Service and the Bureau of Land Management, including data from the Forest Inventory and Analysis program of the Pacific Northwest Research Station (PNWFIA), the Continuous Vegetation Survey program of the Pacific Northwest Region (R6, Region 6), the Forest Inventory program of the Pacific Southwest Region (R5, Region 5), and the Natural Resource Inventory program of the Bureau of Land Management (BLMWO, western Oregon districts only) (Hiserote and Waddell, 2004). The inventory data from these sources have been standardized to include a uniform set of attributes and have been combined within the IDB to provide a high quality comprehensive database of forest inventory information for these states.

Sample plots within the IDB used to define the reference condition were selected by using the following criteria. Column names used in the IDB are shown in a courier font, e.g., `FOREST_TYPE`.

1. Plots were classified as timberland (`GLC` = 20).
2. Plots were located in western Washington or western Oregon.
3. Plots were at elevations less than 2500 ft.
4. Plots were classified as Douglas-fir dominant by the data column `FOREST_TYPE`. The species code for Douglas-fir was 202.
5. Plots had Douglas-fir basal area per acre values that were at least 50% of the total basal area acre.
6. Plots had ages that were at least 100 years and less than 180 years, determined using FIA age codes, column `STAND_AGE`. The relevant FIA age codes were 11 to 17, inclusive, for age classes 100-109 years to 170 to 179 years.

Table 3.3: Numerical summary of the 179 Douglas-fir dominated plots.

Attribute	Mean	Std. Dev.	Minimum	Median	Maximum
Age^{mid} (years)	123.2	15.9	104.5	124.5	164.5
TPA	134.6	77.8	23.9	118.1	513.0
QMD (in)	20.3	5.3	10.2	20.1	34.4
H (ft)	98.9	26.3	43.0	98.0	174.5
H^{40} (ft)	143.3	20.8	87.2	145.0	204.8
BA ($\text{ft}^2\text{ac}^{-1}$)	256.0	68.6	103.3	259.7	404.9
Volume ($\text{ft}^3\text{ac}^{-1}$)	12767.6	4112.8	4428.9	12945.4	23513.5
Elevation (ft)	255.9	254.1	20.0	190.0	1598.0

7. Plots had total volumes that were between 25% and 138% of the average volume of a normal, or fully stocked, stand as defined in McArdle and Meyer (1930). The average total volume for a normal stand was taken as 17240 $\text{ft}^3\text{ac}^{-1}$, and was obtained from McArdle and Meyer (1930).

Plots from western Oregon were included because there were only 31 plots meeting the criteria found in western Washington, a sample size that was to small to be effective. Productive Douglas-fir dominated unmanaged forests in western Washington and western Oregon should, however, have similar stand structures and, therefore, LWD production potential. Finally, small trees do not contribute significantly to LWD, so only trees having DBH values of at least 4 inches were included in the reference data set. These criteria yielded 179 plots with 15491 qualifying trees. The data source, data selection rationale and criteria, and summary statistics for the plots were peer reviewed and found to be appropriate for the intended application and of high quality.

The individual tree data from the selected sample plots provided the tree lists for the LWD simulations. The $N_{TL} = 179$ tree lists (plots) T_l, were distributed over western Oregon and western Washington, each having N_{T_l} trees, $T_l = \{T_{l1}, T_{l2}, \ldots, T_{lN_{T_l}}\}$. Each tree in a tree list T_l was represented by a vector $T_{li} = [N_{li}, D_{li}^{\text{dbh}}, H_{li}, S_{li}]^T$ containing the number of TPA represented by the tree, N_{li}, the DBH of the tree, D_{li}^{dbh}, the height of the tree, H_{li}, and an indication of tree species S_{li}. A numerical summary of the age class midpoints Age^{mid}, stand density TPA, QMD, average height (H), height 40 (H^{40}), total basal area per acre BA, total volume V, and elevation data obtained from the sample plots is provided in Table 3.3.

Attribute values for each plot were computed using the following procedures and were then summarized to obtain the values presented in the Table 3.3. Let $\text{Age}_l^{\text{lower}}$ and $\text{Age}_l^{\text{upper}}$ be the lower and upper bounds of the age class for plot l and ba_{li} be the basal area of tree i on plot l computed using Equation 3.28,

$$\text{ba}_{li} = k \cdot (D_{li}^{\text{dbh}})^2, \tag{3.28}$$

where $k = \frac{\pi}{4 \cdot 144} = 0.005454$. Age class midpoints for each plot were computed using Equation 3.29,

$$\text{Age}_l^{\text{mid}} = \frac{\text{Age}_l^{\text{lower}} + \text{Age}_l^{\text{upper}}}{2} \tag{3.29}$$

and the stand level characteristics TPA, QMD, H, and volume were computed using the formulas in Equation 3.30 through Equation 3.33 for each plot.

$$\text{TPA}_l = \sum_{i=1}^{N_{T_l}} N_{li} \tag{3.30}$$

$$\mathrm{BA}_l = \sum_{i=1}^{N_{T_l}} \mathrm{ba}_{li} \cdot N_{li} \tag{3.31}$$

$$\mathrm{H}_l = \frac{\sum_{i=1}^{N_{T_l}} H_{li} \cdot N_{li}}{\sum_{i=1}^{N_{T_l}} N_{li}} \tag{3.32}$$

$$\mathrm{QMD}_l = \left(\frac{\sum_{i=1}^{N_{T_l}} (D_{li}^{\mathrm{dbh}})^2 \cdot N_{li}}{\sum_{i=1}^{N_{T_l}} N_{li}} \right)^{\frac{1}{2}} \tag{3.33}$$

$$V_l = \sum_{i=1}^{N_{T_l}} V(0, H_{li}; D_{li}^{\mathrm{dbh}}, H_{li}) \cdot N_{li} \tag{3.34}$$

Values of H^{40} for each plot were obtained by computing the average height of the 40 largest diameter trees per acre, or all trees if there were fewer than 40 trees per acre represented.

Chapter 4

Results

Results from the AFLWD simulation model are presented for both volume and piece count as mean expected values and mean cumulative profiles perpendicular to a stream. Results for the mean expected AFLWD volume and piece count values for the five stream size classes ranging from 5.0 ft to 75.0 ft are presented first in Section 4.1. The mean cumulative AFLWD volume and piece count profiles perpendicular to a stream for the five stream size classes follow in Section 4.2.

4.1 Mean expected AFLWD volume and pieces

Simulation results for the expected AFLWD volumes and piece counts appear in Section 4.1.1 and Section 4.1.2, respectively. Combined results for AFLWD volume and piece count are also presented in Section 4.1.3. The expected AFLWD volume and piece counts were obtained simultaneously for each simulation trial and all stream size class given in Table 3.1. Estimates of the AFLWD for the different stream size classes accumulate as the stream size, and the minimum dimensions of functional pieces, decrease. With each smaller stream size class there is an additional contribution of AFLWD volume or pieces from the potential LWD logs that become functional logs for the smaller stream size class, but were excluded for the larger stream size class. That is, the volumes and pieces contributing to AFLWD for stream size class A also contribute to AFLWD for stream size classes B through E, and the increment over the AFLWD of stream size class A for stream size class B contributes to stream size classes C through E, and so on.

4.1.1 AFLWD volume results

Mean values and standard deviations for the expected AFLWD volumes appear in Table 4.1. The mean expected AFLWD volume values ranged from a low of 592.6 ft^3ac^{-1} for the widest streams, stream class A, to a high of 1435.7 ft^3ac^{-1} for the narrowest streams, stream class E. The median expected LWD volume values were all less than their corresponding means indicating that the distributions of the simulated AFLWD volumes were skewed toward larger values. Minimum values for the expected AFLWD volume ranged from a value of 17.7 ft^3ac^{-1} for the largest stream width, stream class A, to a value of 275.7 ft^3ac^{-1} for the smallest stream width, stream class E, tracking the trend of the mean values. Maximum values for the expected LWD volume ranged from a value of 2212.1 ft^3ac^{-1} to a value of 3495.1 ft^3ac^{-1}, and were consistent across all stream sizes, indicating that one tree list with a number of large trees was producing the maximum expected

Table 4.1: Mean AFLWD volume values ($\text{ft}^3\text{ac}^{-1}$) for perpendicular tree fall. Values are for one side of a stream and were computed using all 179 of the available tree lists.

Stream	Mean expected LWD volume ($\text{ft}^3\text{ac}^{-1}$) summaries				
class	Mean	Std. Dev.	Minimum	Median	Maximum
A	592.6	497.2	17.7	405.5	2212.1
B	1403.6	616.0	146.4	1381.8	3491.9
C	1433.7	607.2	271.3	1409.8	3493.9
D	1435.6	606.7	275.5	1411.2	3495.0
E	1435.7	606.7	275.7	1411.3	3495.1

LWD volume. Overall, mean AFLWD volume increased as stream size decreased from stream class A to stream class E, approaching a saturation point near approximately 1440.0 $\text{ft}^3\text{ac}^{-1}$.

Tree size and stand density are both factors that can dramatically impact the production and availability of functional LWD. To examine the possible effects of these attributes, mean expected AFLWD volumes from the simulations for each tree list T_l and stream classes A through D were plotted against height 40 and TPA in Figure 4.1 and Figure 4.2. Results for stream class E were essentially identical to those for stream class D. The plotted values are means plus or minus one standard deviation computed using the $N_S = 100$ expected AFLWD volume values obtained from the simulated riparian stands generated from each tree list.

Expected values for the AFLWD volume increased, on average, as the dominant tree height increased for all stream classes, see Figure 4.1. This trend may be somewhat weaker for stream class A due to higher relative variability caused by many of the volume values being smaller for this stream class than for the other stream classes, indicated by more points being located near the x-axis. The cumulative nature of the expected AFLWD volume values as stream size decreases is also readily apparent, particularly when comparing stream class A with stream class B, where the lower edge of the data has been lifted away from the x-axis. Given the age selection criteria, there were very few stands with dominant height less than 100 ft, but extrapolating the trend to younger stands with smaller trees, would indicate that small expected LWD volumes are likely for dominant heights less than 100 ft. One outlier may also be present, appearing well below the data for stream classes B through D near a dominant height of approximately 175 ft. This point is associated with a stand of very low density, 24 TPA containing a number of very large trees.

Expected values for AFLWD volume were greatest for moderate stand densities, between, approximately, 50 TPA and 150 TPA, for all stream classes, see Figure 4.2. Of particular interest is the range in expected AFLWD volume values within this range of stand densities, with minimum AFLWD volume near zero $\text{ft}^3\text{ac}^{-1}$ and a maximum that was over 2000.0 $\text{ft}^3\text{ac}^{-1}$ for stream class A. The smaller stream classes had equally impressive ranges, and were approximately 275.0 $\text{ft}^3\text{ac}^{-1}$ to 3500.0 $\text{ft}^3\text{ac}^{-1}$. Expected AFLWD volume values were somewhat smaller for stream class A in this range than for the other stream classes, which was expected, and again the incremental nature of the AFLWD volume as the stream size decreased was apparent. The expected AFLWD volumes were generally smaller for lower stand densities, densities less than 50 TPA, and for higher stand densities, densities greater than 150 TPA. The trend in expected AFLWD volume generally decreased as stand density increased, but with some variability. The outlier identified previously is not apparent in the figure. In addition, as stand density increased the variability of the functional LWD volume estimates decreased, indicating that as more, and smaller, trees were represented, the influence on the expected AFLWD volume value of each tree was reduced.

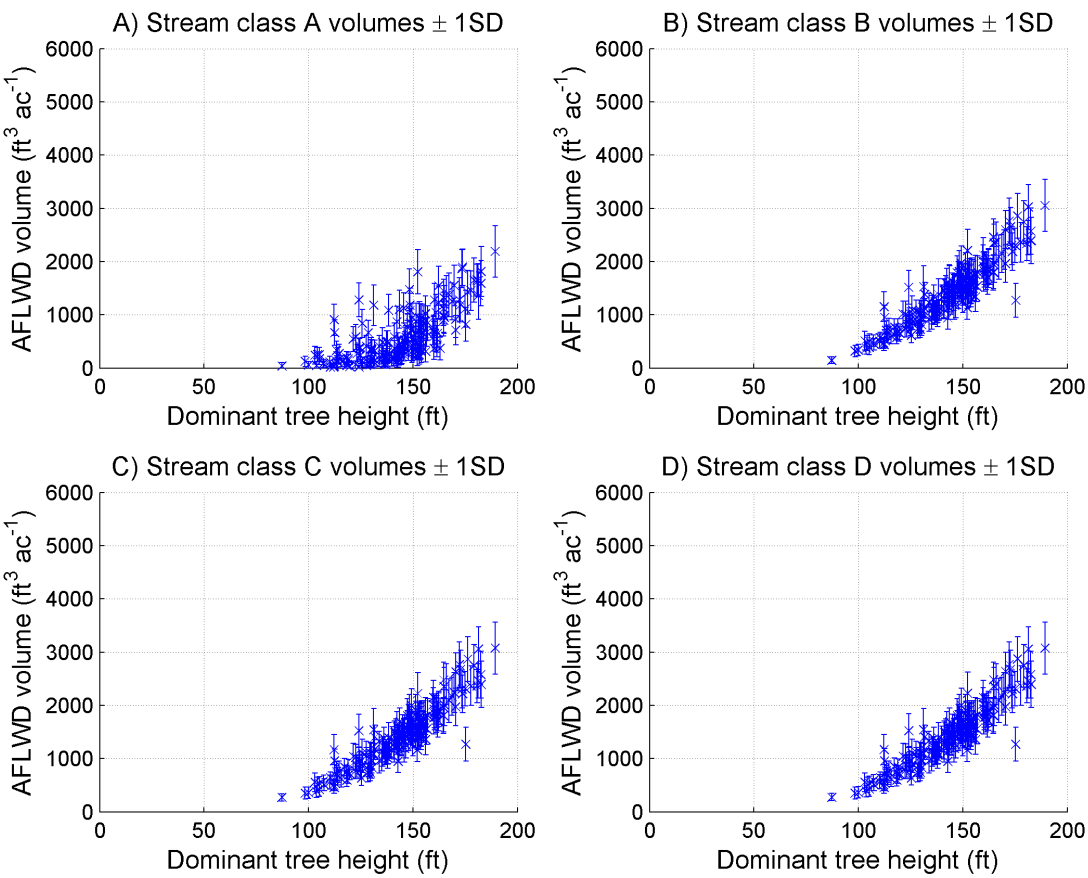

Figure 4.1: Expected values for AFLWD volume (ft^3ac^{-1}) for each tree list T_l and stream classes A through D plotted against dominant tree height. Values are means ± 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

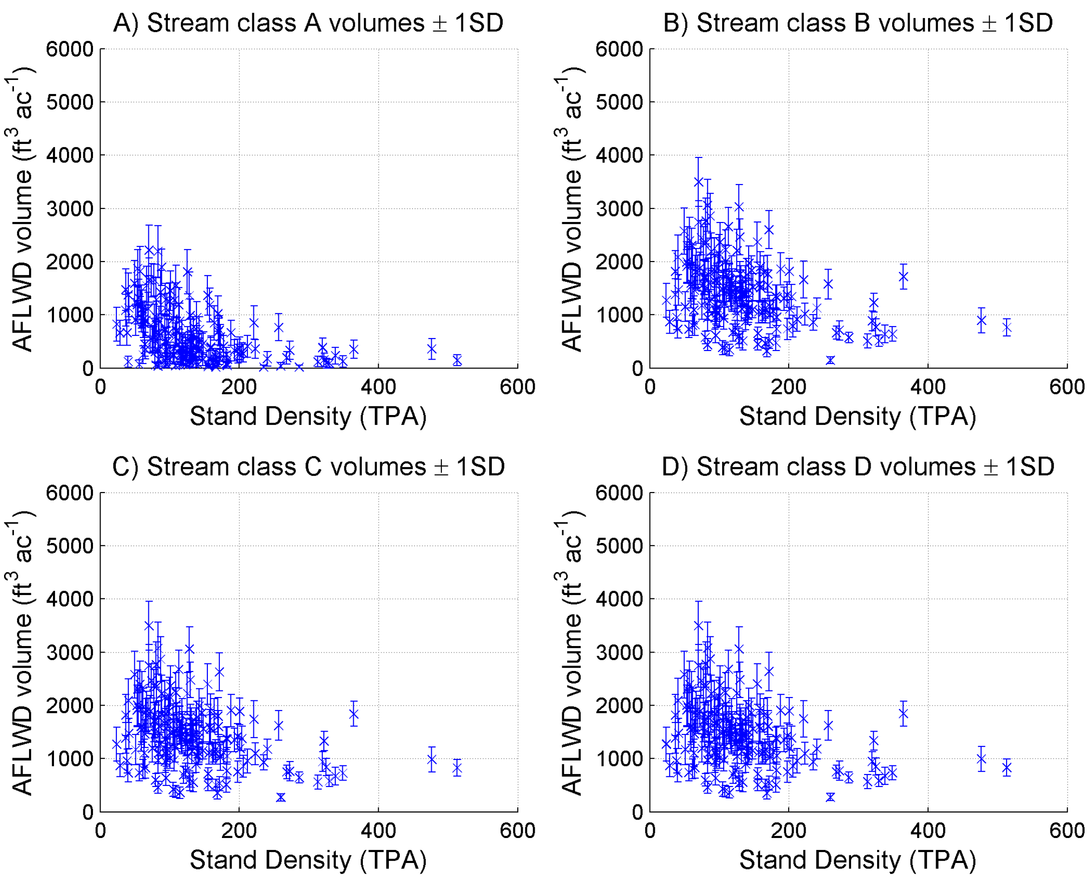

Figure 4.2: Expected values for AFLWD volume ($ft^3 ac^{-1}$) for each tree list T_l and stream classes A through D plotted against stand density. Values are means ± 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

Table 4.2: Mean AFLWD piece count results (n ac^{-1}) for perpendicular tree fall. Values are for one side of a stream and were computed using all 179 of the available tree lists.

Stream	Mean expected LWD piece count (n ac^{-1}) summaries				
class	Mean	Std. Dev.	Minimum	Median	Maximum
A	1.7	1.2	0.1	1.4	5.5
B	12.7	4.3	3.3	12.9	22.5
C	16.6	5.5	5.5	16.2	33.9
D	17.8	5.9	5.7	17.0	36.6
E	17.9	6.0	5.7	17.2	36.8

4.1.2 AFLWD piece count results

Mean values and standard deviations for the expected AFLWD piece counts appear in Table 4.2. The mean expected AFLWD piece counts ranged from a low of 1.7 pieces ac^{-1} for the largest stream width, stream class A, to a high of approximately 17.9 pieces ac^{-1} for the smallest stream width, stream class E. The median expected LWD piece count values showed the same trend as the mean values, but were all smaller than their corresponding means. This implies that the distributions of the simulated AFLWD piece counts may be skewed toward larger values. Minimum values for the expected AFLWD piece counts followed the same trend as the mean values, ranging from 0.1 pieces ac^{-1} for the largest stream class to 5.7 pieces ac^{-1} for the smallest stream classes. Maximum values for the AFLWD piece counts increased rapidly from 5.5 pieces ac^{-1} for the largest stream width, to 36.8 pieces ac^{-1} for the smallest stream width. Overall, mean AFLWD piece count increased as stream size decreased from stream class A to stream class E, approaching a saturation point at approximately 18 pieces ac^{-1}.

To assess the possible impact of tree size and stand density on AFLWD piece count, expected AFLWD piece counts from the simulations for each tree list T_l and stream classes A through D are plotted against height 40 and TPA in Figure 4.3 and Figure 4.4. Results for stream class E were essentially identical to those for stream class D. The values are means plus or minus one standard deviation computed using the $N_S = 100$ expected LWD piece count values obtained from the simulated riparian stands generated from each tree list.

Expected values for AFLWD piece counts increased, on average, as the dominant tree height increased for all stream classes, see Figure 4.3. This is most noticeable for stream classes A and B, With stream classes C, and D showing much weaker trends due to greater variability in the piece count values. The cumulative nature of functional LWD piece count values is readily apparent when moving from stream class A to stream classes B and C, with piece counts increasing as stream size decreases. Given the age selection criteria, there were few stands with dominant height less than 100 ft. Extrapolating the observed trends to younger stands with smaller trees, would indicate that small values for expected AFLWD piece counts were likely for dominant heights less than 100 ft, particularly for larger streams. For smaller streams the range in AFLWD piece counts is quite wide, relative to the mean piece count values throughout the range of dominant heights. There may also be a slight narrowing of the range for plots containing taller trees. Several outliers may be present, as seen in the figures for stream classes C and D. The three possible outliers have piece count values exceeding 30 AFLWD pieces ac^{-1} for dominant heights in the range from approximately 125 ft to 175 ft. An additional outlier may occur for 20 AFLWD pieces ac^{-1} and a dominant height near 85 ft. These points may, however, simply be near the outer edge of the envelope of the data.

Expected values for AFLWD piece counts were greatest for moderate stand densities, between 50 TPA and 150 TPA, for stream classes A and B, and generally increased, to a saturation point, throughout the

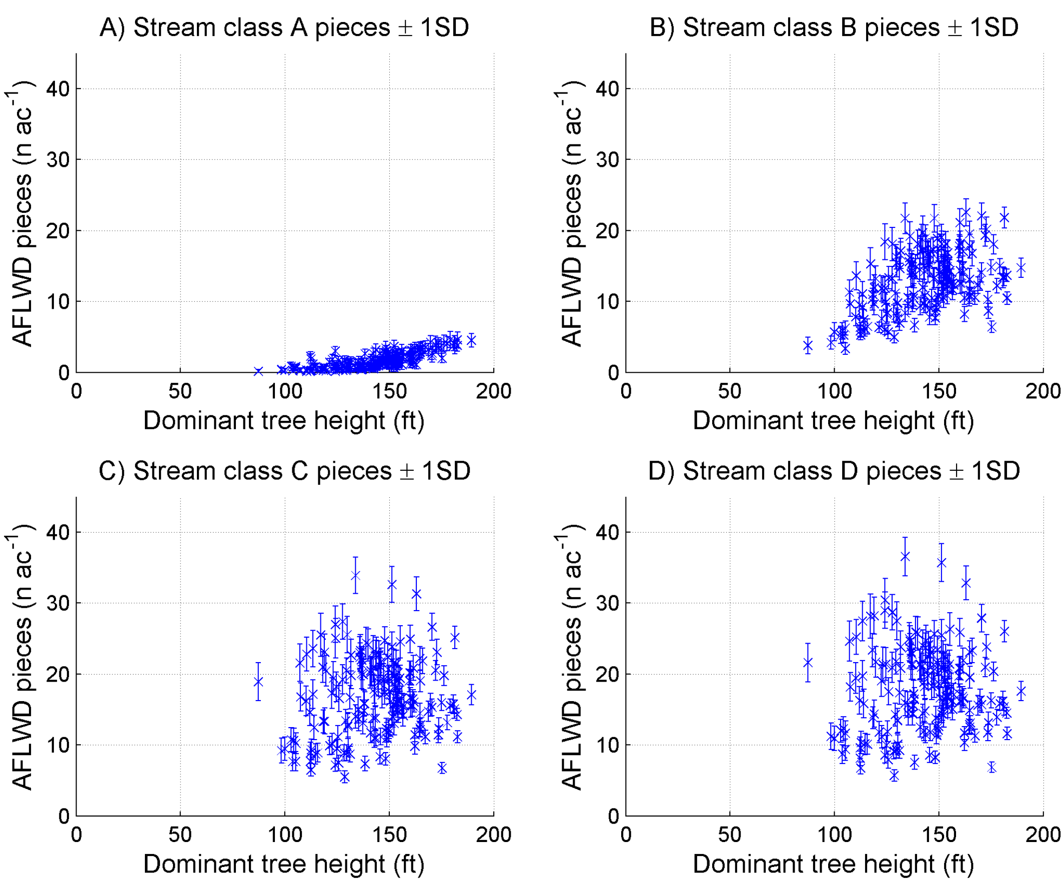

Figure 4.3: Expected values for AFLWD piece count (pieces ac^{-1}) for each tree list T_l and stream classes A through D plotted against dominant tree height. Values are means ± 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

range of stand densities for stream classes C and D, see Figure 4.4. The effects of the minimum functional LWD log dimensions and the cumulative nature of AFLWD for decreasing stream size are readily apparent when moving from a larger stream class to smaller stream classes. The AFLWD piece counts were smallest for the largest stream size, stream class A, having values that were less than 10 pieces ac^{-1}. Piece counts also clearly increased as the stream size decreased. For the largest stream classes, the expected AFLWD piece counts were lower for higher stand densities, densities greater than 200 TPA, particularly for stream class A where the highest stand densities have almost no available LWD. For the small stream sizes there appears to be a curvilinear relationship between stand density and the AFLWD piece count that increases with stand density to a saturation point. Higher stand densities had a somewhat greater variability in their estimates of AFLWD piece counts, most likely due to differences in the tree size distributions among those tree lists.

4.1.3 Combined AFLWD volume and piece count results

The expected values for AFLWD volume and piece count are coupled, or dependent, attributes, and their joint characteristics also need to be examined. Scatter plots of the AFLWD volume *vs.* AFLWD piece counts are presented in Figure 4.5. As stream size decreases the magnitude and range of the number of AFLWD pieces increases quite dramatically, moving from stream class A to stream class C, while the magnitude and range of the AFLWD volume values increases only moderately, most notably between stream classes A and B. The majority of the AFLWD volume, then, was contributed by a relatively small number of larger logs, as the large increases in the number of AFLWD pieces was not associated with a corresponding increase in AFLWD volume. Finally, the limits bounding the range in AFLWD volumes are relatively constant, ranging from 500.0 ft^3ac^{-1} to 2500.0 ft^3ac^{-1} for piece counts in the range from 5 pieces ac^{-1} to 15 pieces ac^{-1} for stream class B, and for piece counts in the range from 10 pieces ac^{-1} to 25 pieces ac^{-1} for stream classes C, and D. Note that equivalent AFLWD volumes may be produced by a wide range of AFLWD piece count values for smaller streams. For example, an AFLWD volume value of 1500.0 ft^3ac^{-1} was produced by AFLWD piece counts that span the range of values from 5 pieces per acre to 35 pieces per acre.

4.2 Mean expected cumulative AFLWD profiles

Cumulative profiles of AFLWD volume and piece count were generated and used to examine the mean distances and accumulation percentages of AFLWD volume and piece count perpendicular to a stream for the 170 ft width of the simulated one acre riparian buffer. The percent accumulation results are presented in Section 4.2.1, and the mean distance to achieve a particular level of accumulation are presented in Section 4.2.2.

4.2.1 Mean LWD accumulation percentages

Mean cumulative AFLWD profiles for volume and piece count, expressed as percent of total AFLWD, computed using the $N_{TL} = 179$ available tree lists are shown in Figure 4.6 for stream classes A through D. The mean cumulative AFLWD profiles for stream class E was indistinguishable from that of stream class D. Mean values and standard deviations for the cumulative AFLWD volume and piece count percentages are presented in Table 4.3 and Table 4.4, respectively, for distances from a stream of 10 ft to 170 ft in 20 ft increments. Results for all five stream classes are presented in the tables.

Accumulation of AFLWD was most rapid for the largest streams, stream class A, indicated by the steeper slopes for the cumulative AFLWD volume and piece count profiles in Figure 4.6. Approximately

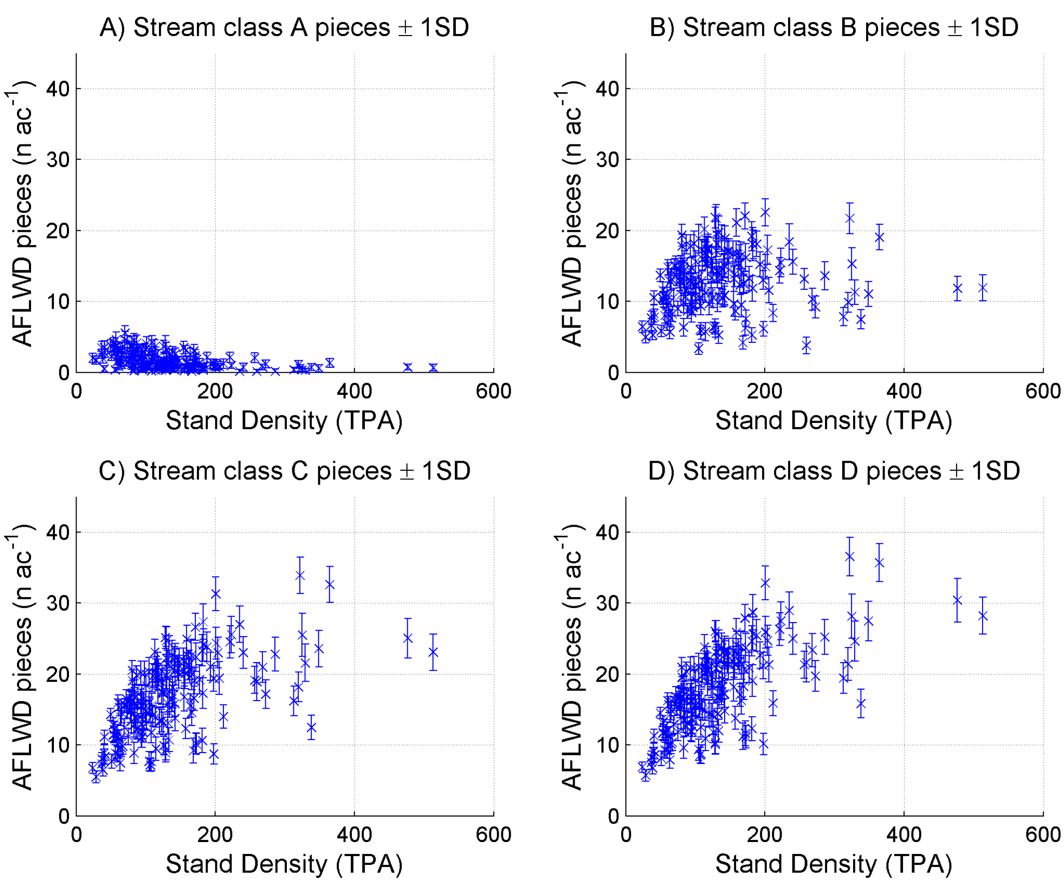

Figure 4.4: Expected values for AFLWD piece counts (pieces ac^{-1}) for each tree list T_l and stream classes A through D plotted against stand density. Values are means ± 1 std. dev. for one side of a stream, and were obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

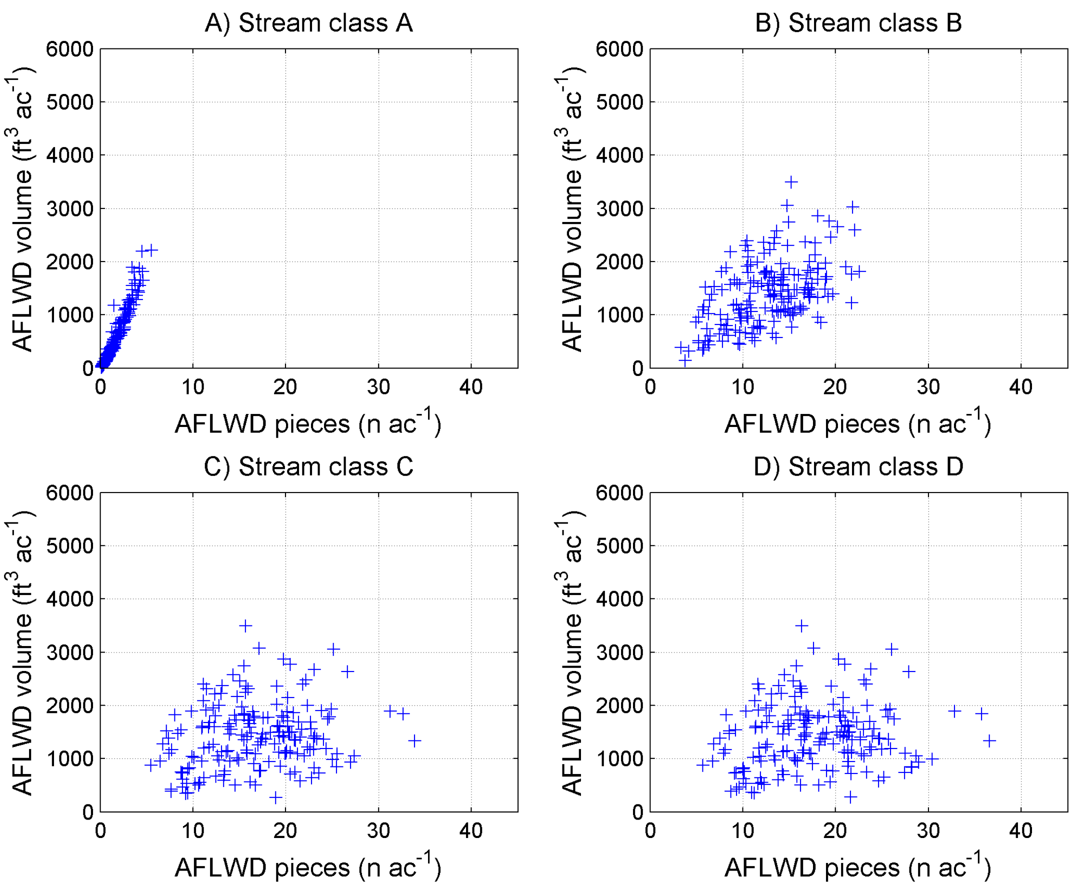

Figure 4.5: Scatter plots of mean expected values for AFLWD volume (ft^{3}ac^{-1}) and piece counts (pieces ac^{-1}) for each tree list T_l and stream classes A through D plotted. Values are means for one side of a stream obtained from the $N_S = 100$ simulated riparian stands generated from each tree list.

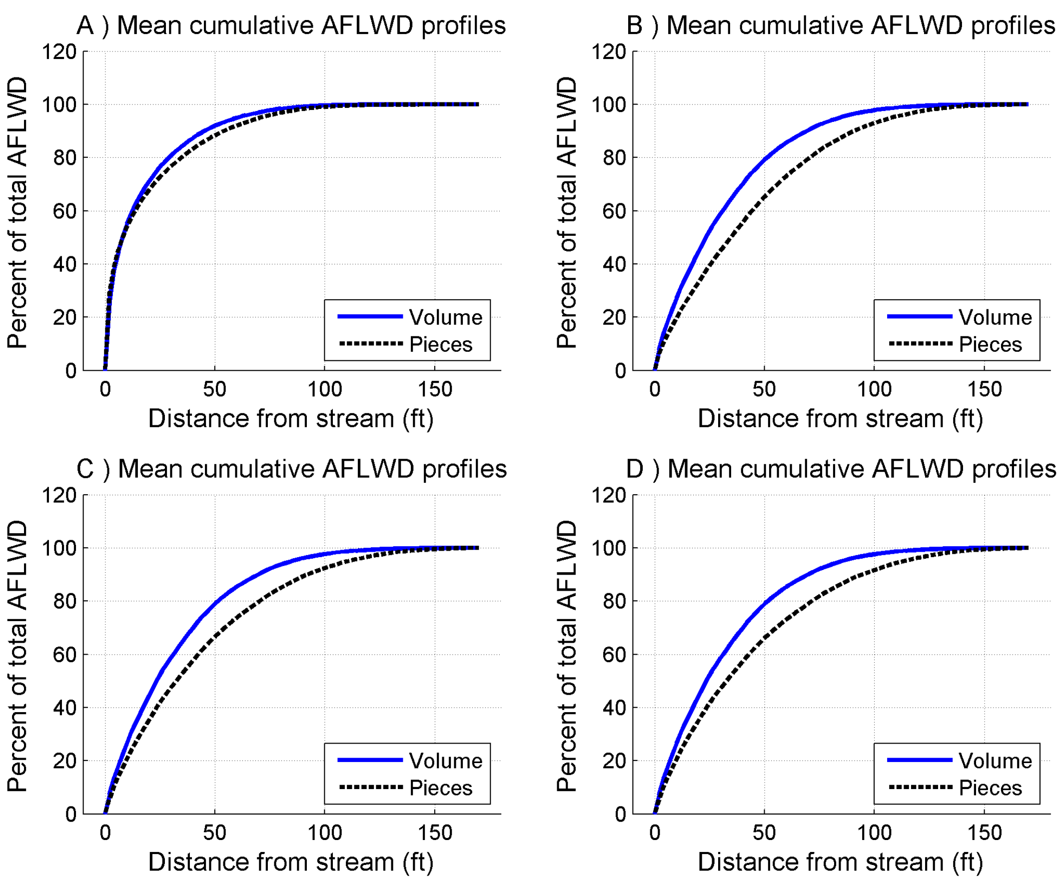

Figure 4.6: Mean cumulative profiles for expected AFLWD volume and piece counts as a percent of the totals for stream classes A through D. The average for each stream class was derived from all 179 available tree lists.

Table 4.3: Mean AFLWD volume accumulation, based on the percent of the total LWD volume produced by each tree list, for distances from a stream of 10 ft to 170 ft in 20 ft increments. Standard deviations are in parentheses. The average for each stream class was derived from all 179 available tree lists.

Distance from stream (ft)	Mean cumulative volume percent Stream Class				
	A	B	C	D	E
10.0	55.1	27.2	26.7	26.6	26.6
Std. Dev.	20.9	5.0	4.4	4.3	4.3
30.0	80.8	58.9	58.8	58.7	58.7
Std. Dev.	14.1	6.8	6.7	6.7	6.7
50.0	91.9	79.2	79.0	79.0	78.9
Std. Dev.	7.8	6.2	6.1	6.0	6.0
70.0	97.0	90.4	90.2	90.1	90.1
Std. Dev.	3.8	4.4	4.4	4.3	4.3
90.0	99.2	96.3	96.2	96.1	96.1
Std. Dev.	1.5	2.5	2.5	2.5	2.5
110.0	99.8	98.8	98.7	98.6	98.6
Std. Dev.	0.5	1.2	1.2	1.2	1.2
130.0	100.0	99.7	99.6	99.6	99.6
Std. Dev.	0.2	0.4	0.4	0.4	0.4
150.0	100.0	100.0	99.9	99.9	99.9
Std. Dev.	0.0	0.1	0.1	0.1	0.1
170.0	100.0	100.0	100.0	100.0	100.0
Std. Dev.	0.0	0.0	0.0	0.0	0.0

91.9% ± 7.8% of the AFLWD volume and 88.4% ± 11.4% of the AFLWD pieces were accumulated for stream class A by a distance of 50 ft from a stream, with the other stream classes having volume accumulations of approximately 79.0% ± 6.0% and piece count accumulations of approximately 66% ± 11% at that distance. At a distance from a stream of 90 ft, the volume and piece count accumulations for stream class A were approximately 99.2% ± 1.5% and 98.2% ± 3.1%, respectively, with volume accumulations for the other stream classes being approximately 96.0% ± 2.5% and piece count accumulations of approximately 89.0% ± 6.8% for stream classes B and C, and piece count accumulations of approximately 88.5% ± 6.8% for the remaining stream classes. The AFLWD volume accumulated more rapidly than AFLWD piece count for all stream size classes.

Table 4.4: Mean AFLWD piece count accumulation, based on the percent of the total LWD pieces produced by each tree list, for distances from a stream of 10 ft to 170 ft in 20 ft increments. Standard deviations are in parentheses. The average for each stream class was derived from all 179 available tree lists.

Distance from stream (ft)	Mean cumulative pieces percent Stream Class				
	A	B	C	D	E
10.0	54.1	19.8	20.8	20.8	20.7
Std. Dev.	23.0	6.9	6.8	7.1	7.1
30.0	76.7	45.1	47.6	47.3	47.2
Std. Dev.	17.5	9.6	11.3	11.4	11.4
50.0	88.4	65.4	66.7	66.1	66.1
Std. Dev.	11.4	10.2	10.9	11.0	11.0
70.0	94.8	79.7	79.9	79.1	79.1
Std. Dev.	6.5	9.1	9.2	9.2	9.1
90.0	98.2	89.8	89.3	88.6	88.5
Std. Dev.	3.1	6.8	6.8	6.8	6.8
110.0	99.5	95.4	94.9	94.3	94.3
Std. Dev.	1.3	4.3	4.4	4.5	4.5
130.0	99.9	98.5	98.1	97.8	97.7
Std. Dev.	0.4	2.0	2.2	2.3	2.4
150.0	100.0	99.7	99.6	99.4	99.4
Std. Dev.	0.1	0.5	0.7	0.8	0.8
170.0	100.0	100.0	100.0	100.0	100.0
Std. Dev.	0.0	0.0	0.0	0.0	0.0

4.2.2 Mean LWD accumulation distances

Mean values and standard deviations for the distances from a stream at which cumulative AFLWD volume and piece count percentages of 100%, 99%, 95%, 90%, 85%, 80%, and 50% of the total occurred for each tree list are presented in Table 4.5 and Table 4.6, respectively. These results complement the accumulation percent results, and values for all five stream classes are provided.

Distances at which fixed percentages of the accumulation of AFLWD volume and pieces were smaller for the larger stream size classes. Stream class A had 100% accumulation occurring within approximately 98.5 ± 42.1 ft of a stream for volume and 97.6 ± 42.8 ft of a stream for piece count. Distances from a stream for 100% of the AFLWD volume accumulation for the other stream classes ranged from 155.4 ± 17.1 ft for stream class B to 164.1 ± 10.8 ft for stream class E, and for piece count values the distance ranged from 155.2 ± 17.8 ft for stream class B to 163.7 ± 11.7 ft for stream class E. Distances from a stream where 95% of the AFLWD volume accumulation occurred were 51.8 ± 23.7 ft for stream class A, 83.1 ± 12.7 ft for stream class B, and approximately 84.0 ± 12.4 ft for stream classes C through E. Distances from a stream where 95% of the AFLWD piece count accumulations occurred were 57.2 ± 28.8 ft for stream class A, 103.0 ± 19.0 ft for stream class B, and approximately 108.5 ± 19.2 ft for stream classes C through E. The distance at which an AFLWD volume accumulation of 50% occurred was 11.1 ± 7.3 ft from a stream for stream class A, and within approximately 24.1 ± 4.3 ft from a stream for all other stream classes. The distance at which an AFLWD piece count accumulation of 50% occurred was 12.6 ± 10.2 ft from a stream for stream class A, and within approximately 34.7 ± 9.3 ft from a stream for all other stream classes.

Table 4.5: Mean distance from stream (feet) necessary to achieve AFLWD volume accumulations of 100%, 99%, 95%, 90%, 85%, 80%, and 50% of the total LWD volume produced by each tree list. Standard deviations are in parentheses. The average distances for each stream class were computed from all 179 available tree lists.

LWD volume accumulation	Mean distance (ft) from stream Stream Class				
%	A	B	C	D	E
100	98.5	155.4	160.6	163.7	164.1
Std. Dev.	42.1	17.1	13.6	11.1	10.8
99	70.0	108.5	110.0	110.7	110.8
Std. Dev.	29.4	16.0	15.5	15.2	15.2
95	51.8	83.1	83.8	84.0	84.0
Std. Dev.	23.7	12.7	12.5	12.4	12.4
90	41.5	68.8	69.2	69.3	69.3
Std. Dev.	20.3	10.9	10.8	10.6	10.6
85	34.7	59.2	59.4	59.5	59.5
Std. Dev.	17.8	9.6	9.5	9.5	9.5
80	29.3	51.8	52.0	52.1	52.1
Std. Dev.	15.7	8.5	8.4	8.4	8.4
50	11.1	24.0	24.1	24.1	24.2
Std. Dev.	7.3	4.4	4.3	4.3	4.2

Table 4.6: Mean distance from stream (feet) necessary to achieve AFLWD piece count accumulations of 100%, 99%, 95%, 90%, 85%, 80%, and 50% of the total LWD pieces produced by each tree list. Standard deviations are in parentheses. The average distances for each stream class were computed from all 179 available tree lists.

LWD piece accumulation	Mean distance (ft) from stream Stream Class				
%	A	B	C	D	E
100	97.6	155.2	160.5	163.4	163.7
Std. Dev.	42.8	17.8	14.4	12.0	11.7
99	74.8	124.1	128.6	132.4	132.8
Std. Dev.	33.6	20.3	20.2	19.4	19.3
95	57.2	103.0	105.7	108.5	108.7
Std. Dev.	28.8	19.0	19.4	19.2	19.2
90	46.4	89.3	90.5	92.6	92.8
Std. Dev.	25.5	17.5	18.1	18.1	18.0
85	39.2	79.2	79.6	81.1	81.3
Std. Dev.	23.0	16.0	16.8	16.8	16.8
80	33.5	71.0	70.6	71.9	71.9
Std. Dev.	20.9	14.6	15.5	15.5	15.6
50	12.6	36.1	34.4	34.7	34.7
Std. Dev.	10.2	8.2	9.1	9.3	9.3

Chapter 5

Discussion

The objectives for the AFLWD simulation model were to produce a model that was in first order agreement with empirical studies and other models for LWD production or recruitment having similar assumptions. In Section 5.1 the agreement between mean expected values for AFLWD volume and piece counts obtained from this model and from empirical studies (Bilby and Ward, 1989, 1991, Fox, 2001, 2003) are examined, and in Section 5.2, the agreement between the cumulative AFLWD volume and piece count profiles perpendicular to a stream obtained from this model and other similar models (McDade et al., 1990, Van Sickle and Gregory, 1990) are explored. Several implications of these results for riparian buffer management are also discussed. Finally, in Section 5.4, impacts of some of the simplifying assumptions on the LWD availability simulation model are discussed and several possible improvements to the model are identified.

5.1 Mean AFLWD volume and piece count

Trends for the mean AFLWD volumes and piece counts estimated by the AFLWD simulation model were in agreement with expectations. The estimated values for AFLWD volumes and piece counts both increased as stream size, measured by bank-full width, decreased, approaching saturation points of approximately 1440.0 ft^3ac^{-1} for volume and 18.0 pieces ac^{-1}. Such a saturation point must occur since the minimum dimensions for functional LWD logs decreased from a maximum base diameter 25.6 inches and length of 44.0 ft, for the largest stream size, stream class A, to values consistent with minimum dimensions for an LWD log, a 4 inch base diameter and a 6.6 ft length, that were used for the smallest stream size, stream class E. Results for stream classes A through C were consistent with the trends that have been reported in empirical studies of functional LWD in riparian areas for larger streams (Bilby and Ward, 1989, 1991), and the results for stream classes D and E were consistent with empirical studies of LWD abundance for smaller streams (Fox, 2001, 2003).

Mean expected values for AFLWD volume and piece count rapidly increased to values near their respective saturation levels as stream size decreased, nearly achieving the saturation point by stream class C, with stream classes D and E being essentially indistinguishable from one another. The primary reason for this effect was that the minimum dimensions for functional LWD were effectively equivalent for stream classes C through E. The base diameter values for these stream classes were 5.3 inches, 4.0 inches, and 4.0 inches, with corresponding length values of 15.0 ft, 7.5 ft, and 6.6 ft, respectively. The relatively small difference in the base diameter 1.3 inches for these stream classes identified essentially the same potential available functional

LWD logs for each of these stream classes. The greater functional base diameter and length of stream class C produced the differentiation in AFLWD values between stream class C and classes D and E, but the small difference in length between stream classes D and E was not enough to matter. The base diameter of the potential LWD logs may, therefore, be driving the selection of the potentially functional LWD logs, more so than the length, that is, meeting a base diameter requirement for functional LWD logs may be more difficult.

The potential availability of AFLWD volume and piece count were influenced by both average tree size and stand density. This was clearly indicated by Figure 4.1 and Figure 4.2 for volume and by Figure 4.3 and Figure 4.4 for piece count. Lower values of AFLWD volume were produced by stands having dominant tree heights less than approximately 100 ft, and by stands having very low densities or densities greater than 200 TPA. Expected values for AFLWD volume were also highly variable throughout the range of tree sizes and stand densities. A strong upward trend in AFLWD volume was demonstrated with increasing tree height, but no trend was readily apparent relative to stand density, other than that mentioned, where AFLWD volume values were widely distributed within the range from 500 $\text{ft}^3\text{ac}^{-1}$ to 3000 $\text{ft}^3\text{ac}^{-1}$.

Larger streams demonstrated a noticeable upward trend in AFLWD piece count as tree size increased, but no trend was apparent for smaller stream sizes, where the AFLWD piece counts were more or less uniformly distributed between 10 pieces ac^{-1} and 25 pieces ac^{-1} throughout the range in height values. The AFLWD piece counts showed a strong relationship with stand density, generally increasing as stand density increased, but with high variability. Potential AFLWD volumes (piece counts) within their range were, then, produced by a broad range in the number of LWD pieces (volumes). A better understanding of the relationship between potentially available LWD volume and piece count requires an understanding of the stand structures that produce their values.

As stand density increased, expected AFLWD volume initially increased and then decreased, while expected piece count values generally increased. These results may indicate a stand level size (height) threshold for the production of AFLWD, and ALWD, for riparian forest stands, occurring near a dominant height of approximately 100 ft, and the existence of a trade-off between AFLWD volume and piece count. The existence of a size–density trade-off in the potential availability of LWD may be of particular importance for managed riparian areas.

Values for AFLWD volume and piece count are also coupled, and are jointly dependent upon the stand density, tree locations, and the size distribution of trees within a riparian stand. The largest AFLWD volumes do not occur for the largest AFLWD piece counts, see Figure 4.5, but rather for intermediate piece counts, between 10 pieces ac^{-1} and 25 pieces ac^{-1}. This indicates that riparian stands containing some large trees are necessary to obtain larger AFLWD, and ALWD, volumes, and, therefore, that management to achieve piece count targets alone may not produce enough trees of sufficient size to obtain desired levels of functioning instream LWD. The existence of a size threshold and a size–density trade-off are consistent with current understanding of the relationships between stand dynamics and LWD production, and the fact that small trees, and trees far from a stream, cannot produce LWD logs having a size that is large enough to contribute significantly to expected LWD volume.

Stand structure, represented by the stand density, the size distribution of the trees, and tree locations relative to a stream, strongly influenced the amounts of potentially available LWD volume and piece counts. To provide some insight into the relationships among stand structure, tree location, and the potential for production of LWD, seven sample stands were selected based on their ALWD values, the AFLWD values for stream class E. Six of the seven stands, stands 1 to 6, were selected to be representative the perimeter of the overall distribution of ALWD volume and piece count values, and the seventh was chosen to be near the center of the distribution. Summaries of the stand characteristics and their mean ALWD values are provided in Table 5.1, with plots of the ALWD values from the $N_S = 100$ simulation trials shown in Figure 5.1. Of particular interest is the variability of the distributions of ALWD volumes and piece counts produced by each

Table 5.1: Stand attributes and simulated potentially available LWD volumes and piece counts for seven sample stands, see Figure 5.1.

Stand	TPA	QMD (in)	H (ft)	Total BA (ft^2ac^{-1})	Total volume (ft^3ac^{-1})	ALWD pieces (n ac^{-1})	ALWD volume (ft^3ac^{-1})
1	476.7	11.3	52.3	331.3	11916.6	30.9	995.0
2	312.7	11.6	50.1	230.0	7697.0	19.8	566.9
3	128.2	24.1	124.5	404.9	23513.5	26.1	3056.1
4	128.9	13.0	63.0	118.9	5336.2	10.4	533.6
5	63.4	22.0	86.0	167.9	8597.8	8.0	1101.4
6	70.2	29.4	148.2	330.7	22655.9	16.4	3495.1
7	164.2	17.5	75.7	275.0	14425.4	17.2	1811.8

of the stands. Only the tree locations relative to a stream were changed for each simulation trial to obtain the different ALWD values in the clusters of points for each stand. The locations and sizes of individual trees relative to a stream are seen to be critical for the potential production of instream LWD. For example, stands having some larger trees produced ALWD volumes having a range of approximately 2000 ft^3ac^{-1}, while stands having few or no larger trees produced volumes having a range of approximately 500 ft^3ac^{-1}. The range in the number of ALWD pieces also depended upon tree sizes and locations, but was influenced by stand density, with stands having a mixture of tree sizes and higher densities, stands 1 and 2, producing the broadest ranges in number of ALWD pieces.

The three stands having smaller average tree sizes, stands 1, 2, and 4, define the lower boundary of the ALWD volume and piece count distribution, and stands having larger tree sizes, stands 3, 5, and 6, define the upper boundary of the distribution. Stands 3 and 4 have almost identical stand densities but different size distributions, and correspondingly different potential to produce LWD. In fact, they appear on opposite sides of the ALWD volume and piece count distribution. The highest density stand, stand 1, produced a distribution of ALWD volumes and piece counts that were intermediate in value, but stand 2, having a lower stand density but nearly equal average tree size produced noticeably less ALWD. The reason for this becomes clear when the total basal area and total volume values for these two stands are examined: stand 1 has some larger trees as indicated by its much greater total basal area and volume, whereas stand 2 did not. Stands 5 and 6 have the lowest densities but larger average tree sizes. Stand 5 produces intermediate ALWD volume values and lower ALWD piece count values, while stand 6, produces the largest ALWD volume values and intermediate ALWD piece count values, while having only 10 more TPA, nearly all of which appear to contribute to the ALWD piece count.

Finally, assuming that there exists some form of regional equilibrium between the potentially available functional LWD in riparian areas and the LWD that has actually been recruited into streams as functional LWD, which seems reasonable, given that the standing live trees adjacent to streams are the source of instream LWD, a direct comparison may be made with results reported in empirical studies of instream LWD (Bilby and Ward, 1989, Fox, 2001). Differences in the way volumes were computed, in the AFLWD simulation model and the two empirical studies precludes a comparison of LWD volume values, so a comparison based only on piece counts was performed. To perform the LWD piece count comparison, the AFLWD values were first standardized to a 328.1 ft reach of stream and scaled to account for both sides of a stream. A scale factor of $2 \cdot (328.1/256.2) = 2 \cdot 1.28 = 2.56$, was used to convert the piece count values for the one acre riparian buffer with a stream reach of 256.2 ft into equivalent values for a 328.1 ft stream reach and both sides of a stream. Means and standard deviations for the standardized expected AFLWD piece count values appear in Table 5.2, along with their medians, their 25% and 75% quartiles, and their ranges.

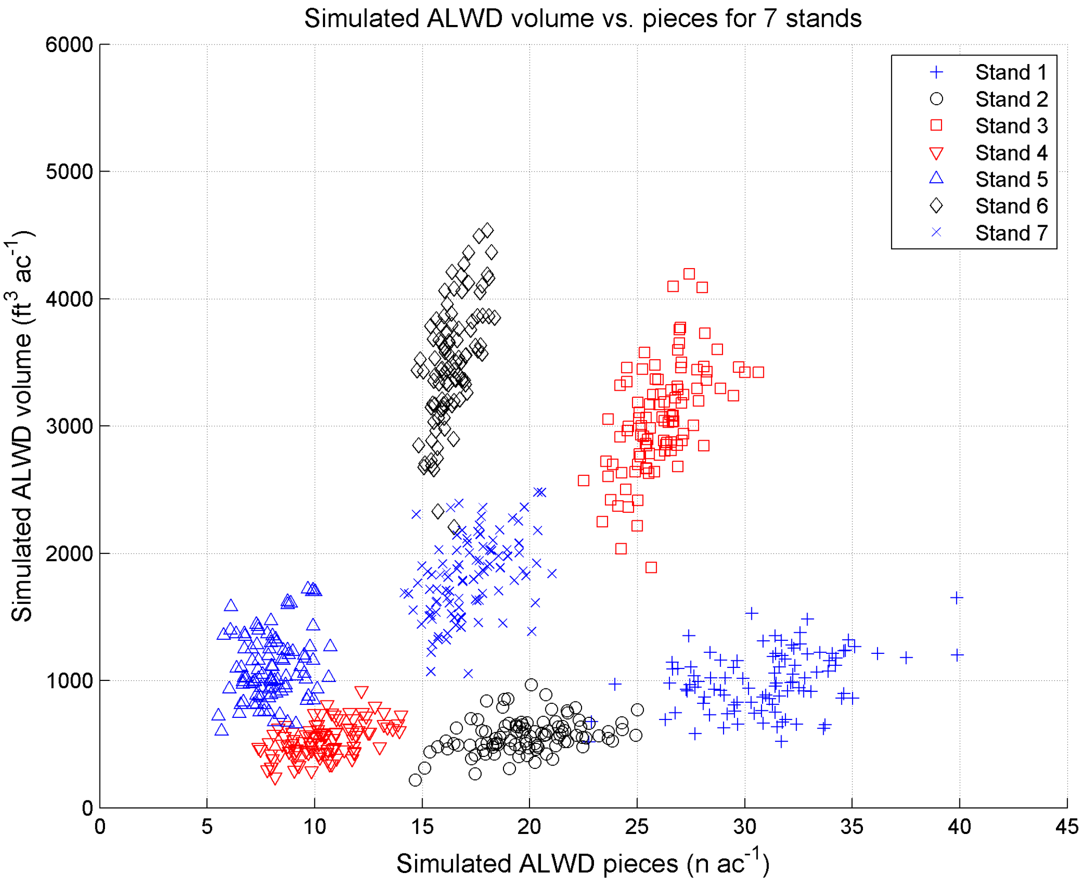

Figure 5.1: Simulated ALWD volumes and piece counts for 7 stands. The points for each stand represent the values from each of the $N_S = 100$ simulation trials from which the mean values for each stand were obtained.

Table 5.2: Estimated AFLWD pieces per 328.1 ft of stream reach.

Stream Class	W_j^{bf} (ft)	Mean	Std. Dev.	Q25	Median	Q75	Range
A	75.0	4.3	3.0	1.8	3.4	6.3	13.8
B	30.0	32.6	10.9	24.8	33.0	39.8	49.2
C	15.0	42.6	14.1	31.6	41.3	52.4	72.8
D	7.5	45.5	15.1	33.5	43.2	54.8	79.1
E	5.0	45.8	15.2	33.6	43.4	55.2	79.6

Table 5.3: Estimated functional LWD piece counts for 328.1 ft of stream reach. The values were obtained from the empirical equation relating the mean number of pieces per unit of stream reach to the bank-full width from Bilby and Ward (1989).

Stream Class	W^{bf} (ft)	Mean Pieces	Lower Bound	Upper Bound
A	75.0	8.7	6.0	10.0
B	30.0	24.2	12.0	41.0
C	15.0	52.6	34.0	69.0

Simulated AFLWD piece counts for larger streams, stream classes A, B, and C, were compared to values derived from an empirical relationship, given in Equation 5.1, relating the mean number of functional LWD pieces per meter of stream reach to the bank-full width, W^{bf}, in meters, for streams in western Washington (Bilby and Ward, 1989).

$$\text{functional pieces per meter} = 10^{-1.12*\log_{10}(W^{\mathrm{bf}})+0.46} \qquad (5.1)$$

The data used to estimate the empirical relationship had a minimum bank-full width of 13.1 ft and a maximum bank-full width value of 65.6 ft. Given the form of the equation, which increases without bound as the bank-full width approaches zero, it could not be used to predict piece count values for the small streams, for which the mean piece count values were expected to saturate at some finite value. The bank-full width of the largest stream class also exceeded the maximum value observed in the data, but extrapolating to larger streams seemed reasonable in this situation. Values predicted by the empirical relationship in Bilby and Ward (1989) for a 328.1 ft reach of stream are given in Table 5.3 for stream classes A through C. Observed values for the frequencies of functional LWD were quite variable, relative to the fitted curve, so in addition to estimates of the mean values obtained from Equation 5.1, visually estimated upper and lower bounds for observed functional LWD frequencies, obtained from Figure 2 in Bilby and Ward (1989), are also provided to give an additional frame of reference for the comparison.

Magnitudes of the mean expected AFLWD piece count values for the three largest stream classes obtained from the AFLWD simulation model were in good agreement with those predicted from Bilby and Ward (1989). The simulation model may underestimate the mean number of functional LWD pieces relative to values from Bilby and Ward (1989) for stream class A, where values of 4.3 and 8.7 pieces per 328.1 ft, respectively, were obtained. An approximate range for this stream size class was from 6 to 10 pieces, and the value of 4.3 obtained from the simulation model is close to the lower bound, and may, therefore, be reasonable, particularly considering that fact that no part of the log on the stream bank was used. For stream class B, the simulation model appears to overestimate the mean number of functional LWD pieces relative to the mean value from Bilby and Ward (1989), giving a value of 32.6 pieces *vs.* a mean of 24.2 pieces per 328.1 ft. The value of 32.6 pieces produced by the simulation model is, however, well within the range of observed values for this stream size, given by the approximate bounds of 12.0 pieces to 41.0 pieces. For stream class C, values of 42.6 and 52.6 functional LWD pieces per 328.1 ft, respectively, were obtained from the simulation model and Equation 5.1, indicating that the simulation model may underestimate the number of functional LWD pieces for streams of this size. Again, however, the value of 42.6 produced by the simulation model is well within the range of observed values for this stream size, with approximate values from 34.0 pieces to 69.0 pieces.

For the smaller streams, stream classes D and E, total LWD piece count values for western Washington streams from Fox (2001, 2003) were used for comparison. The total piece counts were based on a minimum LWD piece size having a diameter of 3.9 inches and a length of 6.6 ft. LWD piece count values for stream classes with bank full widths from 0 ft to 19.7 ft and 19.7 ft to 98.4 ft were reported by Fox (2001) and used here for comparison with the simulated ALWD piece count values. Comparisons were made with both

Table 5.4: Observed total LWD pieces per 328.1 ft of stream reach as reported in Fox (2001).

W^{bf} (ft)	Mean	Std. Dev.	Q25	Median	Q75	Range	N
0.0-19.7	32.5	15.6	25.5	29.0	37.9	67.5	19
19.7-98.4	52.0	33.0	29.2	52.3	63.4	131.7	49

of these stream classes from Fox (2001) because results for the smaller stream class were based on only 19 sample points, which may not have been sufficient to characterize the distribution of LWD piece counts for the smaller streams. In addition to means and variances, Fox also provided median values, 25% and 75% quartiles, and ranges for the total LWD piece counts.

Magnitudes of the mean expected AFLWD piece count values for the smallest stream classes obtained from the AFLWD simulation model were consistent with values from Fox (2001). A mean value of 45.8 pieces per 328.1 ft of stream reach was obtained from the LWD simulation model for stream class E, with Fox reporting mean values of 32.5 pieces for small stream sizes and 52.0 pieces for intermediate stream sizes, values which bracket the value from the LWD simulation model. Similar relationships hold for the median and quartiles. Fox reported values of 29.0, 25.5, and 37.9 for the median, 25% and 75% quartiles, respectively, for the number of LWD pieces for small stream sizes, and values of 52.3, 29.2, and 63.4 for the number LWD pieces in the intermediate stream size class. Values of 43.4, 33.6, and 55.2, for the median and quartiles, were obtained respectively, from the AFLWD simulation model.

The comparison results for the large and small streams indicate that the simulation model may overestimate the mean number of LWD pieces for small streams and that it may underestimate the mean number of LWD pieces for intermediate stream sizes. Before drawing this conclusion, however, two factors must be considered. First is the age distribution of stands sampled in Fox (2001, 2003). The mean values for the total number of LWD pieces in Fox (2001, 2003) were computed from stands having an age range from less than 150 years to over 800 years with the majority of stands having ages in the range of 200 to 500 years, Figure 17 in Fox (2001). The age range for the stands used to obtain the simulated values was 100 to 180 years, with a mean value of approximately 120 years. Differences in the stand ages between Fox (2001, 2003) and the data set used as the basis for the simulations may be influencing the results. In fact, Fox reports that the number of LWD pieces recruited into a stream over the first 150 years is, on average, larger than the number of LWD pieces recruited into streams for the subsequent 400 years, after which the value rises again.

The selection of stands within the stem exclusion and early stand differentiation stages (Oliver and Larson, 1996) may, therefore, be inflating the LWD piece count values, relative to a natural, long term, background level. From Figure 18 B in Fox (2003), the mean number of LWD pieces per 328.1 ft of stream reach for stands having ages less than 150 years was approximately 50, while for stands having ages in the range 150 years to 550 years the mean value was approximately 35. A value of approximately 50 LWD pieces per 328.1 ft of stream reach from Figure 18 B in Fox (2003) for younger stands is very close to the mean value of 45.8 pieces obtained from the simulation model, and the overall mean number of pieces from Fox (2001) for all western Washington streams is 46.6, which is even closer to the simulated value.

Second, larger streams transport more LWD, creating more pieces due to breakage during transport, than smaller streams, and larger streams can accumulate very large amounts of LWD in jams, skewing the piece count distribution toward large values. Transport of LWD logs within a stream and the formation of log jams are not included in the AFLWD simulation model, and this is likely a factor contributing to the underestimation of the mean number of pieces for the intermediate stream class of Fox (2001, 2003). Another contributing factor to the underestimation for intermediate streams is the fact that ALWD logs were computed in a manner that did not include any part of the log resting on the stream bank. If some part of the ALWD logs on the stream bank is included, the number of logs qualifying as LWD for the intermediate size classes will increase, due to an increase in the base diameters of the potential stream intersecting logs, which would, in turn, increase the number of potential LWD logs. Further investigation into these issues is necessary to determine if they are indeed related to the underestimation of LWD piece counts. This investigation is beyond the scope of this work, whose intent was to demonstrate general agreement with the trends and results of empirical studies, which has been done.

5.2 Mean cumulative AFLWD profiles

The cumulative LWD profiles produced using the AFLWD simulation model are in general agreement with results reported by McDade et al. (1990) and Van Sickle and Gregory (1990). The definitions used for LWD logs in these studies were not compatible with those chosen for potential LWD logs, so only the results for the smaller stream classes, which estimate the total abundance of LWD, may be compared. McDade et al. (1990) reported values for LWD piece counts only, and gave empirical results indicating that approximately 70% of LWD piece accumulation occurred within 65 ft of a stream for mature or old-growth conifer forests in western Oregon and Washington, and model estimates indicating that approximately 85% of LWD piece accumulation occurred within 98.4 ft of a stream. Van Sickle and Gregory (1990) reported model estimates for both LWD volume and piece count. They considered two types of stands: a uniform height stand with all trees having a height of 164.0 ft, and a mixed height stand with tree heights ranging from 65 ft to 213.3 ft in height. Their results for the mixed height stand indicated that approximately 95% of the volume and 90% of the pieces occurred within a distance of 65 ft of a stream, and that for the uniform height stand approximately 90% of the volume occurred within a distance of 65 ft, but only approximately 60% of the pieces. These values are in good overall agreement with those obtained from the AFLWD simulation model for the smallest stream size, stream class E, which had cumulative AFLWD volume and piece count percentages of approximately 90.1%±4.3% and 79.1%±9.1%, respectively, at a distance from a stream of 70 ft.

5.3 Implications for management

The mean cumulative profile results for AFLWD identified four characteristics that may have an impact on riparian buffer design. All four characteristics may be related to the idea of an effective buffer width for a stream. While there are many ways that the effective buffer width for a stream could be defined, an effective buffer width based on the likelihood that a tree could fall and produce a functional LWD log seems preferable. An effective buffer width is, then, defined to be the distance perpendicular or slope to a stream delineating a region of the forested buffer adjacent to a stream reach that is most likely to produce a functional LWD log for that stream.

The first characteristic is that larger streams have narrower effective buffer widths, on average, than smaller streams. This is true for both AFLWD volume and piece count. The narrower effective buffer width is a direct result of the fact that functional LWD logs are larger, on average, for larger streams, and that trees must, therefore, be closer to a stream to produce logs that would be large enough to be functional within those streams. Large streams, therefore, require large trees near them to potentially produce functional LWD logs.

The second characteristic is that there exists a point of diminishing returns for LWD volume and piece count that occurs as the buffer width is increased. That is, the marginal gain in AFLWD or ALWD volume or pieces is small relative to the change in buffer width. For example, to move from a 90% AFLWD volume accumulation level to a 99% AFLWD volume accumulation level requires an additional buffer width of 28.5 ft for stream class A and an additional buffer width of approximately 41.4 ft for stream classes D and E, while the first 50% of the AFLWD volume accumulation occurred within 11.1 ft of the stream for stream class A and within, approximately, 24.0 ft of the stream for stream classes D and E. Results for piece count accumulation were similar, requiring an additional buffer width of 28.4 ft for stream class A and an additional buffer width of approximately 39.8 ft for stream classes D and E, while the first 50% of the AFLWD pieces accumulated within 12.6 ft of the stream for stream class A and within, approximately, 34.7 ft of the stream for stream classes D and E. Clearly, trees that are located closer to a stream are much more important for the potential production of LWD than trees that are farther from a stream, and the costs of adding only a marginal amount of potential LWD must be considered when designing riparian buffers.

The third characteristic is that AFLWD volume accumulates more rapidly than AFLWD pieces. For example, the mean distances from a stream for a 90% accumulations of AFLWD volume and pieces were 41.5±20.3 ft and 46.4±25.5 ft, respectively, for stream class A, with a mean difference of 5.2 ft, and 69.3±10.6 ft and 92.8±18.0 ft, for stream classes D and E, with a mean difference of 23.5 ft. This implies that the AFLWD pieces occurring furthest from a stream are not contributing significantly to the AFLWD volume. If the size, measured by volume, of functional LWD logs was more important than their number, then the logs produced by trees further from a stream may not be as relevant fro instream LWD. There may, therefore, be a trade-off between the quality or size and quantity of functional LWD logs, and this trade-off may be dependent on stream size.

If such a volume–piece count trade-off exists, where functional LWD volume is more important than the number of pieces, the trade-off could be used to define an effective buffer width based on both piece count and volume. First the level of volume accumulation desired for each stream size class would be chosen. This would then define mean distances from a stream for each stream size class. Next, the mean distances would be used to obtain the piece count accumulation levels. For example, a 90% AFLWD volume accumulation level would occur at a distance from a stream of 41.5 ft for stream class A and 69.3 ft for stream classes D and E, giving piece count accumulation levels of approximately 85% for stream class A and 80% for stream classes D and E.

The final characteristic affecting the effective buffer width is that consistently large accumulations of AFLWD or ALWD volume occur only when the density of large trees within a riparian stand is high enough that some of the large trees are located near a stream. Riparian stands having high densities may produce many pieces of ALWD, but unless there are some larger trees present in the stand, and located near to the stream, the ALWD volumes will be small. Managed stands adjacent to streams that were planted at high densities and that have been removed from management by the FFR may, therefore, not produce large volumes or large pieces of LWD without some management intervention to put the stands on an appropriate trajectory using one or more thinning treatments to promote the development of larger trees near the stream.

5.4 Impacts of model assumptions

A number of simplifying assumptions were made when implementing the simulation model for estimating expected values for potentially available LWD. These simplifications have a direct impact on the results produced by the model and their relevance. Several of the most important assumptions are considered next and their individual impacts on the results are discussed, with recommendations for model improvements where applicable.

5.4.1 Stream intersection and tree fall directions

The distribution of possible tree fall directions θ was assumed to be uniform in the interval $[-\pi, \pi]$, which produced a uniform distribution of potential stream intersecting tree fall directions in the interval $[-\alpha, \alpha]$. This assumption with the assumption of independent tree fall implied that the local physical environment of the individual trees did not influence the probability of stream intersection, and, therefore, that trees would intersect with a stream independently of one another, if they were to fall.

The probability of stream intersection for a tree, however, is directly affected by its local physical environment. To improve the AFLWD simulation model the stream intersection probability distribution should be modified to include some of the factors from the local physical environment, e.g., tree location, tree size, stand density, and slope. For example, a tree that has other trees between it and a stream, potentially obstructing its fall toward the stream, will be less likely to intersect the stream if it falls than a similar tree the same distance away having no potentially obstructing trees. The simulation model may, therefore, overpredict AFLWD volume and piece count for tree locations further from a stream, increasing estimated effective buffer widths. The assumption of uniformly distributed tree fall directions was used because it was consistent with what others had done (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) and facilitated comparisons with their work.

5.4.2 The dimensions of stream intersecting logs

The point of near bank stream intersection was used as the point of reference for defining the dimensions of a stream intersecting log within the AFLWD simulation model for two reasons. First, using the point of stream intersection ties the dimensions and position of a stream intersecting log directly to a stream, providing a consistent point of reference for all such logs. Second, the length and midpoint diameter of stream intersecting logs, the measurements that have typically been reported (Bilby and Ward, 1989, 1991, Fox, 2001), do not permit a complete specification of the position of a stream intersecting log relative to the stream it intersects. In particular, the point of stream intersection on a log cannot be identified from the midpoint diameter and length. Further, the portion of a stream intersecting log that remains on the stream bank can vary tremendously depending on the size and distance to the stream of the tree that fell to produce it. So, in the absence of additional measurements that would allow a more complete description of the position and characteristics of stream intersecting logs relative to the stream they intersect, the point of stream intersection was used to identify the base the logs.

The size and volume of LWD logs is directly affected by the use of the point of near bank stream intersection to identify the base of a stream intersecting log, since the portion of the LWD log on the stream bank was not included. If some portion of the log in the stream bank is included, AFLWD piece count and volume values will increase for all stream size classes, which could bring some of the AFLWD estimates into better agreement with the empirical studies. As more information about the distributions of LWD log dimensions, locations relative to a stream, and number of pieces created from each tree become available, this portion of the simulation model could be improved by incorporating the additional information. The computational methods used here, however, were consistent with those used by others (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002), and may be easily modified to improve the quantitative agreement of the model with empirical results by changing the minimum functional LWD log dimensions or by including a portion of the log on the stream bank.

Table 5.5: Mean values for potentially available functional LWD volume (ft^3ac^{-1}) for random fall directions. Values are for one side of a stream and were computed using all 179 of the available tree lists.

Stream class	Mean expected LWD volume (ft^3ac^{-1}) summaries				
	Mean	Std. Dev.	Minimum	Median	Maximum
A	426.7	363.9	14.6	286.8	1660.2
B	1071.7	470.4	106.7	1061.1	2613.8
C	1100.7	463.6	209.4	1096.1	2618.8
D	1103.8	463.2	214.9	1100.6	2620.6
E	1104.0	463.1	215.2	1100.8	2620.6

Table 5.6: Mean values for potentially available functional LWD volume (n ac^{-1}) for random fall directions. Values are for one side of a stream and were computed using all 179 of the available tree lists.

Stream class	Mean expected LWD volume (n ac^{-1}) summaries				
	Mean	Std. Dev.	Minimum	Median	Maximum
A	1.3	0.9	0.1	1.0	3.9
B	10.9	3.7	2.7	11.1	19.3
C	14.9	4.9	5.0	14.7	30.2
D	16.7	5.5	5.3	16.0	34.1
E	16.9	5.6	5.4	16.2	34.7

5.4.3 Perpendicular tree fall

The assumption of a perpendicular tree fall direction when computing the dimensions and volume of a potential AFLWD log may cause both AFLWD volume and piece counts to be overestimated. To examine this issue, the simulations were repeated with the perpendicular tree fall direction assumption, $\theta = 0$ for all trees, removed. The new simulations used uniformly distributed tree fall directions for $\theta \in [-\alpha, \alpha]$. This change to the tree fall direction assumption caused a reduction in the average expected AFLWD volume values of approximately 28% for stream class A, 24% for stream classes B and C, and 23% for stream classes D and E. The AFLWD piece count average values were also reduced, by approximately 26% for stream class A, 14% for stream class B, 13% for stream class C, and 6% for stream classes D and E. Results for mean expected AFLWD volume and piece count values from this simulation are provided in Table 5.5 and Table 5.6, respectively.

Using a perpendicular tree fall direction for all trees maximizes the effective buffer width, as well as both the AFLWD volume and piece count for a particular stand configuration, while the random, uniformly distributed fall directions minimizes the effective buffer width and AFLWD volumes and piece counts in the sense that no fall direction is preferred. The results obtained here indicate that the expected AFLWD volume values may be quite sensitive to the tree fall direction. This comes as no surprise, since changes in the tree fall direction can significantly reduce the dimensions of potential LWD logs, subsequently reducing their volumes. Expected AFLWD piece counts are somewhat less sensitive, except for stream class A, where changes in the fall direction reduce the log dimensions, subsequently causing logs that qualified as functional LWD for a perpendicular fall direction to fail to qualify for a nonperpendicular fall direction.

If the expected AFLWD volume and piece count values obtained from the simulations using the perpendicular tree fall assumption were to be used to support the determination of minimum levels of AFLWD for use in practice, the fact that the perpendicular tree fall direction maximizes the AFLWD volume and piece count values would need to be taken into account. In this context, computed AFLWD volumes and piece counts would be conservative, that is larger than expected, and limits should be set accordingly. Alternatively, now that it is implemented, new results based on the random tree fall directions could be used to guide the determination of minimum levels of AFLWD or ALWD. So long as the same computational procedures were used to obtain estimates of AFLWD or ALWD, relative comparisons among results from different sources or from different applications may be performed.

Results from simulations assuming perpendicular tree fall directions and those from simulations assuming a random, uniformly distributed tree fall directions could be used together to provide approximate upper and lower bounds on the expected AFLWD volume and piece count values. With some additional model validation and calibration, if necessary, these upper and lower bounds may be suitable for bracketing actual values for the expected AFLWD volumes and piece counts. If this is indeed feasible, then the upper and lower bounds, and their respective distributions of AFLWD and ALWD could be used to guide the determination of desirable stand structures for managed riparian areas as well as to determine relevant effective buffer widths.

5.4.4 Distribution of tree distances from a stream

The distribution of perpendicular or slope distances of trees from a stream f_{distance} was assumed to be uniform within the 170 ft width of the riparian buffer. The specific shape of this distribution is not known, but an approximation to it could be derived empirically given the requisite data. The possible shapes for this distribution are bracketed by distributions that are skewed toward the stream, having the majority of trees located further from the stream, and by distributions that are skewed away from the stream, having the majority of trees located nearer to the stream, with the uniform distribution being the neutral distribution in the middle of the possible shapes. If the distribution of tree distances from a stream is skewed toward the stream, the assumed uniform distribution would overestimate AFLWD volume and piece counts, since it would locate more trees near the stream. A distribution of perpendicular or slope distances that was skewed away from a stream, having more trees closer to the stream than further away would, conversely, imply that the uniform distribution assumption underestimates AFLWD volume and piece counts. The degree of overestimation or underestimation is difficult to assess since the sizes of the individual trees, and not just location alone, strongly influences the potential LWD contribution. The assumption of uniformly distributed perpendicular distances from a stream is only an approximation, but it is consistent with what others have done (McDade et al., 1990, Van Sickle and Gregory, 1990, Beechie et al., 2000, Welty et al., 2002) and facilitates the comparison of results. This distribution may be modified once a better understanding of this distribution is obtained, or to use a mixture distribution for different species when such a distribution becomes available.

Chapter 6

Conclusions

An individual tree based simulation model for estimating the expected value of potentially available instream LWD was developed and tested. The model emphasized the distributions of characteristics that directly affect the potential availability of instream LWD, in particular the probability of stream intersection, the distribution of tree fall directions, and the distribution of distances from the stream for trees in riparian forests. The AFLWD simulation model was designed in a modular manner, allowing the substitution of alternative distributions, either to incorporate localized information or to adjust the characteristics of the model based on alternative distributions, for increased flexibility. The model described may easily be used with the tree list output from forest growth and yield models or forest stand simulators, as well as actual inventory data.

The AFLWD simulation model was used to estimate mean, regional expected values for potentially available functional LWD volume and piece counts for 120 year old, unmanaged, Douglas-fir dominated, riparian stands in western Washington. The trends in mean AFLWD volume and piece count produced by the simulation model decreased as stream size increased, a response that was in agreement with acknowledged trends for functional LWD. The distributions of the expected mean values for AFLWD volumes and piece counts were both skewed toward larger values, indicating that smaller values were more likely to occur than larger values. The AFLWD volumes and piece counts also had a high degree of variability relative to their mean values. A critical implication for management would be that small values for AFLWD may be more typical than larger values, and that they should, therefore, not be arbitrarily excluded from consideration in managed riparian areas by setting high minimum levels as targets for management, e.g., using a mean or median value as a lower bound for acceptance.

Cumulative profiles for AFLWD volume produced by the simulation model increased more rapidly than those for AFLWD piece count. If LWD volume was more important than the number of pieces, then there may exist a trade-off between the LWD volume and the number of LWD pieces. A similar trade-off may exist between the quality, e.g., size, and quantity of LWD pieces. If smaller functional LWD pieces were of lower quality than larger functional LWD pieces, then LWD produced from trees far from a stream would be less important. These types of trade-offs could have a significant impact on the widths of riparian buffers that are necessary to achieve desired levels of instream LWD, particularly for small streams.

The effective buffer width, the buffer width necessary to deliver a particular proportion of the total potentially available functional LWD into a stream, is generally much smaller than the buffer width defined by a site-potential tree height. The effective buffer width for obtaining 90% of the potentially available functional LWD volume for a small stream is approximately 70 ft, assuming that trees fall perpendicular to a stream, approximately 65 ft for random fall directions, but a site potential tree height based buffer width is 170 ft, which is almost 2.5 times wider. This is of particular importance, since the costs to landowners of wider riparian buffers may be large while providing only marginal gains in potential stream benefit, particularly for small streams. While wider buffers may afford other benefits to a stream they, may not be warranted on the basis of the potential for the production of instream LWD, and economic issues or the conversion of forest land to development may be of greater importance.

The level of detail necessary to support forest management decisions and the determination of forest policy continues to increase. As the level of detail necessary to make decisions or set policy has increased, so has the importance of recognizing the inherent variability in forest stands, or other natural system, whether managed or not. The models used to support forest management and policy decisions must be continually improved to meet the demands for increased detail and to provide estimates of the inherent variability. Simulation models, such as the one described here for potentially available LWD, provide one means for simultaneously meeting the demand for greater detail and estimates of the inherent variability. Distributional assumptions in this type of simulation model may be easily changed as more information is obtained, for example, a better understanding of the distribution of tree distances from a stream or the distribution of tree fall directions, by simply modifying the input distribution used to represent the particular aspect of the model. Simulation models, which are likely to become more prevalent, can be effective, flexible tools supporting forest management and forest policy.

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