ABSTRACT OF THE DISSERTATION OF

Mark Alan Meleason for the degree of Doctor of Philosophy in Fisheries Science presented on April 30, 2001. Title: A Simulation Model of Wood Dynamics in Pacific Northwest Streams.

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Stanley V. Gregory

Conceptually, the dynamics of wood in streams can be viewed in terms of input and in-channel processes. Input processes are associated with both the riparian (tree fall, bank cutting, windthrow) and upslope forests (mass failures). In-channel processes include log breakage, movement, and decomposition. A mechanistic view of these processes is presented and served as the basis for the development of a simulation model. STREAMWOOD is an individual based stochastic model that operates on an annual time step at the reach scale. Stream systems that can be simulated range from a single reach to a small basin. Stream wood dynamics considered are tree entry, breakage, movement, and decomposition. Riparian forest inputs are either from a simplified forest gap model built within STREAMWOOD or from a user-specified input file. The model is run under a Monte Carlo procedure and the results are reported as average conditions per reach. STREAMWOOD was developed for coniferous-forested streams of the Pacific Northwest fifth-order and smaller. Species considered include Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* D. Don ex Lambert), and red alder (*Alnus rubra* Bong.). Single parameter sensitivity analysis of STREAMWOOD concluded that parameters affecting tree growth were the most important in the forest model and decomposition was found to be the most important of the processes tested in the wood model. STREAMWOOD was used to assess long-term implications of selected riparian management regimes on the standing crop of wood in channels. Total wood volume (volume of all pieces intersecting the channel) strongly related to the width of the non-harvested riparian forest. A riparian forest width of 30 m was associated with 90% of the maximum site potential, which was the standing crop associated with a 75-m non-harvested forest. Plantation forests (clear-cut at time intervals up to 120 years) had very little effect on total wood volume in riparian forests with non-harvested forests at least 10 m wide. These results suggest that forest age and width of the non-harvested buffer was more important than the rotation age of plantation forests in providing long-term supplies of wood to the streams.

A SIMULATION MODEL OF WOOD DYNAMICS IN PACIFIC NORTHWEST STREAMS

by

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Mark Alan Meleason, Author

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CONTRIBUTION OF AUTHORS

Dr. Stanley V. Gregory was involved in the development of the conceptual model of wood dynamics in streams. Dr. John Bolte was involved in developing the underlying structure of the simulation model STREAMWOOD and provided guidance on the art of computer programming.

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DEDICATION

This thesis is dedicated to Pete and Mary Ann Meleason.

A SIMULATION MODEL OF WOOD DYNAMICS IN PACIFIC NORTHWEST STREAMS

1. INTRODUCTION

Numerous studies have characterized the amount (volume, density, or biomass) (Harmon et al., 1986) and role of wood in streams (Triska and Cromack, 1980; Thomson, 1991). Functionally, wood serves as habitat for aquatic organisms and a source of long-term nutrient loading and influences channel morphology, hydrology, and sedimentation patterns (Harmon et al., 1986; Bisson et al., 1987; Maser et al., 1988; Samuelsson et al., 1994).

Far less is known about the dynamics of wood than about the functional role of wood in streams. At first glance, dynamics of wood in streams appear straightforward. Trees from the riparian forest enter the channel through tree fall or mass erosion of banks and through mass failures from upslope sources. When a tree falls, it typically breaks into several logs on impact with the streambed and adjacent areas. The force of flowing water can fragment logs and transport all or part of them downstream. Logs decay through microbial activity and by abrasion of the flowing water over the log surface. Although the processes acting on wood in streams are readily identified, many remain largely unquantified.

Many aspects of wood dynamics in streams are difficult to assess because of the extensive temporal and spatial scales required to adequately characterize their complexity. Assessing wood dynamics by examining wood in a given channel reach at one point in time is difficult because of the static view of properties of wood at one time (Van Sickle and Gregory, 1990). A population of wood consists of pieces that have resided in the channel from days to centuries. Pieces in the channel may have originated from the current forest or from a forest that existed prior to a catastrophic disturbance located adjacent, upstream, or upslope of a given reach.

Simulation models are powerful approaches to investigate stream wood dynamics. Most existing wood models were designed to predict riparian forest recruitment (Rainville et al., 1986; McDade et al., 1990; Van Sickle and Gregory, 1990; Malanson and Kupfer, 1993; Minor, 1997; Beechie et al., 2000; Bragg, 2000). Other goals of wood models are simulation of source distance (McDade et al., 1990; Minor, 1997) and riparian forest carbon budget (Malanson and Kupfer, 1993). In-channel processes such as breakage, log movement, or log decomposition have not been considered separately in any exiting model. Several models have incorporated a depletion rate, which includes loss from both downstream transport and decomposition (Murphy and Koski, 1989; Beechie et al., 2000; Bragg et al., 2000). Several studies assume that transport of wood from upstream sources equals output of the reach for a given time interval (Murphy and Koski, 1989; Van Sickle and Gregory, 1990). Only one existing model specified tree location in the riparian forest (Bragg et al., 2000) and few models considered a directional fall regime (Minor, 1997; Bragg et al., 2000).

The objective of this study was to investigate riparian forest and in-channel wood dynamics through simulation modeling. STREAMWOOD is an individual-based model where each tree or log is subjected to various processes. The individual-based approach lends itself to a mechanistic representation of the various processes. To build an individual-based model, a conceptual framework was needed that considered the various components at a mechanistic level. Numerous literature reviews provide a conceptual framework for the dynamics of wood in streams. These reviews have emphasized the general ecology of wood in both aquatic and terrestrial environments (Triska and Cromack, 1980; Harmon et al., 1986; Maser et al., 1988; Samuelsson et al., 1994) or specifically in the stream environment (Swanson et al., 1982; Triska et al., 1982; Sedell et al., 1984; Bisson et al., 1987; Gregory et al., 1987; Bisson et al., 1992). These reviews provide mechanistic descriptions of various aspects of wood dynamics but do not provide the detail required for the development of simulations models. Chapter Two supplements general conceptual views presented in the numerous reviews cited above with a mechanistic perspective on the various processes associated with wood in streams. Chapter Three presents a detailed description of STREAMWOOD as well as the results of a performance evaluation. Chapter Four illustrates the potential use of the model to explore management options associated with long-term recruitment of wood to stream channels.

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2. DYNAMICS OF WOOD IN STREAMS AND THEIR REPRESENTATION IN SIMULATION MODELS

Mark A. Meleason and Stanley V. Gregory

2.1 Abstract

Functional importance of wood in streams challenges managers and scientists to consider the long-term implications of riparian forest management for wood in streams. One way to investigate wood dynamics is through simulation modeling. This paper provides an overview of the various components of wood dynamics in streams and how they are represented in simulation models. Components of wood dynamics include input processes and in-channel processes affecting redistribution and loss. Input processes are associated with riparian forests (e.g., windthrow, bank erosion, and snag dynamics), upslope forests (e.g., mass failures), and channel avulsion (e.g., fluvial erosion of banks and islands). Input varies with changes in forest structure, succession, and basin location. Recruitment of wood to the stream generally increases with forest age, though species composition is also a factor. Tree fall is associated with primary (windthrow, bankcut) and secondary agents (insect and disease, precipitation, suppression). In-channel processes include breakage, movement, burial, and decay. Types of breakage include fragmentation of standing trees, tree entry breakage, and in-channel breakage of logs. Size-class frequency distributions reflect the sources of wood pieces and history of breakage events for a given population of logs. The most important factors associated with log movement are magnitude of stream flow and piece length relative to active channel width. Steady state assumptions about the amount of wood in a channel are required by course resolution analyses of turnover rates and residence times but provides only limited information on in-channel wood dynamics. An alternative approach is to consider wood dynamics in a spatiotemporal framework that accounts for basin position and environmental variation. Individual-based modeling provides a powerful and instructive framework to explore in-channel wood dynamics and links to riparian forest dynamics.

2.2 Introduction

Numerous studies have been conducted on the functional role of wood in streams within the last 30 years (Harmon et al., 1986; Thomson, 1991). Literature reviews have emphasized the general ecology of wood in both aquatic and terrestrial environments (Triska and Cromack, 1980; Harmon et al., 1986; Maser et al., 1988; Samuelsson et al., 1994) or specifically in the stream environment (Swanson et al., 1982; Triska et al., 1982; Sedell et al., 1984; Bisson et al., 1987; Gregory et al., 1987; Bisson et al., 1992). Functionally, wood serves as habitat for aquatic organisms and a source of long-term nutrient loading and influence channel morphology, hydrology, and sedimentation patterns (Harmon et al., 1986; Bisson et al., 1987; Maser et al., 1988; Samuelsson et al., 1994).

Far less is known about the dynamics of wood than about the functional role of wood in streams. At first glance, dynamics of wood in streams appear straightforward. Trees enter streams through a variety of input processes associated with riparian and upland forests. Trees from riparian forests enter the channel through tree fall or mass erosion of banks and through mass failures from upslope sources. When a tree falls, it typically breaks into several logs on impact with the streambed. The force of flowing water can fragment logs and transport all or part of them downstream. Logs decay through microbial activity and by abrasion of the flowing water over the log surface.

Although the processes acting on wood in streams are readily identified, many remain largely unexplored. Many aspects of wood dynamics operate at time scales that prohibit their assessment through field-based studies alone. Simulation models translate conceptual models into quantitative relationships in order to explore system behavior over extended time scales. Several models of wood in streams have been developed (Rainville et al., 1986; Van Sickle and Gregory, 1990; Beechie, 2000; Bragg, 2000). The majority of models focuses on wood recruitment from the adjacent riparian forest under various management and natural disturbance regimes. Since the main focus of these models was on riparian forest recruitment, in-channel processes such as breakage, movement, and decomposition either were not included or highly simplified. A more holistic approach includes both riparian forest development and recruitment (forest growth, forest succession, and tree entry breakage) and in-channel processes (breakage, movement, and decomposition).

The model STREAMWOOD was developed to simulate wood dynamics in Pacific Northwest streams. Although the current version contains the minimum components required by a holistic approach, the model was designed to accommodate additional components (e.g., windthrow, debris flow, channel avulsion, and in-channel burial) without requiring major revisions of the code. STREAMWOOD is an individual based stochastic model where each tree or log is subjected to various processes within the model.

This report integrates general conceptual views presented in previous reviews (Triska and Cromack, 1980; Swanson et al., 1982; Triska et al., 1982; Sedell et al., 1984; Harmon et al., 1986; Bisson et al., 1987; Gregory et al., 1987; Maser et al., 1988; Bisson et al., 1992; Samuelsson et al., 1994) with a mechanistic perspective on the various processes associated with wood in streams. Information presented in this paper was used in the development of STREAMWOOD, a full description of which is documented elsewhere. The specific objectives of this paper are to:

1. Provide an overview of terrestrial input processes and in-channel processes associated with the dynamics of wood in streams.
2. Summarize approaches used to represent a process in previous simulation models. If no model was found that considered a given process, possible approaches are presented.

2.3 Input Processes

2.3.1 Influence of Riparian Forest Development on Input

Riparian forest recruitment to streams is one of the most studied aspects of wood dynamics (e.g., Froehlich, 1973; Lienkaemper and Swanson, 1987; Robison and Beschta, 1990b; McHenry et al., 1998; Beechie et al., 2000). Trees located near the channel enter directly through tree fall. Causes of tree fall include windthrow, snow load, ice load (Oliver and Larson, 1990), bankcutting, high flow events (Johnson et al., 2000), and interaction with other falling trees (Gratkowski, 1956). Tree fall also is influenced by the rate and type of precipitation. For example, heavy snow or ice storms can topple trees with little or no wind (Hubert, 1918; Sampson and Wurtz, 1994). Trees can be weakened or killed by fire, lightning, floods, drought, disease, or insects (Kozlowski and Pallardy, 1997) making them more susceptible to fall. The relative importance of factors responsible for tree fall varies considerably by basin position, season, forest age, and forest structure (Hubert, 1918; Gratkowski, 1956). Trees can fall while alive or as a snags that may have died decades before. The vigor of trees may be compromised by various abiotic and biotic factors making them more susceptible to falling. Abiotic factors, such as drought, flooding, and mineral deficiencies may make trees vulnerable to biotic stresses such as insect infestation and disease (Kozlowski et al., 1991).

Influence of Stand Structure on Riparian Forest Recruitment. The recruitment of wood to the channel, in terms of both volume and number of pieces, varies through time as a stand changes in structure and species composition. General models have been developed describing structural chances in forest development following a major disturbance (Oliver, 1981; Spies, 1997). Idealized stages of stand development include stand initiation (establishment), stem exclusion (thinning), understory reinitiation (transition), and old growth stage (shifting mosaic) (Oliver and Larson, 1990; Spies, 1997; Waring and Running, 1998). The initiation phase depends in part on the type and severity of the disturbance, species composition of the surviving community, and available seed sources (Spies, 1997). Tree establishment after disturbance may be delayed by the establishment and persistence of shrubs (Spies, 1997; Nierenberg and Hibbs, 2000). However, the initial densities and species composition of the new stand influence potential recruitment as the stand develops. For example, in the Pacific Northwest, the establishment of Douglas fir (*Pseudotsuga menziesii*) depends in part on an available seed source within the first few years after the disturbance (Spies, 1997).

The stem exclusion stage is characterized by a closed canopy creating an environment where new individuals rarely establish and mortality rate increases sharply due to competition among individuals (Oliver and Larson, 1990). As suppressed individuals die, the open space is quickly filled by lateral growth from the neighboring trees. Canopy structure begins to differentiate into various strata such as dominant, codominant, intermediate, and suppressed layers depending on the growth rates and shade-tolerances of the species present (Oliver and Larson, 1990).

Contribution of wood to the channel from the first two phases is minimal, though recruitment of individuals from the previous stand (e.g., stand replacement fire) may be substantial (Spies, 1997). For example, Grette (1985) surveyed wood in 27 streams in second-growth and old-growth forests located in the western Olympic Peninsula, Washington. Both deciduous and coniferous wood was recruited from stands as young as 10 years old. However, the total volume recruited to the channel from deciduous species increased slowly in stands < 25 yr old and then increased rapidly in older stands. Volume recruited from conifer species remained relatively low in stands < 50 yr and then increased. In a resurvey 11 years later, total number of pieces remained constant but total volume in the channel decreased across all second-growth stands (McHenry et al., 1998). Reduction in volume of the standing crop was attributed to depletion of larger pieces that originated from the previous stand. Number of pieces did not change because the stem exclusion stage delivers large numbers of small trees.

In the understory reintroduction stage, gaps formed by death of trees cannot be readily filled by lateral growth of the neighboring trees. Openings in the canopy release suppressed trees and encourage the development of understory vegetation (Oliver and Larson, 1990). Low light levels in the understory favor regeneration of shade-tolerant species. As a forest develops, the canopy architecture stratifies into overstory and understory layers both of which can be further divided into dominant, codominant, intermediate, and suppressed strata (Oliver and Larson, 1990). In the Pacific Northwest, forests dominated by shade-tolerant conifers require up to 150 years after a disturbance to reach this stage (Oliver et al., 1985). Dominant trees approach their maximum heights in this stage (Waring and Running, 1998). This stage is characterized by large accumulation of dead wood on the forest floor and in the stream (Spies et al., 1988; Waring and Running, 1998).

The final phase in forest development is the old-growth phase. Structure and species composition of the old-growth stage can be quite similar to the preceding stage, especially when composed of shade-tolerant species (Spies, 1997). The old-growth stage exhibits stands "composed entirely of trees which have developed in the absence of allogenic (events external to the site) processes" (Oliver and Larson, 1990, p 262). High variation in forest structure in old-growth forests reflects disturbance history within the stand (Franklin and Spies, 1991). This stage has also been referred to as the shifting mosaic stage (Bormann and Likens, 1979; Spies, 1997) because small disturbance events (e.g., forest gap-dynamics) alter stand structure at different sites over time, but the relative amounts of various stand types remain relatively constant. Amount of wood recruited to the stream from old-growth forests is substantial, but not necessarily the highest over the stand history because of changes in species composition and mortality rate as the stand develops (based on Spies et al., 1988).

2.3.2 Influence of Succession on Riparian Forest Recruitment

Recruitment of wood to channels from riparian forests also varies through time with successional changes in species composition. Temporal shifts from deciduous to coniferous inputs are attributed to successional changes of the forest (Heimann, 1988). Conceptual models of successional pathways for Pacific Northwest forests (Franklin and Dyrness, 1973; Franklin and Hemstrom, 1981; Spies, 1997) and riparian forests (Fonda, 1974; Hawk and Zobel, 1974; Pabst and Spies, 1999; Nierenberg and Hibbs, 2000) have been proposed. Most tree species in riparian forests in the Pacific Northwest are also common to upland forest communities. Red alder (*Alnus rubra*), a short-lived, early successional hardwood species, achieves its greatest abundance near streams (Harrington, 1990). Pacific Northwest forests are dominated by relatively few long-lived coniferous species present in virtually all successional seres (Franklin and Hemstrom, 1981).

Successional pathways in the Pacific Northwest appear to be strongly influenced by species composition in the stand initiation phase (Spies, 1997), which is determined by disturbance, environmental conditions, and available seed source (Franklin and Dyrness, 1973; Spies, 1997). Pure stands of Douglas fir eventually include more shade-tolerant conifers, though this transition may take 400 to 600 years (Franklin, 1988). Pure stands of red alder generally exclude Douglas fir establishment (Berntsen, 1961). Subsequent seral stages may include shade-tolerant conifers (Franklin and Dyrness, 1973), red alder (Heimann, 1988), or a shrub stage composed of salmonberry (*Rubus spectabalis*) that may last for hundreds of years (Spies, 1997; Nierenburg and Hibbs, 2000). Succession of a mixed alder/Douglas fir stand depends on relative densities of the species (Berntsen, 1961) and site fertility (Binkley and Greene, 1983). Infertile sites favor Douglas fir and fertile site favor red alder (Binkley and Greene, 1983).

Successional pathways are also influenced by the environmental gradient from stream to hillslope (Fonda, 1974; Hawk and Zobel, 1974; Oakley et al., 1985). Species dominance shifts with distance from the stream on unmanaged stands up to 150 yr in the Oregon Coast Range (Pabst and Spies, 1999; Nierenberg and Hibbs, 2000). Conifer basal area increased with distance from stream while hardwood basal area remained relatively constant (Pabst and Spies, 1999; Nierenberg and Hibbs, 2000). Deciduous species were most prominent on valley floors and conifer species were dominant on hillslopes. In addition, relative dominance of conifers was greatest in lower-order streams where valley floodplains are limited (Veldhuisen, 1990).

Representation of Riparian Forest Dynamics in Simulation Models. Simulation of riparian forest recruitment to stream has been represented with growth and yield models (Rainville et al., 1986; Beechie, 2000; Bragg, 2000), forest gap models (Malanson and Kupfer, 1993), and static input tables for a particular stand (Van Sickle and Gregory, 1990). Numerous growth and yield models (Wykoff, 1982; Hann et al., 1994) and gap models (Botkin et al., 1972; Shugart and West, 1977) have been developed for many forest types throughout the world. Growth and yield models were designed to predict forest growth of specific stands over short periods and forest-gap models were designed to predict forest dynamics of a region over long periods (Dale et al., 1985). Few forest models have been developed specifically for riparian forests (e.g., Hanson et al., 1990). In most cases, an upland forest model is modified to simulate riparian forests (Malanson and Kupfer, 1993; Beechie et al., 2000; Bragg, 2000).

2.3.3 Attributes of Riparian Forest Recruitment

Source Distance Analysis. Distance from which wood is delivered to the channel varies through time as the forest develops. Source distance is the slope distance (McDade et al., 1990) or horizontal distance (McDade, 1987; Minor, 1997) between the original tree base and the stream bank. Source distances can be determined for a subset of pieces in the channel. In the Cascade Mountains, approximately half the pieces could be assigned a source distance and these were typically large and immobile (McDade et al., 1990). In 39 streams adjacent to either mature conifer (80 to 200 years old) or old growth conifer (>200 years old) riparian forests in western Oregon and Washington, source distance for 90% of the logs originated within 26 m in mature conifer and 36 m in the old-growth stands (McDade et al., 1990). Difference in source distance between the two forest age classes was related to difference in canopy height, because mature stands were 70% of the height of old-growth stands (McDade, 1987). Variation in community composition, such as the dominance of hardwoods nearest the stream and conifers farther away, will also influence the shape of the source distance curve (McDade, 1987).

Direction of Tree Fall. Tree-fall regime refers to a probability distribution of tree fall direction. In a completely random tree-fall regime, trees have an equal chance of falling in any direction. In a completely directional fall regime, all trees fall in one direction. Van Sickle and Gregory (1990) demonstrated mathematically that, given a stand composed of trees of the same height, number of trees entering the channel would be 32% less if they fell randomly as opposed to falling directly towards the channel.

Tree fall regimes have been described for several riparian forests. In a 600-m reach of old-growth forest in the Cascade Mountains, Oregon, orientation of all pieces not moved by streamflow was not significantly different from a random distribution (Van Sickle and Gregory, 1990). In 13 streams surrounded by old-growth spruce-fir forests in the Bridger-Teton National Forest, Wyoming, fall regime was significantly different from random distribution and most closely fit a trimodal distribution (Bragg et al., 2000). Trees were most likely to fall directly towards, away, or parallel to the channel than in any other direction. Robison and Beschta (1990b) and Minor (1997) both refer to unpublished data (Robert Beschta, Oregon State University) on tree fall direction in the

Oregon Cascades where probability of falling downslope on hillslopes ranging from 17% to 70% slope steepness was often greater than 75%. However, Ursitti (1991) found that orientation of downed wood in the riparian forest and in the channel was not related to hillslope steepness (46%-80%) in 15 streams in Coos and Coquille River basins of southwest Oregon.

Fall regime may vary by basin location, stand age, structure, and composition. In addition, trees located in the interior portions of a riparian forest may have a different fall regime than trees located nearest the channel. Trees growing near the bank commonly develop asymmetrical crowns and lean towards the stream, favoring a fall direction towards the channel (Lienkaemper and Swanson, 1987; Robison and Beschta, 1990a).

Tree fall regime is strongly influenced by the type of the disturbance and basin location. Fall direction of dominant and co-dominant trees was found to be indicative of the direction of the most damaging winds in southeast Alaska (Ott, 1997). In a study of tree fall direction and basin location, random fall regime occurred only in a moist site adjacent to a stream and was attributed to the shallow root systems (Alexander and Buell, 1955). In a study on wind fall direction in riparian buffers, trees on the windward edge fell with the prevalent wind direction but trees in the leeward side of the buffer fell randomly (Andrus and Froehlich, 1992).

Modeling Recruitment from Tree Fall. Tree fall regimes can be represented using a normal probability distribution with a mean fall direction and standard deviation (Van Sickle and Gregory, 1990). Directionality is expressed as a function of the standard deviation--the larger the standard deviation, the more random the fall regime. In addition, directional fall regimes do not have to be limited to unimodal probability distributions. Tree fall regimes can be defined such that trees are more likely to fall in any number of directions (Bragg et al., 2000).

A geometric argument is commonly used to calculate tree recruitment to the stream given tree height, distance to the bank, and fall angle regime (Robison and Beschta, 1990b; Van Sickle and Gregory, 1990; Beechie et al., 2000). This method assumes trees fall from their base, trees do not slide downhill, and stream banks are straight. For a random fall regime, the arc of intersection (range of tree fall angles that result in tree entry) is constant for a tree of a given height and distance to the bank

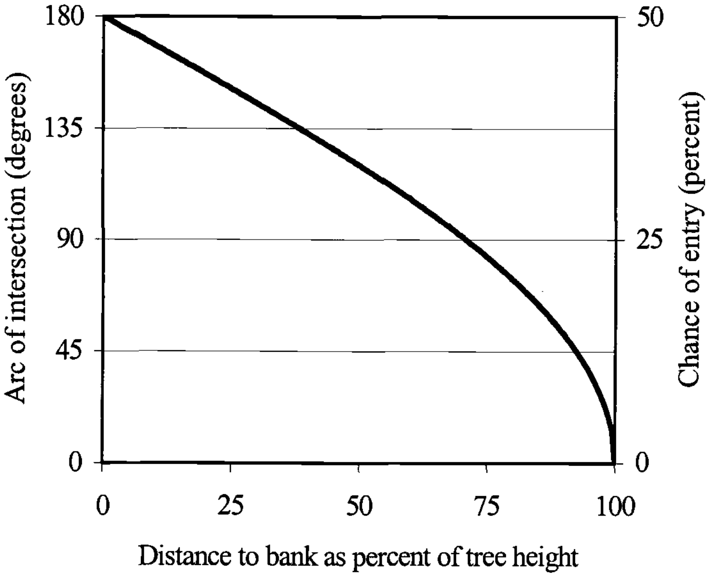
(Figure 2.1). Probability of entry is the arc of intersection over all possible fall angles (e.g., 360 degrees). Provided the tree has an equal chance of falling in any direction, probability of entering the channel can be scaled to the distance to the bank expressed as proportion of tree height (Figure 2.1). This geometric argument has been used to predict proportion of trees entering the channel for random fall (Rainville et al., 1986; Van Sickle and Gregory, 1990) and directional fall as a function of slope (Minor, 1997). This approach has also been used in field surveys to predict the probability individual trees entering the stream assuming a random fall regime (Robison and Beschta, 1990b).

2.3.4 Windthrow

Wind is an important disturbance agent in most forests of the world (Oliver and Larson, 1990; Ott, 1997). Extent of wind damage from a single event ranges from a single tree to an entire forest (Oliver and Larson, 1990). For some streams, windfall is the dominant input process from the riparian forest (Lienkaemper and Swanson, 1987). Trees are uprooted when the force of the wind, intercepted by the crown given the leverage of the stem, is greater than the root-soil holding strength; trees break when the applied force is greater than the stem strength but less than the root-soil holding strength (Curtis, 1943; Kozlowski et al., 1991).

Characteristics that influence the velocity required for wind damage include wind resistance of the canopy (size, density), leverage of the stem (length, taper, flexibility), and root-soil holding capacity (Curtis, 1943; Kozlowski et al., 1991). Shallow, wet, or rocky soils provide less resistance to windthrow than deep, dry soils (Kozlowski et al., 1991). Roots of trees are extracted from wet soils more easily than dry or frozen soils. Wind damage of trees in frozen and dry soils may favor break along the bole as opposed to uprooting (Kozlowski et al., 1991). Species differ in windfirmness because of root and crown characteristics (Curtis, 1943). In Cascade Mountain riparian forests, western red cedar (*Thuja plicata*) was considered most windfirm, followed by western hemlock and Douglas fir (Gratowski, 1956; Steinblums et al., 1984). Individuals of the same species

Figure 2.1. Geometry of tree entry for a random fall regime. The arc of intersection is the range of fall angles resulting in tree entry and is directly related to the chance of a tree entering the stream. Both dependent variables are a function of distance to stream bank expressed as a percent of tree height.



can also differ in windfirmness. Trees conditioned by strong winds develop stronger stems with greater taper and flexibility and more extensive root systems than trees in sheltered sites (Gratkowski, 1956; Oliver and Larson, 1990). Trees are conditioned to resist wind from the prevailing direction and may be less windfirm to winds from another direction (Oliver and Larson, 1990).

Secondary (indirect) causes such as disease and precipitation (in the form of rain, snow, or ice) are commonly associated with wind damage (Hubert, 1918; Kozlowski et al., 1991). Post-storm surveys of downed wood have found a high proportion of wind-damaged trees were infected with stem or root rot (Hubert, 1918). In addition, uprooting of one tree often takes out one or more surrounding trees (Gratkowski, 1956).

Stand age and structure influence the susceptibility of a given site to wind damage. Probability of windfall increases with stand age and height (Hubert, 1918; Behre, 1921; Curtis, 1943). Windthrow of individual trees can be a major source of mortality in older stands where competition-based mortality is relatively low (Spurr and Barnes, 1980; Oliver and Larson, 1990). Root and stem rot generally increases with age, making dominant trees more susceptible (Hubert, 1918; Behre, 1921). In a closed canopy forest, resistance to wind damage varies by canopy position. Wind velocity is greatest above the dominant and codominant canopy layers and decreases to near zero at the forest floor (Spurr and Barnes, 1980). Healthy trees occupying dominant and subdominant canopy positions are generally more windfirm than healthy trees occupying subordinate canopy positions because of greater exposure to the wind during their development (Oliver and Larson, 1990). Trees infected with stem or root rot or in subordinate canopy positions are most susceptible to wind damage (Oliver and Larson, 1990).

Additional wind damage usually follows formation of an opening in the forest canopy. Cause of the opening, by either natural processes or forest management activities, is less important than orientation of forest edges to prevalent winds (Weidman, 1920). Riparian forest buffers are most susceptible to windthrow in the first few years after harvest of the adjacent forest because the most vulnerable trees fall and remaining trees become more windfirm through time (Weidman, 1920; Gratkowski, 1956; Steinblums et al., 1984). Riparian forest buffers oriented perpendicular to direction of destructive winds tend to be most susceptible to wind damage (Alexander and Buell, 1955; Gratkowski, 1956). Wind intensity and direction can be modified by local topographic features sheltering riparian forest from the full intensity of the wind storm (Gratkowski, 1956; Ott, 1997). Trees growing on the stream terrace develop shallow root systems making them less windfirm than trees growing on the adjacent hillslope (Behre, 1921; Andrus and Froehlich, 1992).

Representation of Windthrow in Simulation Models. Windthrow has been represented in several models simulating Pacific Northwest forests (Dale et al., 1986; Mailly et al., 2000). Probability of death from windfall was assumed to increase with tree size. Species were divided into two groups of wind resistance based on root depth and crown structure. This approach represents local wind fall events that occur as stands develop. Several studies developed multiple linear regression models to describe stability of riparian buffers after their initial formation (Steinblums et al., 1984; Andrus and Froehlich, 1992). Dependent variables included local topographic features, orientation, and stand characteristics.

2.3.5 Fire

Fire is an important disturbance in many forests of the world and varies greatly in frequency, intensity, and spatial pattern (Spurr and Barnes, 1980). Forest fires can create convection currents strong enough to cause windthrow (Hubert, 1918). Trees not directly killed by fire may decrease in vigor, making them more susceptible to insect and disease (Oliver and Larson, 1990). Tree species differ in their tolerance to fire (Franklin and Hemstrom, 1981) (e.g., Douglas fir is more fire resistant than western hemlock) and generally increases with age (Franklin and Hemstrom, 1981).

Several models simulate fire regimes over a landscape (Kercher and Axelrod, 1984; Keane et al., 1990; Miller and Urban, 1999; Bragg, 2000; Mailly et al., 2000) but only one model specifically considers recruitment of wood to channels (Bragg, 2000). Approaches used to simulate a fire regime differ in how frequency, extent, mortality, and post-fire recruitment are represented.

2.3.6 Input Processes Associated with Stream Flow

Wood can be recruited to the channel through erosional processes, including floatation of pieces laying on the floodplain, bank erosion, or direct force of the current, which topples the tree. In general, wood recruitment from stream processes increases with stream size and is most prominent in large rivers with well-developed floodplains where lateral channel migration is common (Keller and Swanson, 1979; Murphy and Koski, 1989; Piegay et al., 1999).

In mountain streams, contribution of wood from these processes can be locally important, depending on valley geomorphology, vegetation structure, and disturbance history (Gregory et al., 1991). In sinuous channels, fluvial deposition of wood is most common on outside bank of bends (Odgaard, 1987; Nakamura and Swanson, 1994), which also serves as a source of entrained material during subsequent high flows.

Bank erosion may directly recruit trees by undercutting or indirectly by reducing root strength making trees more susceptible to other input processes such as windfall. Wood can accelerate bank erosion by deflecting streamflow (Keller and Tally, 1979; Duijsings, 1987; Heimann, 1988). Conversely, stream banks can be protected from erosion by logs adjacent to and parallel with the bank (Keller and Tally, 1979). Living root mats stabilize stream banks (Odgaard, 1987) and the degree of protection is related to tree size (Keller and Swanson, 1979; Keller and Tally, 1979).

Bank erosion may be the dominant input process for young stands where relatively short tree heights limit source area and the living root mat is less developed. Dominant input process in Big Creek Basin in the Oregon Coast range was bank erosion for young stands and windthrow for older stands (Long, 1987). In a survey of wood adjacent to mature and old-growth stands in the Cascade Mountains, 11% of the trees that entered the channel originated within one meter where bank erosion could account for input (McDade et al., 1990). Bank erosion was the most important input process in alluvial channels and windthrow in bedrock channel for streams adjacent to old-growth spruce-hemlock forests in southeast Alaska (Murphy and Koski, 1989).

During overbank flows, trees can be toppled by the force of the current (Palik et al., 1998) or impact with wood floating downstream (Johnson et al., 2000). Trees that are not toppled may be damaged, making them more susceptible to disease (Butler, 1978). Extent of injury and mortality to a riparian stand due to prolonged inundation depends on species, genotype, age, and flood conditions (Kozlowski et al., 1991).

Representation of Input Processes Associated with Stream Flow in Simulation Models. Input processes associated with the stream/forest interaction have been represented in simulation models. Bankcutting was included in a model simulating hemlock/fir riparian forests of northern Idaho (Rainville et al., 1986). Recruitment from bankcutting was set at a rate of 20% per decade of live trees ≥ 30.2 cm in diameter within two meters from the bank. Entrainment of terrestrial wood was included in a model simulating the fate of above ground carbon produced by a central Mississippi River valley floodplain forest (Malanson and Kupfer, 1993). Although details of the transport function were not provided, entrainment of wood from the forest floor was a significant loss of wood from the forest floor (Malanson and Kupfer, 1993).

2.3.7 Upslope Input Processes

Trees growing outside the riparian forest can be delivered to the channel through mass failure events. Numerous classification schemes have been developed to distinguish types of mass failures (e.g., Leopold et al., 1964; Hutchinson, 1988). General characteristics include rate of movement, depth of the failure, water to solid concentration, and path (i.e., open slope or channel). Landslides are fast shallow failures usually triggered by heavy precipitation (Roth, 1983; Fannin and Rollerson, 1993) and are most common in the steep headwalls of basins (Benda and Cundy, 1990). The potential for a landslide to occur at a given site depends on slope steepness, soil depth, soil strength, vegetation cover, groundwater drainage regime, and bedrock type (Roth, 1983; Sidle et al., 1985; Fannin and Rollerson, 1993; Cissel et al., 1998). Management activities such as forest harvest and roads (Swanson and Lienkaemper, 1978; Wolfe and Williams, 1986) as well as natural disturbances such as fire (Swanson, 1981) accelerate the rate of mass movement in a landscape. Streams can erode the base of steep banks (especially the outer bend of a sinuous channel) causing landslides directly into the channel (Nakamura and Swanson, 1994). Deposits from landslides that terminate in the stream channel can substantially alter local bed morphology. In larger rivers, material from a landslide may be transported downstream during high flow conditions (Swanson et al., 1987). Landslides can contribute a substantial amount of wood to the stream. The dominant input process along steeper hillslopes in Soguel Creek (Singer and Swanson, 1983 cited in Harmon et al., 1986) and Little Lost Man Creek (Keller and Tally, 1979) in northern California was landslides. Large, deep mass failures often move very slowly (Leopold et al., 1964; Hutchinson, 1988). This soil creep influences tree growth forms (Fantucci, 1999), which may increase the likelihood of trees falling towards the channel.

Debris flows are mass failures associated with streams (Swanson et al., 1987) initiated in or at the head of low-order channels (Hupp, 1984; Benda and Cundy, 1990). Debris flows accumulate sediment, wood, and trees from within the channel and along the debris track (May, 1998). Travel distance of a debris flow depends on the vegetation, slope angle, channel form, and angle of the confluence with the next stream (Swanson et al., 1987; Benda and Cundy, 1990; Fannin and Rollerson, 1993) and typically terminate abruptly as a channel widens and gradient decreases, depositing a pile of wood and sediment over a relatively short distance (Benda and Cundy, 1990; Fannin and Rollerson, 1993; May, 1998).

Geology and topography of a region influence size and frequency of debris flows. Debris flows in the southern Coast Range (Tertiary sedimentary rock) tend to be smaller and more frequent than debris flows in the Cascade Mountains (Tertiary volcanic rock) (Swanson and Lienkaemper, 1985). Small debris flows that travel short distances appear to be far more common than large debris flows that travel long distances (Hupp, 1984; Ryan-Burkett, 1989). For a given initiation site, the recurrence interval for failures may be from one to ten centuries or more (Swanson et al., 1987; Benda, 1994). Recruitment of wood from debris flows can be the most important wood input process in the upper portions of the basin where the majority of events terminate (Naiman et al., 2000). Debris flow deposits can be long-term sources of wood as the deposits are eroded by fluvial processes (May, 1998).

Simulation of Wood Input from Mass Failures. Various models have been developed to predict the location, timing, and magnitude of mass failures at both local

(Smith and Schwartz, 1981; Bergado et al., 1988; Sousa and Voight, 1992) and landscape scales (Dietrich et al, 1993; Benda, 1994). Though no simulation model was found that simulated recruitment of wood to the channel from mass failures, it could be developed based on existing information. Numerous classification systems have been developed to categorize a landscape by potential for mass failure (Carrara et al., 1991; Cissel et al., 1998). Duration and intensity of precipitation were found to be the most important variables associated with initiation of mass failure given slope angle, soil depth and vegetation type (Roth, 1983). Empirical models based on topographic features (channel slope and tributary junction angle) have been developed to predict travel distances of debris flows (Benda and Cundy, 1990; May, 1998). Wood recruitment from mass failures could be simulated by associating probability of mass failure for given precipitation and travel distance predicted from topographic features. Amount of wood delivered to the channel would include what is in the channel and some proportion of trees growing along the debris track. Long-term delivery of wood from debris deposits within the channel could be based on dispersion rates of the deposits (Perkins, 1989).

2.4 In-stream Processes

2.4.1 Breakage

Breakage is a component of wood dynamics in streams that has received little attention. Breakage is any process that creates two or more pieces from an initial piece. Fragmentation is the reduction in volume of a given piece by abrasion or sloughing (Graham, 1982). Fragmentation is discussed with decomposition and breakage is discussed in two sections—breakage of standing stems and in-channel breakage.

Breakage of Standing Trees and Snags. The relative contribution of wood to channels from breakage of standing stems is largely unexplored, though at least in one study, recruitment from snags was significant (Lienkaemper and Swanson, 1987). Causes of breakage include wind, lightning, snow load, and ice cap (Boyce, 1961), and, through the gradual loss of strength from decay, the force of gravity. Growth form anomalies are the most susceptible places for breakage to occur (e.g., crooks and forks) and locations along the stem weakened by rot (Oliver and Larson, 1990). Breakage may be most common when the soil is very dry or frozen (Kozlowski et al., 1991).

Snags may persist through many strong windstorms because of the reduced resistance of a leafless canopy (Alexander and Buell, 1955; Huggard, 1999). Forces required for snag breakage decreases with snag age as wood strength is reduced by decay, animals, insects and physical breakdown (Alexander and Buell, 1955). Decay of snags is highly variable but is influenced by species, size, and decay class (Graham, 1982). Reduction in snag volume is episodic but the initial volume may remain unchanged for years to decades after tree death (Graham, 1982). After initial breakage, snags break apart relatively quickly and the loss of volume can be approximated with a negative exponential decay function (Graham, 1982).

Tree Entry Breakage. Trees that fall and enter the channel may break into numerous pieces upon impact with the valley floor. Few studies (e.g., Lienkaemper and Swanson, 1987) on wood recruitment directly considered tree entry breakage. However, much work has been conducted by forest engineers on improving felling methods to reduce breakage during harvest operations (Rapraeger, 1932; McRae, 1977). Information on number and sizes of pieces resulting from tree felling are not reported, limiting the direct application to tree entry and in-channel breakage. However, these studies do provide guidelines for the influence of tree and site characteristics on breakage patterns.

Location and extent of breakage vary by tree size and condition, species, local topography, and ground composition (Rapraeger, 1932). Rapraeger (1932) found that loss in merchantable board foot volume from breakage was less in western hemlock than Douglas fir for sites of the same slope class (but see Snellgrove et al., 1982). Breakage can be reduced by felling them into surrounding trees, reducing the momentum as the tree hits the ground (Rapraeger, 1932). Uphill felling of large trees results in less breakage and longer logs because the first break usually occurs closer to the top of the tree (Rapraeger, 1932; Studier et al., 1984). Proportion of tree height to the first break was significantly greater for trees felled uphill than felled parallel to the slope in five old-growth harvest units in western Oregon and Washington (Hunt and Henley, 1981).

Location of the first break is approximately 2/3 of the effective height (height to 15 cm top diameter) for trees felled uphill and parallel to the slope. Location of the first break from downhill felling would most likely be equal to or less than those observed in felling parallel to the slope (Rapraeger, 1932; Studier et al., 1984).

Decay affects impact strength more quickly than the static strength of wood (Haygreen and Bowyer, 1989). Extent of decay in a forest is highly variable but tends to increase with stand age (Boyce, 1961). Larger trees, especially those infected with fungi, can break into numerous pieces from the impact with the channel bed contributing numerous pieces to the stream. Breakage caused by a sudden impact tends to form a cleaner break (splinter-free) in decayed wood than wood free of decay (Panshin and De Zeeuw, 1970; Haygreen and Bowyer, 1989).

Several studies have reported on tree breakage associated with stream channels. Breakage was more extensive on steep slopes than gentle slopes, producing a higher proportion of smaller pieces in the channel (McDade, 1987). Lienkaemper and Swanson (1987) conducted a 7 to 9 yr wood study in six Cascade Mountain streams located in the H.J. Andrews Experimental Forest. The majority of wood (73% by volume) was added from falling of live trees and the mean number of pieces per tree fall was five with a range of one to ten. No clear relationship was found between tree size and number of pieces though this could be attributed to the small sample size. Snags were 38% of the trees that entered and contributed 27% of the total volume over the study period (Lienkaemper and Swanson, 1987).

In smaller streams, a substantial portion of pieces span the channel (Bilby, 1985). Two-thirds of all pieces in first and fourth-order streams were suspended above the channel or on side channels in Big Creek, Oregon (Long, 1987). In a study in southwest Alaska, 80% of the debris volume was suspended above or lying outside of bankfull width in first and the smaller second-order streams (Robison and Beschta, 1990a). Trees suspended above the channel eventually break under their own weight.

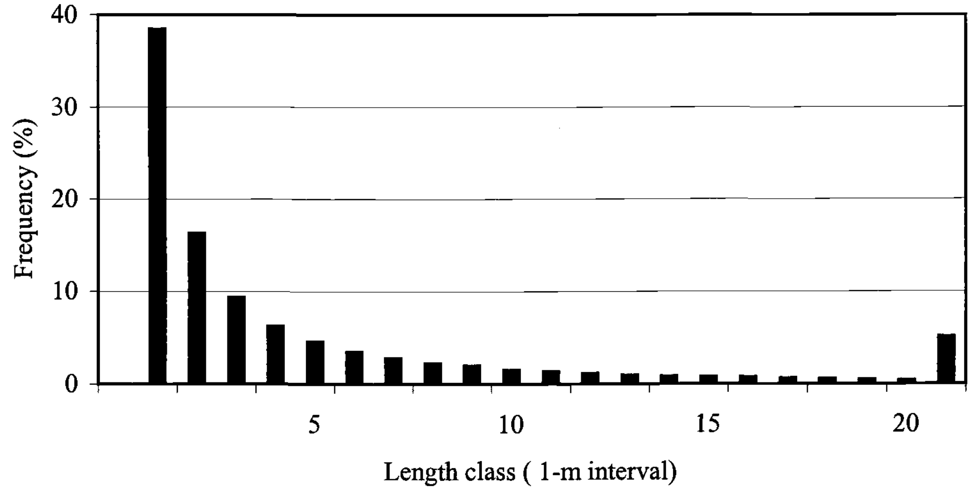
In-channel Breakage. Logs in streams break into smaller pieces (Keller and Swanson, 1979) but this process is largely unexplored. Lienkaemper and Swanson (1987), observed breakage of a log that had retained much wood and sediment. The log broke in a year with moderate flows (10-year recurrence interval). Although the residence time of the log was unknown, it probably experienced flows equal to or greater than the flows of the year it broke. Possible explanations for its breakage may be related to the mechanical properties of wood. The maximum bending strength (modulus of rupture) decreases in time with a sustained load (Panshin and De Zeeuw, 1970) thus the strength of a log retaining sediment decreases through time even without considering loss of strength from decay.

Wood breaks perpendicular to the log axis (snap break) as well as parallel to the log axis (split break). The force required to break a log perpendicular to its axis is proportional to the square of the diameter (Sumiya, 1963). Wood with little or no decay may be highly resistant to breakage (Graham, 1982). The time interval over which a green log will be resistant to breakage can be modeled as a function of size because size is related to decay.

Size Class Frequency Distributions. Size class frequency distribution reflects the collective history of breakage events for a population of logs given the initial sizes of the riparian trees recruited to the channel. Breakage events contributing to a population of logs include tree and snag breakage originating from adjacent and upstream riparian forests, in-channel breakage and breakage associated with mass failures. Reverse-J shaped distributions have been reported for length (Ursitti, 1990; Richmond and Fausch, 1995; Berg et al., 1998), diameter (Ursitti, 1990; Richmond and Fausch, 1995; Berg et al., 1998; McHenry et al., 1998), and volume (Robison and Beschta, 1990a) classes from streams surrounded by old-growth forests (Figure 2.2).

Size class frequency distribution for a reach surrounded by younger riparian forest has proportionately fewer smaller pieces and a narrower range of size classes (Gregory and Wildman, 1998). During the stem exclusion stage of forest development, recruitment of medium-sized trees may increase substantially. Entry breakage of these trees may be moderate, contributing to the medium- to small-size classes. In mature forests, larger trees may be more likely to undergo extensive breakage especially near the top of the tree

Figure 2.2. Length class frequency distribution observed in a section of Mack Creek adjacent to an old-growth forest, western Cascade Mountains, Oregon. The last length class category is for all pieces ≥21 m in length.



where force of impact is greatest. A substantial proportion of the smaller pieces may be created by in-channel breakage as the wood is broken down by fluvial processes.

Relative importance of the various types of breakage (breakage from standing stems, tree and snag fall, in-channel breakage) varies by forest type and age and valley form. Importance of entry breakage increases with stand age. Smaller trees tend to fall into the channel with relatively little breakage, but their small diameters make them susceptible to in-channel breakage. In streams adjacent to old-growth forests, in-channel breakage may be relatively constant as wood is broken down by decay and physical abrasion.

Representation of Breakage in Simulation Models. Reverse-J size frequency distributions observed in many stream wood surveys can be can be produced with the broken stick model, which was used to describe the relative abundance of bird species from various censuses (McArthur, 1957). McArthur (1957) plotted species in the order of relative abundance and found that the broken stick model fit the reverse-J distribution the best. In the broken stick model, n-1 points (where n equals the number of species) are randomly located along a stick of a given length. The stick is then broken at each point and the segments are ranked from largest to smallest producing the reverse J-shaped distribution. Each segment represents a species and its length the relative abundance. To fit the broken stick model to bird censuses from heterogeneous habitats, McArthur (1957) used two sticks of different lengths breaking each into n/2 pieces. The broken stick model was deemed obsolete by its author (McArthur, 1966) and rejected by others because the fit is largely dependent on the sample size and lacks any ecological meaning (Hairston, 1969). The broken stick model can represent breakage of trees and logs by randomly selecting breakage locations along the bole. This approach would fix the size class frequency distribution for all forest types and ages. An alternative model extends the broken stick model by selecting the breakage location with non-uniform distribution functions that are based on the mechanical properties of wood.

The simulation of breakage may be divided into three categories: snag dynamics, tree entry breakage, and in-channel breakage. For all three categories, the simulation of breakage involves a two-step approach. In the first step, the portion of the population that will break for a given time step is identified. For snags and in-channel breakage events, this could be a function of size (e.g., top diameter or length), residence time as a snag or as a log in the channel. The second step is to determine the number and location of the breaks along the bole. Locations can be randomly located using a uniform probability distribution (as in the broken-stick model) or other distributions (e.g., log-normal) that make breakage a function of diameter.

Numerous models have been developed to represent snag dynamics (Graham, 1982; Stone, 1996; Huggard, 1999; Bragg et al., 2000) but only one associated it with stream inputs (Bragg et al., 2000). Tree recruitment included a snag component where the probability of snag failure was related to species, size (diameter) and time since death. All breakage events were assumed to occur during tree entry and in-channel breakage was not considered (Bragg et al., 2000). Tree entry breakage has also been represented by assuming the tree breaks at the stream banks (Van Sickle and Gregory, 1990). STREAMWOOD is the only model that simulates tree entry and in-channel breakage. Location of breaks along the bole in tree entry is based on the modified broken stick model described above and in-channel breakage is a function of diameter and stream residence time.

2.4.2 Redistribution

Fluvial transport of wood in streams has received much attention over the past few decades. Movement has been studied through flume experiments, providing a theoretical basis for wood movement in large streams and rivers (Braudrick et al., 1997; Braudrick and Grant, 2000). Several studies on fluvial transport have examined the characteristics of wood that influence probability of movement in streams. Piece length to bankfull width ratio is a useful measure of the relative stability of a log (Swanson et al., 1984; Bilby, 1985; Lienkaemper and Swanson, 1987; Long, 1987; Bilby and Ward, 1989, 1991). Geometric mean length of stable pieces was found to be slightly less than channel width for stream widths ranging from 4 to 20 m in 21 second- to fifth-order streams in western Washington (Bilby and Ward, 1989). This relationship has been used to operationally define size of relatively immobile logs referred to as key pieces (Beechie et al., 2000). Frequency of stable pieces tends to be greatest in first and second-order streams (Keller and Swanson, 1979; Bilby and Ward, 1989, 1991; Veldhuisen, 1990). In larger streams, frequency of stable pieces in the channel is generally less (Nakamura and Swanson, 1994). Where spanning the channel is not possible or less frequent, length still contributes to stability and wood tends to be distributed in more discrete accumulations (Veldhuisen, 1990).

Length of piece relative to stream width may not be adequate by itself to describe piece stability. Logs with lengths equal to bankfull widths floated downstream several channel widths in a third-order channel in Oregon Cascades (Lienkaemper and Swanson, 1987). In a study located on Prince of Wales Island, Alaska, pieces with lengths equal to half of the stream width floated readily during high flows (Swanson et al., 1984). Other characteristics associated with stability include diameter (Bilby, 1985), volume (Young, 1994), embeddedness (Keller and Tally, 1979; Bilby, 1985; Young, 1994), rootwad (Lienkaemper and Swanson, 1987), portion outside of the channel (Lienkaemper and Swanson, 1987), distance above the bed surface (Young, 1994), and orientation (Hogan, 1987). Stream attributes associated with piece stability in addition to width include gradient, sinuosity, channel roughness (Keller and Tally, 1979) and valley geomorphology (Keller and Tally, 1979; Long, 1987; Nakamura and Swanson, 1994). The flow regime, which includes frequency and magnitude of peak flows, was the single most important factor in determining piece stability in six streams in the central Sierra Nevada, California (Berg et al., 1998).

Newly recruited pieces tend to be highly mobile and move to more stable locations (Bilby, 1985; Lienkaemper and Swanson, 1987). In a study on wood movement following a forest harvest that included the removal of logging slash from the channel, approximately 60% of the tagged pieces moved during the first high flow event (Bilby, 1985). In the next high flow event, which was of similar magnitude, only 10% of the pieces moved. Proportion of wood that moved in subsequent storms was minimal for high flows equal to or less than flows that moved them into their current position.

Ability of stable pieces to capture others in fluvial transport depends on stream position (Swanson et al., 1984) and number of other large stable pieces in the accumulation (Ursitti, 1991). In a long-term (1988 to present) restoration study conducted in Quartz Creek, a third-order stream in the Oregon Cascades, 48 structures of various configurations were placed in the stream (Gregory and Wildman, 1994, 1999). Low amounts of wood were present in the study reach prior to the experiment and frequency of pieces 1 to 2 m in length was less than all length size classes (1-m length interval) between 2 m and 11 m. By 1997, length class frequency distribution was a reverse-J shape, though the middle to largest size classes were slightly underrepresented as compared to a neighboring stream flowing through old-growth forest. Presence of the installed structures, especially large accumulations composed of several key pieces, effectively trapped the smaller pieces.

Distance moved may be influenced by the flow regime, piece length (scaled to bankfull width), and obstructions along the flow path. Young (1994) surveyed two streams in Shoshone National Forest, Wyoming and found that distance moved was significantly correlated to piece length in one of the streams. In a 2-yr study that included six headwater streams in the central Sierra Nevada, California, significantly more pieces moved in the year with flows approximately tens times greater than the previous year (Berg et al., 1998). In Mack Creek, western Cascades, Oregon, preliminary analysis of transport distance for all movers over a 12-year study period fit a single negative exponential function with an r^2 of 0.99. This suggests that once a log is in transport, distance moved appeared to be independent of size for piece lengths less than half the bankfull width--the majority of pieces in the channel.

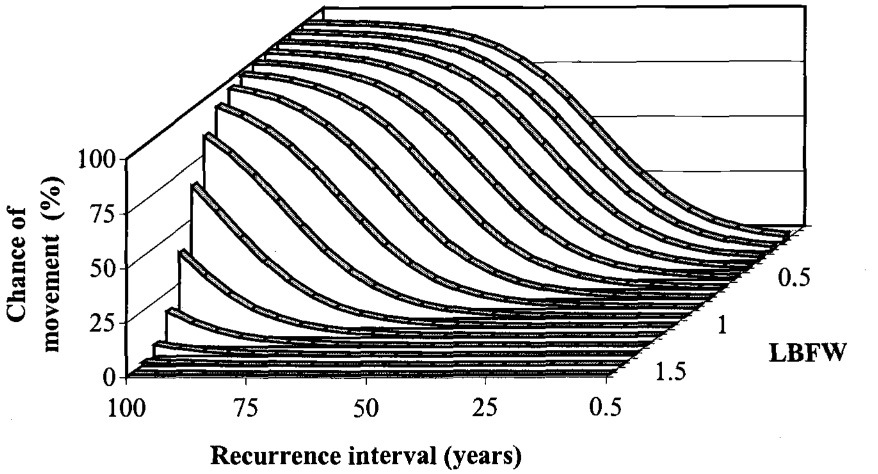
Simulation of Log Movement. The most common approach to simulating wood movement is to assume steady state conditions where exports equal imports from a reach (Van Sickle and Gregory, 1990) or that exports are constant for a given stream width (Beechie et al., 2000; Bragg et al., 2000) and diameter class (Murphy and Koski, 1989). To simulate movement between reaches, the proportion of the population that moves in a given time interval must be determined and then the distances moved determined. A chance of movement function was developed for STREAMWOOD based on data from a long-term stream wood study in Mack Creek, a third-order stream in H.J. Andrews Experimental Forest, Oregon. The riparian forest in the Mack Creek study site is a 500-year-old stand composed of Douglas fir, western hemlock, and western red cedar. The goal of this analysis was not to describe the chance of movement of wood in Mack Creek, but to construct a general model that predicts log movement in small streams in the Pacific Northwest. The chance of log movement was assumed to increase with flow (recurrence interval) and decrease with the ratio of log length to bankfull width, number of key pieces in a reach (categorical variable), and proportion of the log outside the channel. Using these assumptions, a multiple logistic regression model was constructed using the Mack Creek data set. The resulting model can be calibrated to predict the chance of movement for a given stream based on its retentive properties (Figure 2.3). Distance moved was assumed to be independent of length and flow and the distance moved of the population of all movers was assumed to follow a negative exponential distribution.

2.4.3 Burial of Wood in the Channel

Dynamics of burial and exhumation of wood in streams are largely unexplored. Wood can be buried in locations where sediment accumulates and this may be most pronounced during high flow events where the bed is highly mobile. Areas of sediment deposition behind log jams and along the inside bank of a stream bend may store a substantial amount of wood (Church, 1992). When log jams were removed in coastal Oregon streams, a significant number of logs were found buried in sediment deposits retained by the log jams (Baker, 1979). In large streams, lateral channel migration can exhume wood that has been buried for centuries. Wood in the Queets River, Washington had resided in the channel for up to 1400 years (Hyatt and Naiman, 2001). Wood greater than 2,000 years old was found in recent cut banks in four streams in northern Missouri, and the oldest piece found was 8,420 years old (Guyette and Dey, 2000). Ancient wood located along a debris flow path in a headwater channel in H.J. Andrew Forest, Oregon was greater than 40,000 years old (Fredrick Swanson, personal communication).

Little is known about amounts of wood stored in fluvial deposits or the rates of burial and exhumation. Evidence that burial may be an important process in streams is the proportion of wood partially buried in a channel. Veldhuisen (1990) surveyed 25

Figure 2.3. Theoretical model for chance of wood movement in streams. The chance of movement is a function of flow (recurrence interval in years), piece length to bankfull width (LBFW), proportion of the piece outside the channel, and a number of key pieces in the reach. This response surface is calibrated for relatively retentive boulder and coble-dominated streams in the Oregon Cascades.



reaches in first- to fifth-order streams in the Drift Creek basin, Coast Range, Oregon and the proportion of pieces partially buried ranged from 0 to 41% with a median of 7%.

Wood buried deep in streambeds experiences low rates of microbial decay because of the anaerobic environment. However, chemical decay of waterlogged wood involves differential hydrolysis of the cellulose fraction resulting in a higher concentration of lignin (Guyette and Dey, 2000). Burial of 150,000 years may turn wood almost entirely into lignin (Panshin and De Zeeuw, 1970). Mechanical properties change with time and most notably for breakage, the wood becomes increasing brittle (Guyette and Day, 2000). No existing models account for the burial and exhumation of wood in fluvial deposits.

2.4.4 Decomposition

Decomposition of wood in streams includes biological and physical processes. Biological decomposition includes mineralization and fragmentation by microbial, fungal, and invertebrate activity (Lambert et al., 1980). Physical processes involved in decomposition include abrasion from moving water, fragmentation and leaching of soluble compounds. Logs are mineralized slower in streams than in forests (Triska and Cromack, 1980; Harmon et al., 1986; Ward and Aumen, 1986; Sedell et al., 1988). However, total residence time of logs on the forest floor and in streams may be similar because of increased fragmentation and breakage rates in the stream (Harmon et al., 1986; Murphy and Koski, 1989). If a log is completely submerged, it may persist for hundreds of years. Guyette and Cole (1999) studied the age characteristics of white pine (*Pinus strobes*) logs in the lake littoral zone of Swan Lake, Algonquin Provincial Park, Ontario. Minimum residence time was 100 years due to harvest activities around the lake over the last century. Mean and maximum residence times were 333 years and 847 years respectively. Of the 102 logs sampled, 97% of the logs had heartwood free of decay and had a pith (Guyette and Cole, 1999).

Wood submerged in streams decomposes as a thin outer veneer, with minimal decomposition internally. Microbial colonization of wood occurs on the bole's surface to a depth of around 6 mm (Aumen et al., 1983, Sedell et al., 1988). Large pieces decompose slower than smaller pieces of equal combined volume because of the lower surface to volume ratio (Triska and Cromack, 1980). Physical abrasion of wood surfaces by flowing water ranged between 0.5 mm and 11 mm per year depending on decay state of the log (Ward and Aumen, 1986). Many fungal and invertebrate species associated with decomposition of logs in terrestrial environments are aerobic and therefore absent on submerged logs (Anderson et al., 1978; Triska and Cromack, 1980; Sedell et al., 1988). Few invertebrate species found in the Pacific Northwest directly consume waterlogged wood and none bore into sound wood (Anderson et al., 1978). Amount of wood mass consumed by invertebrates was estimated to be around 1% to 1.7% per year (Anderson et al., 1978).

Several decomposition classification schemes partition population of logs into decay categories (Grette, 1985; Murphy and Koski, 1989; Young, 1994). Decay classes are based on external characteristics such as presence of bark and soundness of the log surface. The first class is usually associated with the presence of bark and sound wood and the last class with the absence of bark and decay present in the center of the log. The utility of these classification schemes is the rapid assessment of a population of logs but may not provide an accurate assessment of the degree of decay of the logs themselves because external characteristics alone may not represent extent of decay (Hyatt and Naiman, 2001). Stream residence time has been related to decay state, but these estimates should be interpreted cautiously (Hyatt and Naiman, 2001). In many wood surveys, the majority of the logs are found in the intermediate stages of decay where the range in residence times was found to be the largest (Hyatt and Naiman, 2001). The lowest decay class appears to be most correlated with residence time because bark is shed quickly for most species (Bilby et al., 1999). However, snags can enter in advanced stages of decay, placing the resulting logs in the higher decay classes at the year of entry.

A log that is partially in the channel is exposed to both terrestrial and aquatic conditions, which influences decomposition rates. Terrestrial and aquatic environments differ by communities of microbes, invertebrates, and fungi, and by gradients in temperature, moisture, and oxygen concentrations (Harmon et al., 1986). A log with a residence time of 50 yr or more may contain wood in various stages of decomposition ranging from a solid bole in the stream to a "punky" bole on the forest floor (Triska and Cromack, 1980).

The current stage of knowledge concerning decomposition of stream wood is minimal (Allan, 1995). Two studies in the Pacific Northwest noted that western red cedar decayed the slowest in the stream environment, followed by Douglas fir, western hemlock, and red alder (Swanson et al., 1976; Swanson and Lienkaemper, 1978). Maximum residence times for logs reported in these two studies were greater than 108 yr.

Decomposition rate (by volume) for five species over a five-year period of immersion was determined in a third-order tributary of the Deschutes River in western Washington (Bilby et al., 1999). Logs of three conifer (Douglas fir, western red cedar, western hemlock) and two deciduous species (red alder, and bigleaf maple) were cut from live trees and were between 18 to 28 cm mean diameter and 1.5 m long. Wood density, modulus of rupture, and modulus of elasticity from samples cut from the center of the logs did not change. Log volume changed and was attributed to bark sloughing and surface decay. Loss of bark accounted for 40% of diameter reduction for bigleaf maple and 66 to 78% of the remaining species. Half-life (time required to decay half of the original log volume) ranged from 22 to 27 years for conifers and 18 to 21 years for deciduous species. These decay estimates represent the initial stages of decay accounting for bark sloughing. By the end of the first year, 80% of the bark was lost from all species. Log rafts may have higher rates of bark removal than unattached logs due to the increased contact among the logs and with the streambed (Sedell et al., 1991).

Representation of Decomposition in Simulation Models One approach to represent the loss of wood from a given reach is to apply a constant depletion rate (includes loss from movement and decay) to the standing stock of wood in the channel for each time step. Depletion rates are derived from the current age structure of a current population (Murphy and Koski, 1989; Hyatt and Naiman, 2001) by assuming a stationary age distribution (Huggard, 1999). Alternatively, various decay functions can be applied to at the population or individual level. The single exponential decay model (Jenny et al., 1949, Olson, 1963), initially used in leaf litter decomposition studies, has been widely used in describing log decomposition (Harmon et al., 1986). This model assumes that the wood is homogenous and decays at a constant rate (Moran et al., 1989). Other decay models, such as the summation-exponential model, have been used in log decomposition studies but were found to perform no better in predicting *overall* decay than the single exponential model (Means et al., 1985).

Logs can be partially outside of the channel and thus subjected to contrasting sets of environmental variables—terrestrial and aquatic. One solution is to use an intermediate value between the aquatic and terrestrial decay rates that is based on the proportion of log volume outside the channel. Generally, the mineralization rates of wood in the terrestrial environment are approximately twice that in the aquatic environment (Harmon et al., 1986).

2.5 Discussion

2.5.1 Overview of Wood Dynamics in Streams

All wood in the channel is transported downstream or broken down through physical, chemical, or biological processes (Webster et al., 1999). Arbitrary minimum size definitions and the various ways of measuring it impose their own constraints on conceptualizing the dynamics of wood in streams. Assessment of wood unconstrained by a minimum size may be best viewed in terms a wood component in a carbon or energy budget for a stream (e.g., Cummins et al., 1983). An arbitrary size definition defines the scope of the system under investigation. For example, in one of the initial studies on wood in headwater streams surrounded by old-growth forests in the Pacific Northwest, Lammel (1972) estimated that 10% of the wood by mass was <10 cm in diameter.

The ecology of wood in large rivers is relatively unexplored (Triska, 1984). Wood was present in great abundance in most major North American rivers prior to the European invasion (Sedell et al., 1982; Sedell and Froggatt, 1984). Efforts to tame these rivers included removal of wood from rivers and riparian forests and confinement of river systems to single channels. As a result, the ecological importance of wood in most North American rivers has been greatly diminished making the study of wood in rivers largely historical (Triska, 1984). However, streams in the Pacific Northwest are now managed for the inclusion of wood. These contrasting management strategies impose an arbitrary division between dynamics of wood in streams and dynamics of wood in rivers, which may not be consistent with the ecology of wood in river systems.

Interdependence Among Input Processes. Though the dynamics of wood involve relatively few processes, interactions among them in the context of variable forest and stream environments make wood dynamics highly complex. Recruitment of wood from the riparian forest depends on forest development in terms of both structure and species composition and generally increases with forest age, although successional pathways, basin position, and valley morphology are also important (Pabst and Spies, 1999; Nierenberg and Hibbs, 2000). Episodic input events, such as severe wind storms, are followed by periods of low recruitment while the forest recovers. Whereas mortality from fire is common in understory, windthrow operates mainly on the largest individuals. In a study on landslides in western Cascades, Oregon, Miles et al. (1984) found that one-third of the landslide area could not be restocked with conifer species due to the loose unconsolidated substrate along the failure path, which may influence long-term recruitment from the site. Thus, subsequent stand development and recruitment rate of wood to the channel depends on the disturbance history of the site (Spurr and Barnes, 1980).

The rate of wood input into a stream varies considerably in time and space (Sedell and Triska, 1978; Keller and Swanson, 1979; Triska and Cromack, 1980). For example, input rates may be relatively low over a long time period in the absence of catastrophic disturbance. A single catastrophic event may provide wood to channel orders of magnitude greater than the long-term annual average. A single catastrophic event, such as a debris flow, may provide the majority of wood to a given reach, greatly exceeding the average long-term input rate from the riparian forest (Sedell and Triska, 1977). The relative importance of the various input processes can vary by basin position. For example, bankcutting may be a dominant process in the lower portions of a basin and debris flows may be more important in the upper portions of a basin (Keller and Swanson, 1979).

2.5.2 Simulation of Wood Dynamics in Streams

Steady State Assumption. Amount of wood in a given reach represents the history of inputs and losses at a given the site (Keller and Swanson, 1979). Inputs include wood from the riparian and upslope forests (trees and snags) and fluvial transport from upstream sources and losses include breakage (pieces below minimum size), fluvial export, and decay. When inputs and outputs from instream transport are assumed equal, the standing stock of wood represents a steady state condition in a homogenous environment (independent of basin position) invariable through time (independent of history) (based on Krebs, 1994). For wood budgets based on volume, losses can represented as a depletion rate. For wood budgets based on number, losses from fluvial transport are defined with a constant proportion, although loss from decay is implied. With these assumptions, movement and breakage can be eliminated from consideration. If depletion is assumed constant through time and upslope input processes are assumed to not influence the site, input from the riparian forest represents the single dynamic property required to characterize wood in streams. Under these assumptions, depletion rates (equal to recruitment) of wood in steams can be estimated (Murphy and Koski, 1989; Hyatt and Naiman, 2001). This approach is analogous to a static life table by assuming the current age structure of a population of logs is sufficient to describe the dynamics of the population. The assumption of inputs equal losses in fluvial transport has also been used in several wood models designed primarily to simulate the recruitment of wood to the channel (Van Sickle and Gregory, 1990; Beechie et al., 2000; Bragg et al., 2000), though constant depletion rates have been included (Beechie et al., 2000; Bragg et al., 2000).

Spatiotemporal Variability. Several conceptual frameworks have been proposed to describe the spatial/temporal variability in stream ecosystems (Vannote et al., 1980; Frissell et al., 1986; Gregory et al., 1991). The river continuum concept is based on the premise that a longitudinal gradient of physical conditions exists within the stream system (Vannote et al., 1980). This concept has been extended by viewing valley landforms in a hierarchical arrangement where increases in spatial resolution are associated with a temporal scale of stability (Frissell et al., 1986; Gregory et al., 1991).

This conceptual framework accounts for some aspects of the spatial distribution of wood in stream systems. In smaller streams located predominantly in the upper portions of the basin, wood tends to be randomly distributed because stream flow does not contain the force required for redistribution. In mid-order streams, wood tends to accumulate in distinct clumps because stream power is sufficient to move smaller pieces. In large streams, all size classes of wood can be transported and distribution tends to be associated with channel features. This conceptual framework also accounts for the relative importance of various processes associated with wood dynamics at the landscape scale. For example, debris flows are most important in steeper portion of the basin where floodplain development is minimal and relatively unimportant for mid to lower portions of a basin.

The conceptual framework of Reeves et al. (1995) may be useful for the describing dynamics of wood in the context of the disturbance regime throughout the basin. Episodic disturbances, such as fire, major windthrows, and debris flows, are not uniformly distributed in time or space throughout a basin. A mosaic of conditions is created in both the forest and stream environment in various stages of "recovery". Dynamics of wood throughout the basin are driven by temporal distribution of various disturbances acting on a given basin location. For example, amount of wood in low order channels for a given basin may vary by orders of magnitude depending on time since the last debris flow.

Appropriate Simulation Model Framework. Simulation models of wood dynamics in stream ecosystems have been based largely on the steady state conceptual framework (Rainville et al., 1986; Murphy and Koski, 1989; Van Sickle and Gregory, 1990; Beechie et al., 2000; Bragg et al., 2000). The intended use of these models was to assess recruitment from riparian forests for a single reach, which does not require the inclusion of in-channel processes or spatial representation of stream systems. If however, the intent of the model is to explore the dynamics of wood in streams, a spatiotemporal framework may be most appropriate whereby recruitment, breakage, movement, and decomposition can be explicitly defined. To investigate in-channel wood dynamics, influence of flow regime and basin position need to be considered. The individual-based modeling approach, as adopted in STREAMWOOD, represents each process mechanistically, thus utilizing information presented in this report and provides a means to explore in-channel wood dynamics.

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3. SIMULATION OF WOOD DYNAMICS IN STREAMS OF THE PACIFIC NORTHWEST

Mark A. Meleason, Stanley V. Gregory, and John P. Bolte

3.1 Abstract

Large wood profoundly influences stream morphology, hydrology, habitat complexity, and nutrient dynamics in streams. A computer simulation model, STREAMWOOD, was developed to investigate the dynamics of wood in stream ecosystems ranging from a single reach to a small basin. STREAMWOOD is an individual-based, stochastic model composed of two submodels: a forest model and a wood model. The forest model is a simplified forest gap model that grows riparian forests under various management regimes. The wood model simulates recruitment of trees to the channel and subjects all logs associated with the stream to in-channel processes. Recruitment includes the processes of delivery and breakage, which produces logs that can be partially outside the channel. In-channel processes applied to each log include breakage, movement, and decomposition. STREAMWOOD was developed for forested streams of the Pacific Northwest. Species represented in the model include Douglas fir, western hemlock, western red cedar, and red alder. A single-parameter sensitivity analysis was conducted on each of the two submodels. Parameters affecting tree growth were the most important in the forest model and decomposition was the most important of the processes tested in the wood model. Simulated length frequency distribution, total number, and total volume were consistent with observed data from a third-order stream adjacent to an old-growth forest in Cascade Mountains, Oregon. The relative importance of each of the in-channel processes was found to differ by species through time.

3.2 Introduction

Complex interactions between riparian forests and stream systems influence the biological community and physical environment found in each system (Swanson et al., 1982; Gregory et al., 1991; Malanson, 1993; Naiman and Decamps, 1997). Streams influence forest conditions, which include edaphic, climatic, and disturbance regimes (e.g., Fonda, 1974; Palik, et al., 1998). These influences create riparian forest communities that differ from upland forests in species composition and structure (Viereck, 1970; Hawk and Zobel, 1974). Conversely, riparian forests influence stream conditions such as flow levels (Cleverly et al., 2000), temperature (Brown and Krygier, 1970), and nutrient concentrations (Tabbacchi et al., 1998) and are a major source of sediment and organic materials (Triska et al., 1982; Gregory et al., 1991).

A forest-stream interaction that has received much attention is large wood in streams. Numerous studies have characterized the amount (volume, density, or biomass) (Harmon et al., 1986) and role of wood in stream (Triska and Cromack, 1980; Thomson, 1991). Functionally, wood serves as habitat for aquatic organisms and a source of long-term nutrient loading and influences channel morphology, hydrology, and sedimentation patterns (Bisson et al., 1987; Harmon et al., 1986; Maser et al., 1988; Samuelsson et al., 1994).

Many aspects of wood dynamics in streams are poorly understood because of the extensive temporal and spatial scales required to adequately characterize their complexity. Assessing wood dynamics by examining wood in a given channel reach at one point in time is extremely difficult (Van Sickle and Gregory, 1990). A population of wood consists of pieces that have resided in the channel from days to centuries. Pieces in the channel may have originated from the current or pre-disturbance forests located adjacent, upstream, or upslope of a given reach. Topics of field studies of wood dynamics include recruitment (Long, 1987; McDade et al., 1990), movement (Lienkaemper and Swanson, 1987; McHenry et al., 1998), and decomposition (Bilby et al., 1999). Assuming steady state, residence time (based on nurse tree ages) of diameter classes was used to estimate depletion rates (number of logs removed from the system) for various stream morphologies in southwest Alaskan streams surrounded by old-growth forests (Murphy and Koski, 1989).

Simulation models are powerful approaches to investigate stream wood dynamics. Most wood models predict riparian forest recruitment for a single reach (Rainville et al., 1986; McDade et al., 1990; Van Sickle and Gregory, 1990; Malanson and Kupfer, 1993; Minor, 1997; Beechie et al., 2000; Bragg, 2000). Other goals of wood models are simulation of source distance (McDade et al., 1990; Minor, 1997), riparian forest carbon budget (Malanson and Kupfer, 1993), and influence of various riparian management systems on wood recruitment (Rainville et al., 1986; Van Sickle and Gregory, 1990; Beechie et al., 2000; Bragg, 2000).

Simulation of riparian forest recruitment has been based on deterministic growth and yield models (Rainville et al., 1986; Beechie et al., 2000; Bragg, 2000), stand inventory data with constant mortality rates (McDade et al., 1990; Van Sickle and Gregory, 1990; Minor, 1997), and a stochastic forest gap model (Malanson and Kupfer, 1993). Typically, a riparian forest is divided into a series of zones parallel to the stream bank with all trees located along the mid-point of each zone. Trees are assumed to fall the year they die (not assumed by Bragg et al., 2000), and the number of trees that fall by tree size class for each zone is determined for each time interval (e.g., 10 years). The number of trees that enter a channel is the product of the number of fallen trees for a given size class in a given zone and the chance of entering the stream. Chance of tree entry for a random fall regime equals the proportion of all possible fall angles that result in the tree intersecting the nearest bank. Trees that enter the channel are assumed to either break at both stream banks (Van Sickle and Gregory, 1990; Beechie et al., 2000) or not break at all (Malanson and Kupfer, 1993; Rainville et al., 1986; Minor, 1997; McDade et al., 1990). Only one model was found to consider length of logs outside the channel and entry breakage was simulated using a snag dynamics model (Bragg et al., 2000). Size of the log that enters for a given tree-height class and zone is constant and equals the mean size across all possible fall angles that intersect the nearest channel.

In-channel processes such as breakage, log movement, or log decomposition have not been addressed separately. Several models have incorporated a depletion rate, which includes loss from both downstream transport and decomposition (Murphy and Koski, 1989; Beechie et al., 2000; Bragg et al., 2000). Transport of wood from upstream sources has been assumed to equal output of the reach (Murphy and Koski, 1989; Van Sickle and Gregory, 1990; Bragg et al., 2000) or ignored. No model specifies tree location in the riparian forest and few models considered directional fall regimes (Minor, 1997; Bragg et al., 2000).

3.3 Description of STREAMWOOD

STREAMWOOD is a spatially-explicit individual-based stochastic model that simulates riparian forest and stream wood dynamics over periods of years to centuries using annual time steps. Stream systems can be simulated from spatial scales of a single reach to a small basin (network of reaches) with the minimum resolution of a reach. Wood dynamics represented in the model include tree breakage during entry and log breakage, movement, and decomposition in the stream. Riparian forest inputs are generated from a simplified forest gap model built within STREAMWOOD or from a user-specified input file. The model is run under a Monte Carlo procedure and the results are reported as mean conditions per reach. The current version of STREAMWOOD was developed for fifth-order and smaller streams in the *Tsuga heterophylla* zone of the Pacific Northwest (Franklin and Dryness, 1973). Species considered include Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* Donn ex D. Don), and red alder (*Alnus rubra* Bong.).

3.3.1 Model Overview

STREAMWOOD was written in an object-oriented programming language (Microsoft Visual C^{++}) as a collection of classes. The class structure in the model was based on the hierarchical arrangement of a stream system as described by Gregory et al. (1991) (Figure 3.1). A basin is composed of sections and a section is composed of reaches. Each reach is composed of a riparian forest adjacent to each bank. When the forest model is enabled, each riparian forest contains a matrix of forest plots and each forest plot contains trees of a given species. When the forest model is disabled, each riparian forest contains trees imported from a tree file. In addition, each reach contains logs. Each reach can be initialized with a population of logs imported from an initial logs file.

In the current configuration, only one basin can be defined in a given simulation. Basin-level characteristics include user-specified minimum dimensions for stream wood, geographic region, thermal growth index, and flow regime. Any combination of four main components–forest model, log movement, log breakage, and log decomposition–can be enabled at the basin scale to isolate various processes and assess the relative contribution of each component to model predictions.

Flow is characterized as annual recurrence interval in years. Flow is used in the function determining chance of log movement. Three flow regimes are possible: constant flow, user-defined flow, and program-generated flow using a log-normal distribution.

A basin contains a network of sections. Unidirectional flow is simulated at the section level using a modified binary tree (Lafore, 1998). Wood moves through a user-defined stream network from the top to the bottom of the basin. Since a binary algorithm was used, a maximum of two sections can flow into the lower section.

Each section contains a linear arrangement of reaches. Each reach is defined by a length, mean bankfull (active channel) width, and a roughness coefficient, which is the reciprocal of the average travel distance. Each reach also consists of a riparian forest adjacent to each bank.

STREAMWOOD consists of two sub-models: a forest model and a wood model. Both sub-models are spatially-explicit, individual-based, stochastic models. The forest model grows riparian forests and determines which trees fall for a given year. The wood model converts trees to logs and simulates the dynamics of wood in the stream channel. The main components of the forest model are birth, growth, and death of individual trees and a riparian management component capable of simulating various forest management scenarios. The forest model can be disabled and replaced by a tree recruitment file derived from other forest models or field data. The main components of the wood model are recruitment and entry breakage of individual trees, and instream breakage, movement and decomposition of individual logs.

3.3.2 Forest Model Overview

The forest model is a gap-phase type based largely on the documentation of three existing forest–gap models: ZELIG (Pacific Northwest version by Dr. Steve Garman, Forest Science Laboratory, Corvallis Oregon based on Urban, 1990), JABOWA (Botkin et al., 1972; Botkin, 1993), and CLIMACS (Hemstrom and Adams, 1982; Dale and Hemstrom, 1984; Dale et al., 1986). The STREAMWOOD forest model adheres closely to the first generation of forest gap models (Botkin et al., 1972; Shugart and West, 1977), and shares many of their limitations (Bugmann, 1996; Schenk, 1996; Chave, 1999). All forest gap models are individual-based stochastic models that use a Monte Carlo procedure to simulate recruitment, growth, and death of trees on plots of fixed size. The forest model simulates riparian forest dynamics for managed and unmanaged stands. Output of the forest model for a given year and iteration is a list of dead trees for each forest plot, which are then passed to the wood model.

Riparian Zone Definition in STREAMWOOD. The simulated stream reach consists of a riparian zone on either side of a stream zone (Figure 3.2). Maximum riparian forest width is 100 m and riparian forest length is equal to reach length. A riparian forest consists of a matrix of forest plots of fixed size (25 m X 25 m), which grow independent of each other. Each row of plots, parallel to the stream channel, is initialized with identical conditions that include: initial forest stand, soil moisture level, maximum biomass, and maximum number of trees. Minimum number of forest plots required to encompass the user-defined riparian forest dimensions are simulated and trees located outside of the user-defined boundaries are excluded from stream recruitment.

Riparian forests on either side of a reach can be grown independently (with the same or unique initial conditions) or identically. When the two riparian forests are identical, results from the left riparian forest are doubled, reducing simulation time. In addition, the user can specify regions of random and directional fall for each riparian

Figure 3.1. Class hierarchy in STREAMWOOD is based on the hierarchical arrangement of a stream system as described by Gregory et al. (1991). A basin is composed of sections, which in turn contain reaches. Each reach is composed of a riparian forests on either bank, and each riparian forest is composed of a matrix of forest plots. Forest plots contain trees and reaches contain logs.

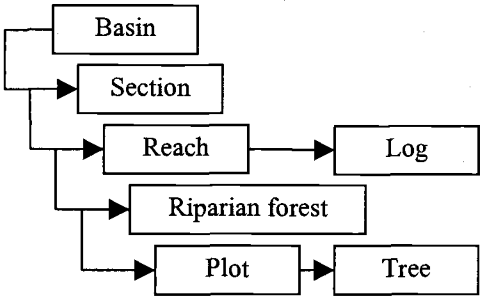
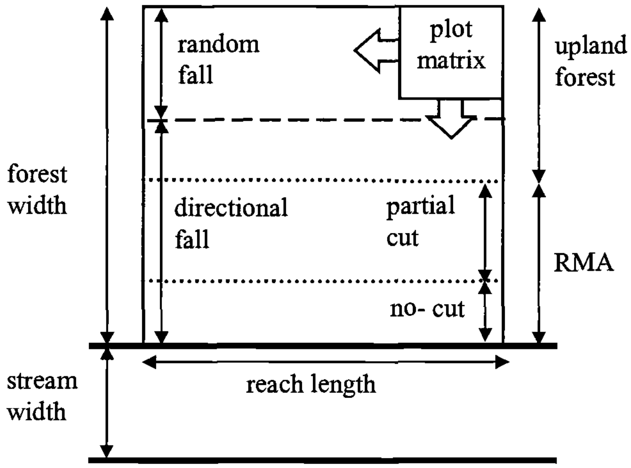


Figure 3.2. Representation of a riparian forest located on both sides of the stream channel. Each riparian forest is composed of a matrix of forest plots. Riparian zones can be partitioned into zones of random and directional fall and be divided into upland forest and riparian management areas (RMA). The RMA can be further divided into no-cut and partial-cut zones.



zone (Figure 3.2). With random fall, a tree has an equal chance of falling in any direction. With directional fall, the angle of tree fall is normally distributed around a specified mean (and standard deviation) relative to the stream bank.

Tree definition. Each tree is characterized by species, position, diameter at breast height (DBH), height, leaf area, leaf biomass, and total stem and bark biomass. Tree form is assumed to be conical with a constant taper. Total tree height (H_T, m) is calculated from DBH (cm) using the asymptotic equation (Chapman - Richards function) reported in Garman et al. (1995).

$$H_T = 1.37 + [h_0(1 - \exp(h_1 * DBH))^{h_2}] \tag{1}$$

Regression coefficients h_0, h_1, and h_2 vary by geographic region (Northern Cascade and Northern Coastal), elevation class (above and below 1,000 m) and site class index (maximum of three levels), though not all levels are reported for each factor. Values for the three regression coefficients were taken directly from Garman et al. (1995).

Estimates of tree leaf area (LA, m^2) are based on the pipe model theory (Shinozaki et al., 1964; Waring et al., 1982), which relates sapwood cross-sectional area at DBH (or base of the crown) to leaf area. Tree leaf area is calculated using a modified Chapman – Richards equation and species-specific regression coefficients (a_1, a_2) presented in Mailley et al. (2000):

$$LA = LSR * a_1[1 - \exp(-a_2 * DBH)^2] \tag{2}$$

where LSR is leaf area to sapwood area ratio (m^2/cm^2) for a given species (Table 3.1). Because regression coefficients available for red alder applied only to sapling-size individuals, leaf area for red alder was calculated using the regression coefficient values for paper birch (*Betula papyrifera*) (Mailley et al., 2000).

Tree leaf biomass (TLB, kg) is a function of leaf area using the coefficients presented in Dale and Hemstrom (1984):

$$TLB = LA * FT / ABR \tag{3}$$

Table 3.1. Species parameters

Species parameter	Symbol	Tree species[1]			
		PSME	TSHE	THPL	ALRU
Aquatic mineralization rate[2]	k_A	0.004	0.008	0.004	0.033[b]
Chance breakage coefficient	pb_1	0.05	0.05	0.05	0.05
Chance breakage coefficient	pb_2	2.0	2.0	2.0	2.0
Leaf area to biomass (m^2 / kg)	ABR	17.44[c]	20.4[c]	17.7[c]	28.2[c]
Degree–days maximum[3]	DDMX	2461[d]	2480[d]	2481[d]	3080[d]
Degree – days minimum[3]	DDMN	441[d]	311[d]	292[d]	400[d]
Growth efficiency constant	G	1400[i]	900[n]	700[i]	2400[n]
Leaf area coefficient	a_1	1637.7[i]	2781.7[i]	2404.1[i]	2009.2[i]
Leaf area coefficient	a_2	0.019[i]	0.0183[i]	0.1818[i]	0.0254[i]
Leaf to sapwood area (m^2/cm^2)	LSR	0.47[i]	0.41[i]	0.56[i]	0.2[i]
Maximum Age (year)	AGE_{MX}	1200[e]	500[d]	1500[d]	100[d]
Maximum DBH (cm)	DMX	300[d]	225[d]	300[d]	150[d]
Maximum number saplings	SAPMX	10	2	3	24
PLA Maximum recruit (m^2/m^2)	PLA_{MX}	5[m]	10[c]	8[c]	5[m]
Minimum water stress (-bars)	WMN	25[c]	18[c]	10[c]	8[c]
Sapling growth time lag (year)	STL	10[a]	15[a]	15[k]	7[h]
Shade tolerance class[4]	STI	I[d]	VT[d]	T[d]	I[d]
Soil moisture tolerance class[5]	SMTC	D[c]	I[c]	I[c]	M[c]
Terrestrial mineralization rate	k_T	0.008[j]	0.016[f]	0.008[o]	0.066
Wood biomass coefficient	b_1	-3.0396[c]	-2.172[c]	-2.0927[c]	na
Wood biomass coefficient	b_2	2.595[c]	2.257[c]	2.1863[c]	na

[1] PSME: *Pseudotsuga menziesii*; TSHE: *Tsuga heterophylla*; THPL: *Thuja plicata*; ALRU: *Alnus rubra*, [2] assumed half of the terrestrial mineralization rate; [3] Degree – days base of 5.5° C; [4] Shade tolerance classes include: I - shade intolerant: s_1 = 1.25977, s_2 = 1.78588, s_3 = .12; T - shade tolerant: s_1 =1.04689, s_2 = 3.29031, s_3 = .06; VT - very shade tolerant: s_1 = 1.02046, s_2 = 4.16533, s_3 = .03;
[5] Soil moisture tolerance classes include: D – dry: w_1 = -10, w_2 = 5, I – intermediate: w_1 = -8, w_2 = 1, M – moist: w_1 = -2, w_2 = 0
[a] Bell and Dilworth (1988)
[b] Bilby et al. (1999)
[c] Dale and Hemstrom (1984)
[d] Steven Garman, personal communication
[e] Franklin and Waring (1980)
[f] Graham and Cromack (1982)
[g] Harmon et al. (1986)
[h] Harrington and Curtis (1986)
[i] Mailley et al. (2000)
[j] Means et al. (1985)
[k] Minore (1983)
[l] Modified from Botkin (1993)
[m] Modified from Dale and Hemstrom (1984).
[n] Modified from Garman, personal communication
[o] Sollins et al. (1987)

where FT is foliage type constant, which converts projected leaf area to total leaf area (2.0 deciduous, 2.5 conifer) and ABR is leaf area to leaf biomass ratio (m^2/kg).

Total bark and stem wood biomass (TSB, kg) is based on the approach used in Dale and Hemstrom (1984), which uses the equations presented in Gholz et al. (1979). For all species except for red alder, the following equation was used to estimate total stem biomass:

$$TSB = \exp(b_1 + b_2 * LN(DBH)) \tag{4}$$

where b_1 and b_2 are species-specific regression coefficients (Table 3.1). For red alder with DBH $\leq$ 40 cm, TSB was calculated as follows:

$$TSB = 0.02 + 2.09 * Z - 0.0015 * Z^2 \tag{5}$$

where $Z = DBH^2 * H_T / 100$. This parabolic equation underestimates total stem biomass of red alder at larger diameters. Total stem biomass for red alder > 40 cm DBH was calculated by multiplying equation (4) for Douglas fir by 0.9142, the ratio between the TSB of Douglas fir and red alder at 40 cm DBH.

3.3.3 Main Components

Growth, death, and recruitment for each annual cycle are applied to the live tree list for a given plot in that order, as suggested by Bugmann et al. (1996). When active forest management is simulated, recruitment is replaced by the management prescription, which includes harvest and replanting.

Death. In most forest gap models, individual tree death consists of inherent risk and suppression mortality (Shugart, 1998; Hawkes, 2000). Inherent risk of death is species-specific and assumes that 2% of healthy trees of a given species reach maximum age (Botkin, 1993).

$$S_I = 1 - (4 / AGE_{MX}) \quad (6)$$

where S_I is annual probability of survival for a given species as a function of its maximum age (AGE_{MX}, year). If a given tree does not die from the first method and its annual diameter growth increment is less than 5% of optimum diameter increment (Mailley et al., 1999), the tree is subjected to suppression mortality. Suppression mortality is based on the assumption that a tree suppressed for ten consecutive years would have a 1% chance of survival by the tenth year. Both mortality functions are stochastic processes using uniformly distributed random numbers generated between zero and one. For inherent risk of death, a tree dies if the random number is greater than the species-specific rate; for suppression mortality, a tree dies if a second random number is greater than 0.632 (Botkin, 1993). Forest harvest is a third type of mortality and is described below.

Growth. Most forest gap models use some version of the fundamental growth equation originally presented in Botkin et al. (1972) (Botkin and Schenk, 1996; Shugart, 1998). Annual growth is simulated as a diameter increment at DBH. The optimum diameter growth for a tree of a given species and diameter is modified by various environmental factors to produce the realized growth for a given year. All environmental factors range between zero and one and are orthogonally related to the optimal growth increment. The environmental factors (EF) in the forest model include shade, soil moisture, thermal growth, and biomass.

The shade tolerance factor (STF) represents the reduction in optimal growth for a given tree caused by shading. The available light (AL) or proportion of light reaching the top of the canopy is a function of the shade leaf area (SLA, m^2/m^2), which is the sum of leaf area for all trees greater than 0.1 m in height (Dale and Hemstrom, 1984):

$$AL = \exp(-0.26 * SLA) \quad (7)$$

Three shade tolerance categories were used to define species response to light (Table 3.1). The shade tolerance factor is a function of available light reaching the tree and shade tolerance category of the species:

$$STF = s_1 * [1 - \exp(-s_2 * (AL - s_3))] \tag{8}$$

where s_1, s_2, and s_3 are regression coefficients for a shade class category (Table 3.1).

The moisture stress factor (MSF) represents a species-specific growth response to soil moisture conditions. At the beginning of a simulation, each row of forest plots can be associated with a unique plant moisture stress level (PMS, -bars), which represents the predawn moisture stress level near the end of the growing season (Dale and Hemstrom, 1984). MSF is calculated using a beta function and species-specific regression coefficients from Dale and Hemstrom (1984):

$$MSF = \frac{(PMS - w_1)*(WMN - PMS)^V}{(w_2 - w_1)*(WMN - w_2)^V}, \; V = \frac{(WMN - w_2)}{(w_2 - w_1)} \tag{9}$$

where w_1 is the negative x intercept, w_2 is the optimum PMS for growth (-bars), and WMN is the minimum water stress value for a species (Table 3.1).

The temperature growth factor (TGF) is a species-specific growth response to the annual heat sum (cumulative air temperature degree-days) reaching the forest. A temperature growth index (TGI, degree-days with a base value of 5.5° C) is generated for each year from a random normal distribution using a mean and standard deviation selected by the user (Dale and Hemstrom, 1984). The parabolic equation used to calculate TGF was originally published in Botkin et al. (1972):

$$TGF = \frac{4*(TGI - DDMIN)*(DDMAX - TGI)}{(DDMAX - DDMIN)^2} \tag{10}$$

where DDMIN and DDMAX are cumulative air temperature limits (degree-days) for growth of a species (Table 3.1).

The biomass maximum factor (BMF) limits the maximum attainable biomass for a given site. This factor represents a measure of resource availability (e.g., nutrients or rooting space) and various versions are common to most gap models (Shugart, 1984; Dale et al, 1985). The default setting for biomass maximum (BMAX) is 10,000 metric tons /ha, which is approximately ten times the measured values for old-growth stands (Franklin and Waring, 1980). In operation, this factor has very little effect on forest dynamics under the default setting. This factor was included to provide greater flexibility in simulating forests of various site potentials. Each row of forest plots can be assigned a unique BMAX. The BMF is a linear equation taken from Dale and Hemstrom (1984):

$$\mathrm{BMF} = 1 - (\mathrm{B_{plot}} / \mathrm{BMAX_{plot}}) \tag{11}$$

where $\mathrm{B_{plot}}$ and $\mathrm{BMAX_{plot}}$ are the total and maximum aboveground biomass on a plot in a given year respectively.

The fundamental growth equation used in STREAMWOOD's forest model is from the Pacific Northwest version of ZELIG (Steven Garman, personal communication). A size factor (SF) accounts for the decrease in optimal growth as a tree gets larger. This equation calculates the annual diameter growth (δD, cm) of a tree in a given year as the product of the optimal diameter increment and the environmental factors (EF):

$$\delta \mathrm{D} = \frac{\mathrm{G} * \mathrm{LA} * \mathrm{SF} * \mathrm{EF}}{\mathrm{DBH} * \mathrm{h_M} * \left(-\mathrm{DBH} * \mathrm{h_1} * \mathrm{h_2} * \mathrm{C} * (1-\mathrm{C})^{(\mathrm{h_2}-1)} + 2.0 * (1-\mathrm{C})^{\mathrm{h_2}}\right)} \tag{12}$$

where

$\mathrm{C} = \exp(\mathrm{h_1} * \mathrm{DBH})$

$\mathrm{SF} = 1 - [\mathrm{DBH} * \mathrm{h_T} / (\mathrm{D_M} * \mathrm{h_{MX}})]$, $\mathrm{h_{MX}} = \mathrm{H_{MX}}*100$, $\mathrm{h_T} = \mathrm{H_T}*100$

$\mathrm{EF} = \mathrm{STF} * \mathrm{MSF} * \mathrm{TFG} * \mathrm{BMF}$

and $\mathrm{h_1}$ and $\mathrm{h_2}$ are tree height coefficients used in equation (1), $\mathrm{h_T}$ and $\mathrm{h_{MAX}}$ are total and maximum height (cm), and $\mathrm{D_{MAX}}$ is maximum DBH for a species (cm).

Sapling Recruitment. Many approaches have been used to simulate recruitment in forest gap-models (Botkin and Schenk, 1996; Shugart, 1998). Maximum potential recruitment is constrained by environmental conditions on the plot (Shugart, 1998). Recruitment in the forest model in STREAMWOOD follows the three stages determine 1) if the species can establish, 2) number of new individual, and 3) initial size (Botkin, 1993).

Species that can establish must be able to tolerate environmental conditions on the plot. These environmental conditions include current projected leaf area, elevation, plant soil moisture, and cumulative temperature regime for that year (see Table 3.1 for species limits). If the species tolerance limits allow it to occur at a site, then likelihood of a species establishing given the current environmental conditions is calculated as follows:

$$SAPENV = MSF * TGF * STF \tag{13}$$

where STF is calculated using the projected leaf area on the plot. Recruitment from a species occurs if SAPENV is greater than a random number between zero and one.

Number of new recruits of a given species depends on its shade tolerance class (based on Botkin, 1993). The number of saplings recruits (SR_I) added in a given year for shade intolerant species is calculated as follows:

$$SR_I = MSF * TGF * STF * SAPMX * rU \tag{14}$$

where SAPMX is the maximum number of recruits for a species and rU is a random number with a uniform distribution between zero and one.

For all other shade tolerance classes, the number of saplings recruits (SR_T) is determined using the following equation:

$$SR_T = SAPMX * rU \tag{15}$$

Saplings are recruited with a DBH selected from a random uniform distribution between 5 and 10 cm. To compensate for the age of the saplings, a species-specific time lag is imposed on its growth (STL, Table 3.1). This lag time represents the average time required for a given species to reach 7.5 cm DBH. Each tree is assigned a unique x-y coordinate within a riparian zone with a minimum distance between trees of 1 m. A limit to the number of trees on a plot for each forest plot row can be imposed by the user. As with maximum plot biomass, the maximum number of trees can be adjusted to represent different site potentials.

Riparian Management. A management approach can be prescribed by the user. A riparian forest can be divided into a riparian management area (RMA) and an upland forest area (Figure 3.2). The RMA can be further divided into non-harvested and partial cut zones. Harvest rotation schedules, (including thinning, clearcutting, and planting), and minimum leave conditions can be prescribed for the RMA and the upland forest area. Leave conditions include minimum basal area targets and number of leave trees greater than a selected diameter as well as the number and species to plant after a clearcut harvest. The minimum leave targets of the RMA include trees in non-harvested portion plus the minimum number of trees in the partial cut zone required for the target level.

Recruitment in the non-harvested portion differs in two respects from the unmanaged forest described above. First, projected leaf area and biomass of the non-harvested area is used in place of projected leaf area and biomass of the entire plot. Second, recruitment for a given year is scaled to the proportion of the non-harvested area of the plot. Probability of a species recruiting in the non-harvested area is proportional to the non-harvested area of the plot. A random uniform number between zero and one is selected. If this random number is greater than the proportion of the non-harvested area, then the number and size of new recruits is determined as above. After a clearcut harvest, both partial-cut and upland forest zones are planted with species and densities prescribed for the simulation.

Tree Input File: An Alternative to the Forest Model. The forest model can be disabled and the results from any forest model or other source can be imported. Each imported file is associated with a given reach and contains a list of trees. Each tree definition requires a species, DBH, riparian zone side, and cycle tree dies. In addition, total height, distance to bank, distance from the top of the reach, and fall angle can be specified by the user or determined by the program. If all eight fields are specified for all trees, riparian forest recruitment is completely deterministic.

3.3.4 Wood Model Description

The purpose of the wood model is to simulate tree recruitment into the channel, and in-channel dynamics of stream wood. The in-channel dynamics, listed in the order called by the model, include breakage, movement, and decomposition. The wood model is an individual-based stochastic model that operates on an annual time step. Trees that have died during the current year, from either the forest model or the tree input file, are then input to the wood model.

Log Definition. The definition of a log consists of a species, position relative to the top of the reach, top and bottom diameters, length, taper and lengths at each end outside of the channel. Log shape is assumed conical with a constant taper. Residence time, volume, distance moved, and lengths outside the channel are updated each time step. All logs must be greater than minimum size (top diameter and length) and at least partially within the channel. Logs that do not fit these criteria are eliminated from the database. Logs are checked for minimum size after each of the four wood model components. If a log's top diameter is below minimum diameter, log length is adjusted to produce a top diameter equal to minimum diameter. If the log length is below minimum length after this adjustment, the log is eliminated from the data base.

Log volume (V, m^3) is calculated using the two-end conic rule (Bell and Dilworth, 1988):

$$V = C_V L_T (D_T^2 + D_B^2 + D_T D_B) \tag{16}$$

where the top (D_T) and bottom (D_B) diameters are in centimeters, total length (L_T) in meters and C_V is a conversion constant equal to 0.0000262.

Tree Recruitment (tree to log conversion). Tree recruitment component determines which of the individuals on the dead tree list enter the channel, delivers the trees to the channel with entry breakage, and determines initial conditions of logs. Characteristics of a dead tree include: species, DBH, total height, position, and year of death. Fall angle depends on the location of the tree with respect to the fall angle zones defined for the riparian forest (Figure 3.2).

Trees in the model fall the year they die. The intersection of the fallen tree with the nearest stream bank is a function of the effective tree height (length to minimum diameter), distance to the nearest bank, and angle of fall (Van Sickle and Gregory, 1990). Little information exists for the development of an entry breakage function but its exclusion was found to produce unreasonable size-frequencies distributions (Van Sickle and Gregory, 1990).

Two modes of tree entry are available in the model. In the first mode, only the portion of the tree that falls within the channel is considered and the portions that fall outside the channel are eliminated from the database. The diameters at the stream banks are calculated and no other breakage occurs during entry. In the second mode, tree entry includes entry breakage events independent of the location of the stream banks. Trees break into various numbers of pieces, and the user defines the maximum number of breaks. The number of breakage events for a given recruitment event is the product of the maximum number of breaks and a random number with a uniform distribution between zero and one. For each subsequent break, one of the two logs from the previous event is selected. Breakage ceases when the number of breaks has occurred or both logs from the preceding breakage event are either below minimum size or completely outside the channel. If both logs from the previous breakage event meet these criteria, each is given an equal chance of breaking in the next breakage event. Logs created from the input breakage function can be partly within the channel; those that are completely outside the channel are eliminated from the database.

Location of the break along the log is determined using one of three break location functions included in the model. Break location functions are used in the second mode of tree entry and in the in-channel breakage component described below. Logs are assumed to break perpendicular to the long axis of the log using one of the following equations:

$$L_{top} = (- rN) * L_p \tag{17}$$

$$L_{top} = \exp(LN(L_P) / 2) \tag{18}$$

$$L_{top} = \exp(LN(L_P * rU)) \tag{19}$$

where L_{top} is the length (m) of the top piece, L_P is the length of the parent log, rN is a random number with a normal distribution between 0 and 1. After each breakage event, length of the bottom piece and the top and bottom diameters, volumes, and lengths outside the channel are calculated for both pieces. Each broken piece inherits the characteristics of the original piece (i.e., species, location, taper, and residence time). By default, equation (17) is used in the second mode of tree entry with a mean and standard deviation of 0.6 and 0.2 respectively. A tree (or log) is assumed to most likely break in the narrow end above the midpoint.

Log Breakage. In-channel breakage component breaks a subset of all logs in a reach for a given year. Very little information exists on fragmentation of wood within the channel. A relationship was developed based on the assumptions that chance of breakage increases with residence time and decreases with log size (top diameter). In addition, newly recruited logs were assumed not to break for a period proportional to its size (top diameter), as observed in the decay of standing dead trees (Graham, 1982). Using these assumptions, a simple linear equation was developed, which determines the chance of log breakage (P_B):

$$P_B = pb_1 * [RT - (D_T / pb_2)] \qquad (20)$$

where pb_1 and pb_2 are species-specific breakage coefficients and RT is log residence time (year). Values for pb_1 and pb_2 are the equal for all species (Table 3.1). A piece breaks if the chance of breakage is greater than a random number with a uniform distribution between zero and one. Logs are broken using one of the break locations functions (equations 17 – 19), with equation (18) set as the default. Each new log is updated as described above.

Log Movement. Log movement component moves a subset of all logs in a reach in a given year. This component requires the simulation of unidirectional flow. Logs in the upstream reaches are considered first, followed by the downstream reaches. Logs can move from reach to reach and those that move out of the defined system (the last reach) are eliminated from the database.

There are two parts to log movement–chance of movement and distance moved. The chance of movement function was based on data from a long-term stream wood study in Mack Creek, a third-order stream in H.J. Andrews Experimental Forest, Oregon. The riparian forest is a 500-year-old stand composed of Douglas fir, western hemlock, and western red cedar. Chance of log movement was assumed to increase with flow and decrease with the ratio of log length to bankfull width, number of key pieces in a reach, and proportion of the log outside the channel. Using these assumptions, a multiple logistic regression model was constructed using the Mack Creek data set. Initial regression results were exponentially smoothed to form a general function. The length to bankfull width term, a categorical variable in the initial logistic regression, was converted to a continuous variable using polynomial regression. The chance of movement (P_M) for a log in a given year and reach is defined as follows:

$$P_M = 1/\left[1 + \exp(-(m_0 + m_1 * FLOW + m_2 * P_{Z4} + KP_i + L))\right] \qquad (21)$$

where: $L = m_3 + m_4 * LBFW + m_5 * LBFW^2$

and FLOW is the annual return interval (years), LBFW is log length to bankfull width, L is the regression coefficient for a log of a given LBFW, and P_{Z4} is the proportion of log length outside of the channel. A key piece is defined as a log having a LBFW ≥ 1 and at least 50% within the channel. The key piece term, KP_i is a categorical variable with four levels, which are defined in terms of the number of key pieces in a given reach (expressed as number /100 m reach) (Table 3.2). Values for the chance of movement coefficients (m_0 to m_5) are presented in Table 3.3. This function can be calibrated to predict the chance of movement for a given stream. A piece moves if the chance of movement is greater than a random number with a uniform distribution between zero and one.

Once a log is predicted to move, the total distance moved is calculated. For a given population of logs in transport, the proportion that ceases to move farther was assumed constant. Based on this assumption, distance moved is calculated using a single negative exponential equation:

Table 3.2. Definition of key piece categories for determination of the chance of movement for the four key piece categories (KP_i).

Key piece category	Key pieces per 100 m	KP_i
none	$n < 10$	0.0
low	$10 \leq n < 20$	0.5
medium	$20 \leq n < 30$	1.5
high	$n > 30$	2.0

Table 3.3. Chance of movement parameter values used in Equation (21).

Parameter	Value
m_0	2.81250
m_1	-0.09600
m_2	0.01900
m_3	0.80835
m_4	0.50830
m_5	4.88090

$$M_{BFW} = LN(rU) / k_M \tag{22}$$

where k_M is the reciprocal of the average travel distance (bankfull width units) for a reach, and rU represents the proportion of individuals that moves farther. The distance moved (M_{BFW}) is initially scaled to the bankfull width of the current reach and then converted to distance moved in meters. A log that has moved is assumed to come to rest completely within the channel (lengths outside the channel are set to zero). The distance a log moves is independent of reach length; final position could be in the current reach, downstream reaches, or downstream of the modeled reaches.

Decomposition. Stream wood decomposes as a thin outer veneer, with minimal decomposition internally (Triska and Cromack, 1980; Aumen et al., 1983; Harmon et al., 1986; Sedell et al., 1988) and tends to decompose slower (biological processing and physical abrasion) than on the forest floor (Triska and Cromack, 1980; Harmon et al., 1986; Sedell et al., 1988). However, total residence time of logs on the forest floor and in the stream may be similar because stream wood is rarely observed in advanced stages of decay due to physical abrasion and increased fragmentation caused by flowing water (Harmon et al., 1986; Murphy and Koski, 1989; Ward and Aumen, 1986). A log that is partially in the channel may contain various decay stages due to the influence of terrestrial and aquatic conditions on decomposition (Triska and Cromack, 1980; Harmon et al., 1986).

All logs are decomposed by volume each year using a single negative exponential decay equation (Harmon et al., 1986). Decay rate used for a log partly in the channel is based on the proportion of log length outside the channel:

$$V_{t+1} = V_t * e^{-k_D}, \ k_D = k_A + P_{Z4} * (k_T - k_A) \tag{23}$$

where V_t and V_{t+1} are total log volumes (m^3) at the beginning and end of the interval, P_{Z4} is the proportion of a log's volume outside the channel, k_A, k_T, and k_D are the aquatic, terrestrial, and calculated decomposition rates for a given species. Top diameter (D_{t+1}, cm) of the log with volume V_{t+1} is calculated with the following equation, which assumes the length and taper remain constant:

$$D_{t+1} = \frac{\sqrt{12 * L_T * C \;\; * V_{t+1} - 3 * L_T^4 * C^2 * T^2} - 3 * L_T^2 * C \;\; * T}{6 * L_T * C} \tag{24}$$

where L_T is total log length (m), T is log taper (cm / m), and C is a conversion constant equal to 0.0000262.

3.4 Model Performance Evaluation

Performance of STREAMWOOD was evaluated by comparing simulation results (total count, total volume, and length frequency distribution) to observational data. The terms validation, verification, corroboration, confirmation, scrutinization, confirmation and "plausible" have all been used to describe model performance tests (Steinhorst, 1979; Oreskes et al., 1994; Haefner, 1996). Haefner (1996) noted that two general characteristics associated with model performance tests are 1) model quality is a continuous variable and 2) model performance evaluation is an ongoing process. Ideally, data sets used in model performance evaluations should be independent of model development (Haefner, 1996), but for many models, including STREAMWOOD, such data are difficult to obtain (Shugart, 1998). Comparison of simulated results to observational data that are not strictly independent of model development assesses the ability of the model to reproduce system characteristics, provided model parameters are realistic (Shugart, 1998).

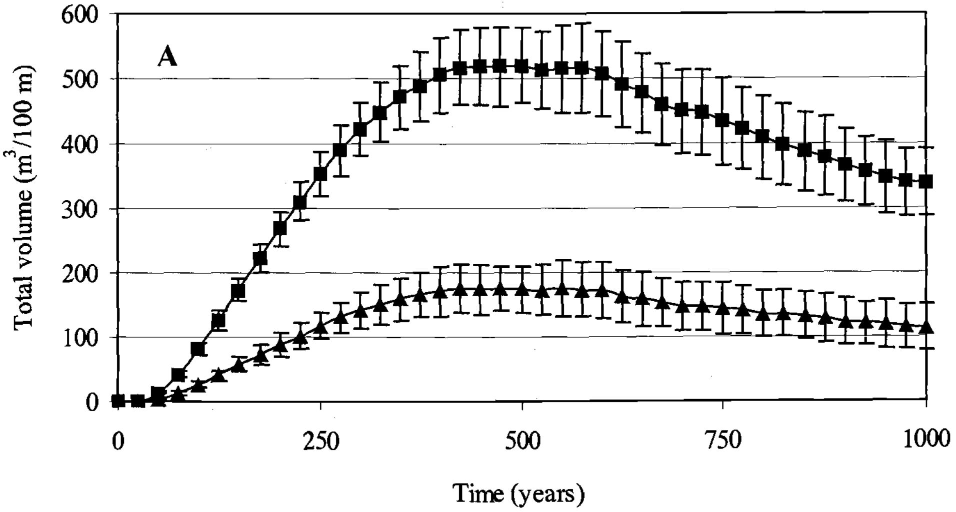
Numerous surveys on wood abundance in Pacific Northwest have been reported for streams not influenced by management activities and range from 2.5 m^3/ha to 4500 m^3/ha (Harmon et al., 1986). Large variability in abundance reflects a wide range of riparian forest conditions (e.g., age, type, successional development, and disturbance history) and channel conditions (e.g., width, substrate composition, and disturbance history) associated with the streams surveyed (Harmon et al., 1986). The large variability in wood abundance estimates also reflects the numerous methodologies employed making comparisons among studies difficult (Bilby and Bisson, 1998). Differences in minimum piece size dimensions (diameter and length) used in surveys influence the number of pieces reported for a given stream because the majority of pieces are in the smallest size classes (Robison and Beschta, 1990; Ursitti, 1990; Richmond and Fausch, 1995; Berg et al., 1998; McHenry et al., 1998). In some survey methods, only the portion of wood within the channel is measured (e.g, Lienkaemper and Swanson, 1987; McHenry et al., 1998). In other survey methods, the entire log is measured, but includes those individuals partially within the channel (e.g., Thom et al., 1999; Thom et al., 2000) or in addition, includes all logs completely outside of but associated with the channel (Robison and Beschta, 1990).

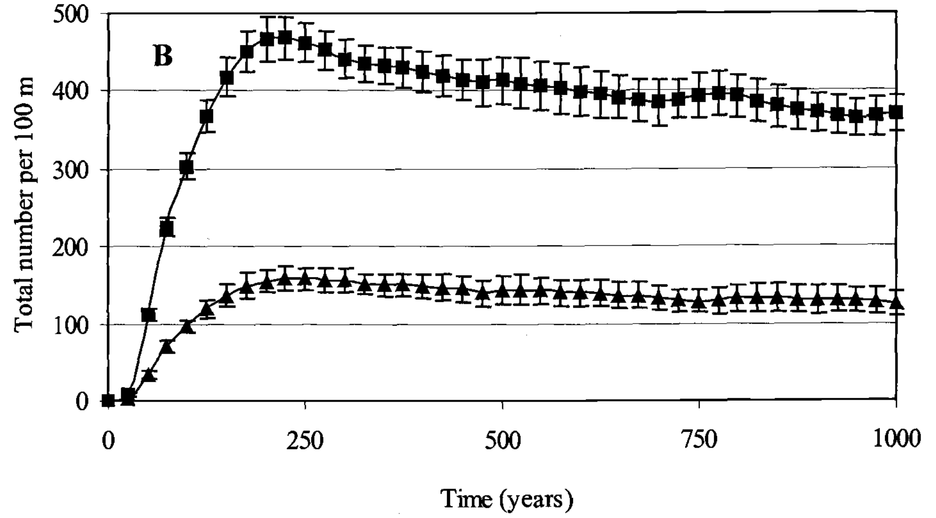
Criteria for model performance data sets included streams adjacent to mature or old-growth forests of known age and forest type, absence of major disturbance events in the forest (e.g., major windthrow event or fire) and stream (e.g., debris flows), and a description of the methodology used in the survey. Older forests were preferred because streams adjacent to young forests may contain wood originating from the previous stand. The best data set available was the Mack Creek wood survey study described above. Since chance of movement function was based on these data and is calibrated to simulate movement of wood in the Oregon Cascade streams, a test involving the Mack Creek data would be considered validation (Shugart, 1998).

Two simulations representing riparian forests and stream conditions of streams in the Cascade Mountains, Oregon were conducted using a hypothetical stream consisting of a linear arrangement of five reaches, each 200 m long and 12 m wide. Results are reported for the downstream reach. Simulated riparian forests were 75 m wide (one potential tree height) using a PMS of -5 bars. Simulations were for 1000 years and 250 iterations and initial conditions included no logs in the channel and no trees in the riparian forests and each.

In the first simulation, trees had an equal chance of falling in any direction (random fall) and in the second simulation, trees fell directly towards the channel (directional fall). These simulations represent the minimum (random fall) and maximum (directional fall) riparian forest recruitment rate in the absence of catastrophic disturbances (Figure 3.3). Given two identical forests, number of trees entering the stream from a riparian forest with a directional fall regime will be three time greater than a riparian forest with a random fall regime (Van Sickle and Gregory, 1990). In

Figure 3.3. Simulated total volume (A) and total number (B) of all logs intersecting the channel from random and directional fall regimes. Symbols represent random-fall (▲) and directional-fall (■) simulations and bars represent ± one standard deviation.





STREAMWOOD, directionality of tree fall is a continuous variable that can be defined between the random fall and directional fall regimes used in these simulations. Wood abundance associated with partial directional fall regimes would be within the range defined by the two fall regimes for a given year (Figure 3.3). These simulations predict the long-term implications of tree fall regime on standing stock, which may never be realized due to the unpredictability of natural disturbances.

Results from STREAMWOOD are reported as means with standard deviations for output parameters (Figure 3.3). The variability in output parameters is a result of stochastic processes within the model, which includes tree fall direction. One measure of variability is the coefficient of variation (CV, standard deviation over the mean expressed as a percent). CV of total volume was greater than the CV of total number because range in volumes a tree could contribute is greater than the range in number of pieces a tree could contribute over all possible fall angles (Table 3.4). CV values for both total number and total volume were greater for random fall than for directional fall because tree fall angle selection was removed as a source of variability for the directional fall simulation (Table 3.4).

Total volume in the random fall simulation at year 500 was 65% of the observed volume in the 1999 Mack Creek survey (264 m^3/100 m of channel length) (Figure 3.3a). Preliminary analysis of the fall regime at Mack Creek suggests that tree fall may not be random, which would contribute substantially more wood to the channel (Figure 3.3a). Tree entry and log breakage components in STREAMWOOD may also be a factor. Total volume in the simulations includes any log that intersects the channel. For example, the volume of a log 30 m long that is barely within the channel would be included in the total volume estimate. If this log breaks, only the piece that intersects the channel is included. Thus, the simulated total volume is directly related to the breakage rates, which may not be representative of a particular site.

Total number of logs in the random fall simulation at year 500 was 72% of the observed number in the 1999 Mack Creek survey (201 per 100 m of channel length) (Figure 3.3b). Length frequency distribution from the random fall simulation was reverse-J in shaped as observed in streams surrounded by old-growth forests (Figure 3.4) (Robison and Beschta, 1990; Ursitti, 1990; Richmond and Fausch, 1995; Berg et al.,

Table 3.4. Coefficient of variation values for total number and total volume from the random fall and directional fall simulations for selected years.

Year	Total number		Total volume	
	Random fall	Directional fall	Random fall	Directional fall
100	9	6	21	12
200	10	6	20	10
300	10	6	19	10
400	10	6	23	12
500	12	7	21	11
600	11	8	25	13
700	12	8	25	14
800	13	7	26	16
900	14	7	30	15
1000	12	6	32	15

1998). Comparison of length frequency distributions of the random fall simulation and the observational data from Mack Creek indicated that the model slightly underestimated the frequency of logs between 2 m and 6 m in length (Figure 3.4). The greatest difference between the simulated and observed data was in the largest length class, which would influence the change of movement (Equation 21).

3.5 Sensitivity Analysis

Sensitivity analyses were conducted on forest model and wood model. The single parameter sensitivity method (reviewed in Haefner, 1996) appears to be the most practical approach used to on stochastic models (Leemans, 1991). In this method, sensitivity is the change in a given output parameter resulting from a fixed change in a given input parameter. Sensitivity index (S) is defined as the standardized change in the output over the standardized change in the input parameter:

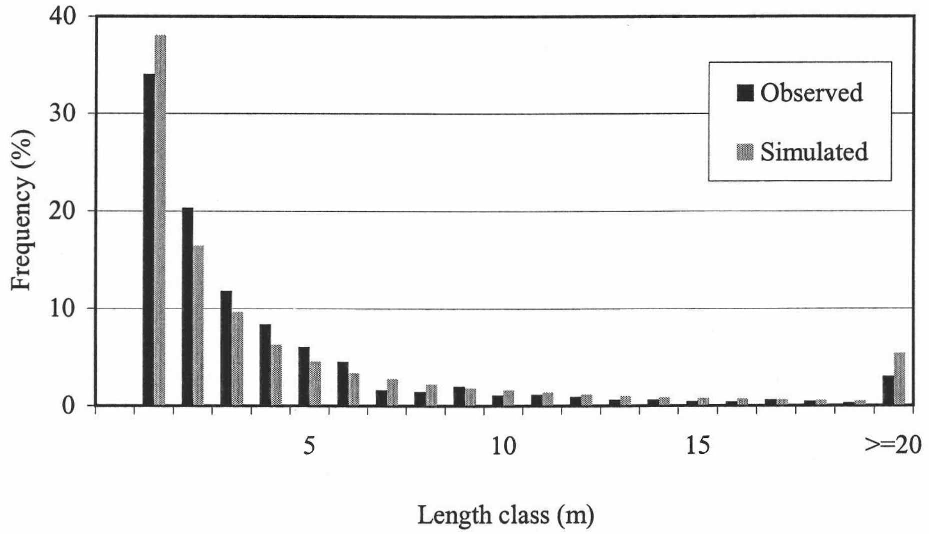
$$S = \left(\frac{R_a - R_n}{R_n} \right) \Big/ \left(\frac{P_a - P_n}{P_n} \right) \tag{25}$$

where R_a and R_n are the adjusted and nominal output parameters and P_a and P_n are the adjusted and nominal input parameters (Haefner, 1996). When $S = 1$, the percent change in output equals the percent change in input.

3.5.1 Sensitivity Analysis of the Forest Model

Most forest model sensitivity analyses have used the single parameter sensitivity method (Kercher and Axelrod, 1984; Keane et al., 1989, 1990; Leemans, 1991; Botkin, 1993; but see Dale et al., 1988). In general, parameters affecting growth rates are most sensitive (Kercher and Axelrod, 1984; Keane et al., 1990), though parameters

Figure 3.4. Comparison of observed and simulated (random fall simulation) length frequency distributions in old-growth study reach in Mack Creek.



associated with recruitment and mortality were found to be moderately sensitive in some analyses (Botkin, 1993).

Sensitivity analysis was based on 250 iterations of 600 years averaged over eight forest plots. Initial conditions were selected to reflect optimum growing conditions for Douglas fir and included PMS of -5 bars and mean TGI of 1500 degree-days. The simulations were conducted for in the northern Cascade Mountain region of Oregon at an elevation of 500 m. Ten forest model parameters where subjected to sensitivity analysis (Table 3.5). For the species variables, only Douglas fir was altered but the effect on western red cedar is also reported. Sensitivity analysis was conducted on basal area and density of all stems ≥10 cm DBH for young (80 years old), mature (600 years) and old-growth (200 years old) stands (Table 3.5).

Most parameters were fairly insensitive using a 10% perturbation level, which is consistent with other forest model sensitivity analyses (Leemans, 1991; Botkin, 1993). In general, factors influencing growth (G), tree leaf area (LSR), and attenuation of light through the canopy (LEC) were most sensitive (Table 3.5). Difference in sensitivities between young and old forests was apparent for some parameters (e.g., LEC for western hemlock density). For western hemlock, changes in basal area were more pronounced than changes in density—a trend that was not apparent for Douglas fir (Table 3.5).

3.5.2 Sensitivity Analysis of the Wood Model

Sensitivity analysis of the wood model was conducted at the process level. Six processes were considered: entry breakage, chance of in-channel breakage, in-channel breakage location, chance of movement, distance moved, and decomposition. Sensitivity of each process was determined by perturbing the output of a process (110% of the default value) for each log in a given year. For example, if chance of movement for a given log were 10% in the base case, it would be 11% for the adjusted case. For entry break, maximum number of breaks was increased from 5 to 6.

Table 3.5. Sensitivity analysis of the forest model for (A) Douglas fir and (B) western hemlock using the single parameter sensitivity method. Each test involved a 10% increase of the base value of the model parameter or the species-specific value for Douglas fir. Results are reported as sensitivity index S, standardized change from the base case basal area and density of trees ≥ 10 cm DBH for young (80-year-old), mature, (200-year-old) and old (600-year-old) stands. See Appendix A for acronym definitions and units.

A) Douglas fir

Parameter	Density			Basal Area		
	Young	Mature	Old	Young	Mature	Old
AGEMX	0.01	0.27	0.25	-0.01	0.18	0.28
δDMN[1]	-0.06	-0.07	0.17	-0.02	-0.03	0.30
DMX	0.00	0.04	0.09	0.03	0.18	0.44
G	-0.23	-0.03	0.24	0.73	0.75	1.01
LEC[2]	-1.06	-1.23	-0.72	-1.00	-1.03	-0.64
LSR	-1.15	-0.94	-0.79	-0.22	-0.05	-0.09
PLA_{MX}	-0.01	0.02	-0.44	-0.03	0.05	-0.32
PMS	0.22	0.26	0.31	0.07	0.12	0.40
STL	-0.16	-0.10	-0.35	-0.19	-0.08	-0.21
TGI	0.20	0.26	0.29	-0.25	-0.11	0.14

B) Western hemlock

Parameter	Density			Basal Area		
	Young	Mature	Old	Young	Mature	Old
AGEMX	-0.03	-0.05	0.03	-0.08	-0.26	-0.07
δDMN[1]	0.08	0.03	0.12	0.04	0.09	-0.01
DMX	-0.10	-0.11	0.07	-0.14	-0.06	-0.09
G	-0.18	-0.07	0.06	-0.91	-0.51	-0.20
LEC[2]	-0.31	-0.49	-0.83	-0.68	-0.61	-0.81
LSR	-0.25	-0.05	0.03	-1.12	-0.42	-0.06
PLA_{MX}	0.06	-0.05	0.12	0.05	0.01	0.07
PMS	-0.20	-0.11	0.06	-0.71	-0.56	-0.29
STL	0.06	-0.04	0.02	0.45	0.08	-0.09
TGI	-0.23	-0.19	-0.10	-0.40	-0.52	-0.61

[1] Minimum proportion of optimum diameter increment required for suppression mortality.

[2] Light extinction coefficient used to calculate available light.

Two tree input files were constructed using the forest model. Single iteration simulations consisted of even-aged stands of red alder and Douglas fir, both starting from bare plots with riparian forest widths of 50 m. From these two input files, 16 base cases were constructed using a full factorial design of four factors at two levels each. The four factors included species (red alder and Douglas fir), flow (low vs. high), age of stand (young vs. old), and input rate (low vs. high) (Table 3.6). The two age levels were defined as young (80-years-old) and mature (200-years-old) for Douglas fir, and young (30-years-old) and mature (60-year-old) for red alder. The two levels for flow consisted of low (5-yr recurrence interval), and high (30-year return interval). Input levels were defined by the tree fall regimes where random fall defined low input and completely directional fall defined high input, which differ by a factor of 3.14 (Van Sickle and Gregory, 1991). The species base case consisted of two forest types: pure stands of red alder and Douglas fir.

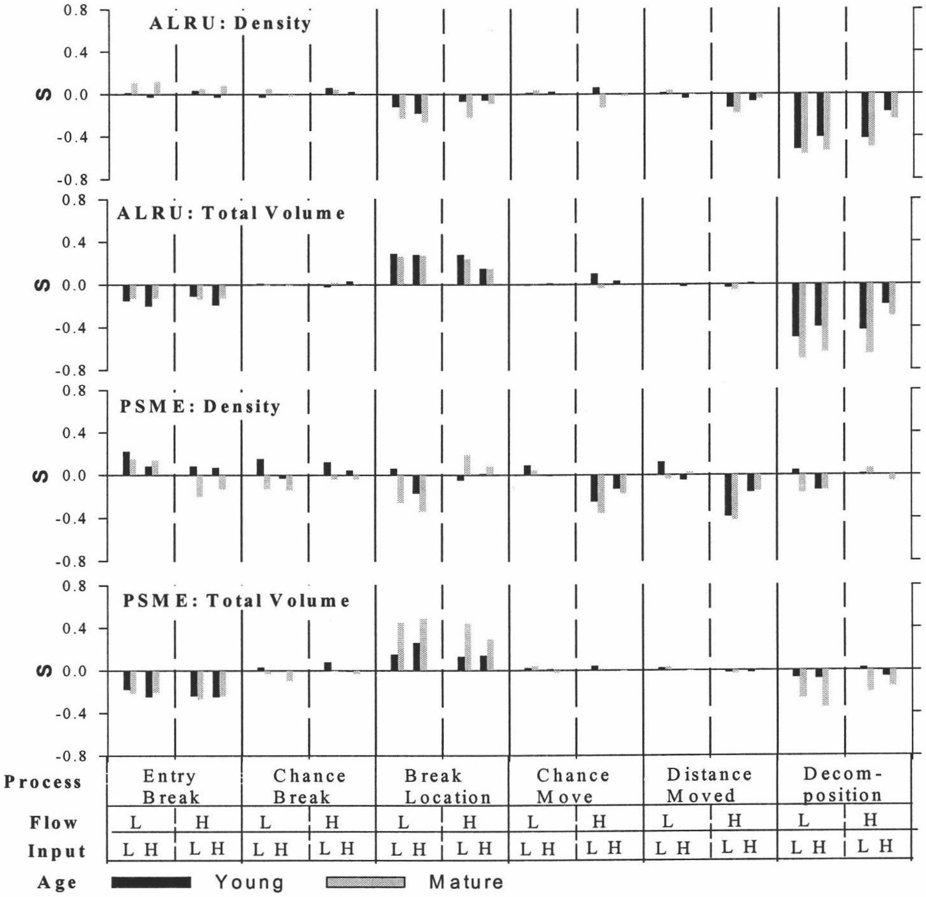
Sensitivity analysis consisted of seven simulations per base case (each of the six single processes and the control) for each of the 16 base cases. All simulations were conducted on stream systems consisting of a linear arrangement of four reaches each 12 m wide and 500 m long. All results were based on most downstream reach and reported in terms of percent change in density and volume of all logs at least partially intersecting the channel.

None of the processes tested were highly sensitive and several processes, distance moved and chance of break, were found to be fairly insensitive (Figure 3.5). In general, 10% increase in process level decreased volume and total number of logs. In most cases, the two levels for age, flow, and input responded similarly though exceptions were found. The greatest difference between levels was for species. The most sensitive process was decomposition for red alder, which was approximately twice as sensitive to a 10% increase than Douglas fir. This difference can most likely be attributed to the higher decomposition rate of red alder.

Table 3.6. Scenarios used in the wood model sensitivity analysis. ALRU is red alder and PSME is Douglas fir.

Scenario	Base Cases			
Number	Species	Flow	Input	Age
1	ALRU	Low	Low	Young
2	ALRU	Low	Low	Old
3	ALRU	Low	High	Young
4	ALRU	Low	High	Old
5	ALRU	High	Low	Young
6	ALRU	High	Low	Old
7	ALRU	High	High	Young
8	ALRU	High	High	Old
9	PSME	Low	Low	Young
10	PSME	Low	Low	Old
11	PSME	Low	High	Young
12	PSME	Low	High	Old
13	PSME	High	Low	Young
14	PSME	High	Low	Old
15	PSME	High	High	Young
16	PSME	High	High	Old

Figure 3.5. Results of the sensitivity analysis on the wood model. The single parameter sensitivity method (10% increase from base value) was applied at the process level to six processes. Sensitivity, S, is the standardized change in output for each base case scenario.



3.6 Discussion

3.6.1 Model Structure

In STREAMWOOD the individual log is the fundamental modeling unit for tracking wood dynamics through time and space. Each individual riparian tree is established, grows each year, and eventually dies. A tree that falls into the stream may break into several logs. Each log has unique characteristics (size and proportion outside of the channel) as well as characteristics common to the tree that produced them (year of entry, species, and initial reach position). Each log has a unique history in response to the various in-channel processes (breakage, movement, and decomposition.). In this approach, population-level response is a collection of unique individual responses and not a collection of individuals with identical "average" responses (McCauley et al., 1993). Representation of individuals in the model parallels the unit of measure in the field and leads to a mechanistic representation of the various processes acting on the individual (Pascual and Levin, 1999).

The advantage of an individual-based model is the added realism in describing population-level dynamics of a system (McCauley et al., 1993; Judson, 1994). Individual-based approach is increasingly used to simulate population dynamics of various entities where age and size distributions or other characteristics differentiate the response of the individuals in a variable environments (Huston et al., 1988; Lomnicki, 1992). The disadvantages include the computational time required (Rose et al., 1993) as well as determining the order of the processes acting on the individual (McCauley et al., 1993). Each individual (log or tree) in STREAMWOOD is subjected to a sequence of processes for a given time step. In the forest model, all trees were subjected to death, growth and then recruitment as recommended by Bugmann et al., (1996). In the wood model, the sequence of processes is breakage, movement, and decomposition. This sequence assumes that logs break and then move as opposed to the reverse order. From field observations, many pieces that have moved are often small, though the reduction in size could have occurred before, during, or after the move. Theoretically, the three processes occur simultaneously but, operationally, an order must be assigned.

The performance evaluation of the forest model was consistent with those found for other forest gap models. In general, the model is moderately sensitive to insensitive to a 10% increase at the process level. A highly sensitive model suggests that the outcome depends heavily on the value of the various model parameters. In this case, where many of these parameters were estimated based on first principles, a moderate sensitivity response suggests that precise values for the parameters would not greatly influence the results. It was interesting to note the most sensitive process varies by species and year. This suggests that the relative importance of the various parameters is not constant through time.

3.6.2 Advances in Simulating Wood Dynamics in Streams

Differences between STREAMWOOD and previous wood models include separate representations of in-channel processes (e.g., breakage, movement, and decomposition) and spatial presentation of stream ecosystems. STREAMWOOD is a spatially explicit model in which a given reach is influenced by processes occurring upstream. Previous wood models have focused on recruitment of wood to the channel from riparian forests for a single reach (Murphy and Koski, 1989; Van Sickle and Gregory, 1990; Beechie et al., 2000; Bragg, 2000). In-channel wood dynamics (breakage, movement, and decomposition) have been ignored (Van Sickle and Gregory, 1990) or represented collectively using a constant depletion rate (Murphy and Koski, 1989; Beechie et al., 2000; Bragg et al., 2000). A constant depletion rate assumes a steady state condition because movement of wood into and out of a reach are assumed equal and losses from breakage and decay are independent of stream flow regime and log characteristics such as size and species. In STREAMWOOD, losses occur through movement, decomposition, and breakage if resulting pieces are below minimum size. Wood is delivered from riparian forest recruitment and from movement from upstream reaches.

Steady State Test. Two simulations were conducted to explore stream length required to achieve a steady state condition in stream systems that differed by probability of piece movement. Since riparian forest inputs were identical for all reaches in both simulations (Douglas-fir input file used in the wood model sensitivity analysis), distance required to achieve steady state conditions along a linear arrangement of reaches is directly related to amount of wood moving into and out of a reach. In this test, when standing stocks of wood are similar in two adjoining reaches, input from upstream sources equal outputs and the location of the reach relative to the upstream reach is the distance required to achieve steady state conditions. Each simulation was for 400 years and 250 iterations using a flow regime with a log-normal distribution and median recurrence interval of 2.5 yr and consisted of a series of contiguous reaches 250 m long.

In the first simulation, the chance of movement parameter (m_0) was set to the default value (Table 3.3) used in all standard runs. Steady state conditions were achieved by the fifth downstream reach for in-channel number of logs and third downstream reach for in-channel volume (Figure 3.6). In the second simulation, m_0 was set to 50% of the value used in the standard runs, which increases the chance of movement (Equations 21). In this less retentive stream system, in-channel number of logs approached steady state conditions by the seventh reach and channel volume by the fifth downstream reach (Figure 3.7). In both simulations, number of reaches required to achieve steady state conditions was less for volume than number because volume in transport is composed primarily of small pieces, which have the greatest mobility. Volume exported is proportionately less than number exported from the standing stock of a given reach.

Exclusion of In-channel Processes. A series of simulations were conducted to assess the relative importance each of the in-channel processes (entry breakage, in-channel breakage, movement, and decomposition) on standing stock of wood in the channel. Douglas fir and red alder tree input files, which were used in the wood model sensitivity analysis, were used in a series of simulations where each in-channel process was excluded and compared to the standard run, which included all in-channel processes. All simulations were for 250 iterations using a flow regime with a log-normal distribution and median recurrence interval of 2.5 yr.

In the Douglas-fir simulations, movement had the greatest influence on both in-channel number (number of logs completely within the channel) and total number (Figure 3.8) but only a marginal influence of in-channel volume and total volume (Figure 3.9), which suggests that the majority of pieces affected where small. In-channel number and total number increased for the first 200 years of the simulation and then remained relatively constant for the next 200 years. This suggests that number of pieces recruited from the forest and number of pieces produced from tree entry and in-channel breakage exceeded the number of pieces lost through decay and in-channel breakage, which produces pieces below minimum size and are removed from the data base. Through time, the number of small pieces increases as a result of in-channel breakage and decomposition forming the reverse-J length class distribution (Figure 3.4). Since smaller older pieces have the highest chance of in-channel breakage (Equation 20), their removal from the database is roughly equivalent to gains in piece numbers by year 200.

In contrast, the no-movement simulation for red alder increased in-channel and total number of pieces only marginally (Figure 3.10) and had very little effect on volume (Figure 3.11). Differences in movement between Douglas fir and red alder are attributed to the flow regime. Major fluctuations in both number and volume correspond to years with large floods. For example, the most pronounced fluctuation in the Douglas-fir simulations corresponds to the largest flood event at year 312 with a 81-yr recurrence interval (Figure 3.8 and Figure 3.9). Largest flood event in the first 80 years, the duration of the red alder simulations, was 60-yr recurrence interval at year 19. In the red alder standard run, the proportion of logs completely in the channel increased from 38% in year 15 to 61% in year 20. This indicates that much of the alder moved but not out of the reach. Average travel distance (reciprocal of k_D) was set at 120 m and given a 250-m reach, the average log would need to move several times to exit the reach. The chance of movement function parameter values used in these simulations represented a retentive stream system. A less retentive stream can be represented by decreasing the chance of movement parameter (m_0), which increases the probability of movement (Figure 3.12).

In general, exclusion of entry breakage and in-channel breakage decreased number of logs and increased volume (Figure 3.8 to Figure 3.11), though relative importance of breakage type differed through time and by species. For Douglas fir, entry

Figure 3.6. Number of logs completely within the channel (A) and total in-channel volume (B) in four contiguous reaches from riparian forests composed of Douglas fir using standard value for chance of movement parameter (m_0, Table 3.3). Symbols for upstream sequence of reaches, each 12 m wide and 250 m long, are reach 1 (▬), reach 2 (◆), reach 3 (■), reach 4 (▲), and reach 5 (∗).

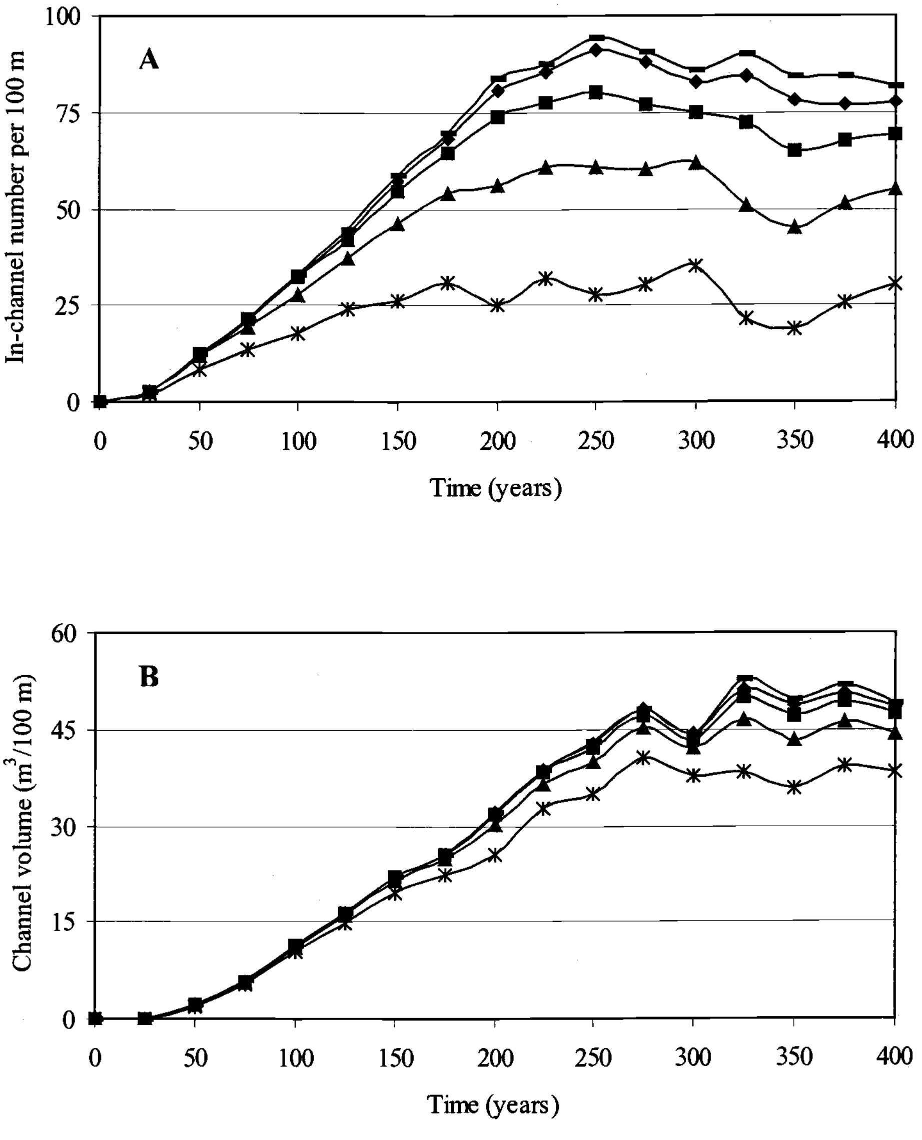
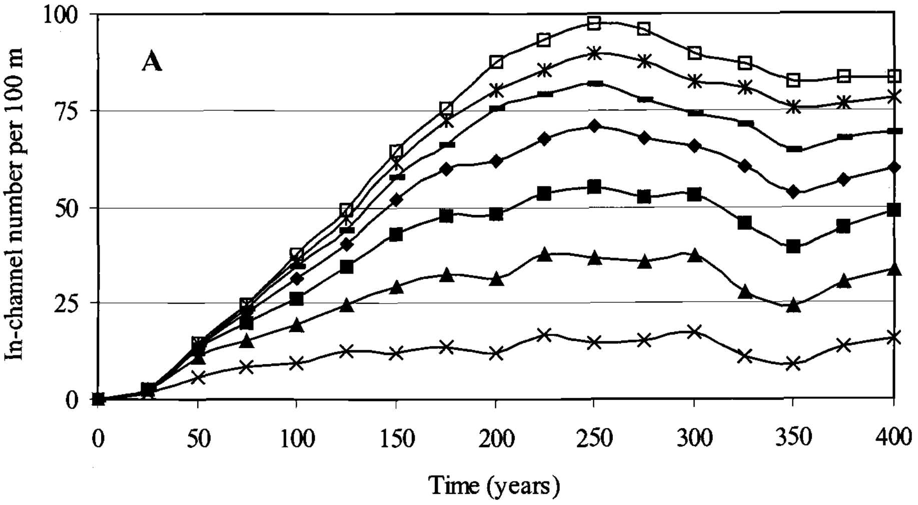


Figure 3.7. Number of logs completely within the channel (A) and total in-channel volume (B) in seven contiguous reaches from riparian forests composed of Douglas fir using chance of movement parameter (m_0) 50% of the standard value (Table 3.3). Symbols for upstream sequence of reaches, each 12 m wide and 250 m long, are reach 1 (□), reach 2 (∗), reach 3 (▬), reach 4 (◆), reach 5 (■), reach 6 (▲), and reach 7 (×).



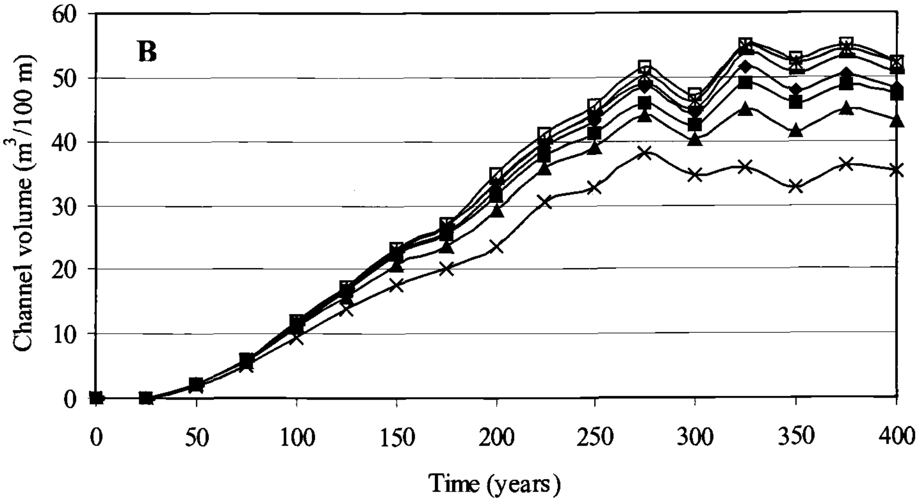


Figure 3.8. Influence of in-channel processes on number of pieces in the upstream reach from Douglas-fir riparian forests. (A) number of logs completely within the stream and (B) total number of logs per 100 m of stream length. Symbols represent simulations that included no entry breakage (◆), no in-channel breakage (■), no movement (▲), no decomposition (×), and standard run, which included all in-channel processes (▬).

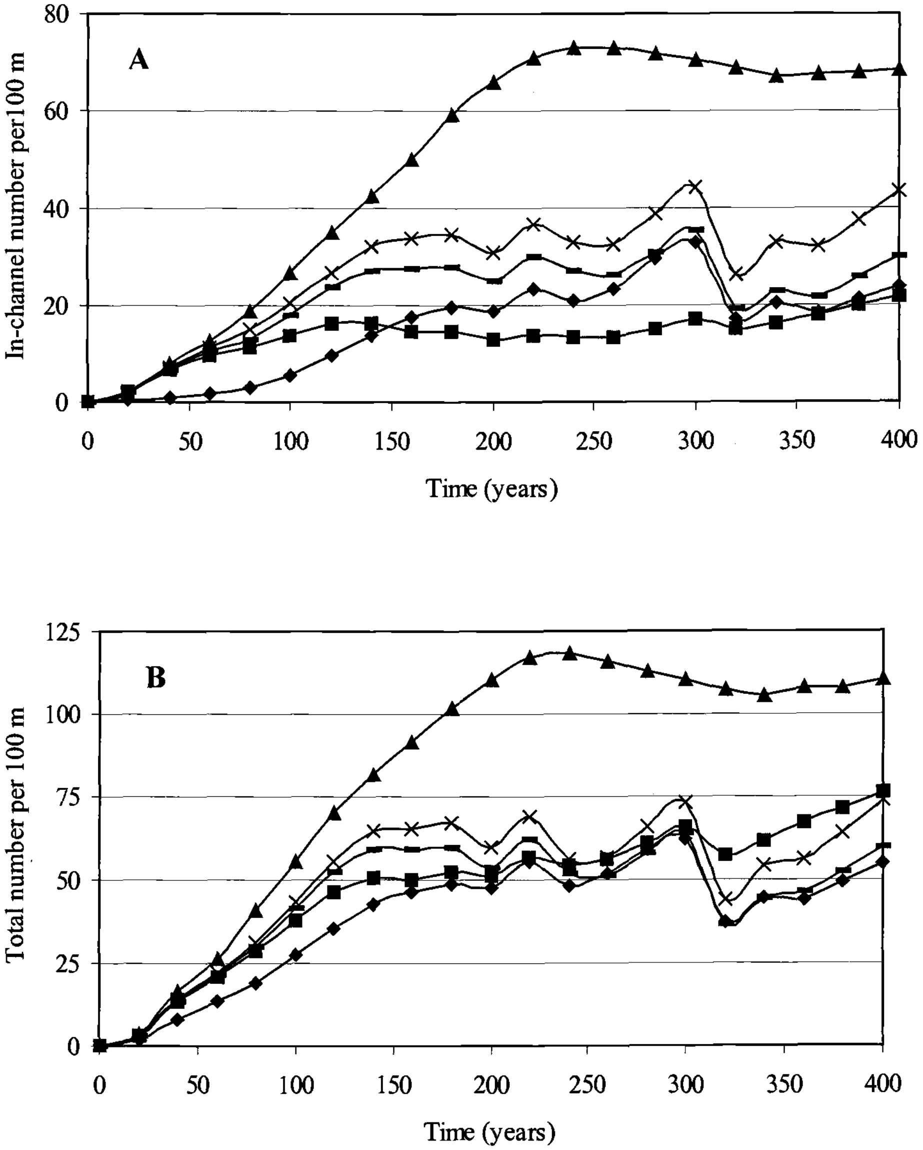


Figure 3.9. Influence of in-channel processes on wood volume in the upstream reach from Douglas-fir riparian forests. (A) in-channel volume and (B) total volume per 100 m of stream length. Symbols represent simulations that included no entry breakage (◆), no in-channel breakage (■), no movement (▲), no decomposition (x), and standard run, which included all in-channel processes (▬).

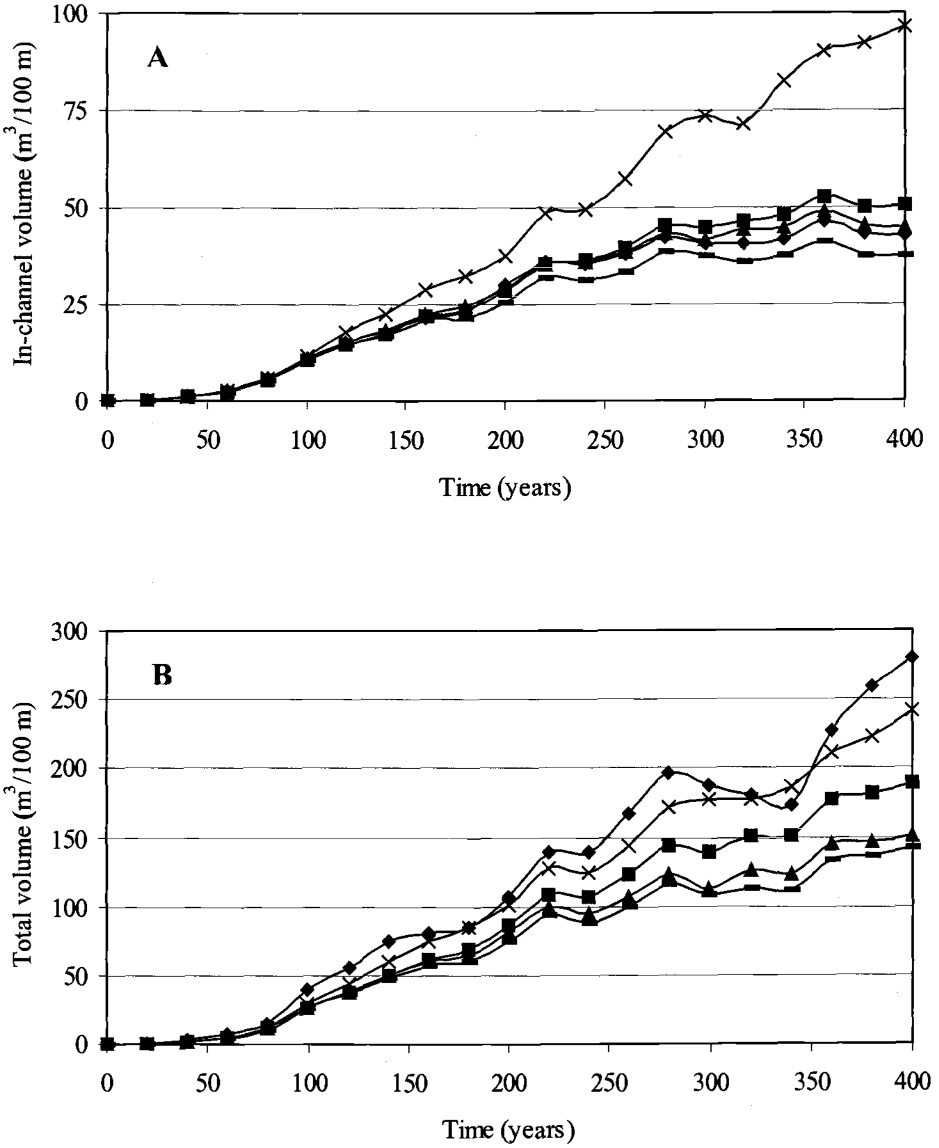


Figure 3.10. Influence of in-channel processes on number of pieces in the upstream reach from red-alder riparian forests. (A) number of logs completely within the stream and (B) total number of logs per 100 m of stream length. Symbols represent simulations that included no entry breakage (♦), no in-channel breakage (■), no movement (▲), no decomposition (×), and standard run, which included all in-channel processes (-).

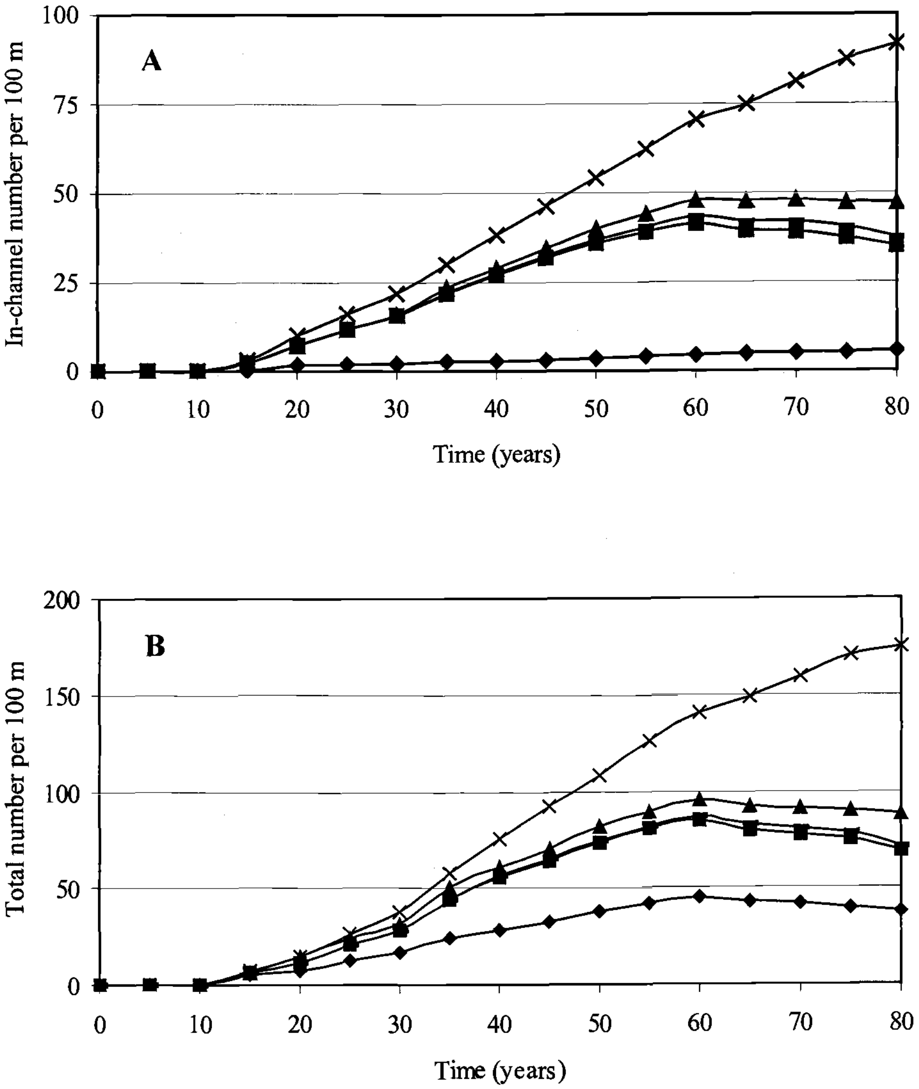
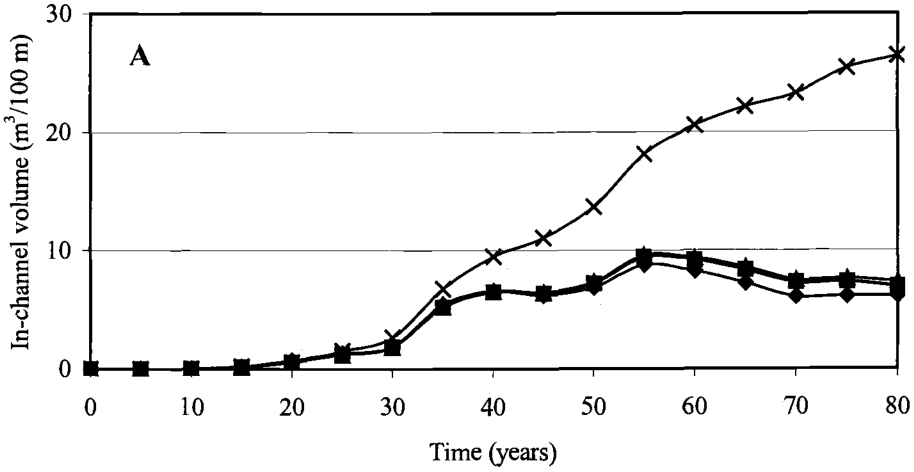


Figure 3.11. Influence of in-channel processes on wood volume from the upstream reach from red-alder riparian forests. (A) in-channel volume and (B) total volume per 100 m of stream length. Symbols represent simulations that included no entry breakage (◆), no in-channel breakage (■), no movement (▲), no decomposition (×), and standard run, which included all in-channel processes (▬).



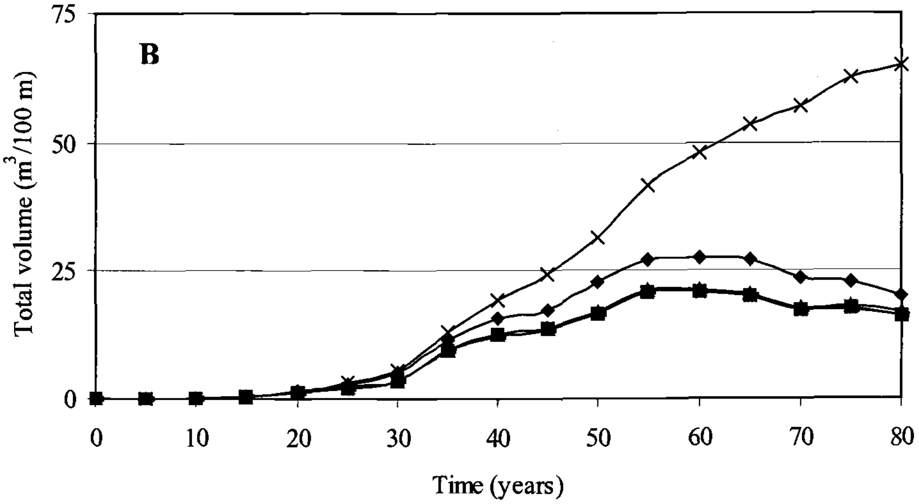


Figure 3.12. Comparison of annual movement rates for the last 11 years of three simulations that differed by the chance of movement coefficient m_0 (default value listed in Table 3.3), where a decrease in the default value results in an increase in chance of movement (Equation 21). Movement rates are for the downstream reach and Douglas-fir input file was used as the source of riparian tree recruitment for all three simulations.

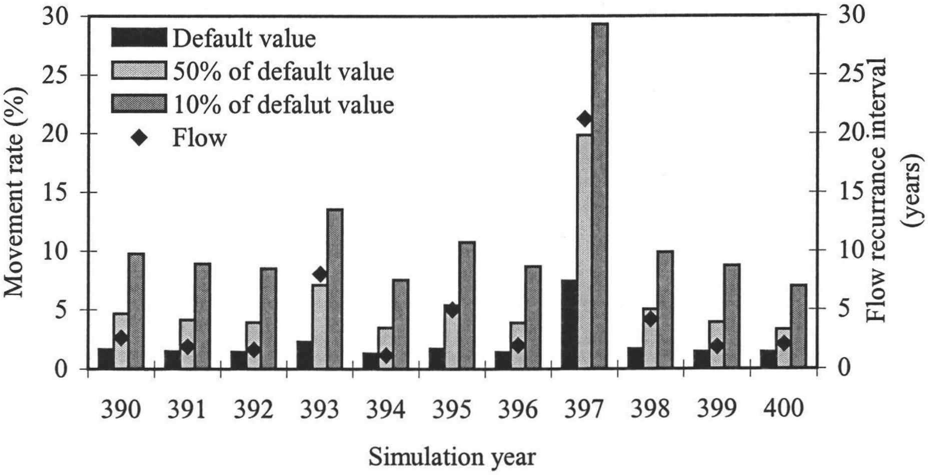
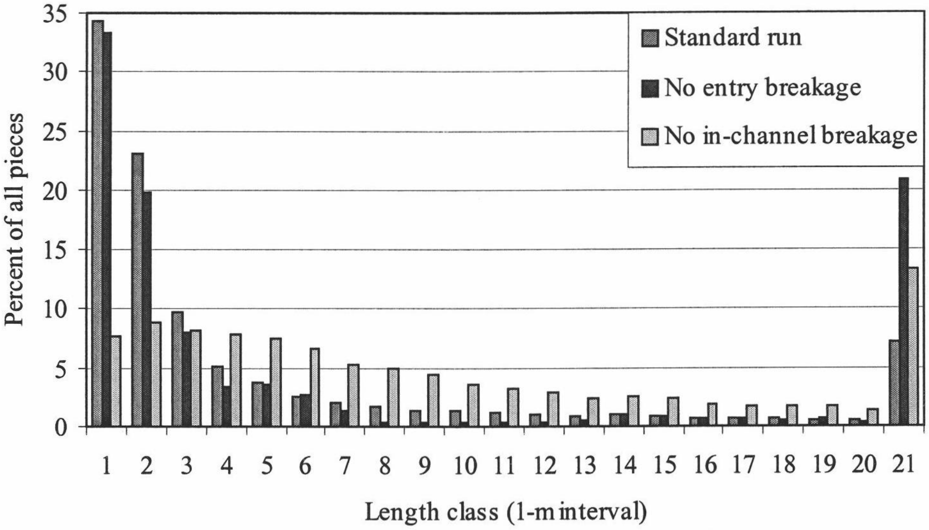


Figure 3.13. Influence of tree entry and in-channel breakage on the length frequency distribution in year 400 for the downstream reach. Riparian forests were composed of Douglas fir. Standard run included both entry breakage and in-channel breakage.



breakage had the greatest influence on in-channel number and total number in the first 200 years of the simulation. In-channel breakage had a greater effect on reduction of in-channel number than on total number (Figure 3.8). Lack of in-channel breakage increased total number of logs by the end of the simulation because fewer pieces were removed from the data base because of minimum size. Both breakage types similarly influenced in-channel volume but no entry breakage substantially increased total volume through time as the trees increased in size (Figure 3.9). Exclusion of entry breakage and in-channel breakage influenced length frequency distributions (Figure 3.13). Entry breakage had the largest influence on the proportion of logs in the largest size classes and in-channel breakage had the largest influence on the proportion of pieces in the smallest size categories (Figure 3.13).

For red alder, in-channel number and total number were strongly affected by entry breakage, but the influence of in-channel breakage was minimal (Figure 3.10). Since red alder is a smaller tree than Douglas fir, smaller logs were initially recruited and in-channel breakage produced relatively more pieces that were below minimum size (using Equation 18), which was also indicated by the lack of influence on in-channel volume (Figure 3.11).

Exclusion of decomposition increased number and volume for both species but was the most influential in-channel process for red alder (Figure 3.10 and Figure 3.11). The difference between species can be attributed to the species-specific decay rates (k_A and k_T, Table 3.1) used in the decay function. Douglas fir decayed much slower than red alder and, relative to the other in-channel processes, decomposition had less influence on number and volume.

3.6.3 Design Goals and Future Work

Many of the processes represented in STREAMWOOD are poorly understood. Relatively few studies have been published on the development of unmanaged riparian forests in the Pacific Northwest (e.g., Pabst and Spies, 1999; Nierenberg and Hibbs, 2000), especially for older forests. Limited information exists on the factors that influence the tree fall regime, such as tree size and hillslope steepness. Little is known about breakage for both tree entry and in-channel breakage. Based on felling studies (Rapraeger, 1932), some information is available but its direct application is difficult because the results are typically expressed as the proportion of unmerchantable volume associated with tree fall. In the current version, logs are assumed to break perpendicular to the log axis. Field observations suggest that logs also break with the axis of the log but this process was omitted from the current version of the model.

This model provides a useful framework for identifying needs for new information on wood dynamics. The forest model was designed to include only the essential components necessary to simulate stream wood recruitment under different riparian management regimes. Numerous advances in gap-model design (e.g., Shugart, 1998) were not incorporated because their computational expense outweighed their improvement in simulating stream wood recruitment. In addition, far less is known about the dynamics of riparian forests as compared to upland forests, making it difficult to adequately calibrate a riparian forest model. For example, the edge effect at the forest–stream interface may be an important consideration in simulating riparian forest dynamics (Malanson and Kupfer, 1993).

Most of the model components can be modified or replaced without substantial modification to STREAMWOOD's underlying structure. In addition, numerous processes associated with stream wood dynamics are not considered in the current version. For example, catastrophic events such as debris flows are important sources of wood to streams (e.g., Triska and Cromack, 1980). STREAMWOOD was designed for the inclusion of additional processes (e.g., debris flows, burial, snag dynamics, wind throw, entrainment from the floodplain) without requiring major revision of the code.

3.7 Acknowledgements

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3.9 Appendices

Appendix A. Definition of acronyms for parameters used in the forest model and the units of measure for each parameter.

Name	Definition	Units
δD	annual diameter growth for a given tree	cm
δDMN	minimum diameter growth for suppression mortality	cm
a_1, a_2	leaf area from DBH parameters	
ABR	leaf area to leaf biomass ratio	m^2/kg
AGE_{MX}	species-specific maximum age	year
AL	available light reaching a given tree	
b_1, b_2	TSB from DBH parameters	
BMAX	riparian forest biomass maximum	tons/ha
$BMAX_{plot}$	forest plot biomass maximum	kg / plot
BMF	biomass maximum factor	
B_{plot}	total biomass for a given plot	kg/plot
C	diameter growth parameter	
DBH	tree diameter 1.37 m from base	cm
DDMAX	species-specific degree-day maximum	degree-days
DDMIN	species-specific degree-day minimum	degree-days
DMX	species-specific maximum diameter	cm
EF	environmental factors product of all growth factors	
FT	foliage type constant used to calculate TLB	
G	species-specific fundamental growth parameter	
h_0, h_1, h_2	species-specific height from diameter parameters	
h_M	total tree height	cm
h_{MX}	species-specific maximum tree height	cm
H_T	total tree height	m
LA	tree leaf area	m^2
LEC	light extinction coefficient	
LSR	leaf area to sapwood area ratio	m^2/cm^2
MSF	moisture stress factor	
PLA_{MX}	maximum projected leaf area for species recruitment	m^2/m^2
PMS	predawn moisture stress	-bars
rU	random number with uniform distribution from 0 to 1	
s_1, s_2, s_3	species-specific shade tolerance parameters	
SAPENV	environment factor for sapling recruitment	
SAPMX	annual maximum number of saplings for a given species	
SF	size factor for a given tree	
S_I	annual probability of inherent tree survival	
SLA	shade leaf area a given tree experiences	m^2/m^2
SR_I	saplings recruited for shade-intolerant species	
SR_T	saplings recruited for shade-tolerant species	
STF	shade tolerance factor	
STL	sapling growth time lag	year
TGF	temperature growth factor	
TGI	temperature growth index	degree-days
TLB	tree leaf biomass	kg
TSB	total tree bark and stem wood biomass	kg
V	MSF parameter	
w_1, w_2	MSF parameters	
WMN	species-specific minimum moisture stress	-bars
Z	red alder TSB parameter	

Appendix B. Definition of acronyms for parameters used in the wood model and the units of measure for each parameter.

Name	Definition	Units
C	log decay conversion constant	
C_V	log volume constant	
D_B	log bottom diameter	cm
D_T	log top diameter	cm
D_{t+1}	log top diameter after decay	cm
FLOW	annual maximum peak flow return interval	year
k_A	log decay parameter for aquatic environment	
k_D	log decay parameter based on k_T and k_A	
k_M	distance log moves parameter	BFW units^{-1}
KP_i	key piece category parameter for log movement	
k_T	log decay parameter for terrestrial environment	
L	chance of log movement parameter	
LBFW	log length to bankfull width ratio	m / m
L_p	log length of the parent log before breakage	m
L_T	log length	m
L_{top}	log length of top piece after break	m
m_0 to m_5	probability of movement parameters	
M_{BFW}	distance log moves in bankfull width units	BFW units
P_B	probability of breakage for a given log	
pb_1, pb_2	probability of log breakage parameters	
P_M	probability of movement for a given log	
P_{Z4}	proportion of log length outside active channel	
rN	random number with normal distribution from 0 to 1	
RT	log residence time	year
rU	random number with uniform distribution from 0 to 1	
T	log taper	cm/m
V	log volume	m^3
V_t	log volume before decomposition	m^3
V_{t+1}	log volume after decomposition	m^3

4. IMPLICATIONS OF RIPARIAN MANAGEMENT STRATEGIES ON WOOD IN CASCADE MOUNTAIN STREAMS OF THE PACIFIC NORTHWEST

Mark A. Meleason, Stanley V. Gregory, and John P. Bolte

4.1 Abstract

In the Pacific Northwest, riparian forest management plans must consider long-term supply of wood to the channel. The simulation model STREAMWOOD was used to evaluate the effects of riparian management scenarios on the standing stock of wood in a stream channel. STREAMWOOD simulates riparian forest growth, tree entry (including breakage), and in-channel processes (log breakage, movement, and decomposition). Results of three simulation experiments are reported. The first experiment assesses total wood volume in the channel from forest plantations clearcut to the stream bank using three rotation periods (60, 90, and 120 years). Without a forested riparian management zone, accumulation of wood in the channel was minimal and did not increase through time. In the second experiment, response of total wood volume to forested riparian management zones of widths between 6 m and 75 m was evaluated. Total wood volume associated with the 6-m wide non-harvested forest for forest ages ≥240 years was 32% of the standing stock associated with a non-harvested forest buffer one potential tree height in width. Maximum standing stock associated with the channel for non-harvested riparian forests ≥30 m required 500-year-old forests. In the third experiment, contribution of wood from forest plantations beyond non-harvested forests of various widths was explored. Forest plantations of the rotation lengths modeled associated with non-harvested riparian buffers with widths >10 m had no effect on total wood volume associated with the stream. These results suggest that forest age and width of the non-harvested buffers were more important than the rotation age of plantation forests in providing long-term supplies of wood to the streams.

4.2 Introduction

In the Pacific Northwest, recognition of declining salmonid populations has encouraged much research on effects of land management practices on stream systems (Meehan, 1991). By the middle of the 1970's, most state and federal land management agencies in the Pacific Northwest had adopted riparian forest regulations that offered some level of protection to stream systems (Gregory, 1997). One goal of riparian management strategies is to maintain ecologically adequate amounts of wood in streams though time while maintaining sustainable levels of timber production (Chamberlin et al., 1991). Land managers must now consider future recruitment of wood to streams at levels adequate to conserve the functions of wood in streams. Amount of wood in channels are highly variable and depend on geographic region, stream geomorphology, basin position, natural disturbance regimes, management history, and site characteristic that influence the structural and successional development of riparian forests.

A common feature in riparian management regulations is a fixed riparian management zone (RMZ) width adjacent to channels where forest harvest is limited or excluded (Gregory, 1997). State and federal RMZ guidelines differ considerably in the Pacific Northwest (e.g., FEMAT, 1993; Oregon Department of Forestry, 1994). Generally, riparian rules require more narrow widths for riparian zones on smaller streams. Various approaches have been developed to regulate the amount harvested within a RMZ. In this report, RMZ is a non-harvested area with natural tree recruitment. Management of forests outside of the RMZ includes clearcut harvest followed by planting of high-yield tree species. Douglas-fir plantations are most common in the Pacific Northwest and harvested at ages between 40 to 120 years (Williamson and Twombly, 1983; Chamberlin et al., 1991). Wood can be recruited to the channel from forest plantations provided trees are of sufficient height relative to the distance to the channel.

The temporal scale required to investigate long-term implications of various riparian management strategies on amounts of wood in streams prohibits the assessment through short-term field studies. Computer simulation models offer a method for exploring the likely consequences over long time period and many alternative strategies.

Several models have been used to investigate the implications of various riparian management regimes of recruitment of wood to streams (Rainville, et al., 1986; Van Sickle and Gregory, 1990; Beechie et al., 2000; Bragg et al., 2000). Most models of wood in riparian forests and streams focus on the potential recruitment of wood to the stream. In-channel processes such as tree entry breakage and log breakage, movement, and decomposition have not been considered separately. Several models have incorporated a depletion rate, which includes loss from both downstream transport and decomposition (Murphy and Koski, 1989; Beechie et al., 2000; Bragg et al., 2000). Transport of wood from upstream sources has been assumed to equal output of the reach for a given time interval (Murphy and Koski, 1989; Van Sickle and Gregory, 1990) or ignored. In this paper, we explore the consequences of riparian management strategies using a simulation model that incorporates stand dynamics, mortality, wood input, breakage, stream transport, and decay.

This study assesses the long-term consequences of various riparian management strategies on stream wood volume in the absence of catastrophic events. Influence of catastrophic disturbances such as fires (Bragg, 2000), major wind storms (Steinblums, et al., 1984), insect infestation (Bragg, 2000), or debris flows (May, 1998) can substantially influence amounts of wood in streams. However, development of management prescriptions are concerned with long-term potential of the sites, which may or may not be realized due to the unpredictability of major episodic events. In this study, three approaches for riparian forest management were explored. In the first approach, wood was recruited from forest plantations clearcut to the stream bank under three rotation periods. In the second approach, wood was recruited from RMZs (non-harvested area) that ranged between 6 m and 75 m wide. In the third approach, wood was recruited from both the RMZ and forest plantations under various combinations of each.

4.3 Methods

4.3.1 Model Description

STREAMWOOD is an individual-based stochastic model that simulates riparian forest and in-channel wood dynamics. A detailed description of this model is presented in Meleason et al. (in prep). Stream systems can be simulated from a single reach to a small basin. The model is run under a Monte Carlo procedure using an annual time step and the results are reported as average conditions per reach. The current version of STREAMWOOD was developed for fifth-order and smaller streams in the coniferous forests of the Pacific Northwest. Species considered include Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* Donn ex D. Don), and red alder (*Alnus rubra* Bong.). STREAMWOOD consists of a forest model and a wood model. The forest model simulates riparian forest dynamics under various management regimes. Output of the forest model is the input to the wood model and is a list of trees that have died in the current year. The wood model simulates recruitment of trees into the channel and subjects individual logs to in-stream processes that includes breakage, movement, and decomposition.

The forest model is a forest-gap model based largely on ZELIG (Pacific Northwest version by Dr. Steve Garman, Forest Science Laboratory, Corvallis Oregon), JABOWA (Botkin et al., 1972; Botkin, 1993), and CLIMACS (Dale et al., 1986; Dale and Hemstrom, 1984). The forest model adheres closely to the original design of Botkin et al. (1972) and Shugart and West (1977), and thus shares many of their limitations (Schenk, 1996). Riparian forests in the model range 0 m to 100 m wide and includes the width of any non-harvested area (RMZ) and the harvested area (forest plantation). Harvest rotation schedules (which include thinning, clearcutting, and planting regimes) can be defined for each riparian forest. The forest model includes soil moisture that influences the species composition and growth rate. For the simulations reported here, the soil moisture term was set sufficiently dry to exclude the initial dominance of red alder.

Output of the forest model is the input to the wood model and is a list of trees that died in the current year. Trees are assumed conical in form and fall the year they die. Tree entry is a function of distance from the stream bank, effective tree height (height to 10 cm diameter), and tree fall angle. Trees that intersect the channel undergo a randomly selected number of breakage events between zero and maximum number of breaks. The location for each break is randomly selected using a normal distribution with a user–defined mean break (and standard deviation) location. The settings used in the simulation reported here include a maximum of five breakage events for a given tree and a mean and standard deviation breakage location of 0.6 and 0.2, respectively. Since trees do not break with respect to the location of the channel bank, logs can be partly outside of the channel. Logs that are completely outside the channel or logs that are below minimum size (10 cm diameter and 1 m in length) are not considered in these simulations. Total volume is volume of all logs that are at least partly in the channel.

Following entry, all logs are subjected to in-channel processes in the following order: breakage, movement, and decomposition. In-channel breakage consists of two functions: chance of breakage and breakage location. Chance of log breakage is a stochastic function based on the assumptions that likelihood of a log breaking increases with decreased size and increases with residence time. Breakage occurs at half the natural logarithm of length. The log movement component includes functions for chance of movement and distance moved. Likelihood of a log moving is assumed to increase with greater annual flow and decrease with increased ratio of log length to bankfull width, proportion of the piece outside the channel, and number of key pieces in the reach. Annual peak flow is represented as a recurrence interval between 1 and 100 years and generated with a random number generator using a log normal distribution. The same flow regime is used in all iterations of all simulations. The chance of movement function can be adjusted to the retentive properties of a given system, and was set conservatively to represent a relatively retentive system such as a boulder and coble-dominated streams in the Oregon Cascade Mountains. Distance a log moves is assumed to follow a negative exponential distribution where the reciprocal of the slope is the average travel distance and was set to 120 m for all simulations reported here. Logs are decomposed using a single exponential model with species-specific decomposition rates. Decomposition rate for logs partially in the channel is a linear extrapolation between terrestrial and aquatic decay rates as a function of the proportion of the log outside the channel.

4.3.2 Initial Conditions

The hypothetical riparian forest and stream conditions represent a third-order channel in the Oregon Cascade Mountains at approximately in 500 m elevation. Recruitment of wood to the channel was limited to recruitment from the riparian forest and fluvial transport from upstream reaches. All simulations started with no trees in the forest and no logs in the stream. Soil moisture and other site conditions were set to favor the establishment of a productive Douglas fir-western hemlock forest (Figure 4.1). Riparian forests in the RMZ grew under unmanaged conditions. Management of the forest plantations included planting 1,000 Douglas fir seedlings per hectare the year of the clearcut and thereafter no other trees were permitted to establish on the site (Figure 4.2). In simulations that included both an RMZ and plantation forest, total width of the forest was 75 m and width of the plantation forest was the difference between the total width and RMZ width.

Each reach included a riparian forest adjacent to each bank and grown independently but with identical riparian management prescriptions. Trees were assumed to fall the year they die and have an equal chance of falling in any direction. The hypothetical stream system consisted of four consecutive reaches each 200 m long and 12 m active channel width. Results for all simulations used in the analysis were from the farthest downstream reach with the three upstream reaches serving as sources of wood through fluvial transport. Standing stock of wood was reported as total wood volume, which includes the entire volume of all pieces intersecting the channel. Logs were assumed to be conical in form and at least 1 m in length and 10 cm in diameter.

Figure 4.1. Basal area per hectare for each species and total forest for the old-growth forest simulation (B75R0) in the standard run. The species acronyms are Douglas fir (PSME), western hemlock (TSHE), and western red cedar (THPL).

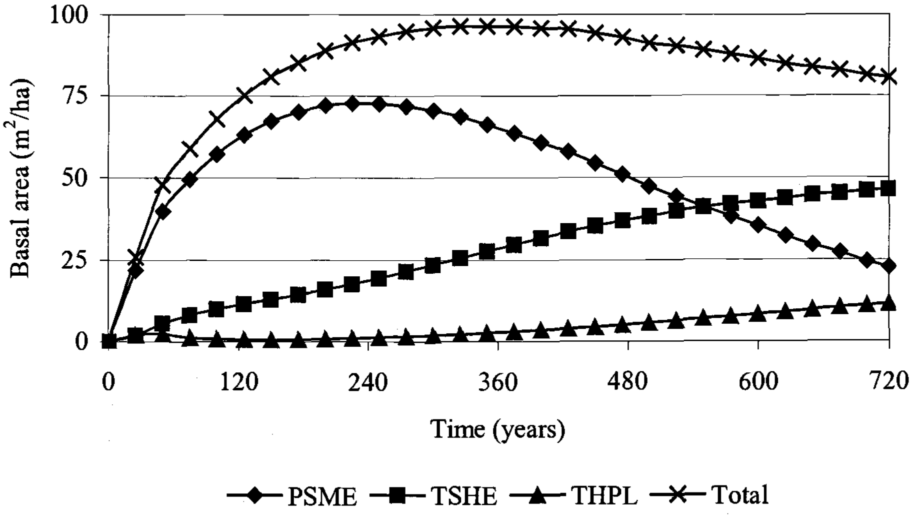
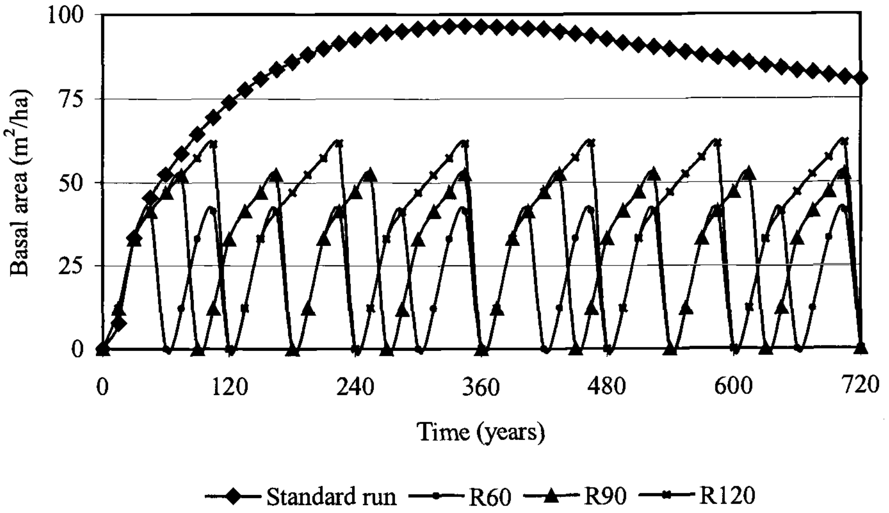


Figure 4.2. Total basal area per hectare for the three simulations without RMZs and total basal area per hectare of the standard run for the old-growth forest. The three simulations without buffer differ by rotation age with 60-yr (B0R60), 90-yr (B0R90), and 120-yr (B0R120) rotation periods.



4.3.3 The Modelling Experiment

A total of 30 simulations were conducted using an incomplete matrix design of ten non-harvested buffer widths (0 m, 6 m, 10 m, 15 m, 20 m, 25 m, 30 m, 35 m, 40 m, and 75 m) by four harvest rotation periods (non-harvest, 60 years, 90 years, and 120 years) (Table 4.1). Each simulation is named by RMZ width (B) and the rotation age (R). For example, B6R60 is the simulations with a 6 meter non-harvested buffer width and a forest plantation cut every 60 years. The rotation period for simulations with riparian buffers only (a non-harvested portion without a forest plantation) are designated as R0. For example, B6R0 represents the simulation with a 6-m buffer without a plantation forest. Since recruitment from the riparian forest did not include upslope input processes, a buffer width equal to one maximum tree height is the maximum buffer width where a tree could fall and enter the stream. A buffer width of 75-m, approximately one maximum tree height, is wide enough to include all input events from the riparian forest and is referred to as the standard run because it represents the maximum potential recruitment to the stream from the riparian forest.

All simulations were for 720 years and 250 iterations. The first series of simulations (Table 4.1, non-harvested column) varied the RMZ width from 6 m to 75 m and did not include any wood contributed from beyond the buffer. The second series of simulations (Table 4.1, last three columns) varied each of the three harvest rotation periods by seven RMZ widths that ranged from 0 m to 30 m. Total volume includes the entire volume of any log that intersects one of the stream banks. Total wood volume is the standing stock associated with the stream and is subjected to in-channel processes (log breakage, movement, and decomposition).

Table 4.1. Total of 30 simulations were conducted using an incomplete matrix design of 10 RMZ widths (non-harvested forests) by four harvest rotation periods. The simulations were divided into three series. In the first series, the riparian forest was clearcut to the stream bank at three rotation periods (row 1). In the second series, recruitment was limited to the non-harvested buffer (non-harvested column). The third simulation included recruitment from the RMZ and forest plantation for all combinations of 3 rotation periods and 6 RMZ widths (indicated by box). NA represents simulations that are not included in the analysis and standard run is the simulation of a forest with a RMZ width of 75 m, which represents the maximum recruitment to the stream.

Buffer Width (m)		Harvest Rotation (years)		
	non-harvested	60	90	120
0	NA	B0H60	B0H90	B0H120
6	B6R0	B6R60	B6R90	B6R120
10	B10R0	B10R60	B10R90	B10R120
15	B15R0	B15R60	B15R90	B15R120
20	B20R0	B20R60	B20R90	B20R120
25	B25R0	B25R60	B25R90	B25R120
30	B30R0	B30R60	B30R90	B30R120
35	B35R0	NA	NA	NA
40	B40R0	NA	NA	NA
75	standard run	NA	NA	NA

4.4 Results and Discussion

4.4.1 Total Wood Volume from the Standard Run

The forest in the standard run simulation consisted of a 75-m wide RMZ with a maximum basal area of 96 m^2/ha (Figure 4.1). Total wood volume for a given time in the standard run simulation represented the maximum wood standing stock at any time for the hypothetical stream. A little over 50 years was required to exceed 5 m^3/100m of stream length (Figure 4.3). Maximum total wood volume accumulated was 176 m^3/100 m of stream length at year 525 and then declined to 150 m^3/100 m of stream length by year 720 (Figure 4.3). The decline in total volume after 525 years resulted from changes in species composition of the forest (Figure 4.1). Initially, the forest was dominated by Douglas fir, a shade-intolerant species, but was eventually replaced by western hemlock, a shade-tolerant species. Since maximum height of Douglas fir commonly obtained exceeds western hemlock by 15 m (Franklin and Waring, 1980), eventual dominance of western hemlock decreases total volume of wood in the channel.

4.4.2 Total Wood Volume From Forest plantations

In the first series of simulations (Table 4.1), riparian management consisted of Douglas-fir plantations cut to the stream bank using three rotation periods. The forest for these simulations achieved maximum basal areas of 45, 55, and 65 m^2/ha on the year of the harvest for the 60, 90, and 120 year rotation cycles (Figure 4.2). Total wood volume from the three simulations without RMZs was similar to the standard run up to their first harvest cycle (Figure 4.3). Maximum total wood volumes for the 60-yr, 90-yr, and 120-yr simulations were 13, 28, and 44 m^3/100 m of stream length. After each harvest event, total volume of wood decreased indicating that depletion from in-channel processes exceeded recruitment. The time required after harvest for recruitment rate to equal depletion rate was approximately half the rotation period allowing accumulation of standing stock of wood only in the last half of rotation. As a result, this management approach provides only a fraction of the potential volume for a site (Figure 4.3).

4.4.3 Total Wood Volume as a Function of RMZ Width

In the second series of simulations (Table 4.1), recruitment to the channel was limited to the RMZ of the riparian forest. All forests were identical to the standard run in terms of density, species composition, and basal area (Figure 4.1). Wood recruitment to the channel was limited to the simulated RMZ, which ranged from 6 m to 40 m in width. Buffer width strongly influenced total wood volume in the stream (Figure 4.4). The difference between total wood volumes associated with any two RMZ widths represents the volume gained with an increase in RMZ width. In addition, differences in total wood volume also varied with time (Figure 4.4). For example, the difference between the 6-m and 10-m RMZ at 120-yr was 6.5 m^3/100 m and the difference increased to 24.2 m^3/100 m by year 360. For forest ages greater than 360 years, the difference in wood volume between the 6-m and 10-m buffer was fairly constant, indicating that recruitment was limited by RMZ width and not tree height.

Total wood volume was very similar to the standard run for all buffer widths ≥30 m (Figure 4.4), indicating that the majority of total volume is contributed within the first 30-m from the stream. This result is consistent with the field observation reported in McDade et al. (1990), who examined source distance (slope distance from the stream bank to the base of the source tree) in 39 streams adjacent to either mature conifer (80 to 200 yr old) or old-growth conifer (>200 yr old) riparian forests in western Oregon and Washington. Approximately 90% of the logs originated within 26 m of the channel in mature conifer and 36 m of the channel in the old-growth stands (McDade et al., 1990). Total volume of wood through time was reported for all simulations, which is a more conservative measure of wood abundance than the number of pieces. For the 120-year forest, 90% of total wood volume originated within 25 m from the bank. For stand ages of 240, 360, 480, and 720 yr, 90% of the total wood volume originated within 30 m from the stream (Figure 4.5). However, 90% of the total wood volume for a 600-yr stand

Figure 4.3. Total volume associated with the channel from plantation forests under three rotation periods and compared to the maximum potential standing stock of the site. Total volume includes all logs intersecting at least one stream bank and is expressed in $m^3/100$ m of channel length. Symbols represent standard run (+) and clearcut rotations at 60-yr (•), 90-yr (▲), and 120-yr (▪).

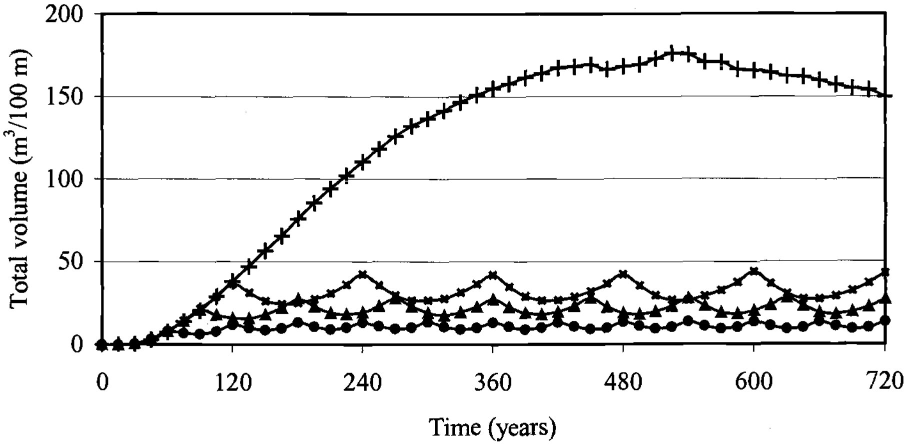
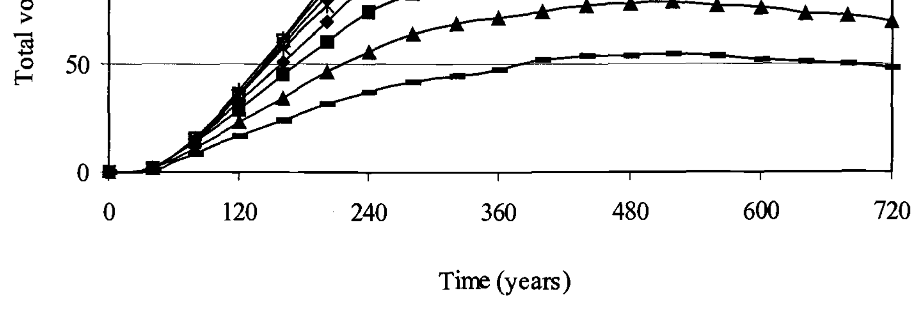


Figure 4.4. Total volume of all logs associated with the stream for all simulations that did not include recruitment from the forest plantation. Symbols represent RMZ widths of 6-m (−), 10-m (▲), 15-m (▪), 20-m (◆), 25-m (*), 30-m (○), 35-m (△), 40-m (□), and standard run with 75-m buffer (+).



originated within 35 m of the channel, which may be attributed to the recruitment of large Douglas firs. Canopy height does not always increase with stand age because maximum height of each seral stage is not necessarily greater than the previous sere. In this case, height of the forest decreased with the decline of Douglas fir and eventual dominance of western hemlock.

Contribution of total wood volume by buffer width can also be expressed as a proportion of the standing stock associated with the 75-m non-harvested buffer, which represents the proportion of the maximum potential for a given buffer width (Figure 4.6). For each RMZ width, potential recruitment is fully realized at a specific stand age, as indicated by an asymptotic standing stock. For example, the 6-m RMZ width achieved its maximum potential relative to the standard run by 200 yr, and thereafter was approximately 32% of the potential total wood volume for the hypothetical stream (Figure 4.6). The proportion of the maximum potential for buffer widths ≥ 30 m were 90% or greater for all stand ages (Figure 4.6).

4.4.4 Contribution of Wood Beyond the RMZ

The third series of simulations (Table 4.1) determined the contribution of wood from forest plantations for riparian forests that also included recruitment from RMZs. All combinations of three rotation ages by six RMZ widths were simulated (Table 4.1). Total wood volume contributed from the forest plantation is the difference between the simulation that included recruitment from both the non-harvested and plantation forest and the simulation that recruited wood recruited from the non-harvested area only (Figure 4.7 and Figure 4.8). The largest contribution of wood from the forest plantation was with a 6-m buffer. The percent of total wood volume contributed by the forest plantation was greatest in the year of the first cutting cycle for each rotation period. The forest plantation accounted for 39%, 51%, and 58% of the total volume for rotation ages 60, 90, and 120 yr, respectively. Percent gain associated with the forest plantation in all three simulations declined after the first rotation. The actual increase in volume did not exceed

Figure 4.5. Total volume of wood as a function of RMZ width without recruitment from the forest plantation for selected years. RMZ widths correspond to those in Figure 4.4. Symbols represent following simulation years: 120-yr (+), 240-yr (−), 360-yr (▲), 480-yr (■), 600-yr (◆), and 720-yr (∗).

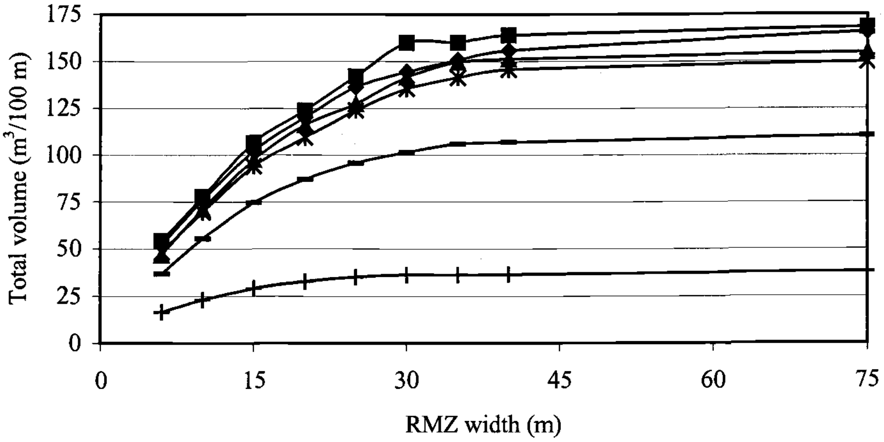


Figure 4.6. Total volume associated with the channel by RMZ widths expressed as a percent of the standing stock from the non-harvested, 75-m forest simulation. Symbols represent RMZ widths of 6-m (−), 10-m (▲), 15-m (■), 20-m (◆), 25-m (∗), 30-m (○), 35-m (△), and 40-m (□).

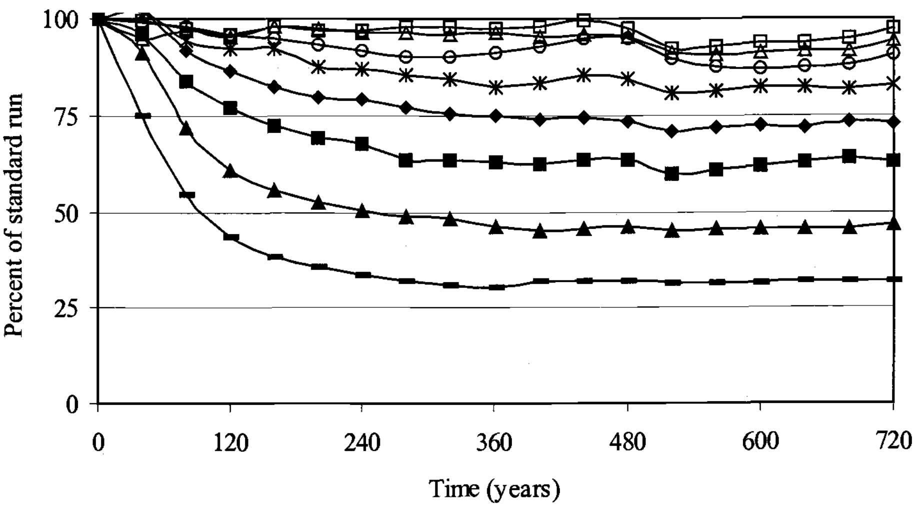


Figure 4.7. Total wood volume from the 6-m RMZ with plantation forests. Symbols represent 6-m RMZ (▬), and 75-m RMZ (+) compared to 6-m RMZ with plantation forests harvested at rotation ages of 60-yr (▲), 90-yr (■), and 120-yr (◆).

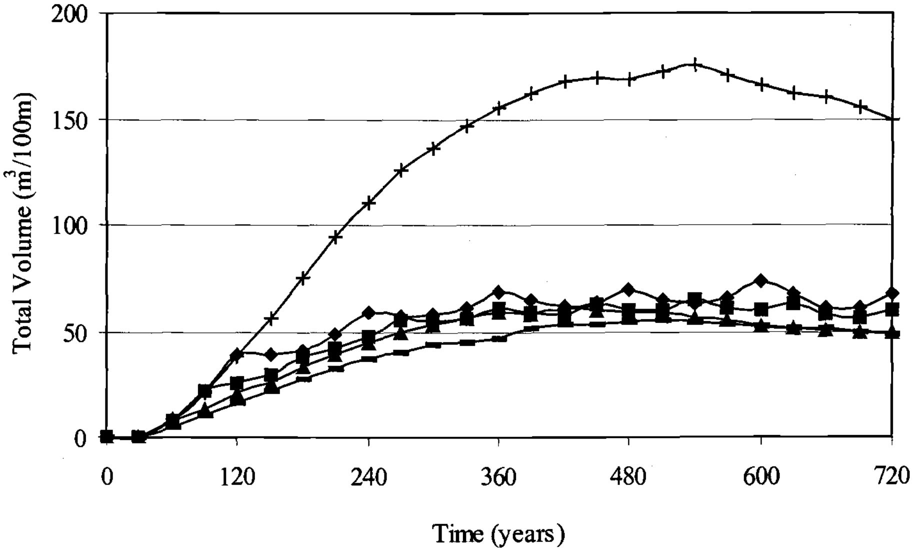
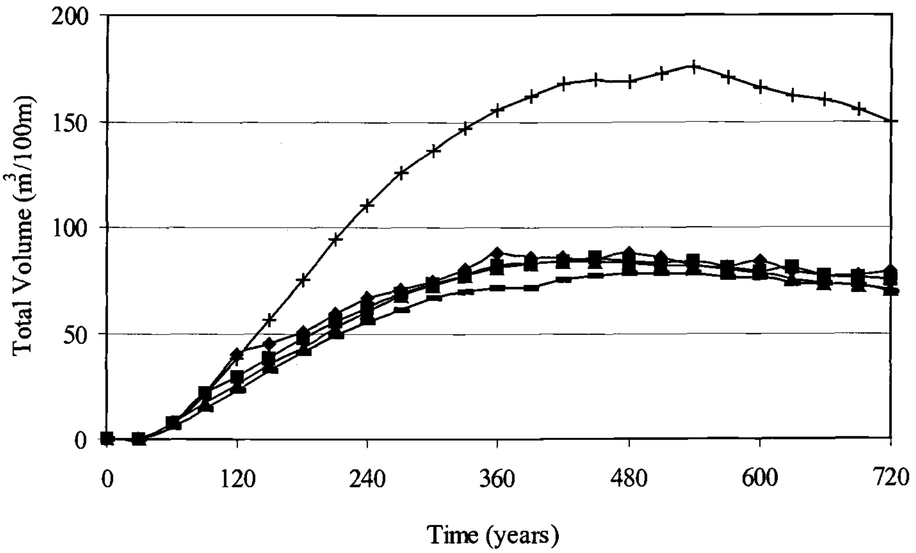


Figure 4.8. Total wood volume from the 10-m RMZ with plantation forests. Symbols represent 10-m RMZ (▬), and 75-m RMZ (+) compared to 10-m RMZ with plantation forests harvested at rotation ages of 60-yr (▲), 90-yr (■), and 120-yr (◆).



13, 14, and 22 m^3/100 m of stream length for the 60, 90, and 120 yr rotations. With buffer widths ≥10 m, contribution from the harvested portion of the riparian forest was minimal, indicating that total wood volume was limited more by tree height than distance to the stream bank (Figure 4.8). These results suggest that for rotation ages up to 120 years, plantation forests have very little influence on standing stock associated with the channel if the non-harvested buffer are at least 10 m wide.

4.4.5 Limitations of the Study

The goal of these simulations was to compare consequences of various riparian management strategies for long-term recruitment of wood to streams. All non-harvested forests were identical in structure and species composition (Figure 4.1) and differed only by RMZ width. Likewise, all forest plantations were identical even-aged stands of Douglas fir and differed only by rotation age (Figure 4.2). Plantation forests were not thinned because a variety of thinning prescriptions could be applied to each of the three rotation ages, which would result in a variety of recruitment rates from the plantation forests (Beechie, et al., 2000). Criteria used in these simulations included growth of plantation forests and non-harvested buffer forests that were equivalent in basal area for a given forest age (Figure 4.2).

Distribution and abundance of wood in a particular stream varies depending on the local conditions and history of disturbances (Harmon et al., 1986). Total volume in the standard simulation at year 500 was 65% of the observed volume (264 m^3/100 m of channel length) in a section of Mack Creek adjacent to a 500-yr old riparian forest in Cascade Mountains, Oregon. The underestimate in total volume may be due to the random tree fall regime and the entry breakage component used in the simulation. Preliminary analysis of the fall regime at Mack Creek suggests that tree fall may not be random, which would contribute substantially more wood to the channel. Tree entry and log breakage components in STREAMWOOD may also be a factor. Total volume in the simulations includes any log that intersects the channel. For example, the volume of a log 30 m long that is barely within the channel would be included in the total volume estimate. If this log breaks, only the piece that intersects the channel is included. Thus, the simulated total volume is directly related to the breakage rates, which may not be representative of a particular site.

Total wood volume was selected as the measure to compare in this analysis because it is less sensitive to the stochastic nature of in-channel processes. In these simulations, total wood volume is the standing stock of wood associated with the channel and is subjected to in-channel processes (breakage, movement, and decomposition) each time step. In STREAMWOOD, movement is a function of piece length, proportion of the log outside the channel, annual peak flow, and number of key pieces in the reach. For a given flow event, a greater proportion of in-channel volume moves than the total wood volume. The hypothetical stream system consisted of four identical reaches with identical riparian forest input rates and therefore, differences in volume among the reaches resulted from fluvial transport. Results were reported for the most downstream reach because volume into the reach from upstream sources equaled volume exported from the reach, which accounts for the influence of movement on volume.

Structure and relative species dominance in riparian forests of the Cascade Mountain, Oregon are highly variable (Kauffman, 1988; Naiman et al., 1998). The simulated riparian forests represented productive, conifer-dominated forests with very little recruitment of red alder in the early stages of development. Trees were assumed to fall the year they died and assumed to have an equal chance of falling in any direction.

These simulations did not take into account the influence of catastrophic events such as windthrow, fire, landslides, and debris flows on standing stock of wood associated with streams. Therefore, these simulations represent long-term potentials for a given buffer width and forest age, which may or may not be realized due to the unpredictability of major episodic events. Narrow buffers have been found to be extremely vulnerable to windthrow within the first decade of formation (Steinblums et al., 1984; Sherwood, 1993). The susceptibility to windthrow depends on the exposure of the site to the most damaging winds. For these simulations, the sites were assumed to be well protected from windthrow.

4.5 Summary and Conclusion

Riparian forest management goals in Pacific Northwest include the long-term supply of wood to the channel. In this report, long-term implications of selected riparian management strategies were explored with a computer simulation model. The model STREAMWOOD was used to predict the standing stock of wood in the channel through time and accounted for recruitment of wood from the riparian forest and from fluvial transport from upstream, and the influence of breakage, movement, and decay.
A maximum buffer width of 75-m was chosen to represent one potential tree height and therefore, maximum potential recruitment from the riparian forest. Plantation forests clearcut to the stream bank at rotation ages up to 120 yr provided only a fraction of the long-term potential of the site. For non-harvested forests, a buffer width of 6-m required forests of ages ≥240 years to provide approximately one-third of the long-term site potential. Buffer widths ≥30 m required approximately 500 years to provide 90% of the long-term potential of the site.

In the Pacific Northwest, riparian forest management plans must consider long-term supply of wood to streams. Simulation modeling provides a platform to examine standing stocks in streams over time scales associated with forest succession and development of Pacific Northwest forests. These results suggest that width of the non-harvested buffer and age of the forest are the most important factors associated with providing a long-term supplies of wood to streams. Plantation forests with rotation ages up to 120 yr, even in combination with a non-harvested buffer, can provide only a fraction of the long-term potential of the site.

4.6 Acknowledgments

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4.7 References

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5. SUMMARY

Recognition of the functional importance of wood in streams challenges managers and scientists to consider the long-term implications of riparian forest management on wood in streams. One way to investigate wood dynamics is through simulation modeling. Chapter Two presented an overview of the various components of wood dynamics in streams their representation in simulation models. Components of wood dynamics include input processes and in-channel processes. Input processes are associated with the riparian forest (e.g., windthrow, and bankcut) and with the upslope forests (e.g., mass failures). Recruitment varies with changes in forest structure, succession, and basin location. The majority of wood recruited to the stream is from the latter stages of forest development. Tree fall is associated with primary agents (windthrow, bank erosion, snow or ice loading) and secondary agents (insect and disease infestations and tree mortality from suppression and old age) that may interact to various degrees. In-channel processes include breakage, movement, burial, and decay. The types of breakage include fragmentation of standing trees, breakage from tree fall, and in-channel breakage of logs. Size class frequency distribution reflects the history of breakage events for a given population of logs. The most important factors associated with log movement are magnitude of stream flow and piece length relative to active channel width. The assumption that wood in a channel achieves a steady state condition provides useful information at a coarse level but is limited in simulating in-channel wood dynamics. An alternative approach is to consider wood dynamics in a spatiotemporal framework that accounts for basin position and environmental variation. The individual-based modeling approach may provide the most instructive framework to explore in-channel wood dynamics.

Chapter Three presented a description of the simulation model STREAMWOOD. STREAMWOOD was developed to investigate the dynamics of wood in stream systems ranging from a single reach to a small basin. STREAMWOOD is an individual-based stochastic model composed of two sub-models: a forest model and a wood model. The forest model is a simplified forest gap model that grows riparian forests under various management regimes. The wood model simulates recruitment of trees to the channel and subjects all logs associated with the stream to in-channel processes. Recruitment includes an entry breakage component, which produces logs that can be partially outside the channel. In-channel processes applied to each log include breakage, movement, and decomposition. The current version of STREAMWOOD was developed for coniferous-forested streams of the Pacific Northwest fifth-order and smaller. Species considered include Douglas fir, western hemlock, western red cedar, and red alder. A single parameter sensitivity analysis was conducted on each of the two submodels. Parameters effecting tree growth were found to be the most important in the forest model and decomposition was found to be the most important of the process tested in the wood model. A comparison was made between an observed and simulated data for wood in an old growth system. The length frequency distribution and total volume from the simulation was consistent with the observed data.

Chapter Four presented an application of the model STREAMWOOD. In the Pacific Northwest, riparian forest management plans must consider long-term supply of wood to the channel. The simulation model, STREAMWOOD was used to evaluate the effects of various riparian management scenarios on the standing stock of wood in the channel for a hypothetical stream in the Cascades Mountains, Oregon. Results of three simulation experiments were reported. In the first experiment, riparian management prescriptions were designed to assess the total wood volume (volume of all pieces intercepting the channel) from clearcutting to the stream bank using three rotation periods (60, 90, and 120 years). The results of these simulations suggested that without a non-harvested buffer, accumulation of wood in the channel was minimal and did not increase through time. In the second experiment, total wood volume was associated with non-harvest forests of widths between 6 m and 75 m. Total wood volume associated with the 6-m buffer accounted for 32% of the standing stock associated with a 75-m wide forest. A buffer width of 30-m provided approximately 90% of the standing stock simulated for the 75-m non-harvested forest. In the third experiment, total wood volume associated with a riparian forest that included both a non-harvested forest and a forest plantation was explored. Forest plantations associated with buffer width >10-m were found to have no effect on the volume of wood associated with the channel. These results suggest that width of the non-harvested buffer was more important than the rotation age of plantation forests in providing long-term supplies of wood to the streams.

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