American Fisheries Society Symposium 37:315–335, 2003

Modeling the Dynamics of Wood in Streams and Rivers

STAN V. GREGORY
Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97331-3803, USA

MARK A. MELEASON
National Institute of Water & Atmospheric Research, P.O. Box 11115, Hamilton, New Zealand

DANIEL J. SOBOTA
Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97331-3803, USA

Abstract.—Extensive research over the last 30 years has documented the abundance and ecological functions of wood in streams and rivers. Most studies have focused on amounts and distributions of wood in streams, and a small number of studies have explored critical processes that determine quantities and patterns of wood in streams—riparian tree mortality, input, breakage, decomposition, mechanical breakdown, and transport. Empirical studies describe the outcomes of the stand dynamics, disturbance history, and human management at a site, but questions about long-term dynamics or landscape patterns and distributions are difficult to answer based on empirical observation alone. General properties of simulation models that have been developed recently to explore long-term or large-scale implications of wood dynamics are reviewed. Most existing models are not stochastic, and those that incorporate variation and unpredictable change do not incorporate interactions between processes. Models consistently indicate that forest age directly influences abundance of wood in streams, and sensitivity analysis demonstrates that most models of wood dynamics are most sensitive to estimates of decomposition rates and rates of input.

Introduction

Research since the early 1970s has documented the abundance, distribution, and ecological functions of wood in streams and rivers. Most studies have focused on amounts and distributions of wood in streams, and a small number of studies have explored critical processes that determine quantities and patterns of wood in streams—riparian tree mortality, input, breakage, decomposition, mechanical breakdown, and transport. Outcomes of stand dynamics, disturbance history, and human management at a site may be described by empirical studies, but questions about either long-term dynamics at time periods of multiple generations of trees or humans or broad landscape patterns at spatial extents of thousands of square kilometers are difficult to answer based on empirical observation.

Dynamics of wood in streams and rivers of the world reflect complex landscape processes that differ by geographic region, time interval, hydrologic regime, basin geology, channel form, network structure, forest composition, disturbance processes, and human influence. Modeling provides a major tool for integrating results of short-term empirical observations and exploring the implications of alternative management practices and long-term disturbance patterns. This chapter will describe the properties of simulation models that have been developed in recent years to explore long-term or large-scale implications of wood dynamics. We will compare approaches for modeling wood and discuss the implications of these approaches for investigating the dynamics of wood. Major contributions of modeling for understanding the dynamics of wood in world rivers are illustrated for several key characteristics of wood and ecological processes.

What is a model? Haefner (1996) defined a model simply as ". . . a description of a system. A system is any collection of interrelated objects. An object is some elemental unit upon which observations can be made, but whose internal structure either does not exist or is ignored." Such descriptions of systems are abstract representations developed by and interpreted by humans. Models can be conceptual, diagrammatic, physical, or formal mathematical models (Haefner 1996). All of the models reviewed in this chapter are formal mathematical models that were developed from conceptual descriptions of selected processes of wood dynamics. Mathematical models can be classified further as (1) mechanistic or descriptive, (2) dynamic or static, (3) continuous or discrete, (4) spatially heterogeneous or homogeneous, or (5) stochastic or deterministic (Haefner 1996).

Evaluation of models must consider the fundamental properties of model performance—realism, precision, generality (Levins 1966)—and relate these properties to the intended use of the model. Models generally are used for understanding, prediction, and control or management (Karplus 1977). Models of wood in streams and rivers have been used largely to (1) understand the processes that shape the abundance and distribution of wood at local sites or along river networks and their interactions, or (2) predict the abundance and distribution of wood that would result from different types of riparian forests or landscape dynamics as a basis for management decisions. A model developed for understanding fundamental ecological processes requires generality and realism, with less demand for precision (Haefner 1996). On the other hand, a wood model developed to predict amounts of wood in specific stream reaches requires precision and reality, but does not require generality if the model has been developed from local observations and quantitative information.

Simple mathematical relationships, such as negative exponential decay rates, directionality of tree fall, and negative exponential rates of log transport, are simple forms of models. Many studies have identified quantitative relationships between a small number of independent variables and a wood response. In this chapter, we will consider both these simple models as well as their applications in more complex, integrated models of wood dynamics.

History of Wood Models

Over the last two decades, 14 models of wood dynamics in streams and rivers have been developed for different processes, purposes, and regions (Rainville et al. 1986; Murphy and Koski 1989; Van Sickle and Gregory 1990; McDade et al. 1992; Malanson and Kupfer 1993; Minor 1997; Benda and Sias 1998, 2003; Kennard et al. 1999; Bragg 2000; Beechie et al. 2000; Downs and Simon 2001; Fleece 2002; Meleason et al. 2002, in press; Welty et al. 2002; Table 1). We will present a history of wood model development and briefly describe the general characteristics of each model.

Of the 14 models of wood dynamics in streams and rivers, 11 have been developed in the Pacific Northwest (Rainville et al. 1986; Murphy and Koski 1989; Van Sickle and Gregory 1990; McDade et al. 1992; Minor 1997; Kennard et al. 1999; Bragg 2000; Beechie et al. 2000; Fleece 2002; Meleason et al. 2002, in press; Welty et al. 2002; Benda and Sias 2003), two for the midwest region of North America (Malanson and Kupfer 1993; Downs and Simon 2001), and one for the Rocky Mountain region of North America (Bragg 2000). The strong regional bias for the Pacific Northwest, in part, reflects the longer history of wood research in the region than in other parts of the world. The lack of wood models from other countries is surprising, but some of these models are being adapted for other countries and regions. For example, the model of Meleason et al. (in press) is being parameterized for New Zealand forests through the National Institute of Water and Atmospheric Research (NIWA).

The earliest wood models were designed to simulate the delivery of wood to streams from adjacent riparian forests (Rainville et al. 1986; Van Sickle and Gregory 1990; Malanson and Kupfer 1993; Minor 1997). Murphy and Koski (1989) approximated input rates and depletion rates by measuring standing stock and age of wood (from nurse trees) and assuming that wood volume was at steady state (that is, inputs equal outputs). Recent models have attempted to describe dynamics of wood by integrating input processes, retention, decomposition, and redistribution over either long time periods and/or large portions of river networks (Kennard et al. 1999; Beechie et al. 2000; Bragg 2000; Downs and Simon 2001; Meleason et al. 2002, in press; Welty et al. 2002; Benda and Sias 2003).

Most of the existing models are deterministic models that produce single estimates of outcomes with no variance (Table 1). Disturbance

Table 1. A. Comparison of published simulation models of wood dynamics.

Model characteristics	Rainville et al. 1985	Murphy and Koski 1989	McDade et al. 1990	Van Sickle and Gregory 1990	Malanson and Kupfer 1993	Minor 1997
<u>General model characteristic</u>						
Model type	deterministic	deterministic	deterministic	deterministic	stochastic	deterministic
Purpose/goal	recruitment; harvest	depletion rate	source distance	recruitment	carbon budget	source distance
Harvest schedule	thins at 25, 75 years	pre/post	none	none	none	no thinning
Multiple reach	no	no	no	no	no	no
Both riparian sides included	no	yes	no	yes	no	no
Time interval modeled	300 years	250 years	N/A	old growth	500 years	old growth
number of iterations	1	1	1	1	10	1
Time step	10 years	1 year	N/A	10 years	1 year	N/A
Results as number or volume	number of key pieces	number	number	number by length-class and fall angle	biomass	number of key pieces
Region	Idaho	SE Alaska	PNW	PNW	Iowa River	PNW
Species	TSHE, ABGR, ABLA	TSHE/PISI	TSHE/PSME/THPL	PSMA, TSHE	Iowa floodplain spp.	PNW species
Stream width						
<u>Riparian zone description</u>						
Width	90 ft	>30 m	60 m	user defined	27 m wide	60 ft
Length	variable	100 m	N/A	user defined	undefined length of river	variable
Subzone definition	10 ft	N/A	N/A	user defined	27 rows, 1 m wide	2 ft for first 40 ft, 40 to 60
<u>Stream wood definition</u>						
Minimum diameter	N/A	10 cm	10 cm	10 cm	N/A	6 in
Minimum length	N/A	3 m	1 m	1.5 m	0.5*tree ht	3 ft

TABLE 1. A. Continued.

Model characteristics	Rainville et al. 1985	Murphy and Koski 1989	McDade et al. 1990	Van Sickle and Gregory 1990	Malanson and Kupfer 1993	Minor 1997
Size categories	no	4 classes; 10 cm - <90 cm		length: 5-m classes	no	2″ tree diameter classes; 12–52 in
Key pieces only	yes	no	no	no	N/A	yes
Key piece definition	10 in, 8 ft	none	none	none	N/A	24-in mean diameter, 33 ft
Riparian forest						
Dead tree size categories	6 diameter classes	N/A	N/A	height: 10-m classes	no	2″ tree diameter classes; 12–52 in
Type of forest model	growth and yield (Prognosis)	none	N/A	stand table	Gap model (FORFLO)	stand table
Sapling recruitment	no	no	N/A	no	yes	N/A
Growth included	yes	no	N/A	no	yes	N/A
Types of mortality	tree fall	tree fall; bank erosion	tree fall	tree fall	tree fall, bank erosion	tree fall
Bank undercut	first 6 ft, 20% per decade	yes	no	no	within 1 m, 70% chance	no
Tree position	center subzone	N/A	center subzone	center subzone	center subzone	center subzone
Entry						
Fall along subzone midpoint	yes	N/A	yes	yes	yes	yes
Entry Pi/360 * N	yes	N/A	yes	yes	yes	yes
Entry breakage	no	N/A	no	banks	no	banks
Fall regime	random	N/A	random	random or	random	random or
Entry mechanism	vol mort converted to cnt/dcat, then dom ht used cal	used 1/age for dcat as recruitment rate = depletion rate	same as VanSickle and Gregory	Ps = arcInt/360; vary fall angle by 5-deg interval, mean L from ht, dist cat	same as VanSickle and Gregory	same as VanSickle and Gregory, except for a function of slope in Ps

Table 1. A. *Continued.*

Model characteristics	Rainville et al. 1985	Murphy and Koski 1989	McDade et al. 1990	Van Sickle and Gregory 1990	Malanson and Kupfer 1993	Minor 1997
Instream breakage	no	N/A	no	no	no	no
Instream movement	no	in = out	no	in = out	no, but move off floodplain	no
Decomposition	no	depletion rate	no	no	terrestrial, not aquatic	no
Field data comparison	no	no	no	yes	yes	no
Sensitivity analysis	no	no	no	no	yes	no

Table 1. B. Comparison of published simulation models of wood dynamics. Note that Beechie et al. 2000 is fundamentally the same wood model as Kennard et al. (1999) and Welty et al. (2002).

Model characteristics	Beechie et al. 2000*	Bragg 2000	Downs and Simon 2001	Benda and Sias 1998, 2003	Meleason et al. 2003, in press	Welty et al. 2002
General model characteristic						
Model type	deterministic	stochastic	deterministic	deterministic	stochastic	deterministic
Purpose/goal	recruitment; pool formation	recruitment: individual and catastrophic mortality	recruitment from channel meandering	Recruitment; mass failure and debris flows	recruitment	recruitment, shade
Harvest schedule	thinning is user defined	clearcut	none	none	thinning is user defined	thinning is user defined
Multiple reach	no	no	no	yes	yes	no
Both riparian sides included	yes	yes	yes	yes	yes	yes
Time interval modeled	150 years	300 years	NA	800–1,800 years	500 years	240 years
number of iterations	1	20	1	1	500	1
Time step	10 years	10 years	10 years	10 years	10 years	10 years

Table 1. B. Continued.

Model characteristics	Beechie et al. 2000*	Bragg 2000	Downs and Simon 2001	Benda and Sias 2003	Meleason et al. in press	Welty et al. 2002
Results as number or volume	number, (volume), pools	number and volume	number and volume	number and volume	number and volume	number and volume
Region	PNW	Rocky Mountain	Mississippi, USA	PNW	PNW	PNW
Species	PSME/TSHE/ ALRU/ACMA	PIEN,ABLA, PICO	midwest deciduous spp.	PNW spp	PSME/THPL/ TSHE/ALRU	PSME/TSHE/ ALRU/ACMA
Stream width	5–30 m	user defined	6–20 m	user defined	user defined	user defined
<u>Riparian zone description</u>						
Width	ht. of tallest tree	user defined	10 m	undefined	100 m	user defined
Length	user defined	30.5 m	50 m	100 m	user defined	user defined
Subzone definition	cites Van Sickle and Gregory	9 rows, user defined	no	no	5 rows, user defined	2–4 rows
<u>Stream wood definition</u>						
Minimum diameter	function of BFW	10 cm	5 cm	10 cm	10 cm	10 cm
Minimum length	function of BFW	1 m		2 m	1 m	1 m
Size categories	2: small and pool forming	1–20 classes			user defined	user defined
Key pieces only	yes	both	no	no	both	both
Key piece definition	Dmin = 2.5*BFW	user defined	>0.25 m dbh		length = channel width	user defined
<u>Riparian forest</u>						
Dead tree size categories	N/A	N/A	5-cm intervals	N/A	N/A	N/A
Type of forest model	growth & yield; ORGANON	growth & yield	none	none	gap (modified Zelig)	growth & yield; ORGANON
Sapling recruitment	yes	yes	no	N/A	yes	yes
Growth included	yes	yes	no	N/A	yes	yes
Types of mortality	tree fall	tree fall, catastrophic	meander	tree fall, bank undercut	tree fall	tree fall
Bank undercut	no	no	yes	yes	no	no

Table 1. B. Continued.

Model characteristics	Beechie et al. 2000*	Bragg 2000	Downs and Simon 2001	Benda and Sias 2003	Meleason et al. in press	Welty et al. 2002
Tree position	center subzone	center subzone	N/A	N/A	center subzone or defined location	center subzone
Entry						
Fall along subzone midpoint	yes	yes	no	no	yes	yes
Entry Pi/360 * N	yes	no	no	yes	user defined	yes
Entry breakage	banks	yes	no	modified entry	yes	user defined, 2 pieces
Fall regime	random	directional	random	random	user defined	random or "fall bias factor"
Entry mechanism	cites Van Sickle and Gregory	tree fall	knickpoint migration	tree fall, undercutting, mass failure	same as Van Sickle and Gregory with functions for slope	tree fall
Instream breakage	no	yes	no	no	yes	no
Instream movement	no input; output is depletion	constant attrition of volume	no	yes	yes	overall depletion; user defined
Decomposition	number: depletion rate	constant attrition of volume	no	depletion rate	decay rates until piece smaller than minimum	overall depletion; user defined
Field data comparison	yes	yes	yes	no	yes	yes
Sensitivity analysis	no	yes	no	incremental	yes	yes

processes in most wood models are simulated based on fixed scenarios of long-term disturbance events. In contrast, three models are stochastic models based on probabilities of selected wood processes and rates of processes. One of these three stochastic models (Bragg 2000) is predominantly deterministic because only the processes of snag creation and fall are stochastic. The stochastic models provide both mean outcomes and the variance associated with those outcomes. These stochastic models allow analysis of both the central tendencies or means as well as the influence of stochastic factors on variance in wood dynamics. Even projections of wood dynamics and spatial and temporal variation from stochastic models are limited by the assumptions about statistical distributions of the probability functions (such as normal, lognormal, exponential, binomial) used for specific processes or rates.

All models of wood dynamics in streams and rivers must represent the adjacent riparian forests and the delivery of wood to the channel. Some models maintain a fixed riparian composition and delivery of a fixed proportion of the stand through time. These models clearly are simplistic representations of riparian forests. Stand dynamics models that represent regeneration, growth, and mortality of riparian forests are important elements of most existing wood models. Such models either operate externally or are embedded as a major component within a wood dynamics model. Stand dynamics models that have been used with existing models of wood dynamics include ORGANON (Hester et al. 1989), Forest Vegetation Simulator (Wykoff et al. 1982), ZELIG (Shugart and West 1977), and versions of forest gap models (Botkin 1993). These forest dynamics models are developed for specific tree species and ranges of stand ages, but most stand dynamics models have been developed for upland forests rather than riparian forests.

Several fundamental wood processes are represented only in one or two models. Most models are based primarily on delivery of wood from adjacent stands. Delivery from adjacent riparian forests generally is modeled as direct mortality and fall, windthrow, bank undercutting, or an overall composite mortality of all of these sources. Two models from the Midwest, USA (Malanson and Kupfer 1993; Downs and Simon 2001) simulate channel avulsion and bank erosion in rivers. Only one model (Benda and Sias 1998, 2003) from the Pacific Northwest simulates wood delivery through landslides and mass failure. Although one of the early models (Van Sickle and Gregory 1990) concluded that numbers of wood pieces are underestimated if a model does not account for breakage, only one model (STREAMWOOD, Meleason et al. 2002, in press) simulates the breakage of trees as they fall into streams and breakage of wood as it is subsequently transported. Bragg (2000) combines breakage during tree fall and breakage during storage and transport into a single breakage function. Most models also combine the processes of decomposition, breakage, and export into an overall depletion estimate, but these processes are explicitly represented only in STREAMWOOD.

Rainville model

In the mid-1980s, the first model of wood dynamics in streams was developed by Rainville and coauthors and was published in the proceedings of a conference of the Society for American Foresters (Rainville et al. 1986). The Rainville model is a deterministic model of wood input into a stream reach based on riparian forest stand conditions within 30 m of the stream. Wood enters the channel as a result of tree mortality in the stand (individual tree death) and bank undercutting, based on a table of probabilities as a function of tree size and distance from the stream. Tree fall angle is random, and trees do not break when they fall into streams. The model does not estimate or include standing stocks of wood, decomposition, or instream movement. Stand thinning and harvest intensity are evaluated as a riparian management practice. This model was the first attempt to (1) use a stand dynamics model for a forest to simulate the delivery of wood to stream channels, and (2) use modeling as a tool to evaluate the consequences of land-use practices on the delivery of wood to stream ecosystems.

Murphy and Koski model

A simple model of wood input, decomposition, and output was developed for streams in southeast Alaska (Murphy and Koski 1989). The model is based partly on empirical information and partly on assumptions of input and output. Volumes of wood were measured in Alaskan streams, and the ages of nurse trees on wood in the streams were estimated. Based on the assumption that wood volume is at steady state (inputs = outputs), the depletion rate can be estimated by dividing the standing crop by the average age of wood in the stream. This model was the first to estimate standing stock of wood in streams and incorporate a function for depletion through decay, breakage, and transport.

Van Sickle and Gregory model

Van Sickle and Gregory (1990) published a simple model of wood delivery into stream reaches from adjacent riparian forests. This model is a deterministic model based on the probability of fall and the geometric basis for the tree to intersect the stream channel as a function of tree height, distance from the channel, and fall direction. The model was evaluated by comparing simulations with data on wood characteristics in a stream in an old-growth forest.

The model concluded that simulations of wood volumes were relatively consistent with field observations, but estimates of numbers of pieces of wood delivered were underestimated if fall breakage was not included in the model. The model also identified the potential importance of directionality of fall. If tree and snag fall is not random and totally directed toward the channel, estimates of wood volume delivered are threefold greater than a model with random fall direction.

McDade model

McDade et al. (1990) measured the distance from the stream to the point on the hillslope where in-channel wood originated in streams of the Pacific Northwest. These measurements were integrated with the Van Sickle and Gregory delivery model to create a simple deterministic model of wood delivery and source distance.

This simple model was the first to identify the lateral riparian distance required to deliver specific proportions of total wood inputs to streams (for example, 85% of wood delivered from old-growth coniferous forest is located within 30 m of the channel) and to distinguish the behavior of deciduous and coniferous riparian forests (for example, 90% of total wood was delivered within 25 m for mature deciduous forests, 48 m for mature coniferous forests, and 55 m for old-growth coniferous forests).

Malanson and Kupfer model

Most models of wood dynamics have been developed for streams in the Pacific Northwest region of North America, but Malanson and Kupfer (1993) developed a stochastic model of wood delivery into large rivers of the Midwest region of North America. This also was the first model to incorporate bank erosion and channel avulsion in large rivers, which are physical processes that have received little attention in research and modeling (Piégay and Gurnell 1997). This unique application incorporates models of (1) bank erosion and channel avulsion developed for the Iowa River, and (2) dynamic floodplain forest regeneration (FORFLO). The model also represents movement of wood out of the floodplain forest and into the river. Decomposition is not modeled for wood in the river, but terrestrial wood on the floodplain decays prior to lateral transport.

This model is distinctive because it was the first stochastic model of large wood dynamics, and it was the first model of wood dynamics related to channel avulsion and floodplains in large rivers.

Minor model

A simple model of key piece delivery was developed by Minor (1997) to estimate the delivery of key pieces (>24-in diameter) from a 60-ft wide riparian zone to a single stream reach. Tree distributions and sizes are derived from fixed stand tables for composition, size, and location. Fundamentally, the model relates the number of trees delivered to the stream to the overall stand mortality rate, fall directionality, and the influence of slope on directionality.

The model illustrated the potential influence of directionality and influence of slope on wood loading into streams (empirical data on the relationships were not reported).

Riparian-in-a-Box model

A deterministic model for predicting the effects of timber harvest on wood delivery from riparian forests was developed by researchers at the University of Washington in cooperation with scientists from the Weyerhaeuser Corporation (Beechie et al. 2000; also reported in Kennard et al. 1999). Riparian-in-a-Box is a deterministic model of key piece delivery from managed riparian stands over as long as 150 years at decadal time steps and incorporates thinning and harvest. Riparian forests develop through time based on a growth and yield model. Length of wood delivered to the stream is represented in the model as a function of bank-full width, and key pieces are defined as 2.5 times bank-full width. This model also simulates pool formation in stream channels based on relationships between the relative size of wood and the dimensions of the stream channel.

Bragg model

The second major stochastic wood model was developed by Bragg (2000) for conifer stands in Wyoming. The Bragg model simulates the input, storage, and depletion of large wood from pine and fir forests of the Rocky Mountain region, expressed as means and variance of both numbers and volumes of wood. The model has the capacity to represent either scheduled timber harvest or catastrophic mortality events over 300-year periods. Wood in the channel is depleted as a result of decay, transport, and mechanical losses. This is one of the most complete representations for the ecological processes of riparian stand dynamics and instream processes related to wood dynamics.

The Bragg model was the first stochastic model to integrate stand dynamics, wood delivery into streams, and in-channel processes (transport, decay, mechanical loss). It also extended the application of wood models to forest types of the Rocky Mountain region. It included comparison of model output with field observation and sensitivity analyses. In many respects, this was the first complete model of wood dynamics in streams.

Downs and Simons model

A second model that incorporates bank erosion and channel avulsion was developed by Downs and Simon (2001) for a small river, the Yalobusha River in central Mississippi, USA. Delivery of wood to the river was modeled based on estimates of numbers, sizes, and volumes of trees in riparian forests along the banks and a civil engineering model of bank stability and knick-point migration. This channel evolution model was based on earlier models of channel formation phases or stages (Simon 1989; Hupp and Simon 1991) and included analysis of shear strength and bank stability (factor of safety analysis for current and future conditions). This deterministic model estimated future top width, calculated channel widening to stable bank angle, and used empirical knickpoint migration rates to calculate the number of trees and volume of wood recruited/m length. Field measurements of riparian forests were used to estimate the recruitment of large wood through bank erosion. Potential to trap wood was assessed on the basis of tree length to channel width and angle relative to flow.

The model results indicated that overall channel-formation processes may influence the outcome of wood delivery processes from streambank erosion. This model complements the Malanson and Kupfer model and demonstrates approaches for modeling wood that incorporate both the geomorphic processes that modify floodplains and riverbanks in large rivers and the characteristics of floodplain forests.

RAIS model

Models of wood delivery and riparian shading were combined in a deterministic model called Riparian Aquatic Interface Simulator (RAIS; Welty et al. 2002). Riparian stand dynamics are modeled with ORGANON, a growth and yield model for Douglas-fir that was adapted for western hemlock, red alder, and bigleaf maple. The model allows the user to define the thinning prescriptions and harvest rotations. Wood is delivered to the channel as a result of tree mortality based on the wood delivery model developed by Beechie et al. (2000) and Kennard et al. (1999).

This model is an extension of the Beechie model, coupled with a stand growth and yield model, for evaluating alternatives for riparian forest management. It allows the user to modify thinning and harvest approaches to assess the potential outcomes for large wood and shade in streams. This model also was the first wood model to be available to be downloaded from the Internet at http://www.weyerhaeuser.com/rais.asp.

Benda and Sias model

Landslides and mass failures are major sources of wood recruitment in steep, highly erosive landscapes. While most wood models acknowledge these sources of input, few incorporate these processes explicitly in the model. Benda and Sias (1998, 2003) developed a deterministic model of wood loading potential and transport in coastal streams of the Pacific Northwest that incorporates landslides, mass failures, and bank undercutting, as well as windthrow and adjacent stand mortality.

The Benda and Sias model was the first model of wood dynamics that explicitly modeled delivery of wood to streams through the geomorphic processes of mass failure and local bank undercutting in steep mountain streams. This model of montane streams complements the models of wood delivery through channel erosion in lowlands developed in the Midwest, USA (Malanson and Kupfer 1993; Downs and Simon 2001). The model also was the first to readily simulate wood loading for multiple stream reaches throughout a river network.

STREAMWOOD model

STREAMWOOD is a stochastic model that simulates wood dynamics in streams and riparian forests (Meleason et al. 2002, in press). Wood inputs, storage, and transport can be simulated for either single reaches or multiple reaches in a stream network. A forest gap model (modified Zelig model) is used to simulate tree regeneration, growth, and mortality and subsequently deliver wood from live trees and snags in adjacent riparian forests. Individual trees in the stand (four conifer species, alder, and a user-defined species) are modeled. A Monte Carlo procedure generates hundreds to thousands of simulations for each model scènario, estimating mean responses and variances. The model simulates delivery of trees into the channel and breakage as trees fall, based on either random or directional fall direction. Recent empirical observations of fall direction indicate that riparian trees are more likely to fall towards the stream channel (Sobota 2003); fall direction is not affected by hillslope steepness, but variance decreases with increasing slope. Individual logs in the stream are modified through time by breakage, movement, and decomposition.

STREAMWOOD is unique because it is stochastic; models both conifer and deciduous tree species; operates at single or multiple stream reaches; and includes probability functions for fall breakage, directionality of fall, in-channel breakage, transport, and decomposition. Recent research by this group also provides empirical data on directionality of fall for riparian forests in the Pacific Northwest and Intermountain regions, USA (Sobota 2003). STREAMWOOD can be downloaded from the Internet at http://www.fsl.orst.edu/lter/data/tools/models/streamwood.cfm.

Fleece model

Low-level remote sensing of riparian vegetation was used to predict wood inputs into streams within a 28-km² study area in the Pacific Northwest (Fleece 2002). Height and composition of riparian vegetation were estimated from Light Detection and Ranging (LIDAR) data, which detects reflectance of 0.5-m laser pulses spaced less than 6 m apart across a 4,500-m scan width. LIDAR data provide estimates of ground elevation, slope, tree height, and vegetative cover type. Wood delivery was based on the tree density, probability of falling into a stream, and the rate of tree fall (determined from mortality estimates from ORGANON growth and yield model).

Remotely sensed estimates of riparian forest density, composition, or volume can be utilized by most wood dynamics models. This simple application of tree density, fall rate, and delivery into stream channels illustrates the application of wood delivery models at larger spatial extents than single reaches and the use of remotely sensed forest cover information. The predicted rate of wood delivery into streams within this study area was within the range observed for streams in the H. J. Andrews Experimental Forest in Oregon, and the recruitment distance was similar to field observations in the region.

Major Results from Models of Wood Dynamics in Streams and Rivers

Models provide a method for exploring the implications of our current understanding of wood dynamics. The following section describes recent applications of models to explore long-term trends and spatial patterns of inputs and storage of wood in streams and rivers.

Influence of forest age on wood in streams

Models of wood dynamics have proved to be one of the most valuable tools for exploring the influence of riparian forest age on rates of delivery of wood to streams and rivers and its subsequent storage in the channels. Empirical field studies of wood abundance commonly are compromised by differences between research sites in terms of disturbance histories, human modification of the site, channel characteristics, basin characteristics, forest composition, and climate. One of the first applications of simulation models of wood dynamics was to project rates of wood input or wood storage through time. All simulation models to date have indicated that maximum rates or input or storage of wood in channels are attained 150–200 years after stand replacement by harvest or disturbance, depending on the dominant forest species. The first wood model (Rainville et al. 1986) was developed to explore the effects of riparian thinning on temporal patterns of wood recruitment to streams. In thinned stands, the mortality rate of riparian trees reached its maximum after 110–150 years, but the maximum recruitment of wood in terms of numbers of trees per distance along the stream channel was not attained until 150–180 years. Subsequent models for the Pacific Northwest (Beechie et al. 2000; Meleason et al. 2002, in press) and the Intermountain region of western North America (Bragg and Kershner 1997; Bragg 2000) also projected maximum rates of wood recruitment and storage after 150 years. These models also provide a basis for comparing temporal patterns of wood recruitment in natural riparian forests and in harvested riparian forests (Figure 1). These model results demonstrate that land use practices that decrease the age of riparian forests will ultimately lead to reduced numbers and volumes of wood in streams and rivers.

Source area for wood

One of the most important ecological questions about riparian dynamics in the late 20th century was "What distance into an adjacent riparian forest is required to deliver large wood to streams?" Field observations of down wood in riparian areas provided initial estimates (McDade 1987; Murphy and Koski 1989; Minor 1997). A simple model was developed based on empirical data to provide linear relationships of the cumulative wood recruitment as a function of lateral distance from the stream channel for different types of riparian forests (McDade et al. 1992). Because of the smaller height of deciduous trees, wood recruitment occurs within a more narrow zone adjacent to the stream in deciduous forests. For example, 90% of total wood was delivered within 25 m for mature deciduous forests, but 48 m was required in mature coniferous forests to provide an equivalent proportion of total wood loading, and 55 m was required for old-growth coniferous forests. In second-growth coniferous riparian forests in the Oregon Coast Range, 70–84% of the total instream wood was recruited from within 15 m (Minor 1997). Field studies and simulation modeling of western Washington riparian forests found that 90% of the wood loading occurred within 20 m of the stream channel (Welty et al. 2002). Empirical field studies in Alaska found that shorter distances were required to deliver equivalent proportions of wood (Murphy and Koski 1989). In these Alaskan streams, 95% of the wood in the channel was derived from trees within 20 m of the stream, and 99% of the wood loading occurred within 30 m. These studies illustrate the importance of forest composition for wood recruitment and the utility of wood models for exploring wood dynamics in different regions.

Source processes for wood

Researchers around the world have independently identified several major processes that deliver wood to streams and rivers—simple tree fall, snag fall, windthrow, bank undercutting, landslides, sediment debris flows, bank and floodplain avulsion (Harmon et al. 1986; McDade et al. 1992; Malanson and Kupfer 1993; Piégay and Gurnell 1999; Piégay et al. 1999; Benda et al. 2002, in press). Field studies in several regions have evaluated the relative magnitude of different processes that deliver wood to streams and rivers. Models provide a tool for exploring mechanisms for wood delivery and the implications for patterns of wood storage along river networks. All of the wood models described previously include a representation of recruitment of wood laterally from adjacent stands (such as tree fall, snag fall, windthrow, bank undercutting). Benda and Sias (1998, 2003) developed a model that incorporates delivery of wood from mass failures (such as landslides, sediment debris flows, hillslope slumping, and gradual mass failure). Two models simulate avulsion of floodplains and riverbanks and the subsequent delivery of wood into lowland rivers (Malanson and Kupfer 1993; Downs and Simon 2001). Malanson and Kupfer (1993) estimated that lateral bank cutting could increase wood delivery to a Midwest river by 55%. Bank failure contributed 28.3 m^3 of wood/year in the Yolabusha River, Mississippi (Downs and Simon 2001).

Influence of forest type on wood in streams

Tree species exhibit important differences in growth, stature, mortality, and decomposition. Simulation models provide a powerful tool for examining the consequences of riparian forest

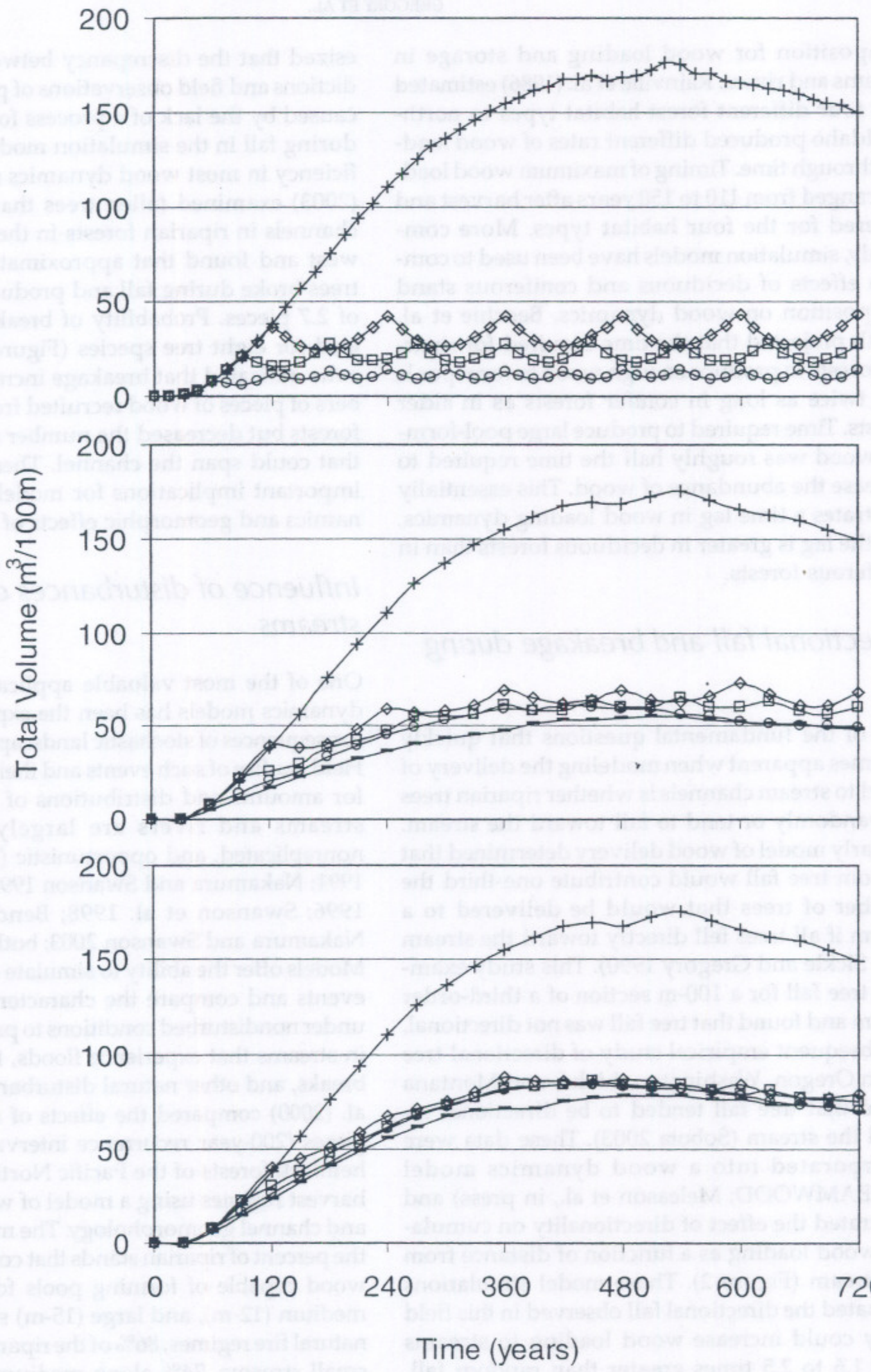

FIGURE 1. Total volume of wood stored in a stream channel through time from riparian management zone of different widths and rotation age as compared to a 75-m riparian area with no harvest over 720 years (from Meleason et al., in press). Riparian management widths are (A) 0 m, (B) 6 m, and (C) 10 m, and plantation forests are clear-cut at 60-year (○), 90-year (◇), and 120-year (□) intervals. (+ equals old-growth without harvest.) Total volume associated with the channel includes total volume of all logs intersecting at least one streambank.

composition for wood loading and storage in streams and rivers. Rainville et al. (1986) estimated that four different forest habitat types in northern Idaho produced different rates of wood loading through time. Timing of maximum wood loading ranged from 110 to 150 years after harvest and differed for the four habitat types. More commonly, simulation models have been used to compare effects of deciduous and coniferous stand composition on wood dynamics. Beechie et al. (2000) projected that the time required for riparian forests to produce enough wood to form pools was twice as long in conifer forests as in alder forests. Time required to produce large pool-forming wood was roughly half the time required to increase the abundance of wood. This essentially illustrates a time lag in wood loading dynamics, and the lag is greater in deciduous forests than in coniferous forests.

Directional fall and breakage during fall

One of the fundamental questions that quickly becomes apparent when modeling the delivery of wood to stream channels is whether riparian trees fall randomly or tend to fall toward the stream. An early model of wood delivery determined that random tree fall would contribute one-third the number of trees that would be delivered to a stream if all trees fell directly toward the stream (Van Sickle and Gregory 1990). This study examined tree fall for a 100-m section of a third-order stream and found that tree fall was not directional. A subsequent empirical study of directional tree fall in Oregon, Washington, Idaho, and Montana found that tree fall tended to be directional toward the stream (Sobota 2003). These data were incorporated into a wood dynamics model (STREAMWOOD; Meleason et al., in press) and illustrated the effect of directionality on cumulative wood loading as a function of distance from the stream (Figure 2). These model simulations estimated the directional fall observed in this field study could increase wood loading to streams from 1.6 to 2.5 times greater than random fall, depending on slope steepness.

The Van Sickle and Gregory (1990) model of wood delivery found that the model accurately predicted the orientations of pieces of large wood in a third-order Cascade Mountain stream (Oregon, USA), but it overestimated the lengths of wood pieces in the stream. The authors hypothesized that the discrepancy between model predictions and field observations of piece length was caused by the lack of a process for tree breakage during fall in the simulation model. This is a deficiency in most wood dynamics models. Sobota (2003) examined fallen trees that touch stream channels in riparian forests in the Pacific Northwest and found that approximately 40% of the trees broke during fall and produced an average of 2.7 pieces. Probability of breakage was modeled for eight tree species (Figure 3). Model results indicated that breakage increased the numbers of pieces of wood recruited from the riparian forests but decreased the number of wood pieces that could span the channel. These results have important implications for models of wood dynamics and geomorphic effects of wood.

Influence of disturbances on wood in streams

One of the most valuable applications of wood dynamics models has been the exploration of the consequences of stochastic landscape disturbances. Field studies of such events and their consequences for amounts and distributions of large wood in streams and rivers are largely descriptive, nonreplicated, and opportunistic (Lamberti et al. 1991; Nakamura and Swanson 1993; Reeves et al. 1996; Swanson et al. 1998; Benda et al. 2003; Nakamura and Swanson 2003; both this volume). Models offer the ability to simulate such stochastic events and compare the characteristics of wood under nondisturbed conditions to patterns of wood in streams that experience floods, fire, insect outbreaks, and other natural disturbances. Beechie et al. (2000) compared the effects of natural fire regimes (200-year recurrence intervals) in western hemlock forests of the Pacific Northwest to forest harvest regimes using a model of wood dynamics and channel geomorphology. The model projected the percent of riparian stands that contributed large wood capable of forming pools for small (4-m), medium (12-m), and large (15-m) streams. Under natural fire regimes, 86% of the riparian areas along small streams, 74% along medium streams, and 64% along large streams were capable of delivering pool-forming wood. Under 80-year harvest rotations, these percentages were reduced to 63%, 25%, and 0%, respectively. Under 60-year and 40-year rotations, riparian forests along medium and large streams did not contribute large pool-forming wood to the channels. In small streams, 50% of

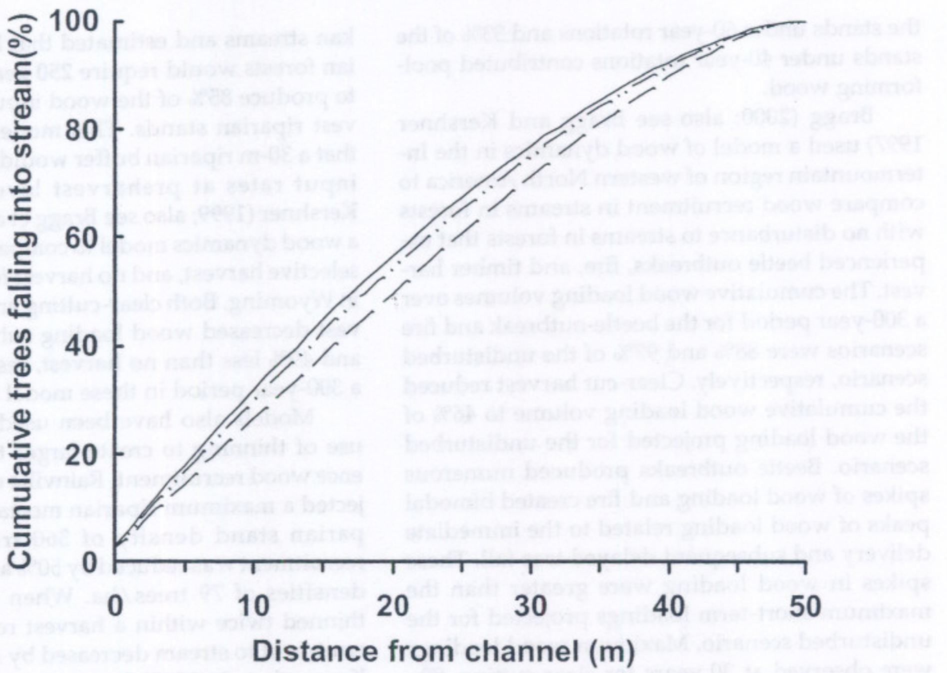

FIGURE 2. Cumulative delivery of falling trees as a function of distance from the channel for trees 50 m in height (Sobota 2003). Fall directions for each scenario were random: 1/360 chance to fall in any direction (——); side slopes 0–10%, direction toward stream, variance ± 80° (- - -); side slopes > 90%: direction toward stream, variance ± 40° (— —).

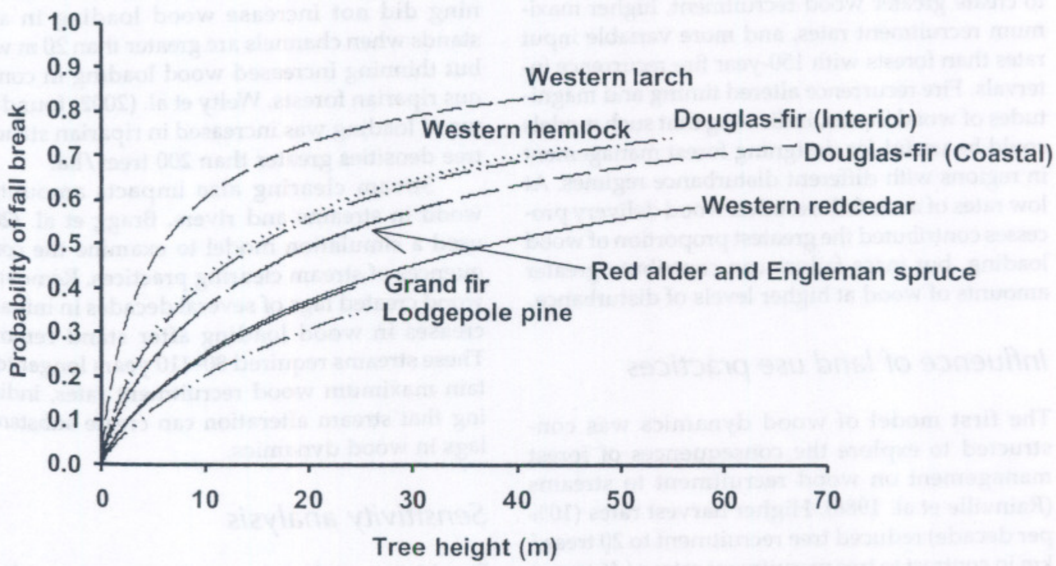

FIGURE 3. Model predictions of the probability that a riparian tree breaks on fall as a function of tree height with linear combinations of differences among species along study sites in the Pacific Northwest, USA (from Sobota 2003). Lines extend to maximum tree heights of each species observed in the study.

the stands under 60-year rotations and 33% of the stands under 40-year rotations contributed pool-forming wood.

Bragg (2000; also see Bragg and Kershner 1997) used a model of wood dynamics in the Intermountain region of western North America to compare wood recruitment in streams in forests with no disturbance to streams in forests that experienced beetle outbreaks, fire, and timber harvest. The cumulative wood loading volumes over a 300-year period for the beetle-outbreak and fire scenarios were 88% and 97% of the undisturbed scenario, respectively. Clear-cut harvest reduced the cumulative wood loading volume to 46% of the wood loading projected for the undisturbed scenario. Beetle outbreaks produced numerous spikes of wood loading and fire created bimodal peaks of wood loading related to the immediate delivery and subsequent delayed tree fall. These spikes in wood loading were greater than the maximum short-term loadings projected for the undisturbed scenario. Maximum wood loadings were observed at 30 years for clear-cutting, 80–150 years for beetle outbreaks and fire, and 250–300 years for undisturbed riparian forests.

A wood dynamics model that incorporated landslides and debris flows explored the consequences of fire cycles in coastal forests of the Pacific Northwest (Benda et al. 2002). Forests with 500-year fire recurrence intervals were projected to create greater wood recruitment, higher maximum recruitment rates, and more variable input rates than forests with 150-year fire recurrence intervals. Fire recurrence altered timing and magnitudes of wood inputs, indicating that such models could be useful for designing forest management in regions with different disturbance regimes. At low rates of mass failure, other wood delivery processes contributed the greatest proportion of wood loading, but mass failure can contribute greater amounts of wood at higher levels of disturbance.

Influence of land use practices

The first model of wood dynamics was constructed to explore the consequences of forest management on wood recruitment to streams (Rainville et al. 1986). Higher harvest rates (10% per decade) reduced tree recruitment to 20 trees/km in contrast to tree recruitment rates of 46 trees/km at lower harvest rates (3% per decade). Stand composition also affected the difference in wood loading between different harvest rates. Murphy and Koski (1989) modeled wood inputs for Alaskan streams and estimated that harvested riparian forests would require 250 years after harvest to produce 85% of the wood input of the preharvest riparian stands. This model also indicated that a 30-m riparian buffer would maintain wood input rates at preharvest levels. Bragg and Kershner (1999; also see Bragg et al. 2000) applied a wood dynamics model to compare clear-cutting, selective harvest, and no harvest for three streams in Wyoming. Both clear-cutting and selective harvest decreased wood loading substantially (77% and 49% less than no harvest, respectively) over a 300-year period in these model simulations.

Models also have been used to explore the use of thinning to create larger trees and influence wood recruitment. Rainville et al. (1986) projected a maximum riparian mortality rate at a riparian stand density of 360 trees/ha. Wood recruitment was reduced by 50% at riparian stand densities of 79 trees/ha. When the stand was thinned twice within a harvest rotation, tree recruitment to stream decreased by more than half. Kennard et al. (1999) found that small streams in thinned stands had less pool area than streams in nonthinned stands, but the opposite was true for large streams. They attributed this difference in channel response to the effect of thinning on creating large pieces of wood that were more effective in pool formation in larger streams than the smaller wood. Beechie et al. (2000) found that thinning did not increase wood loading in alder stands when channels are greater than 20 m wide, but thinning increased wood loading in coniferous riparian forests. Welty et al. (2002) found that wood loading was increased in riparian stands at tree densities greater than 200 trees/ha.

Stream clearing also impacts amounts of wood in streams and rivers. Bragg et al. (2000) used a simulation model to examine the consequences of stream clearing practices. Removal of wood created lags of several decades in initial increases in wood loading after stand removal. These streams required 80–110 years longer to attain maximum wood recruitment rates, indicating that stream alteration can create substantial lags in wood dynamics.

Sensitivity analysis

Sensitivity analysis is a valuable approach for understanding of the performance of models and the sensitivity of the model to specific relationships or interactions between functions within the model. Several researchers have explored the sensitivity of their models of wood dynamics, revealing commonalities that may be important for future research. Kennard et al. (1999) found that the Riparian-in-a-Box model was most sensitive to the quantitative representations of tree growth, mortality, and instream depletion. When depletion (that is, combined decay, breakage, and transport) was decreased from 15% to 5%, estimates of functional wood numbers increased by 100%. They also observed that relative outputs for different simulation scenarios were not as sensitive as absolute outputs. Benda and Sias (1998, 2003) found that their model was most sensitive to estimates of decay rates and bank erosion. Welty et al. (2002) observed that their model performance was most sensitive to depletions rates, stand composition, and tree densities. Meleason et al. (in press) conducted a simultaneous sensitivity analysis of multiple factors and found that the model was most sensitive to estimates of decay rates. All four models of wood dynamics that have evaluated the sensitivity of their models have concluded that the performance of the models is strongly influenced by the estimates of decay rates of wood or the estimates of overall depletion rates. If models continue to exhibit this sensitivity to estimates of instream decay or depletion, future research may provide more extensive and informative estimates of these processes and improve the performance of simulation models of wood dynamics in streams and rivers.

Development of Future Models of Wood Dynamics in Streams and Rivers

The last two decades have witnessed the development of our ability to represent complex dynamics of wood in streams and rivers over long temporal and spatial extents. Early pioneering attempts to develop models of wood processes (Rainville et al. 1986; Murphy and Koski 1989; Van Sickle and Gregory 1990; McDade et al. 1992; Malanson and Kupfer 1993) provided a basis for the development of more complex models that more fully represent the array of processes that determine the abundance and distribution of wood throughout stream and river networks. These models have allowed researchers to explore the implications of local short-term studies at specific study sites over long time frames (100–500 years) and across broad geographic extents (10–30,000 km^2). These models have provided critical information for land managers about the amounts of wood that would be expected in streams in late successional forests, the consequences of different forest composition, and the influences of geomorphic processes in streams and their basins. From the first model of wood dynamics to the present, these models have been used to evaluate the potential effects of timber harvest, thinning practices, riparian area management, stream clearing, channelization, and off-site practices, such as road development, bridge construction, and other land-use practices. The utility of models of wood dynamics in streams and rivers is clear, and several areas of research will contribute to more robust and easily applied models in the future.

As discussed earlier, models can be evaluated on their performance (realism, precision, generality) in relation to their intended uses (Levins 1966). Models of wood in streams and rivers have been used primarily to understand the processes that shape the abundance and distribution of wood and to predict the abundance and distribution of wood that would result from different management practices.

Models developed to understand fundamental ecological processes in streams and rivers will require generality and realism, with less demand for precision (Haefner 1996). Such models may require more explicit representation of basic geomorphic (channel erosion and deposition, mass failure, floodplain formation, and loss), hydrologic (flooding, drought, snowmelt, rain-on-snow events), or biological processes (tree growth and competition, tree mortality, snags, breakage, decomposition, mechanical abrasion and breakage, transport, burial). Representation of these processes in simulation models allows researchers to explore the implications of different processes, rates, and interactions that are difficult to study through field observation and manipulative experiments. Model validation or extensive comparison with field observations on the array of processes and rates may be essentially impossible; thus, detailed knowledge about the precision and accuracy of such models will be limited.

In contrast, models predicting amounts of wood in specific stream reaches or responses to a specific set of management practices require precision and reality, but do not require generality if the model has been developed from local observations and quantitative information. Such models can be calibrated to local conditions and processes by adjusting model parameters based on field observations of a limited number of processes or rates. Such calibration can improve the accuracy of the simulated amounts and distributions of wood in that local region or management application, but broader application to other systems may be limited by extensive local calibration. If the reality of the models also is simplified by combining several fundamental processes into a single overall process, prediction may be maintained or improved, but understanding of causal mechanisms will be reduced. Examples of such simplification that are common in models of wood dynamics are (1) use of overall depletion rates instead of decay, breakage, and transport; or (2) use of proportional stand delivery instead of tree regeneration, growth, competition, mortality, snag formation, and tree fall.

Development and application of future models will be guided by both the precision and accuracy of our existing data on wood dynamics and our mechanistic understanding of the processes that influence wood dynamics in streams and rivers. A conceptual diagram of the current state of knowledge in these two aspects of wood dynamics illustrates the potential implications for model development (Figure 4). Some processes are relatively well understood, and empirical data are available, such as tree mortality (though riparian studies are less common). We understand the causal mechanisms for some processes (such as wood decomposition, mass failure, snag formation) based on studies of other systems, such as upland forests. Causal mechanisms for other processes are poorly understood, such as tree fall directionality, but some empirical data are available to allow model development. Similarly, mechanisms for some processes, such as wood movement and transport, are poorly understood (Braudrick and Grant 2000), but general mathematical relationships, such as negative exponential models, provide relatively accurate representations of the overall process. And finally, some processes are poorly understood, and empirical data are almost

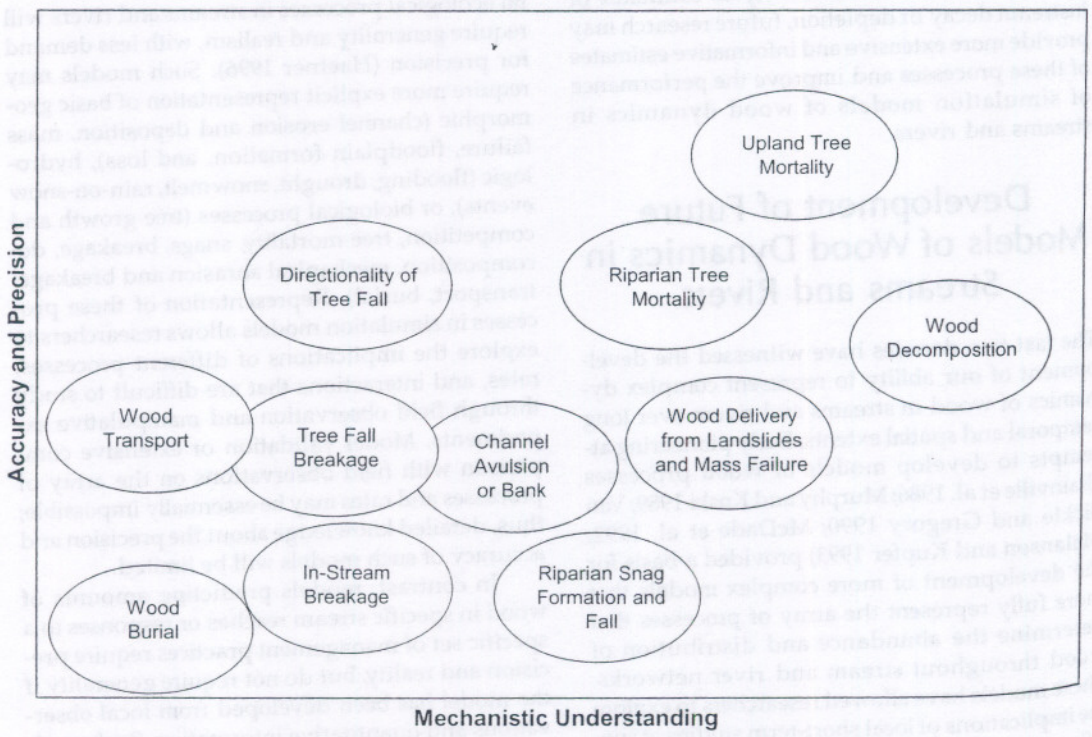

FIGURE 4. Conceptual diagram of the relative accuracy and precision of existing data on wood processes as compared to the current conceptual understanding of the mechanisms responsible for the processes. Positions of specific processes are relative and simply illustrate the potential differences in information and understanding that create challenges for modeling of wood dynamics in streams and rivers.

nonexistent, such as wood burial. Development of future models of wood dynamics can be used to guide field research to develop our understanding of the processes that shape the patterns and amounts of wood in stream and rivers.

Desirable characteristics of future models of wood dynamics

The last two decades have witnessed the application of simulation modeling for synthesizing existing information on the dynamics of wood and exploring the consequences of land and river management on wood in world rivers. Future models can build on the lessons learned from these existing models and expand the power of simulation modeling for research and management. Future models would benefit from the following attributes:

- stochastic functions that predict trends and variance in those trends
- robust stand dynamics models calibrated for riparian forests
- multiple mechanisms for delivering wood into streams and rivers
- directional fall and breakage during fall
- separate functions for decay, breakage, and transport of wood in streams
- representation of multiple reaches throughout dendritic river networks
- user-defined parameters for functions, probabilities, and probability distributions
- user-defined land-use practices (such as harvest rate, harvest rotation interval, thinning)
- sensitivity analysis of model structure and performance
- direct comparisons between model outputs and empirical observations

Additional features that would make simulation models of wood dynamics easier to use and more widely available for researchers and managers include (1) intuitive user interfaces, (2) flexible graphical output that can be defined by the user, and (3) online libraries of data for riparian forests and wood processes in streams.

Models are abstract representations of our knowledge about a given phenomenon or process and are inherently limited by the information from which they are developed. Likewise, empirical or field observations are limited by the history of the location and the portion of the landscape or river network they represent. Researchers and managers tend to champion one approach over another, sometimes rejecting models as being too abstract or field studies as being too geographically limited. The power of both simulation modeling and field investigations is greatest at the interfaces between these methods of inquiry. Research on the ecology of wood in world rivers has been strengthened by the application of simulation models for synthesizing information on the complex array of processes that result in the regeneration, growth, and mortality of riparian forests; major disturbance processes; and processes that influence wood in streams, such as decay, breakage, transport. These models can project the outcomes of these processes over long time periods and across complex networks of streams and rivers. Patterns of wood dynamics predicted by such models and the sensitivity of the models to specific processes can guide future field studies or experimental manipulations to increase our understanding of critical determinants of the dynamics of wood. Integration of sound empirical information and robust models of wood dynamics provides essential tools for resource managers to make decisions about the management of wood in the diverse streams, rivers, and riparian forests of different geographic regions of the world.

References

Beechie, T. J., G. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in Northwestern Washington streams. North American Journal of Fisheries Management 20:436–452.

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003. Wood recruitment processes and wood budgeting. Pages 49–73 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Benda, L., P. Bigalow, and T. Worsley. 2002. Processes and rates of in-stream wood recruitment in old growth and second-growth redwood forests, northern California. Canadian Journal of Forest Research 32:1460–1477.

Benda, L. E., and J. C. Sias. 1998. Landscape controls on wood abundance in streams. Earth Systems Institute, Seattle, Washington.

Benda, L. E., and J. C. Sias. 2003. A quantitative framework for evaluating the wood budget. Forest Ecology and Management 172:1–16.

Benda, L., C. Veldhuisen, and J. Black. In press. Debris flows as agents of morphological heterogeneity at low-order confluences, Olympic Mountains, Washington. Geological Society of America Bulletin.

Botkin, D. B. 1993. Forest dynamics: an ecological model. Oxford University Press, New York.

Bragg, D. C. 2000. Simulating catastrophic and individualistic large woody debris recruitment for a small riparian system. Ecology 8:1383–1394.

Bragg, D. C., and J. L. Kershner. 1997. Evaluating the long-term consequences of forest management and stream cleaning on coarse woody debris in small riparian systems of the central Rocky Mountains. Fish Habitat Relationships Technical Bulletin 21:1–9.

Bragg, D. C., and J. L. Kershner. 1999. Coarse woody debris in riparian zones. Journal of Forestry April:30–35.

Bragg, D. C., J. L. Kershner, and D. W. Roberts. 2000. Modeling large woody debris recruitment for small streams of the central Rocky Mountains. U.S. Department of Agriculture, Rocky Mountain Research Station, General Technical Report RMRS-GTR-55, Fort Collins, Colorado.

Braudrick, C. A., and G. E. Grant. 2000. When do logs move in rivers? Water Resources Research 36:571–583.

Downs, P. W., and A. Simon. 2001. Fluvial geomorphological analysis of the recruitment of large woody debris in the Yalobusha River network, central Mississippi, USA. Geomorphology 37:65–91.

Fleece, W. C. 2002. Modeling the delivery of large wood to streams with light detection and ranging (LIDAR) data. Pages 71–83 *in* W. F. Laudenslayer, Jr., P. J. Shea, B. E. Valentine, C. P. Weatherspoon, and T. E. Lisle, editors. Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests. USDA Forest Service General Technical Report PSW-GTR-181, Pacific Southwest Research Station.

Harmon, M. E., J. F. Franklin, F. J. Swanson, and others. 1986. Ecology of coarse woody debris in temperate ecosystems. Advances in Ecological Research 15:133–302.

Haefner, J. W. 1996. Modeling biological systems: principles and applications. Chapman and Hall, New York.

Hester, A. S., D. W. Hann, and D. R. Larson. 1989. Organon: southwest Oregon growth and yield model user manual, version 2.0. Forest Research Lab, College of Forestry, Oregon State University, Corvallis.

Hupp, C. R., and A. Simon. 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. Geomorphology 4:111–124.

Karplus, W. J. 1977. The place of systems ecology models in the spectrum of mathematical models. Pages 225–228 *in* G. S. Innis, editor. New directions in the analysis of ecological systems. Part 2. Simulation Councils Proceedings Series. Volume 5, Number 2. The Society for Computer Simulation (Simulation Councils, Inc.), La Jolla, California.

Kennard P., G. R. Pess, T. J. Beechie, B. Bilby, and D. Berg. 1998. Riparian-in-a-Box: a manager's tool to predict the impacts of riparian management on fish habitat. Pages 483–490 *in* M. K. Brewin and D. Monita, editors. Proceedings of the Forest-Fish Conference: Land Management Practices Affecting Aquatic Ecosystems. Informational Report NOR-X-356. Natural Resources Canada, Canadian Forest Service Northern Forestry Centre, Edmonton, Alberta, Canada.

Lamberti, G. A., S. V. Gregory, L. R. Ashkenas, R. C. Wildman, and K. M. S. Moore. 1991. Stream ecosystem recovery following a catastrophic debris flow. Canadian Journal of Fisheries and Aquatic Sciences 48:196–208.

Levins, R. 1966. The strategy of model building in population biology. American Scientist 54:421–431.

Malanson, G. P., and J. A. Kupfer. 1993. Simulated fate of leaf litter and woody debris at a riparian cutbank. Canadian Journal of Forest Research 23:582–590.

McDade, M. H. 1987. The source area for coarse woody debris in small streams in western Oregon and Washington. M.S. thesis. Oregon State University, Corvallis.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. Van Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20(3):326–330.

Meleason, M. A., S. V. Gregory, and J. Bolte. 2002. Simulation of stream wood source distance for small streams in the western Cascades, Oregon. Pages 457–466 *in* W. F. Laudenslayer, Jr., P. J. Shea, B. E. Valentine, C. P. Weatherspoon, and T. E. Lisle, editors. Proceedings of the Symposium on the Ecology and Management of Dead Wood in Western Forests. USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW-GTR-181, Albany, California.

Meleason, M. A., S. V. Gregory, and J. Bolte. In press. Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecological Applications.

Minor, K. P. 1997. Estimating large woody debris recruitment from adjacent riparian areas. Master project. Oregon State University, Corvallis.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implementation for streamside management. North American Journal of Fisheries Management 9:427–436.

Nakamura, F., and F. J. Swanson. 1993. Effects of coarse woody debris on morphology and sediment storage of a mountain stream in western Oregon. Earth Surface Processes and Landforms 18:43–61.

Nakamura, F., and F. J. Swanson. 2003. Dynamics of wood in rivers in the context of ecological disturbance. Pages 279–297 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Piégay, H., and A. M. Gurnell. 1997. Large woody debris and river geomorphological pattern: examples from S. E. France and S. England. Geomorphology 19(1–2):99–116.

Piégay, H., A. Thevenet, and A. Citterio. 1999. Input, storage and distribution of large woody debris along a mountain river continuum, the Drome River, France. Catena 35(1):19–39.

Rainville, R. C., S. C. Rainville, and E. L. Linder. 1986. Riparian silvicultural strategies for fish habitat emphasis. Pages 186–196 *in* Forester's future: leaders or followers. Society of American Foresters National Conference Proceedings. SAF Publication 85–13, Society of American Foresters, Bethesda, Maryland.

Reeves, G., L. Benda, K. Burnett, P. Bisson, and J. Sedell. 1996 A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. Pages 334–349 *in* J. L. Nielsen and D. A. Powers, editors. Evolution and the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society, Symposium 17, Bethesda, Maryland.

Shugart, H. H., and D. C. West. 1977. Development of an Appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight. Journal of Environmental Management 5:161–179.

Simon, A. 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14(1):11–26.

Sobota, D. J. 2003. Fall directions and breakage of riparian trees along streams in the Pacific Northwest. M.S. thesis. Oregon State University, Corvallis.

Swanson, F. J., S. L. Johnson, S. V. Gregory, and S. A. Acker. 1998. Flood disturbance in a forested mountain landscape. BioScience 48:681–689.

Van Sickle, J., and S. V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Canadian Journal of Forest Research 20:1593–1601.

Welty, J. W., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002. Riparian Aquatic Interaction Simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. Forest Ecology and Management 162:299–318.

Wykoff, W. R., N. L. Crookston, and A. R. Stage. 1982. User' s guide to the Stand Prognosis Model {FVS}. USDA Forest Service, Intermountain Research Station, General Technical Report INT-133, Ogden, Utah.

The Ecology and Management of Wood in World Rivers

Edited by

Stan V. Gregory

Department of Fisheries and Wildlife, Oregon State University
Corvallis, Oregon 97331, USA

Kathryn L. Boyer

USDA Natural Resources Conservation Service
Wildlife Habitat Management Institute, Department of Fisheries and Wildlife
Oregon State University, Corvallis, Oregon 97331, USA

Angela M. Gurnell

Department of Geography, King's College London
Strand, London WC2R 2LS, UK

American Fisheries Society Symposium 37

International Conference on Wood in World Rivers
held at Oregon State University, Corvallis, Oregon
23–27 October 2000

American Fisheries Society
Bethesda, Maryland
2003

The American Fisheries Society Symposium series is a registered serial. Suggested citation formats follow.

Entire book

Gregory, S. V., K. L. Boyer, and A. M. Gurnell, editors. 2003. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Chapter within the book

Abbe, T. B., A. P. Brooks, and D. R. Montgomery. 2003. Wood in river rehabilitation and management. Pages 367–389 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Printed in the United States of America on acid-free paper.

Library of Congress Control Number 2003112769
ISBN 1-888569-56-5
ISSN 0892-2284

American Fisheries Society website address: www.fisheries.org

American Fisheries Society
5410 Grosvenor Lane, Suite 110
Bethesda, Maryland 20814-2199
USA