PROCESS BASED MANAGEMENT OF LARGE WOODY DEBRIS AT THE BASIN SCALE, SOQUEL CREEK, CALIFORNIA

Report presented to

California Department of Forestry and Fire Protection

and

Soquel Demonstration State Forest

BY

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October 1, 2003

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ABSTRACT

Catastrophic floods occurred five times from 1898 to 2003 in the Soquel Creek basin, Santa Cruz County, California, when logjams at local bridges diverted flow into populated areas. In response, managers removed wood from the basin to prevent clogging and failure of bridges and culverts. Most large woody debris (LWD) management programs are unsuccessful in preventing flood and roadway damage as they fail to consider basin-wide processes of LWD recruitment and transport. In particular, bridges and culverts are installed without knowledge wood sizes that are mobilized during floods. A more ecologically and economically sustainable approach is to design infrastructure to pass wood in order to maintain habitat and reduce management effort.

This research examined the characteristics of LWD in study reaches, developed a model to simulate wood transport and assess the effects of management on wood transport, and compared the economic costs of current wood management to a wood passing approach. We identified two LWD reach types: 1) source reaches that were the source of wood for the basin, 2) transport reaches that receive wood from the source reaches. Wood remained in source reaches until flushed out to transport reaches during large storms, thus the current practice of wood removal from transport reaches had little effect of preventing catastrophic logjams. The model showed that current management techniques, such as piece size reduction and wood removal, increase the pressure of infrastructure to pass LWD by mobilizing greater volumes of wood and increasing travel distance by eliminating natural logjams. The economic comparison estimated that a wood passing approach reduced current management costs by more than 50%.

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ACKNOWLEDGEMENTS

We are grateful for the funding support provided by the California Department of Forestry and Fire Protection and for the opportunity to conduct research within the Soquel Demonstration State Forest (SDSF). We would like the thank SDSF Forest Manager Thom Sutfin for his support and guidance, without his efforts this research would not have been possible. Thanks to the following people for donating their time either through field assistance, research input, or reviewing drafts of this dissertation: Mark Eischeid, Kyle Tse, Jeremy White, Anthony Falzone, Toby Minear, Jennifer Risch, Laura Nardi, Jason Weissman, Patrick Reilly, Will Stockard, Mitch Swanson (Swanson Hydrology and Geomorphology), Kris Vyverberg (CDFG), Dominic Roques (Central Coast Regional Water Quality Control Board), Barry Hecht (Balance Hydrologics), Shawn Chartrand (Balance Hydrologics), Jennifer Nelson (CDFG), Annette Pennock, Pete Cafferata (CDF), Tom Spittler (California Geological Survey), Steve Railsback, Herve Piegay, Joe McBride, Dave Hope (Regional Water Quality Control Board), Terry Reynolds (County of Santa Cruz), and Vance Wagner (County of Santa Cruz). Many thanks to Ed Orre, SDSF Assistant Forest Manager, the entire SDSF staff, and the outstanding crew of the CDF helicopter that provided an unforgettable bird's eye view of the Soquel Creek Basin: Pilot Bob Conrado, Fire Captain Chris Jauregui, and Firefighter Uriah Hare.

1 INTRODUCTION

1.1 IMPORTANCE OF LWD

Logs, stumps, and branches that enter and are transported by rivers and streams are important influences on channel morphology and aquatic ecology. Large woody debris (LWD), generally defined as wood ≥10 cm diameter and ≥1 m length, obstructs streamflow, stores and distributes sediment, and creates channel features, such as pools, riffles, and waterfalls. Wood intercepts organic matter traveling downstream, allowing this material to be processed by instream organisms. Macroinvertebrates and fish occupy and use pools and riffles as habitat, and sediment deposits are sites for riparian forest regeneration.

The ecological importance of wood is not limited to the instream environment. On the forest floor, woody debris is both a nutrient source and a habitat element for plants, insects, and vertebrates. In estuaries and near shore ocean environments, LWD provides nursery habitat, protection, and a nutrient source for various organisms. Reviews by Harmon et al. (1986), Sedell et al. (1988), and Triska and Cromack (1980) thoroughly treat these topics.

1.2 MANAGEMENT OF LWD

In urbanized and semi-urbanized basins, flood control and road maintenance concerns surrounding in-channel wood typically override ecological concerns (Singer and Swanson 1983, Williams and Swanson 1989). Despite the extensive scientific literature describing the ecological significance of LWD, much in-channel wood is

removed or eliminated from stream networks by managers for flood control purposes, where wood is removed to maintain conveyance, and road maintenance purposes to keep bridges and culverts clear of water transported debris (Froehlich 1970, Marzolf 1978, Shields and Nunnally 1984).

Wood removal is generally unsuccessful in preventing flood and roadway damage, as it fails to consider basin-wide processes of LWD recruitment and transport. Much of the wood that contributes to flood damage enters and is transported during large storms. Even if all in-channel wood is removed, fresh wood enters during storms, is mobilized by high flows, and accumulates upstream of bridges and culverts, rendering removal a futile exercise, much like raking leaves. Also, bridges and culverts are installed with little knowledge on the sizes of wood that are mobilized during floods. These structures are not designed or evaluated for their wood-passing ability. Unfortunately, when wood removal is unsuccessful in preventing potentially catastrophic LWD bottlenecks, wood is viewed as the problem, not the presence of inadequately sized infrastructure. This leads to further wood removal and can seriously degrade the health of rivers and streams.

Loss of LWD related habitats is a contributing factor in the decline of native salmon and trout populations along the Pacific Coast (Bilby and Bisson 1998). The losses are implicitly recognized through programs to restore wood-related habitats. The programs rely on instream enhancement structures that attempt to mimic the physical effects of wood on channel form. In most instances instream enhancement structures are simply pieces of wood secured to the streambed or streambanks. The structures

may create habitat in the short term, but are prone to damage and failure, and are typically unsuccessful at maintaining habitat in the long run (Frissell and Nawa 1992, Lassettre 1997). The structures do not address the processes of habitat formation and the root causes of habitat degradation, but rather create a habitat form that is not maintained in the long run (Kondolf 1998). A more sustainable and long-term approach to restore wood-related habitats is to restore the natural input, volume, and transport of wood within stream networks.

1.3 PURPOSE OF RESEARCH

The purpose of this research is to determine the characteristics of large woody material in the Soquel Creek basin to develop a conceptual picture of wood input and transport, create a model of wood movement through the basin, and compare a revised wood passing approach to wood management with a conventional wood management style.

The alternative to wood removal is to design bridges and culverts that permit the passage of woody debris down the channel network. Under this alternative, inadequately sized infrastructure is the problem that must be removed or resized by basin managers, while wood remains in stream channels. This perspective is the opposite of conventional flood control and road maintenance approaches where wood is seen as a problem that must be removed, while inadequately sized infrastructure remains. The alternative allows wood to remain in streams and rivers to perform essential geomorphic and ecological roles, and reduces the economic costs of wood

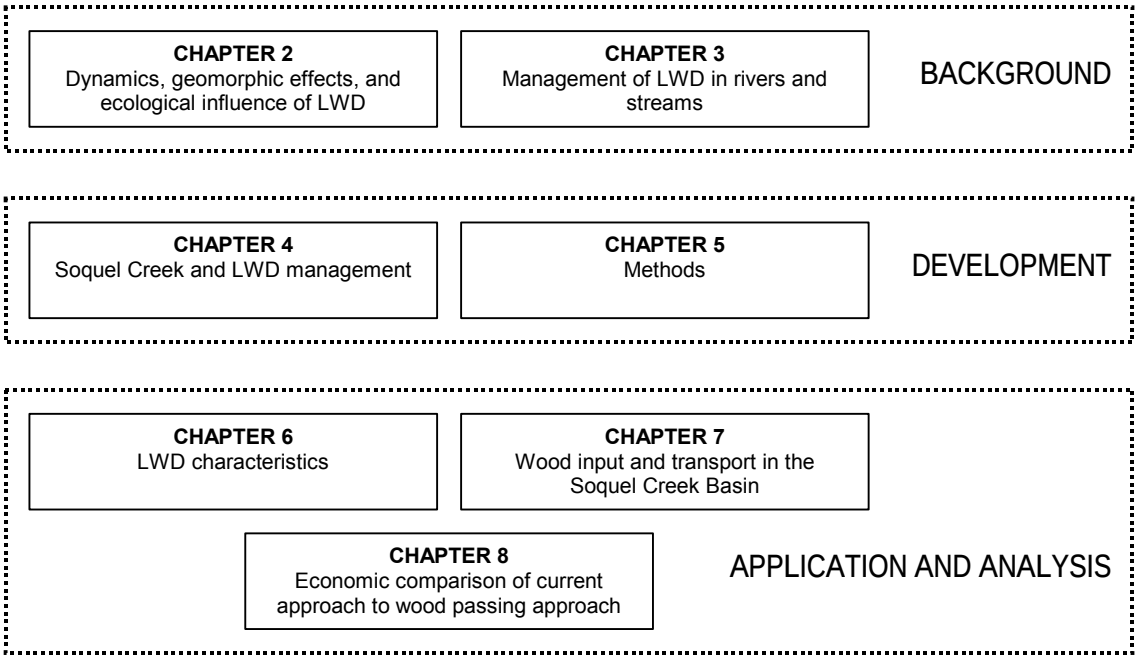
removal, damage to infrastructure, and flood damage. Also, since wood remains in the channel, the need for restoration of wood related habitats is eliminated.

The study area is the Soquel Creek basin, California approximately 200 kilometers south of San Francisco, which supports a population of the threatened anadromous fish, Steelhead trout (*Oncorhynchus mykiss*), and has a history of conflicts between flood control and fish conservation goals. In the basin, wood is removed or cut into small pieces by managers to prevent flooding, and habitat structures are installed to restore fisheries habitat lost due to lack of wood. Sometimes, both activities occur in the same reach.

1.4 FORMAT OF REPORT

This report contains ten chapters including the introduction, conclusion, and literature cited (**Figure 1.1**). Chapter two reviews literature on LWD dynamics: the role of woody debris in sediment storage, influence on channel dimensions, pool formation, nutrient dynamics, its effect on macroinvertebrate and salmonid populations, and in creating riparian habitat.

Figure 1.1. Format of this report.



Chapter three reviews the influence of timber harvest, flood control, and road maintenance activities on the geomorphic and ecological roles of wood, and management alternatives to preserve LWD in stream channels.

Chapter four describes the Soquel Creek Basin, detailing the flood history, the conflicts between wood and infrastructure, the current and past wood management activities, and limitations to these activities. Chapter five explains the methods we used in the study. The three basic categories of methods are the characteristics of in-channel wood, model development, and economic comparison.

The last three chapters present the results of data collection, model development, and the economic analysis. Chapter six presents the characteristics of in-channel wood that are used to develop the model of wood movement. The model predicts the size of and distance moved by wood at increasing flow. The economic analysis is based on a

combination of written and oral information, and compares the current management system to a proposed management system that allows wood to remain in channels and pass downstream unimpeded.

2 DYNAMICS, GEOMORPHIC EFFECTS, AND ECOLOGICAL INFLUENCE OF LARGE WOODY DEBRIS IN RIVERS AND STREAMS

2.1 DYNAMICS OF LWD IN RIVERS AND STREAMS

2.1.1 LWD input, storage, and distribution

Large woody debris (LWD) loading refers to the weight or volume of wood per square meter of stream channel (kg/m^2 or m^3/m^2). Temperate coniferous forests of the Pacific Coast exhibit the greatest levels of terrestrial and aquatic woody debris in North America, while eastern deciduous forests have lower log masses (Harmon et al. 1986). Along the Pacific Coast, loading is greatest in the Coast Redwood (*Sequoia sempervirens*) forests of Northern California, and decreases in northern temperate and sub-arctic forests, such as southeastern Alaska sitka spruce (*Picea sitchensis*) forests, and in warmer southern systems, such as Mediterranean and sub-tropical systems, although published examples of LWD loading in the latter regions are scarce (**Table 2.1**, Bilby and Bisson 1998).

Table 2.1. Loading of LWD (m^3/m^2) in streams flowing through unmanaged forests of North America.

LOCATION	FOREST TYPE	LOADING
Alaska	Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*),	0.019 m^3/m^2
British Columbia, Canada	Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*)	0.068 m^3/m^2
Oregon	Douglas-fir (*Pseudotsuga menziesii*)	0.057 m^3/m^2
Northern California	Coast Redwood (*Sequoia sempervirens*)	0.181 m^3/m^2
Southern France	*Salix spp., Populus spp., Alnus spp.*	2.72 * 10^{-6} to 6.34 * 10^{-6}
Idaho	*Picea engelmannii*	0.0276 m^3/m^2
New Hampshire	*Picea-Tsuga*	0.011 m^3/m^2
Tennessee	*Assorted hardwood*	0.063 m^3/m^2

Within a stream network, the loading and distribution of LWD is influenced by channel size and dominant input mechanism (Bilby and Ward 1989, Beechie and Sibley 1997). Debris loading is greatest in low order streams and generally decreases in the downstream direction (**Table 2.2**, Keller and Swanson 1979, Keller et al. 1985, Lienkaemper and Swanson 1987, Robison and Beschta 1990, Montgomery et al. 1995). Low order channels (> 0.05 gradient and <10m bankfull width) have greater rates of LWD input than intermediate (0.05 to 0.01 gradient and 10m to 50m bankfull widths) or high orders (<0.01 gradient and >50m bankfull width) due to the dominance of episodic input mechanisms. Episodic LWD input mechanisms are generally triggered by storms and include mass wasting, windthrow, and bank erosion. Narrow, low-order channels lack the streamflow necessary to transport and redistribute most fallen logs (Swanson and Lienkaemper 1978). Unless transported by debris torrents or flood flows, logs remain randomly distributed in the channel as single isolated pieces or in jams (**Table 2.3**, Swanson et al. 1976, Keller and Swanson 1979). Logs may remain stationary for long periods of time (greater than 200 years in some cases), but will become more mobile as they break down in size (Tally 1980, Harmon et al. 1986, Murphy and Koski 1989).

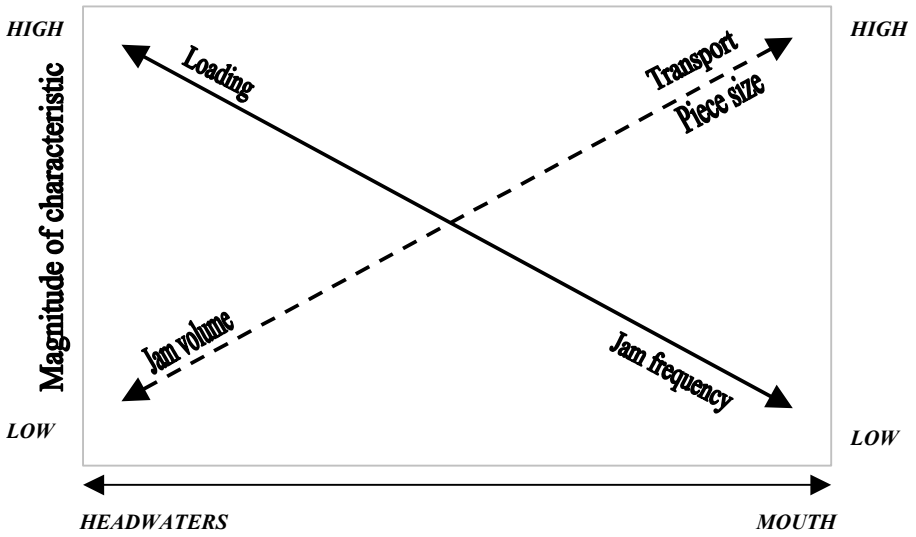
Table 2.2. LWD loading in five McKenzie River (Oregon) streams showing decrease in LWD loading (adapted from Keller and Swanson 1979).

STREAM	ORDER	w_{bkf}	GRADIENT	AREA (km^2)	LOADING (m^3/m^2)
Devilsclub Creek	1	1.0m	0.40	0.2	0.087
Watershed 2 Creek	2	2.6m	0.26	0.6	0.076
Mack Creek	3	12.0m	0.13	6.0	0.057
Lookout Creek	5	24.0m	0.03	60.5	0.023
McKenzie River	6	40.0m	0.006	1024.0	0.001

Table 2.3. The distribution and mechanisms of LWD input and transport from low to high order streams.

	LOW ORDERS	INTERMEDIATE ORDERS	HIGH ORDERS
DISTRIBUTION	• Random • Single piece	• Clumped in jams within streams	• Clumped in jams on bars and floodplains
DOMINANT INPUT MECHANISMS	• Windthrow • Bank erosion • Mass Wasting	• Windthrow • Bank erosion • Fluvial transport	• Bank erosion • Fluvial transport
TRANSPORT MECHANISMS	• Debris flows • Flotation	• Flotation	• Flotation

Figure 2.1. Schematic representation of the general trend of LWD characteristics along the channel network.



Intermediate order channels are wide and deep enough to move and redistribute in-channel wood (Swanson and Lienkaemper 1978, Bilby and Ward 1989). The main input mechanisms are windthrow, bank erosion, and fluvial transport from upstream reaches (**Table 2.3**, Keller and Swanson 1979). Wood accumulates within the channel, along channel margins, or on meander bends in irregularly spaced but distinct jams that have significant influence on stream morphology and ecology (Fetherston et al. 1995, Abbe and Montgomery 1996, Hogan et al. 1998). Jam frequency (number of jams per meter) decreases as channels become larger and are more able to transport wood, while along the same gradient, the volume of LWD jams increase (Keller and Tally 1979,

Bisson et al. 1987). The trend of increasing LWD jam volume down the channel network runs counter to the trend of decreasing LWD loading, however, both are a consequence of the capacity of streams to transport wood (**Figure 2.1**).

In high order streams, most wood enters through bank erosion and fluvial transport (Keller and Swanson 1979). Wood deposits on gravel bars or terraces along the river margin (**Table 2.3**, Keller and Swanson 1979, Bisson et al. 1987). Wood collecting on bars or islands is frequently out of contact with the low flow channel and may have a limited effect on channel morphology (Keller and Swanson 1979). Woody material still provides important ecological services for salmonids, such as escape and hydraulic cover, and for riparian forest development (Harmon et al. 1986, Fetherston et al. 1995).

In low gradient rivers and streams, channel width and sinuosity are important factors controlling the abundance and distribution of LWD accumulations (Nakamura and Swanson 1994). Wide, unconstrained reaches bordered by floodplains and terraces possess abundant storage and depositional sites for transported logs. Reaches flowing through wide valleys develop secondary channels at the base of terraces and along valley walls that trap wood mobilized during large floods. The mouths of secondary channels may be significant LWD storage sites (Swanson and Lienkaemper 1979, Nakamura and Swanson 1994). Constrained reaches have less extensive floodplain area and store fewer pieces of large wood.

2.1.2 LWD size and volume

As LWD loading decreases down the channel network, the volume (m^3) and average size (length and diameter) of instream wood increases (**Figure 2.1**, Bilby and

Ward 1989, 1991). As stream area increases, the volume of instream wood may also increase, but because stream area increases more rapidly than LWD volume, LWD loading actually decreases (**Table 2.4**). When comparing LWD loads in streams and rivers, it is important recognize the network position of the LWD loads, as similar loads may represent dissimilar volumes (**Table 2.5**). Also, as channels become wider and deeper, the average size of a stable piece of wood increases. In progressively larger channels, a larger proportion of small pieces are removed, leading to a greater average size of in-channel LWD (Bisson et al. 1987, Bilby and Ward 1989).

Table 2.4. LWD loading and volume in five McKenzie River (Oregon) streams flowing through old growth Douglas-fir forests showing decrease in loading, but increase in volume (adapted from Keller and Swanson 1979).

STREAM	ORDER	w_{bkf}	GRADIENT	AREA (km^2)	LOADING (m^3/m^2)	VOLUME (m^3)
Devilsclub Creek	1	1.0	0.40	0.2	0.087	7.8
Watershed 2 Creek	2	2.6	0.26	0.6	0.076	26.7
Mack Creek	3	12.0	0.13	6.0	0.057	205.0
Lookout Creek	5	24.0	0.03	60.5	0.023	167.0
McKenzie River	6	40.0	0.006	1024.0	0.001	32.0

Table 2.5. LWD loading and volume for streams of varying width: loading remains constant while bankfull width and LWD volume increase (adapted from Harmon et al. 1986).

STREAM	w_{bkf}	REACH LENGTH	LOADING (m^3/m^2)	VOLUME (m^3)
Christy Creek Tributary	2.7	120	0.04	12.96
School Creek	4.6	120	0.04	22.08
Prairie Creek at Campground	18.5	395	0.04	292.3

2.1.3 Influences on LWD transport

The stability of LWD depends on the physical characteristics of the piece and piece orientation within the channel. Log length and diameter are major controls on the movement of wood in rivers and streams (Swanson et al. 1976, Bilby 1984, Nakamura

and Swanson 1994). Most transported pieces are shorter than bankfull width, indicating that length may be a rough estimate of wood susceptibility to transport (Bilby 1984, Lienkaemper and Swanson 1987, Nakamura and Swanson 1994). Shorter pieces encounter fewer instream obstructions, have less contact with the bank, and move more easily than longer pieces, leaving fewer opportunities for pieces to deposit and accumulate (Bilby 1984). In low to intermediate order streams Lienkaemper and Swanson (1987) found that all transported pieces traveling more than 10 m were shorter than bankfull width. Nakamura and Swanson (1994) observed that most transported pieces were shorter than bankfull width, while 20% of un-transported pieces were longer than bankfull width. Rootwads increase the stability of logs by increasing the surface area available for snagging on instream obstructions and potentially increasing log diameter to greater than the average bankfull depth (Sedell et al. 1988).

Log position influences the degree to which a piece is exposed to streamflow and potentially transported. Important positional factors contributing to the stability of in-channel wood are the percent of the piece anchored to the bank, the proportion of the piece in the water, and the angle of orientation to flow (Bryant 1983). Burial of one end in the streambed or along the banks reduces piece exposure to streamflow and significantly increases LWD stability. Pieces buried at both ends are extremely stable and may remain in place for decades (Bilby 1984). Increased stability also results when LWD only partially resides in the stream, with one end either buried or simply resting above the bankfull channel.

Within the channel, pieces oriented increasingly perpendicular to flow are transported more easily than pieces oriented in a downstream direction (Bryant 1983).

Bryant (1983) observed a southeastern Alaska stream and developed criteria that identified the most stable pieces of wood as those with 70% of their mass anchored to the stream bank, 15% of their mass touching the water, both ends buried, and oriented 30 degrees to flow. However, precise relationships between physical characteristics, piece orientation, and wood transport are yet to be established. Braudrick and Grant (2000) performed flume experiments with pieces shorter than bankfull width and found that orientation to flow, presence of a rootwad, log density, and log diameter were the most influential factors in LWD transport. Braudrick et al. (1997) simulated wood movement through a system, using flume experiments, and observed three distinct transport regimes based on the degree of piece congestion. The transport regime depended on the rate of log input compared to stream discharge. The results showed that low order channels with high rates of wood input and relatively low discharge have a congested transport regime, while high order channels with low wood input rates and greater discharge are uncongested.

2.1.4 LWD transport mechanisms

The mechanisms of wood transport vary down the stream network with respect to channel size (**Table 2.3**, Keller and Swanson 1979). During debris torrents triggered by heavy rainfall transports wood in small, steep, low order tributaries (Swanson et al. 1976, Keller and Swanson 1979, Nakamura and Swanson 1993). Debris flows usually originate in 1st and 2nd order channels with bank slopes that exceed 50%; torrents are rare in intermediate order streams with moderately sloping banks (Swanson et al. 1976, Swanson and Lienkaemper 1978). Torrents bring material from hillslopes into stream channels, transporting logs and sediment short distances to form large accumulations, or

transport wood and sediment over longer distances to lower gradient reaches (Keller and Swanson 1979). In some cases, debris flows scour existing in-channel debris and sediment, leaving a bedrock channel that is devoid of complexity (Swanson et al. 1976, Swanson and Lienkaemper 1978). In wider channels, flotation is the main transport mechanism. Flotation of logs occurs infrequently in small channels, mainly during storms that also trigger debris torrents (Swanson et al. 1976, Singer and Swanson 1983). The transport of wood during elevated flows is most common in larger streams, and is an important LWD recruitment mechanism in reaches that have relatively low input of trees from the adjacent riparian forest (Keller and Swanson 1979).

2.2 LWD AND CHANNEL MORPHOLOGY

2.2.1 Sediment storage

In low order streams, in-channel LWD produces open storage sites that collect and store sediment during high flows (Keller et al. 1985). Logs are the primary structural component in the formation of step pools that dissipate stream energy and form sediment deposition sites just upstream of waterfalls and on the margins of plunge pools (Heede 1972, Bilby and Bisson 1998). The storage capacity of these LWD-created sites can be quite large. Tally (1980) estimated that wood stored 200 years worth of bedload in undisturbed reaches flowing through Redwood National Park, with enough space for another 100 years worth of sediment yield. In the Oregon Coast Ranges, Swanson et al. (1976) estimated that the sediment yield of forested streams was less than 10% of the material in storage, and found that in one 100m section of stream,

wood trapped and stored 230m^3 of sediment. In Idaho batholith streams, logs accounted for 34% of channel obstructions and 50% of sediment storage (Megahan 1982).

The displacement or removal of log steps significantly increases sediment transport out of low order stream reaches by reducing the amount of available storage sites. Winter high flows transported 5000m^3 of sediment out of a 250m stream reach in western Washington after Beschta (1979) experimentally removed all pieces of in-channel wood. Bilby (1981) removed wood from a New Hampshire stream and saw a 500% increase in sediment export during the next year. In steep mountain reaches, log steps are a natural influence on hydraulic geometry and play an important role in channel slope adjustment (Swanson et al. 1976, Keller and Swanson 1979, Tally 1980, Heede 1985a, b). Gravel bars eventually replaced log steps removed from an Arizona stream, and assumed control over the drop in elevation (Heede 1985a,b). The removal of naturally occurring log steps caused an increase in the movement of bedload coarse sediment.

The relative contribution of LWD obstructions to sediment storage decreases down the stream network (**Figure 2.2**, **Table 2.6**). In low-order channels, Bilby and Ward (1989) found that 40% of debris pieces were associated with sediment accumulations. An examination of progressively wider streams (with decreasing gradient) revealed that <30% of debris pieces in channels between 7m to 10m, and <20% of debris pieces in channels >10m were associated with sediment accumulations. Thus, in high gradient reaches, LWD obstructions have a greater role in bedload storage and in controlling the release of sediment (Nakamura and Swanson 1993).

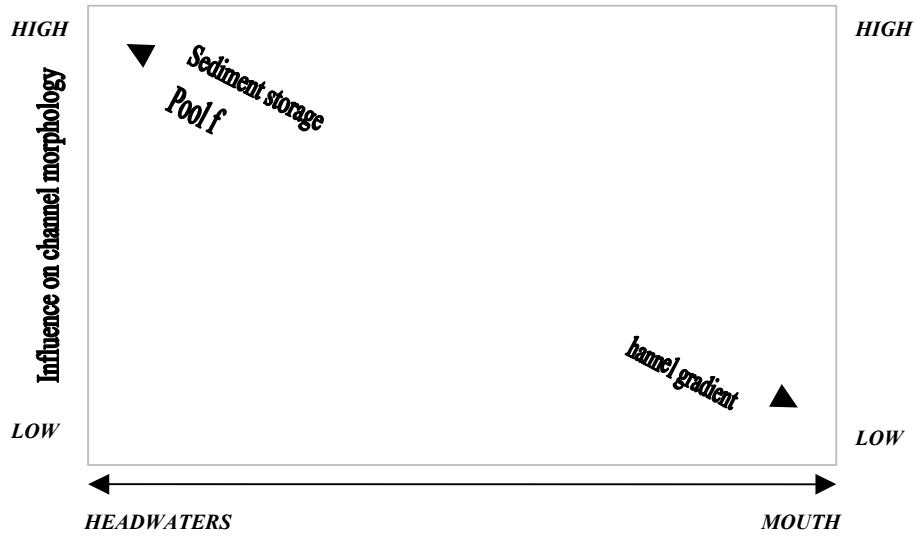
Table 2.6. The predominant storage sites and pool types associated with LWD from low to high order streams.

	LOW ORDERS	INTERMEDIATE ORDERS	HIGH ORDERS
DOMINANT SEDIMENT STORAGE SITES	• Upstream of log steps • Margins of plunge pools	• Downstream of single pieces and log steps	• Floodplains and gravel bars
DOMINANT POOL TYPES	• Plunge pools • LWD formed lateral scour	• LWD formed lateral scour	• Hydraulically formed lateral scour

Narrow, low order streams often lack significant floodplains and gravel bars, which are significant sediment storage sites in intermediate to high orders. In wider streams and large rivers, LWD obstructions create zones of locally high shear stress upstream of the piece and a low energy depositional site just downstream of the piece (**Table 2.6**, Lisle 1986b, Fetherston et al. 1995, Abbe and Montgomery 1996). Log-formed channel margin gravel bars and mid-channel islands build in elevation by accumulating additional LWD and sediment. The surfaces are sites for riparian regeneration and forest development, further stabilizing accumulated sediment (Fetherston et al. 1995, Abbe and Montgomery 1996).

In low gradient reaches, wood has a limited effect on sediment accumulation and transport (**Figure 2.2**, **Table 2.6**, Nakamura and Swanson 1993). Large woody debris may actually limit sediment storage by influencing and retarding floodplain and bar development (Smith et al. 1993b). LWD deflects the channel thalweg, resulting in irregular wood controlled lateral scour and increased local sediment export (Smith et al. 1993b, Nakamura and Swanson 1993). After removing log obstructions from a southeastern Alaska stream, Smith et al. (1993b) observed that streamflow initially mobilized sediment causing an increase in net sediment yield. After the channel re-adjusted, the loss of turbulence and increased resistance associated with bar formation resulted in a more regular sequence of bars that stored greater amounts of sediment.

Figure 2.2. Schematic representation of the general trend of the effects of LWD on channel morphology along the stream network. The effect of LWD on large rivers has a negligible effect on high orders.



2.2.2 Channel dimension

The presence of LWD influences local channel gradient and channel width. In low orders, log-formed steps create waterfalls where the stream abruptly drops in elevation. Step forming LWD accounted for 30% to 80% of the elevation drop in moderate to steep gradient streams along the coasts of Northern California and Oregon (Swanson et al. 1976, Keller and Swanson 1979, Keller and Tally 1979). As channel gradient decreases, and channels widen, fewer pieces of wood are able to span the channel and form steps, decreasing the occurrence of waterfalls and lessening LWD control on elevation (Figure 2.2, Keller et al. 1985, Bilby and Ward 1989). In very steep reaches, however, wood may rest on top of large boulders and have a limited effect on sediment storage, waterfall formation, and gradient control (Keller and Tally 1979).

In unconfined reaches, LWD increases local channel width (**Figure 2.2**, Swanson et al. 1976, Bryant 1980, 1983). Partially spanning fallen trees deflect the thalweg laterally, causing the stream current to diverge and widen the stream channel (Bisson et al. 1987). In moderate to low gradient streams along the Pacific Coast, studies show that the scour around single pieces of wood and large jams widens the channel by 50% to 200% over average bankfull width (Keller et al. 1985, Keller and Swanson 1979, Bryant 1980, 1983, Nakamura and Swanson 1993). In low gradient southeastern Alaska streams, Robison and Beschta (1990) found that the volume of LWD per 100m of channel in study reaches best explained the difference in average bankfull width between streams. The widest streams were those with the greatest volume of wood along their length.

2.2.3 Influence on pool formation

In low and intermediate order streams, wood obstructions are the primary element in pool formation (**Figure 2.2**, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997). Studies along the Pacific Coast show that 20% to 80% of pools are formed in association with LWD (Lisle 1986b, Andrus et al. 1988, Carlson et al. 1990, Robison and Beschta 1990, Nakamura and Swanson 1994, Montgomery et al. 1995, Wood-Smith and Buffington 1996, Montgomery and Buffington 1997).

In narrow, steep gradient streams, a large proportion of fallen logs fully span the channel and obstruct streamflow to form cascades and plunge pools (**Table 2.3**, Bilby and Ward 1989, 1991, Robison and Beschta 1990, Richmond and Fausch 1995). Other instream obstructions, such as boulders, are active in the formation of cascades and

plunge pools, but wood exerts the greatest control over pool creation (Keller and Swanson 1979).

In wider, low gradient streams most pieces extend only partway across the channel and are oriented diagonal to flow (Gregory et al. 1993, Richmond and Fausch 1995). Scour pools form adjacent to partially spanning pieces, as streamflow is forced under and around obstructions. Dominant LWD pool types shift from step-pools to scour pools down the channel network from step-pool to plane bedded reaches (**Table 2.6**, Bilby and Ward 1989, 1991, Robison and Beschta 1990, Richmond and Fausch 1995). Bilby and Ward (1989) surveyed western Washington streams and found that plunge pools were the most common (40%) pool type in streams <7m bankfull width, while scour pools were the most common (60%) pool types in stream >10m bankfull width. Bilby and Ward (1991) witnessed the same general shift in pool types among both logged and undisturbed basins.

Farther down the channel network, in pool-riffle reaches, the interaction between streamflow and sediment transport is the most important element in pool formation (Leopold et al. 1964, Montgomery and Buffington 1997). The presence of wood has a lesser effect on pool formation and the frequency of LWD associated pools generally decreases with increasing channel width (Bilby and Ward 1991). In stream gradients ranging from 0.01 to 0.05, Montgomery et al. (1995) and Beechie and Sibley (1997) found a strong relationship between the number of pools and LWD loading, while in stream gradients from <0.01 to <0.02 the relationship was significantly weaker. Smith et al. (1993a, b) removed wood from a low gradient southeastern Alaska stream and found similar pool spacing before and after wood removal. The results indicate that

hydraulic factors rather than channel obstructions exert a greater control over the formation of pools in low gradient rivers and streams (Swanson and Lienkaemper 1978, Montgomery et al. 1995, Beechie and Sibley 1997). In large rivers, most wood deposits in the active channel on bars, islands, or in secondary channels, out of contact with the low flow water surface (Piegay et al. 1999). In these cases, pool formation in the main channel may be independent of LWD presence, but wood along shallow channel margins or in small secondary channels does create pools that are important refuge for salmonids (Bisson et al. 1987).

2.3 LWD AND STREAM ECOLOGY

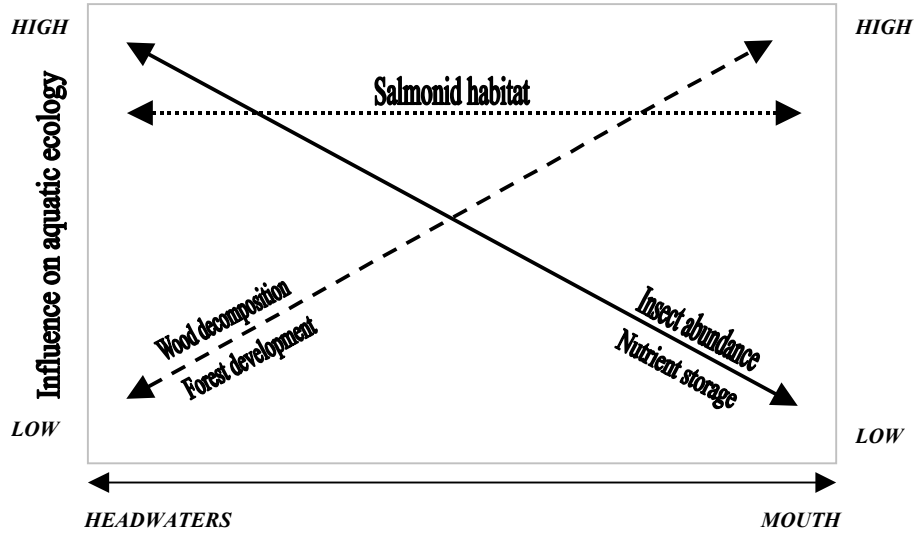
2.3.1 Nutrient dynamics

Allochthonous material from the riparian forest is a primary energy source for undisturbed rivers and streams (Gregory et al. 1991). Wood obstructions store large amounts of externally derived organic matter (**Figure 2.3**). In Rocky Mountain streams of various successional stages, Trotter (1990) found that reaches with LWD stored twice as much organic matter as reaches where wood was removed experimentally. Bilby and Likens (1980) removed LWD from a low order stream in New Hampshire and observed significant increases in the export of dissolved organic carbon (18% increase), fine particulate organic matter (<1mm; 638% increase), and coarse particulate organic matter (>1mm; 138% increase). During high discharges, the same reaches showed a 500% increase in the export of fine particulate organic matter and coarse particulate organic matter (Bilby 1981). Mediterranean systems characterized by sparse

woody vegetation possible have fewer LWD obstructions and a lower retention capacity of allochthonous material (Gasith and Resh 1999).

Salmon carcasses are an important source of organic matter for stream systems (Cederholm and Petersen 1985, Cederholm et al. 1989). In western Washington streams, twenty-two species of mammals and birds were found to consume coho salmon (*Oncorhynchus kisutch*) carcasses (Cederholm et al. 1989). Woody debris plays an important role in making nutrients available from dead fish by preventing the rapid transport of carcasses downstream. Cederholm and Petersen (1985) found a positive relationship between LWD loading and the number of retained coho salmon carcasses. Branches and logs obstruct the movement of dead fish, and the distance a carcass drifted downstream in a controlled release experiment was inversely related to the amount of LWD. In a separate experiment, pools were the most common carcass deposition sites and most pools that retained dead fish were formed by LWD (Cederholm et al. 1989).

Figure 2.3. Schematic representation of the general trend of the effects of LWD on stream ecology down channel network. The importance of LWD for salmonid habitat is equally important throughout the basin, although the role of wood varies.



Accumulations of organic matter behind log debris dams are sites for the uptake of nutrients. The sediment associated with LWD is high in organic matter content and maintains locally elevated respiration rates. Hedin (1990) found that community respiration was three times higher in sediment behind log debris dams than elsewhere on the streambed. As an attachment substrate for microorganisms that uptake nutrients, woody material is active in nitrogen and phosphorous removal (Aumen et al. 1990).

Wood is a potential nutrient source for stream ecosystems. Logs contribute fine particulate organic matter through macroinvertebrate processing and physical abrasion. In streams with high debris loads, logs are a greater source of fine particulate organic matter than leaves or pine needles (Ward and Aumen 1986). The physical production of fine particulate organic matter is greatest in winter, when logs are shattered by high flow and through collisions with mobilized substrate.

The decomposition of wood into basic nutrient forms occurs very slowly in water (Sedell et al. 1988). Fungi and macroinvertebrate decomposers require an aerobic environment, but waterlogging prevents the deep penetration of oxygen into the wood interior. Pieces partly submerged beneath the water surface show variable rates of decomposition, with sections exposed to air breaking down more rapidly. In small streams that are shallow and narrow, wood is partly or completely submerged only during the high flows of winter and spring. Wood decomposition rates may be much more rapid in the summer, when pieces are exposed to air (Sedell et al. 1988). Intermediate stream orders are wide and deep enough to submerge logs during high and low flow periods, and may have relatively slow wood decomposition rates. In large

rivers, wood is deposited on banks and islands frequently out of contact with the water surface, possibly encouraging rapid rates of LWD break down (**Figure 2.3**).

Physical abrasion and macroinvertebrate grazing gradually expose more wood surface area and increase oxygen penetration. As logs decompose, the concentration of essential nutrients, such as nitrogen, increases partly through nitrogen fixation (Sedell et al. 1988). The nitrogen fixation occurring on fallen wood may account for 5% to 10% of the annual nitrogen supplied to streams (Sedell et al. 1988).

2.3.2 Macroinvertebrates

The macroinvertebrate fauna associated with LWD ranges from obligate restriction to purely opportunistic use (Dudley and Anderson 1982). In coastal and Cascades Oregon streams, Dudley and Anderson (1982) found 45 taxa closely associated with wood and over 80 taxa facultatively associated. Obligate groups are mostly xylophagous and rely on wood as a direct nutrient source. Obligates are mainly comprised of borers and gougers, which remove and process log particles. Most obligate groups are found on soft, rotten wood or grooved, textured wood with a large surface area. Major xylophagous species are the wood gouging caddisfly *Heteroplectron californicum* and elmid beetle *Lara avara.* Anderson et al. (1978) found caddisflies to be the most conspicuous and diverse wood associated insects, however, the density and abundance of *L. avara* was more strongly associated with the amount of wood available, irrespective of stream size. Higher densities of xylophagous insects occur on hardwoods than on conifers (Anderson et al. 1978). Hardwoods have a higher nutritional value due to greater microbial activity and nitrogen content (Sedell et al. 1988). Two possible mechanisms for wood exploitation by macroinvertebrates are

consumption to obtain digestible carbon and nitrogen from microbial flora to meet energy and nutrient requirements, and cultivation and retention of a gut flora to provide nutrients and aid in digestion of wood fiber (Anderson et al. 1978).

Facultative groups use wood as an attachment substrate for filter feeding and grazing, as refugia during high flows and protection from predators, and as an oviposition site. Wood acts as a stable feeding platform for net spinning caddisflies and may channel flow along surface features to maximize filter-feeding efficiency (Dudley and Anderson 1982, Harmon et al. 1986). Wood is also used in case construction, particularly by *Limnephilidae* caddisflies (Merritt and Cummins 1996). Smooth, firm wood is a suitable attachment site for filter feeders and macroinvertebrates grazing on biofilm (Dudley and Anderson 1982). In New York, Hax and Golladay (1993) found macroinvertebrate densities on wood substrates to be higher than densities on leaves and other detritus. Densities were correlated with the amount of biofilm, which was highest on logs. Biofilm is a food source for grazing aquatic insects. Collector/gatherers occurred in higher proportions on leaves, while collector/filterers preferred wood attachment sites.

The primary basis of association for most facultative taxa is cover from predators and refuge from abiotic stress (Dudley and Anderson 1982). Grooves and cracks support high densities of macroinvertebrates presumably seeking escape cover, as many times predators dominate the total biomass within these microhabitats. Most groups are found on grooved or textured surfaces (Dudley and Anderson 1982). In Australia, O'Connor (1991) compared different wood surfaces and found that grooved snags supported higher densities of aquatic insects. The results supported a habitat

complexity hypothesis predicting an increase in species richness with increasing habitat complexity. Physically complex substrates provide more habitat opportunities for algae, microbes, and macroinvertebrates. Depositional sites upstream of log obstructions may support locally high macroinvertebrate densities as organisms gather to process organic material. Log obstructions also act as refugia during high discharge by creating areas of low water flux and low bedflow (Palmer 1996). These areas retain existing populations and encourage deposit of drifting organisms.

The sequence of macroinvertebrate colonizers on a newly fallen piece of wood follows the stage of decay (Sedell et al. 1988). Fresh logs are primarily attachment substrates for algae and microbes, which in turn support populations of grazers and collector/gatherers. Early colonizers include chironomid midges and scraping mayflies, such as *Cinygma* spp. and *Ironodes* spp. (Merritt and Cummins 1996). As wood decays through decomposition and physical abrasion, populations of xylophagous macroinvertebrates colonize the wood surface. Gougers and borers, such as the caddisfly *H. californicum* and the elmid beetle *L. avara*, graze on the soft wood, creating a mottled surface, which increases the surface area available for algae attachment and speeds microbial decomposition. In later stages of decay, chironomid and tipulid (*Liposothrix* spp.) detrivores continue decomposition into basic nutrient elements. However, the role of aquatic macroinvertebrates in wood decomposition and processing is limited compared to terrestrial insects, with aquatic organisms consuming less than 5% of all available wood (Pereira et al. 1982, Sedell et al. 1988).

The abundance and community structure of wood associated macroinvertebrates changes in relation to stream characteristics (**Table 2.7**, Dudley and Anderson 1982).

High gradient reaches with coarse substrates and exposed logs support an abundant fauna of xylophilous insects, comprised of borers, gougers, scrapers, and groups colonizing wood surfaces and crevices. In moderate gradient reaches, the accumulation of silt and fine organic matter excludes many gougers, borers, and scrapers, limiting the fauna to collectors and predators. In large rivers, physical abrasion diminishes most populations. Additionally, wood may be deposited on high banks and terraces, out of contact with the water surface and unavailable to aquatic invertebrates (Dudley and Anderson 1982, Piegay et al. 1999).

Table 2.7. Wood associated insect fauna and role of LWD in salmonid habitat from low to high order streams.

	LOW ORDERS	INTERMEDIATE ORDERS	HIGH ORDERS
MACRO-INVERTEBRATE FUNCTIONAL FEEDING GROUP	Borers Gougers Scrapers Collectors Predators	Collectors Predators	Limited, wood out of channel
ROLE IN SALMONID HABITAT	Pool formation Cover	Pool formation Cover Spawning	Cover

2.3.3 Salmonids

Along the Pacific Coast, wood is crucial in creating and maintaining the area and complexity of salmonid habitat (**Figure 2.3**, **Table 2.7**, Bisson et al. 1987). An important role of LWD in forming salmonid habitat is the creation of pools. Pools provide fish with a low energy environment to minimize energy expenditures in running water, provide maximum exposure to drifting food organisms, and are used as escape cover by individuals avoiding predators (Bisson et al. 1987, Bjornn and Reiser 1991). In moderate to high gradient streams, LWD is a significant element in pool formation (Keller and Swanson 1979, Beechie and Sibley 1997). Most pools are formed in association with LWD and wood-formed pools occupy a large proportion of the total

stream surface area and total stream volume (Fausch and Northcote 1992, Crispin et al. 1993). Other instream obstructions, such as boulders, interact with flowing water to form pools. However, in addition to altering bed morphology, debris-formed pools provide other habitat values, such as cover and nutrient trapping, not offered by boulder-formed pools. Thus, streams with high volumes of wood typically support higher fish densities. In southeastern Alaska, summer periphyton biomass and the volume of instream debris best predicted the winter density of coho salmon and LWD volume alone predicted the summer and winter density of Dolly Varden (Murphy et al. 1986).

Large woody material obstructions also create zones of differential scour and deposit, leading to the creation of gravel bars, which are used by salmonids as spawning habitat. After adding logs to western Oregon streams, House and Boehne (1986) observed a 25-fold increase in gravel bar area. In a separate study, Crispin et al. (1993) observed a 4-fold increase in coho salmon (*Oncorhynchus kisutch*) spawning activity.

In the early to mid-twentieth century, managers manipulated trout populations by installing log structures in order to increase habitat area and wood cover (Tarzwell 1937, Boussu 1954). Recent studies use manipulation to demonstrate the influence of woody debris loading on salmonid populations and fish biomass. Stream reaches with reduced levels of in-channel wood support lower salmonid populations compared to reaches with near natural LWD loading. Despite using selective techniques to remove wood from a southeastern Alaska stream and observing no significant changes in average channel width or depth, Dolloff (1986) found that the abundance of coho salmon and Dolly Varden (*Salvelinus malma*) was lower in cleared reaches. Similarly,

Bryant (1985) found that the densities of coho salmon, steelhead trout (*Oncorhynchus mykiss*), and Dolly Varden were consistently lower in reaches with reduced LWD loading. Coho fry were particularly sensitive to the presence of wood, decreasing in density as the volume of individual LWD accumulations decreased. After removing LWD, Elliott (1986) noted a decrease in benthos abundance and an elimination of most instream overhead cover. The reduced food supply and increased susceptibility to displacement in high flows contributed to the numerical decline of Dolly Varden. Log structures installed in northern Colorado streams increased pool volume and total cover, which encouraged immigration of fish from nearby unmanipulated reaches, leading to increases in the abundance and biomass of age 2+ brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*), and rainbow trout (Gowan and Fausch 1996).

An important function of instream wood is providing high flow refuge during winter. Salmonids prefer logs, tree roots, and undercut banks as cover, and streams with abundant cover elements support high winter densities of fish (Heifetz et al. 1986, Tschaplinski and Hartman 1986, Dolloff and Reeves 1990, Bjornn and Reiser 1991). Ideal winter cover sites combine low velocity, shade, and three-dimensional complexity (McMahon and Hartman 1989). Quinn and Peterson (1996) found that overwintering survival of coho was correlated with LWD abundance and volume and habitat complexity at the end of the summer, prior to winter high flows. Cederholm et al. (1997) found little or no change in spring and fall coho populations after log additions, but saw a significant increase in winter populations. The results indicate the importance of LWD in providing winter habitat. In high flows, reaches with an abundance of complex LWD created pools retain the greatest amount of fish (Harvey 1998).

Salmonids occupy stream positions adjacent to structures that increase habitat complexity (Murphy et al. 1986). In British Columbia, 99% of coho fry and 83% of steelhead parr occupied positions near mid-channel rootwads in drought, normal, and high flow conditions (Shirvell 1990). Coho remained near the shore, while steelhead preferred more distant wood associated sites. An artificial channel experiment showed that coho abundance increased in areas of high overhead cover complexity (McMahon and Hartman 1989). Young of the year fish preferred LWD derived lateral habitats. Moore and Gregory (1988) increased lateral habitat by 2.4-fold through the addition of woody debris and increased the number of age 0 cutthroat trout (*Oncorhynchus clarkii*) by 2-fold. McMahon and Holtby (1992) found that complex woody debris pieces also influence the distribution and abundance of fish in streams and estuaries. Eighty percent of coho smolts occurred within 1m of debris pieces and 95% occurred within 2m of debris pieces. The results support the need to retain LWD for smolt production in both habitat types.

2.3.4 Riparian habitat

The age structure of floodplain riparian forests reflects the history of LWD deposition and fluvial disturbance. In moderate to steep gradient streams of the Pacific Northwest, LWD parallel or oblique to flow influences the development of forested floodplains (Fetherston et al. 1995). Downed logs trap alluvium and colluvium in upstream near-bank sites, providing areas for riparian seedling establishment. The logs create low velocity environments where sediment and organic material deposit, speeding soil development and providing nutrients for riparian stands. Additionally woody debris provides nutrients as nurse logs for young trees, and in this capacity also

creates an elevated establishment site that minimizes competition between seedlings and other forest floor vegetation. Established forests eventually contribute LWD back to the stream during disturbance events, continuing the process of riparian forest development (Bilby and Bisson 1998).

In exposed channel bars, LWD protects downstream riparian sites by obstructing streamflow and shielding vegetation from high flows, allowing species such as alder to become established (Sedell et al. 1988). The sediment deposition, nutrient deposition, and protection afforded by LWD help streamside vegetation quickly reach a mature stage and better withstand floods.

As channel confinement increases, the influence of LWD on riparian forest development and distribution lessens due to a general decrease in the size of wood-associated sediment deposition sites (**Figure 2.3**, Bilby and Ward 1989, Bilby and Bisson 1998). Narrow channels also lack extensive floodplain area and are more prone to debris flows that remove soil and vegetation, further limiting riparian forest development (Fetherston et al. 1995, Bilby and Bisson 1998).

In low to moderate gradient reaches, wood accumulates in large distinct jams within the channel and on the floodplain, providing abundant sites for forest establishment (Bisson et al. 1987, Abbe and Montgomery 1996). In northwest Washington, Abbe and Montgomery (1996) observed a diverse riparian forest structure dotted with anomalous old growth patches. The old growth patches were associated with LWD accumulations located in alluvial terrain characterized by frequent disturbance. The accumulations formed around key member logs, which were originally the largest streamside trees, creating distinct, stable LWD jams. Downstream

of these jams, three factors facilitated the development of riparian forest: 1) local flow deceleration and decreased basal shear stress, 2) sediment deposition, 3) abundant accumulation of organic matter. Logjams create upstream arcuate gravel bars and downstream central gravel bars, which become sites for forest patch establishment and are stable as long as the wood accumulations exist. The observation of forest patches within the zone of active channel migration suggests that some LWD structures provide long-term refugia for floodplain riparian communities and remain stable despite repeated integration into the active channel.

3 MANAGEMENT OF LARGE WOODY DEBRIS IN RIVERS AND STREAMS

3.1 FOREST MANAGEMENT IMPACTS ON LWD

3.1.1 LWD input

The impacts of forest management on LWD dynamics and on the geomorphic and ecological roles of LWD are summarized in **Table 3.1.** Forest management activities alter the volume of wood contributed to rivers and streams (Bisson et al. 1987). Clearcut logging, often with no buffer strips surrounding the stream channel, commonly occurred throughout the Pacific Northwest and Alaska until the late 1980s (Dominguez and Cederholm 2000). Recovery time for wood inputs to return to pre-harvest conditions is decades long. Fifty years after logging, a managed stand adjacent to a western Oregon stream contributed only 14% to the total LWD volume and only 7% of the pieces from the managed stand contributed to pool formation (Andrus et al. 1988). Murphy and Koski (1989) estimated that after clearcutting full recovery of LWD input volume in a southeastern Alaska stream exceeded 250 years. The results indicate that managed stands must grow many years before contributing LWD in volumes and in functionality similar to pre-managed forests.

Forest practice rules now require uncut or selectively cut buffers adjacent to rivers and streams. The purpose of buffers is to maintain ecological services, such as shading and temperature regulation, provided by the forest to aquatic systems. Buffer width determines the amount of LWD available for recruitment to the stream channel (**Table 3.1**, FEMAT 1993). Field studies and models show that 80% to 90% of wood input comes from within 30m to 40m of the stream margin (Lienkaemper and Swanson

1987, Murphy and Koski 1989, McDade et al. 1991). Buffers that are wider than 40m have input rates equal to that of uncut stands, but narrower zones show a marked decrease in LWD delivery (McDade et al. 1990). Also, management on the upslope edge of the buffer affects wood recruitment. Buffers adjacent to clearcuts are exposed to increased local wind velocities and have higher rates of windthrow than buffers adjacent to uncut and thinned stands and are rapidly depleted of available wood (Reid and Hilton 1998).

Near-stream logging can also increase the rate of LWD input by destabilizing hillslopes and increasing the likelihood of debris avalanches (Swanson and Lienkaemper 1978).

Table 3.1. The effect of timber harvest on the characteristics and abundance of LWD within stream systems. Timber harvest temporarily reduces input or changes the physical characteristics of subsequent inputs.

TIMBER HARVEST EFFECT ON LWD	REFERENCES
• Temporary reduction in LWD input	Bryant 1980, Andrus 1988, Murphy and Koski 1989
• Second growth input smaller in size and volume	Ralph et al. 1994
• Smaller size of LWD input alters frequency and type of pools formed by wood	Bilby and Ward 1991
• Removal of logging residue along with naturally occurring wood simplifies habitat by removing habitat-forming logs	Swanson et al. 1976, Swanson and Lienkaemper 1978, Beschta 1979, Bryant 1980, Keller and MacDonald 1983, Bilby 1984, Bisson et al. 1987, Bilby and Ward 1989
• Logging material reduces intragravel flow, increases biological oxygen demand, reduces space available for invertebrates, and blocks fish migration	Hall and Lantz 1968, Narver 1970, Brown 1974
• Destabilization of hillslopes and increase in debris avalanches	Swanson and Lienkaemper 1978
• Narrow buffer strips (<20 m to 30 m) potentially reduce wood input	McDade et al. 1990, Van Sickle and Gregory 1990
• Buffer strips adjacent to clearcuts have higher occurrence of windthrow and deplete large wood sources	Reid and Hilton 1998

3.1.2 LWD size and volume

Timber harvest rotation changes the size and species composition of the forest and of recruited wood (**Table 3.1**, Murphy and Koski 1987, Bilby and Ward 1991). Older trees contribute larger diameter logs than younger trees (Bilby and Ward 1991, Ralph et al. 1994). Ralph et al. (1994) compared unlogged, moderately, and intensively logged basins and found that streams in unlogged basins contained more large logs (>50 cm diameter) and had higher volumes of wood than streams in moderately or intensively harvested streams (Ralph et al. 1994).

During timber operations small, unharvested pieces of wood, or logging debris, accumulate on the banks and in channels. The volume of leftover logging debris depends on the harvest method, but frequently it is cleaned up or removed by work crews (Froehlich 1973). Historically, in forested regions such as the Pacific Northwest, clean-up operations removed of all pieces of downed wood without distinguishing between natural LWD and logging debris (Swanson and Lienkaemper 1978, Bisson et al. 1987). Indiscriminant stream cleaning reduced the abundance of large, stable logs that were "key" pieces in logjam formation and habitat creation, leaving smaller more easily mobilized pieces (Swanson et al. 1976, Swanson and Lienkaemper 1978, Bryant 1980, Keller and MacDonald 1983).

3.1.3 Stream morphology

Changes in wood size and abundance alter stream morphology. Small logs from recently managed stands form fewer and smaller pools than logs from older stands. Ralph et al. (1994) found that intensively harvested streams contained small logs (10cm to 20cm) creating shallower and smaller pools than streams flowing through unlogged

and moderately logged basins. The authors related pool characteristics to smaller log sizes and the increased mobility of wood. Most logs were deposited out of the channel during high flows and did not interact with the streambed.

Logs span the channel in narrow streams, creating steps, plunge pools and waterfalls, which dissipate energy and control gradient. Bilby and Ward (1991) found that narrow streams in second growth forests had fewer spanning logs than old growth streams. The second growth streams had fewer LWD formed waterfalls and more lateral scour pools, formed by pieces extending only partway across the channel, than old growth streams (Bilby and Ward 1991). Logging in steep, narrow streams reduced the control of wood on stream gradient, and shifted the dominant pool type from plunge to lateral scour.

Large logs also play an important role in bedload storage. Their removal eliminates potential sediment storage sites and simplifies aquatic habitat by causing pools to fill with sediment (reducing pool area), and by smoothing channel gradient (Beschta 1979, Bilby 1984, Sullivan et al. 1987, Bilby and Ward 1989, Dominguez and Cederholm 2000).

3.1.4 Stream ecology

Excessive logging material left in the stream may harm fish populations. Fine debris woody debris blanketing the gravel surface impedes intragravel flow and reduces subsurface dissolved oxygen levels (Hall and Lantz 1969, Narver 1970, Brown 1974). Reduced oxygen availability retards the development of salmonid embryos lying within the gravel, and microbial decomposition of woody particles increases biological oxygen demand (Narver 1970). Tannins and lignin-like substances leached from wood cloud

water and absorb sunlight to reduce periphyton growth. Small pieces of wood and bark occupy interstitial space between gravels and reduce the living space available for stream invertebrates (Narver 1970).

Large human induced accumulations of wood can sometimes prevent the upstream migration of anadromous fish (Brown 1974). In the past, managers removed LWD in logged streams to allow fish passage, without distinguishing between naturally occurring logjams and unnatural barriers to fish migration. Crews removed many habitat-creating logjams unnecessarily (Bilby and Bisson 1998).

Managers often modify salmonid streams with artificial structures designed to mimic the hydraulic and habitat forming effects of LWD (House and Boehne 1986, Riley and Fausch 1995, Wallace et al. 1995). The long-term success of instream structures in creating and maintaining salmonid habitat is poor (Frissell and Nawa 1992, Lassettre 1997). Frissell and Nawa (1992) surveyed 92 structures throughout the Pacific Northwest of the United States and found that fewer than ten still functioned as intended three years after installation. In the short-term, structures create habitat, but do not address the long-term causes of degradation, such as the interruption of wood input and transport (Kondolf 1998). Subsequently, short-term habitat gains are lost when structures are damaged under the stresses of normal streamflow and no longer function as intended, yet the causes of habitat degradation remain (Lassettre 1997).

3.2 FLOOD CONTROL AND ROAD MAINTENANCE IMPACTS ON LWD

3.2.1 Flood control

The body of literature detailing the effects of flood control (and road maintenance) on the role of in-channel wood is small compared to that on the effects of timber harvest. We found twelve papers on the effect of roads and related maintenance on LWD and over 100 on the effects of timber harvest. The main activity associated with flood control is the removal of large woody debris from stream channels (**Table 3.2**). Logs and riparian vegetation increase channel roughness, reduce conveyance, and are commonly removed by flood control managers to maintain flood capacity (Marzolf 1978, Singer and Swanson 1983, Young 1991, Gippel et al. 1996). The effects of wood removal on stream geomorphology and ecology in flood control channels have been examined in the literature, but can be inferred from research on the roles of LWD in natural and disturbed systems (**Table 3.3**).

Table 3.2. Flood control and road maintenance activities generally result in the removal of in-channel wood.

FLOOD CONTROL AND ROAD MAINTENANCE EFFECTS ON LWD	REFERENCES
• Remove wood to decrease channel roughness, increase conveyance, and maintain flood capacity	Marzolf 1978, Young 1991, Gippel et al. 1996
• Remove wood and clear jams to keep culverts and bridges free of debris and reduce structural damage during storms	Singer and Swanson 1983, Diehl 1997
• Debris control structures upstream of bridges and culverts trap mobile wood that is then discarded by managers and lost from the system	Federal Highway Administration 1990

In mid-order streams, wood creates pockets that store many years of sediment yield and dampen the flow of large inputs of sediment, while in larger rivers, wood has a minimal impact on sediment storage (Nakamura and Swanson 1993). The possible impact of LWD removal is a decrease in storage capacity, resulting in an increase of

sediment transported downstream, and the aggradation of downstream channels. The aggradation of downstream channels would actually reduce flood conveyance. Logs are primary element of pool formation in moderate gradient streams, while in low gradients logs have a minor effect on the presence of pools (Beechie and Sibley 1997). An obvious impact of wood removal is the reduction in the number of wood formed pools, which are important for aquatic species.

Table 3.3. The impacts of flood control and road maintenance on the geomorphic and ecological roles of LWD, and on wood transport.

GEOMORPHIC IMPACTS
• Decrease in sediment storage capacity • Increase in sediment transport • Aggradation of downstream channels • Reduction in number of wood formed pools
WOOD TRANSPORT
• Increased mobility of pieces • Increased travel distance due to lack of jams • More pieces obstructed by bridges and culverts
ECOLOGICAL IMPACTS
• Decrease in organic material storage capacity • Increased transport of organic material • Shorter nutrient retention times • Reduced energy base for macroinvertebrate production • Reduction of usable salmonid habitat

The ecological impacts of wood removal are summarized in **Table 3.3.** Logs obstruct allochthonous material, allowing this material to be processed by stream organisms. Log removal shortens the nutrient retention time and capacity, thus nutrients may not be processed or broken down, and lost from the system (Bilby 1981, Bilby and Likens 1980). The impact in large rivers is probably minimal, although a main nutrient source for wide channels is fine organic material that has been processed by stream organisms as the material travels downstream (Vannote et al. 1980). In moderate gradient streams, logs support a diverse assemblage of macroinvertebrate

families that process allochthonous material and use woody debris as a substrate for feeding, reproduction, and refuge. Log removal reduces macroinvertebrate habitat area and production, and may alter the composition of functional feeding groups. In lower gradients, salomonids use logs and logjams as hydraulic and escape cover. It is well explored in the research that the absence of wood results in a lack of usable salmonid habitat and can reduce fish populations (Dollof 1986, Elliott 1986). In the riparian zone, downed wood is used as a nutrient source and as a hydraulic refuge by seedlings and creates multi-age riparian stands (Fetherston et al. 1995). Log removal leaves fewer acceptable seedling establishment sites and may lead to a reduced extent of the riparian forest and even aged riparian stands.

3.2.2 Road maintenance

Similar to the example of flood control, few studies examine the effect of road maintenance on the roles of LWD. Wood mobilized during high flows frequently becomes trapped on channel spanning bridges and culverts, leading to road overtopping and eventual structure failure. Managers clear wood and jams to keep structures free of obstructions and to reduce damage to river crossings (Williams and Swanson 1989). These management activities eliminate LWD or only the largest pieces of wood that pose the greatest hazard, but which are most important to habitat formation. Managers also use debris control structures, such as racks or cages, upstream of culverts and bridges to catch mobile woody debris (FHWA 1990). The caught woody debris is usually discarded and lost from the system.

The impacts of flood control on the geomorphic and ecological roles of wood that we inferred above also hold true for road maintenance (**Table 3.3**). But, the focus

of road maintenance activities is on mobile woody debris and the interaction of wood with infrastructure.

In moderate and low gradient streams, the main LWD transport mechanism is flotation during high flow. The removal or the size reduction of wood for road maintenance has no impact on the dominant transport mechanism, but reducing the size of pieces to permit passage through bridge and culvert openings increases the mobility and decreases the stability of in-channel wood. Increased mobility of logs will quickly deplete the stock of in-channel wood leading to lower wood volumes and loading, and also a reduction in the number of key pieces. Jams create natural obstructions to wood transport and are a limit on the distance a piece of wood travels during a storm (Martin and Benda 2001). Log removal increases jam spacing and the distance that pieces travel during storms, as there are no jams to obstruct pieces. With fewer natural obstructions (jams) to limit wood transport distance, wood that naturally settles in jams can collect upstream of bridges and culverts. Jam removal or piece size reduction may actually increase the amount of wood obstructed by bridges and culverts and cause greater damage to roads and overcrossings.

3.3 FOREST MANAGEMENT ALTERNATIVES FOR LWD

3.3.1 Buffer strips

Buffer strips wider than the zone of LWD input, typically 30m to 40m, may maintain a reservoir of terrestrial wood for future input of aquatic LWD (**Table 3.4**, Lienkaemper and Swanson 1987, McDade et al. 1990, Van Sickle and Gregory 1990). Some researchers call for wider buffers, or a selectively logged fringe buffer adjacent to

an unmanaged buffer, to reduce abnormally high rates of windthrow and preserve natural input rates (Reid and Hilton 1998).

Ideally, buffer strips will contribute logs that are large enough to influence channel morphology. Forest managers can ensure the future supply of functional wood by retaining large trees in the adjacent forest (Fetherston et al. 1995, Abbe and Montgomery 1996). There is no formula for determining the amount of wood required in a given stream. Species, diameter, and wood decay rates influence the amount of wood potential recruitment necessary (Murphy and Koski 1989).

Table 3.4. Some management practices to preserve LWD input, transport, and presence within the stream channel.

FOREST MANAGEMENT ALTERNATIVES	REFERENCES
• Buffer strips should be wider than zone of LWD input	McDade et al. 1991, Van Sickle and Gregory 1990
• Fringe buffers can protect streamside buffers from premature wood depletion	Reid and Hilton 1998
• Selective management in buffers should consider future input required based on instream surveys	Bilby and Ward 1989, Murphy and Koski 1989
• Selective management should leave large trees that will be stable and influence channel morphology	Fetherston et al. 1995, Abbe and Montgomery 1996
• Active management of buffer zones can increase recruitment of certain species and sizes of wood	Beechie and Sibley 1997
• Removal of logging debris best dealt with by selective removal	Bryant 1983, Bilby 1984, Gurnell et al. 1995
• Knowledge of habitat conditions, and the size and abundance of LWD required to maintain conditions must be considered when removing instream wood	Bryant 1983, Bilby 1984
• Characteristics of unmanaged streams should guide re-introduction of wood	Smith et al. 1993a, b, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997

Forest managers can increase the recruitment of certain species that produce the largest and longest lasting LWD by actively managing riparian zones to establish and grow desired species (**Table 3.4,** Beechie and Sibley 1997). This strategy should be considered in relation to channel network position: small channels (<10 m width) can form pools around smaller pieces of wood than larger channels (>10m) (Bilby and

Ward 1989). Data on variations in the size and amount of woody debris with changing stream size could be used to develop plans for numbers and sizes of trees to be achieved (Bilby and Ward 1989).

3.3.2 Woody debris clearance

If debris is to be removed from a stream by machinery, it is best accomplished by selective maintenance to ensure channel stability and ecological function (Gurnell et al. 1995). An adequate amount of leftover LWD is essential to maintain wood related habitat structure (Lisle 1986a). In southeastern Alaska, Lisle (1986a) found that debris dams were more frequent in clear-cut reaches that were not cleaned after harvest than in undisturbed reaches. The clear-cut reaches showed greater residual pool depth and length, and the remaining LWD stored more bedload sediment than logs in undisturbed reaches. Leftover wood eventually deteriorates through decomposition and physical abrasion, and streams eventually decrease in physical complexity if LWD is not replaced through natural inputs (Lisle and Napolitano 1998).

Indiscriminate removal of in-channel LWD can have a major influence on channel processes (Beschta 1979, Bilby 1984). Knowledge of habitat conditions and the size of LWD required to create these conditions are considerations when removing instream wood. Bilby (1984) developed a dichotomous key based on local channel conditions and size of LWD to determine whether to remove or leave logs in the channel. Bryant (1983) used an inventory of piece length, percent of piece in the water, angle of orientation to flow, and location of anchor point to determine piece stability and suggested general removal guidelines based on the age of debris and stream gradient.

3.3.3 Woody debris placement

In streams lacking LWD, re-introduction or placement of logs as instream structures provides a short-term solution to maintain wood created habitats until natural recruitment processes recover (Sullivan et al. 1987, Gurnell et al. 1995). The characteristics of unmanaged streams, such as the variability in species, size, and spacing of LWD accumulations and the goals of the project should guide the re-introduction of wood (Dominguez and Cederholm 2000). Dominguez and Cederholm (2000) developed a flow chart for determining candidate streams for rehabilitation based on fish habitat needs and characteristics of the stream and surrounding forest. Any logs added should be structured to mimic effects of natural obstructions in streams. Through careful placement of existing logs, managers may be able to engineer jam configurations that efficiently enhance pool formation.

The sensitivity of stream channels to wood addition varies with channel gradient. Moderate gradient reaches are highly sensitive to the presence of LWD (Sullivan et al. 1987, Montgomery et al. 1995, Abbe and Montgomery 1996, Beechie and Sibley 1997, Montgomery and Buffington 1997). Beechie and Sibley (1997) predict that increases in log abundance will lead to more rapid increase in the number of pools and pool area in moderate slope channels than in lower slope channels. The presence of pools in low gradient reaches may be independent of LWD presence (Smith et al. 1993a, b). The placement of instream structures maintains pools in the short-term, but ignores dynamic ecological and physical processes. Effective management of LWD will depend on information relating vegetative and physical characteristics of riparian areas to input of LWD (Bilby and Ward 1989).

3.4 FLOOD CONTROL AND ROAD MAINTENANCE ALTERNATIVES FOR LWD

Flood control programs that encourage the removal of woody debris rarely undergo technical scrutiny, and do not always have a significant effect on flood levels (**Table 3.5**, Williams and Swanson 1989, Young 1991, Dudley et al. 1998). Channel roughness depends on many factors, and the claims of reduced frequency and duration of over bank flooding, used to justify debris removal, are not unequivocally proven in the field (Gippel 1995). In Australia, Young (1991) found that the average amount of wood in lowland rivers seldom had a significant effect on flood levels, and suggested that larger pieces may be rearranged for hydraulic reasons and habitat preservation. Clearance of wood to maintain bridges and culverts is usually undertaken during low flow conditions, yet much wood enters streams and rivers during storms, through debris avalanches, bank erosion, and windthrow, reducing the effectiveness of removal programs (Singer and Swanson 1983). The use of hydraulic models may aid in the planning of debris management programs. However, in re-introducing LWD to stream channels as part of riparian restoration or instream habitat enhancement, managers must understand the geomorphic context of wood function to guide the effective placement for long-term log stability (Braudrick et al. 1997). A quantitative understanding of wood movement is needed to assess stability of re-introduced wood and to prevent unstable logs from becoming a safety hazard.

Table 3.5. Some possible management practices to preserve LWD input, transport, and presence within the stream channel.

FLOOD CONTROL AND ROAD MAINTENANCE ALTERNTATIVES	REFERENCES
• Must gain quantitative understanding of effect of wood on flood heights and how moves through a system	Young 1991, Braudrick et al. 1997, Braudrick and Grant 2000
• Design and modify bridges and culverts to allow for passage of woody debris	Diehl 1997, Flanagan et al. 1998
• Develop management that recognizes ecological value and impact of wood on human infrastructure and public safety	Singer and Swanson 1983, Piegay and Landon 1997

The alternative is to design bridges and culverts that allow passage of woody debris. A major item in the calculation of flood damages is crossings that obstruct wood movement and cause damage to the road system (Froehlich 1970). Froehlich (1970) hypothesized that aside from removing all debris to reduce flood damage, alternatives are to remove only the largest debris jams, build structures to act as debris barriers (eliminating LWD transport altogether), or to modify and build structures that pass wood. Diehl (1997) examined drift damage to bridges across the United States and suggested adequate freeboard, wide spans, solid piers, rounded pier noses, and pier placement out of the path of drift to reduce jam accumulation. Flanagan et al. (1998) suggested methods to determine the potential of culvert crossings to impede downstream movement of logs based on the ratio of culvert width to channel width (w^*), degree of upstream widening and stream approach angle to the culvert. Culverts with $w^* < 1$ are prone to clogging. Channel widening immediately upstream of culverts encourages ponding and creates eddies that orient wood perpendicular to flow and promote formation of large jams. In streams approaching crossings at a severe angle, wood cannot rotate parallel to flow and is less likely to pass through the culvert. Surveys on the size distribution of instream wood should also be included in studies assessing log-passing capacity and considered before construction or modification of structures (Singer and Swanson 1983).

The management of wood in basins that are directly influenced by human infrastructure must balance ecological and safety concerns. Piegay and Landon (1997) proposed a system that recognizes the impact of LWD on public safety and human infrastructure, and the ecological value of wood. The sectored LWD maintenance plan

was based on mapping of three areas: 1) woody debris supply areas, 2) areas where log jam formation is most probable, 3) areas of floodplain occupation to determine human vulnerability to flooding. The plan allowed for recruitment of LWD and the formation of jams in areas that posed little safety hazard. Intensive maintenance of instream wood occurred near flood prone areas and upstream of bridges.

4 SOQUEL CREEK AND LWD MANAGEMENT

4.1 PHYSICAL SETTING

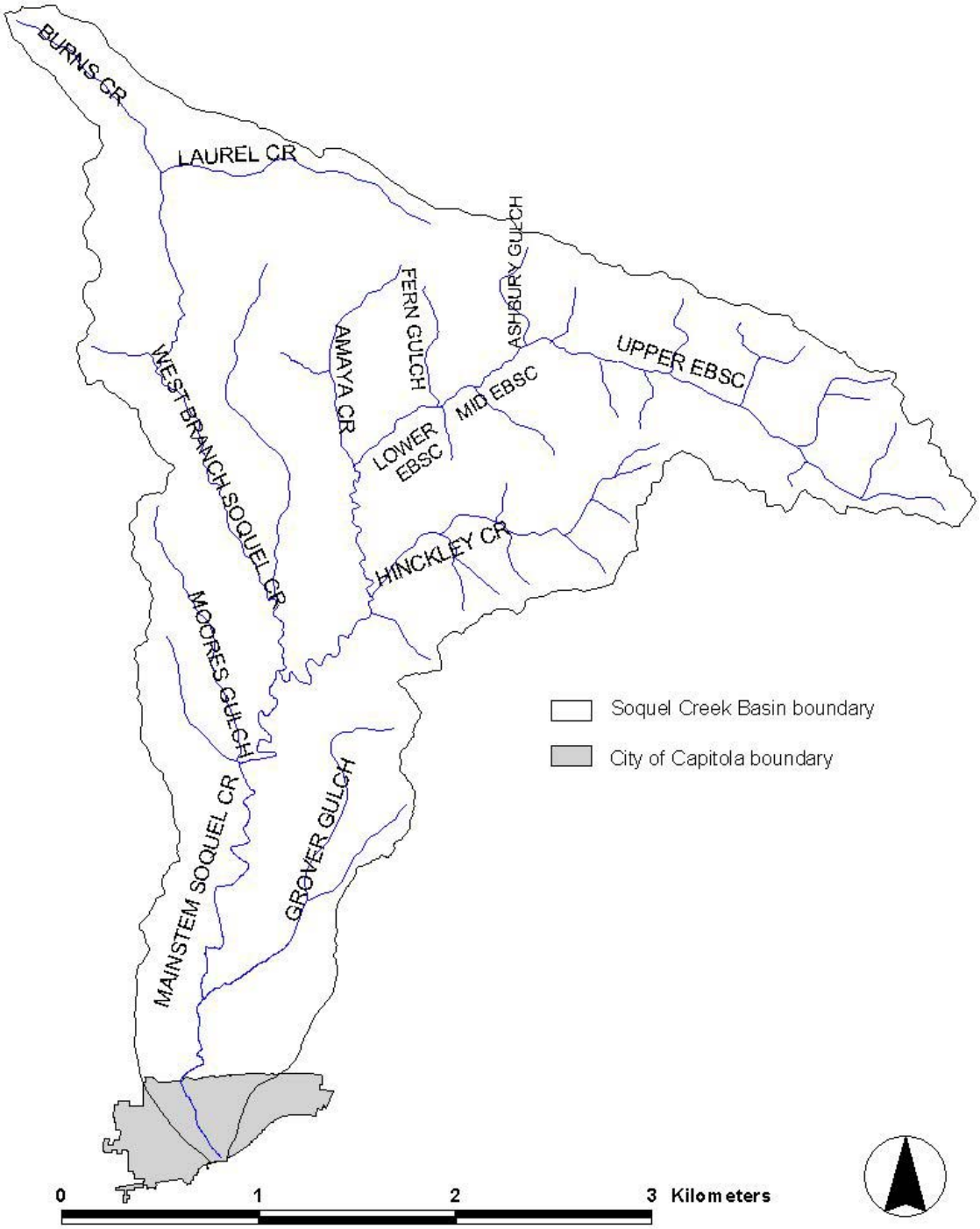
4.1.1 Soquel Creek Basin

The Soquel Creek Basin (Santa Cruz County, California) drains 104km^2 on the central California coast before emptying into the Monterey Bay and the Pacific Ocean (**Figure 4.1**, Singer and Swanson 1983). The triangular shaped basin is 24km long, less than 1km wide near its mouth at Capitola, and 20km wide near its headwaters at the crest of the Santa Cruz Mountain Range at 900m elevation (Swanson 1988).

Mainstem Soquel Creek, which flows directly into the Pacific Ocean, is formed by the union of the West and East Branches, 11km upstream of the mouth. Including the West and East Branches, the Soquel Creek Basin drains six significant sub-basins: Hinkley Creek, Hester Creek, Bates Creek, and Moores Gulch. The total length of all streams is approximately 80km. The lower portion of the basin along the Mainstem is a gently sloping, irregularly meandering channel flowing through a terraced alluvial valley. The average gradient in the lower reaches is less than one percent. Steep, bedrock channels with gradients up to fifteen percent that flow through narrow gorges with oversteepened, unstable hillslopes characterize the upper reaches (Singer and Swanson 1983).

The climate is Mediterranean with cool, wet winters and warm, dry summers. The average rainfall varies from 38cm per year at the mouth to 114cm per year in the upper basin, with most rainfall occurring in the fall and winter from November to April (Singer and Swanson 1983).

Figure 4.1. The Soquel Creek basin located in Santa Cruz County, California approximately 200 kilometers south of San Francisco. The basin is 104km^2 and drains directly into the Monterey Bay



Along streambanks and floodplains the major woody vegetation types are riparian sycamore (*Platanus racemosa*), alder (*Alnus spp.*), cottonwood (*Populus spp.*), big leaf maple (*Acer macrophyllum*), and California bay (*Umbellularia californica*) (Singer and Swanson 1983; Faber and Holland 1988). Found on hillslopes and near the stream channel in the upper reaches are coast redwood (*Sequoia sempervirens*) and douglas-fir (*Pseudotsuga menziesii*). On dry, southern facing hillslopes throughout Soquel Creek are Pacific madrone (*Arbutus menziesii*), and various oaks (*Quercus* spp.) (Singer and Swanson 1983, Faber and Holland 1988).

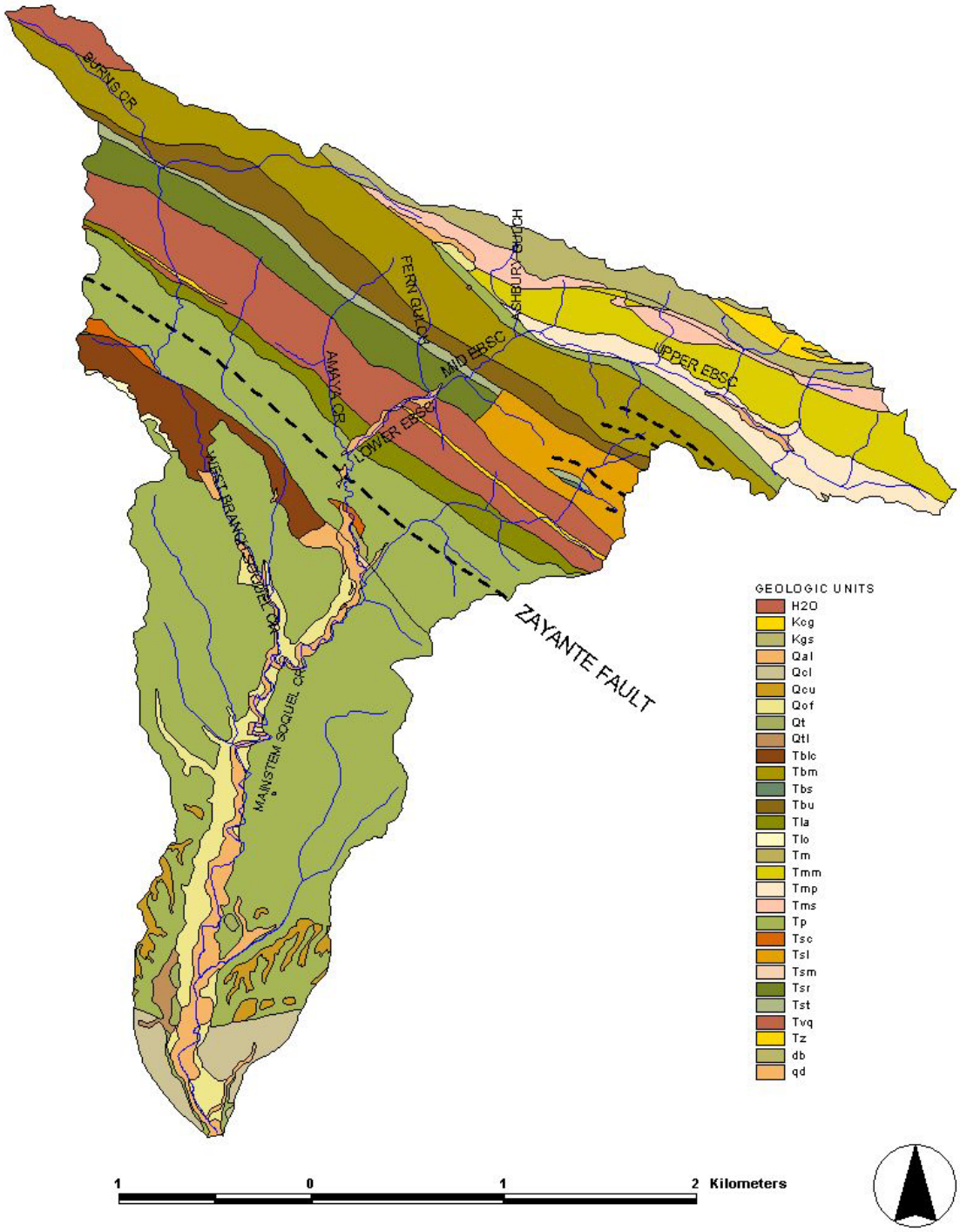
The lower portion is urbanized, occupied by the towns of Soquel (pop. 9,188) and Capitola (pop. 10,033) (Santa Cruz County 2003). In this portion, three major roads and a state freeway intersect Mainstem Soquel Creek. A combination of residential uses, orchards, plant nurseries, and horse stables characterizes the middle of the basin. The upper portion of the basin is forested with second growth and old growth conifer species, and maintains some residential development. Logging in the upper basin has occurred intermittently since the late 1800s, and still continues at moderate levels along the East Branch within the Soquel Demonstration State Forest (SDSF).

Fine-grained sedimentary rocks with small granite outcrops underlie the basin (Singer and Swanson 1983). The major geologic controls are the San Andreas Fault, which runs across the top of the basin through the Santa Cruz Mountain Range, and the sub-parallel Zayante fault, two miles to the southwest (**Figure 4.2**). Between these two faults lies a downthrust wedge of early to mid-Tertiary marine sedimentary rocks. The main rock types are Eocene Butano formation and Oligocene Vaqueros formation, both consisting of interbedded sandstone and siltstone, and the Pliocene Purisima formation

consisting of marine sandstones and siltstones. All of the units are highly weathered and easily erodible (Singer and Swanson 1983).

Landslides are common throughout the basin. The combination of weathered parent material, steep hillslopes, seismic activity, and punctuated rainfall contribute to the overwhelming number of occurrences (Singer and Swanson 1983). The most common type of mass movement is debris flows that are triggered by storms. Collectively, these events contribute large amounts of woody debris and sediment to Soquel Creek Basin streams. The basin is also dotted with large rotational landslides that start at the ridge tops. These larger landslides are activated by large earthquakes, such as those in 1906 and 1989 earthquakes (Singer and Swanson 1983).

Figure 4.2. Geology and active fault zones within the Soquel Creek Basin.



4.1.2 Upper EBSC

We investigated five study reaches within the Soquel Creek basin (**Table 4.1**). Four of the study reaches, Amaya Creek and Lower, Mid, and Upper East Branch Soquel Creek (EBSC), were located in (SDSF). The remaining reach encompassed Mainstem Soquel Creek. We concentrated LWD data collection in Amaya Creek and Lower EBSC, and collected ancillary data in the remaining reaches.

East Branch Soquel Creek begins along a low gradient sag on the trace of the San Andreas Fault, through a narrow cascade section before crossing the Zayante fault and gently smoothing out in a flat alluvial valley. It flows 18km downstream to the confluence of the West Branch where they form Mainstem Soquel Creek. Before reaching the mainstem, the East Branch collects Amaya and Hinkley Creeks. Hinkley Creek is 7km long with a 0.06 average gradient and flows through the Forest of Nisene Marks State Park in a V-shaped valley with steep, unstable hillslopes that are prone to landslides.

Upper EBSC study reach drains 11km^2 and flows downstream 4.6 kilometers from the public entrance of SDSF to Ashbury Falls, a 1.1km stretch through a narrow, high gradient (0.09) canyon (**Table 4.1**). The reach average gradient is 0.07 and, upstream of Ashbury Falls, is a deeply incised canyon with highly unstable slopes dominated by nearly continuous landslides and bank failures that bring large quantities of wood and sediment into the channel (**Figure 4.3**).

Table 4.1. Characteristics of the study reaches examined within this study.

STUDY REACH	STREAM ORDER	GRADIENT	REACH LENGTH	w_{bkf}	DRAINAGE AREA
Amaya Creek	2	0.06	2.1km	6 m	6.5km^2
Lower EBSC	3	0.02	2.1km	12 m	19km^2
Mid EBSC	2	0.03	3.4km	12m	16km^2
Upper EBSC	2	0.07	4.6km	10m	11km^2
Mainstem Soquel	5	0.004	11km	60m	104km^2

Figure 4.3. Unstable slopes bringing LWD and sediment into Upper EBSC (photograph by Neil Lassettre 2001).

4.1.3 Mid EBSC

Mid EBSC has a drainage area of 16km^2 and extends downstream 3.4 kilometers from the base of Ashbury Falls to Fern Gulch over a gradient of 0.03 (**Table 4.1**). Mid EBSC flows into the top of the flat-bottomed alluvial valley out of which Lower EBSC eventually drains.

4.1.4 Lower EBSC

The Lower EBSC study reach begins at the confluence of Fern Gulch and EBSC, extending downstream 2.1 kilometers to the confluence with Amaya Creek (**Table 4.1**). Lower EBSC drains 19km^2 while flowing through a low gradient (0.02)

alluvial valley flanked by a vegetated terrace (intermixed with red alder (*Alnus rubra*), big leaf maple, willow, and coast redwood) that gradually widens downstream (Poole 1993, Cafferata and Poole 1993).

4.1.5 Amaya Creek

Amaya Creek flows 4 kilometers and drains 6.5km^2 before its confluence with Lower EBSC (**Table 4.1**). The tributary flows through an unstable v-shaped canyon with an average gradient of 0.06 (Cafferata and Poole 1993). The basin is intersected by the Zayante Fault zone and is characterized by landslides and significant bank erosion along its length. The study reach covered the lower 2.1 kilometers of Amaya Creek, upstream of the confluence with Lower EBSC.

4.1.6 Mainstem Soquel Creek

Mainstem Soquel Creek flows from the confluence of the East and West Branches downstream 11 kilometers to the Monterey Bay (**Figure 4.1, Table 4.1**). The channel drains 104km^2 and descends at an average gradient of 0.004 through terraced sandstone valley covered with a thin layer of alluvium (Singer and Swanson 1983). The irregularly meandering channel frequently collides with the valley walls producing high sandstone cliffs on the outside of bends. Low flows are typically contained within a shallow bedrock channel and higher flows inundate adjacent floodplains (Singer and Swanson 1983).

4.1.7 Soquel Demonstration State Forest

This study is centered within SDSF, which encompasses 11km^2 along East Branch Soquel Creek (**Figure 4.1**, Cafferata and Poole 1993). The purpose of

California State Demonstration Forests is to demonstrate forest management practices, promote public recreational uses, and host research projects (California Department of Forestry and Fire Protection 2001). Intensive clearcut harvesting between 1870 and 1940 removed most old growth Redwood and douglas-fir trees from SDSF (Poole 1993). The forest today is a mixture of second growth coast redwoods and mixed evergreens on the hillslopes, and riparian hardwoods along streambanks and floodplains. Selective harvest of second growth trees has occurred over the past thirty years. The Forest of Nisene Marks State Park borders SDSF to the southeast, a private timber parcel borders on the east, and to the north and northwest is mainly residential. The southern portion of the forest is bordered by the Olive Springs Quarry, which produces sand, gravel, and asphalt products (**Figure 4.4**, Singer and Swanson 1983).

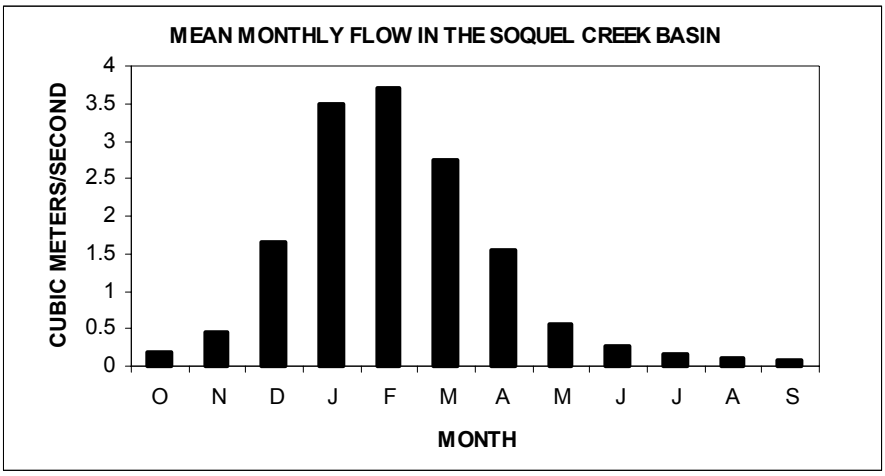
Figure 4.4. The Olive Springs Quarry located at the southern portion of the Soquel Demonstration State Forest (photograph by Neil Lassettre 2001).

4.2 FLOODING HISTORY WITHIN THE SOQUEL CREEK BASIN

4.2.1 Floods of December 1955

Flow in Soquel Creek is variable and is closely tied to the magnitude and intensity of winter storms. At the United States Geological Survey (USGS) stream gauge, Soquel Creek at Soquel, located 4km upstream of the mouth, flow averaged 1.36m^3/second (water years 1952 to 2001). The seasonal hydrograph reflects the Mediterranean climate, variable with base flow in the summer and early fall, and high flow in the wet winter months (**Figure 4.5**). The flow pattern is caused by winter storms that bring warm subtropical moisture and produce intense, short bursts of rainfall (Mount 1995). Storms moving westward from the Pacific Ocean are forced over the Santa Cruz Mountains releasing orographic rainfall. Floods in Soquel Creek tend to develop and dissipate rapidly, normally within six to 24 hours (USACE 1966).

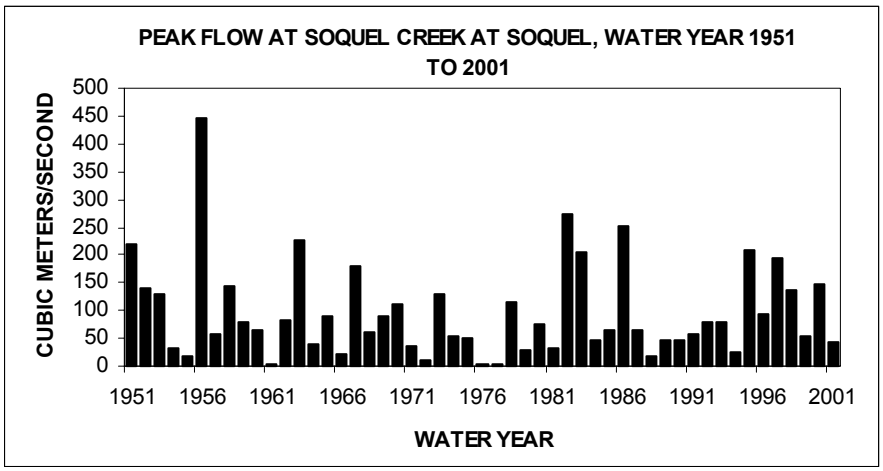
Figure 4.5. Mean monthly flow at the Soquel Creek at Soquel stream gauge from 1952 to 2001.



The largest recorded storm in the Soquel Creek basin was in December 1955 when it rained 21cm in a 72-hour period and Soquel Creek reached a peak of 450m^3/s

(**Figure 4.6**, USACE 1966). Based on the hydrologic record then available, the United States Army Corps of Engineers estimated its return period at 30 years (USACE 1966).

Figure 4.6. Peak flows at the Soquel Creek at Soquel stream gauge.



The town of Soquel occupies 0.3km^2 of floodplain in the valley of lower Soquel Creek (Swanson 1988). The creek flows along the eastern border of the floodplain, within a 20m to 40m wide riparian corridor. Discharges above 170 m^3/s (six to eight year events) overflow into secondary channels that pass through the downtown area, damaging any development in this path. Projected water surface elevations for the 100-year flood cover most of downtown (Swanson 1988). The December 1955 flood covered the town of Soquel to maximum depths of 1.5m, forcing residents and downtown merchants to evacuate. The Soquel Drive Bridge, located in Downtown Soquel, blocked passage of waterborne large woody debris and created a large logjam. The logjam diverted flows out of the channel and into downtown Soquel, and contributed to the failure of the bridge (Swanson 1988). The estimated damages to downtown Soquel amounted to approximately $6 million in 2003 dollars ($1 million in

1965 dollars) (USACE 1966, Federal Reserve Bank 2003). This estimate included the replacement of the Soquel Drive Bridge.

The flooding and related damages led the citizens of Soquel and neighboring Capitola to consider flood control alternatives. The United States Army Corps of Engineers completed a report in 1966 that discussed flood and allied purposes within the basin (USACE 1966). The report developed seven solutions to control flooding, six of which were reservoirs covering the upper reaches, the seventh solution called for downstream channel improvements. The preferred alternative was a multi-purpose flood control, water supply, and recreation reservoir that controlled the upper 81km^2 of the basin, covering 3.4km^2 in area. The Army Corps study estimated a 97% reduction in flood damages if built. The basin supports two types of anadromous salmonids, Steelhead trout (*Oncorhynchus mykiss*) and Coho salmon (*Oncorhynchus kisutch*) and project planners expected the reservoir and dam to significantly reduce fish populations. The planners proposed a fish hatchery to mitigate losses. The Santa Cruz County board of supervisors gave initial approval to the project, but reversed this decision after mixed local reaction

4.2.2 Floods of January 1982

In early January 1982, a large subtropical storm moved across Northern California. While most warm Pacific storms move across the basin in four to six hours, this one met a mass of cold air causing the storm to stall over the Soquel Creek Basin and deposit 28cm of rain over a 28-hour period (Singer and Swanson 1983, USACE 1983). The Soquel Creek at Soquel stream gauge recorded peak flows at 275m^3/second, a 16-year event (Swanson 1988). The recurrence interval for rainfall greatly exceeded

the recurrence interval for streamflow. Over a 24-hour period, the rainfall intensity surpassed that of a 100-year event (Singer and Swanson 1983). The storm soaked the hillsides and triggered landslides throughout the basin. Floods covered downtown Soquel to depths of 1.5m, inundated >120 structures, and caused an estimated $4.2 million dollars ($2.2 million 1982 dollars) in flood damages (USACE 1983, Federal Reserve Bank 2003). Another jam of large woody debris formed behind the Soquel Drive Bridge (newly built after the 1955 flood) and diverted water into the downtown area (**Figure 4.7**).

Figure 4.7. On the left, Soquel Drive Bridge in 1997 during low flow and on the right, Soquel Drive Bridge in 1982 after logjam formed upstream of structure (photographs by Neil Lassettre 1997 and Mitch Swanson 1982).

The flooding again led citizens to consider flood control alternatives. The Soil Conservation Service issued a storm damage recovery plan in 1983 detailing the conditions leading up to storm, the reasons for flooding, and potential measures to

reduce future flooding (Singer and Swanson 1983). Among the recommended measures were the replacement of the Soquel Drive Bridge, installation of structural flood control measures, and the initiation of a watershed planning process. A subsequent report suggested the construction of a 300m floodwall just upstream of downtown Soquel (Swanson 1988). An environmental planning process led to rejection of the structural methods in favor of a new downtown plan focused on land-use policies. The policies suggested relocating or redesigning buildings within the floodplain, and designing a river park along the banks to accommodate high water. The Soquel Village plan also recommended replacing the Soquel Drive Bridge (Oberdorfer and Associates 1990).

4.2.3 Interaction of wood with infrastructure

On eight different occasions over the past 100 years, storms (including those described above) have formed logjams in downtown Soquel upstream of the Soquel Drive Bridge (**Table 4.2**, Singer and Swanson 1983). The logjams diverted flow out of the channel and into the downtown business district, causing severe damage. Santa Cruz County replaced the bridge in 1890, 1922, and 1956 because of wood related flood damage, and replaced the bridge in 2003 to prevent future logjams (**Figure 4.8**, Santa Cruz Sentinel 1955, Singer and Swanson 1983).

Table 4.2. List of logjam occurrence at the Soquel Drive Bridge over the last 100 years (adapted from Singer and Swanson 1983).

DATE	WATER THROUGH TOWN	LOGJAM AT SOQUEL DRIVE BRIDGE	LANDSLIDING IN BASIN
Jan 25, 1898	Unknown	Yes	Yes
Jan 20, 1906	Yes	Unknown	Yes
Jan 1, 1914	Yes	Unknown	Yes
Dec 29, 1934	Yes	Unknown	Yes
Feb 14, 1937	Yes	Yes	Yes
Feb 28, 1940	Yes	Yes	Yes
Dec 26, 1955	Yes	Yes	Yes
Jan 4, 1982	Yes	Yes	Yes

Figure 4.8. New Soquel Drive Bridge alongside 1956 constructed Soquel Drive Bridge (Photograph by Neil Lassettre 2002).

The Soquel Drive Bridge is the most conspicuous debris catching structure in the basin, but the entire stream network is intersected by overcrossings that potentially impede water transported logs. The Soquel Creek Storm Damage Recovery Plan suggests assessing the log passing capacity of all Soquel Creek Basin bridges (Singer and Swanson 1983). Prior to beginning work on this dissertation, we conducted a preliminary study comparing the size of in-channel wood to the dimensions of bridges

and culverts. We measured the dimensions of in-channel wood in Amaya Creek, and measured the dimensions of several bridges and culverts, and found that most pieces of wood were either longer than the width of openings or had a diameter greater than the opening size. The structures we measured were potentially too small to allow log passage and were potential flood hazards (Lassettre, unpublished, 1998). Although not as dramatic as the scene at the Soquel Drive Bridge, damage at culverts and small bridges is both a maintenance and public safety problem. According to a former Senior Resource Planner of Santa Cruz County in charge of watershed management, logjams are the main driver behind culvert maintenance and replacement (Hope, personal communication, 1999).

4.2.4 Current management of LWD

Currently, Santa Cruz County performs only minimal management of in-channel wood due to budget restrictions and difficulty of management (Vance Wagner, Personal Communication 2002). In the recent past, to prevent flooding and damage to structures, the county flood control and public works department manually removed logs from stream channels, cut logs into small pieces to facilitate passage down the network, or moved logs from the center of channel to the margins in order to armor banks and prevent erosion (Singer and Swanson 1983). The activities took place in the late summer and early fall, when flows were the lowest.

As recently as 1986, the Santa Cruz County Planning Department had a program to improve the fisheries resource within the Soquel Creek Basin by identifying and treating sources of chronic sediment input (Santa Cruz County 1986). As part of this program crews identified landslides and logjams that were thought to be damaging to

fish populations and an endangerment to public and private property (Santa Cruz County 1986). Logjams were viewed as barriers to fish migration or barriers that may divert streamflow onto the banks causing erosion and property damage. If access permitted, heavy machinery and crews removed logjams from tributaries and the mainstem of Soquel Creek. The volume of wood removed from the basin is unknown, but a 1986 county survey identified 37 logjams within the basin, 33 of which were thought to be fish barriers and 7 of which were thought to be diversions that cause erosion. The survey recommended removing 25 of the logjams.

4.2.5 Limitations to current management

Unfortunately, few technical woody material management plans exist. Most management of woody material is based on the judgment of field crews and basin managers. While not discounting the expertise of basin management personnel, conventional management techniques may have limited success and significant ecological and economic costs for a basin and its stakeholders.

The major source of woody debris in the Soquel Creek Basin is landsliding that occurs during storms (Singer and Swanson 1983, Santa Cruz County 1986). Most transport of woody material down the channel network occurs during high flow. With this context, the practice of wood removal during low flow conditions makes little sense. Before the 1982 flood, the county removed nearly all logjams from basin streams, yet the flood was the most destructive in recent history, due in part to the interaction of wood with infrastructure (**Figure 4.7**, Hope, Personal Communication 2001, Singer and Swanson 1983). After the flood, a stream inventory revealed the presence of 59 new logjams (Santa Cruz County 1983). The Soquel Creek Storm

Damage Recovery Plan notes that "the major source of logs…was forested hillslopes that failed during the flood," and that "pre-existing in-channel logs and woody debris played little, if any, role in the logjam that formed at the Soquel Drive Bridge" (Singer and Swanson 1983).

Aquatic habitat loss due to wood removal is implicitly recognized by the installation of salmonid habitat enhancement structures in Soquel Creek. The habitat enhancement structures attempt to mimic the physical and ecological effects of LWD and create usable habitat for populations of Steelhead trout (*O. mykiss*) and Coho salmon (*O. kisutch*) (Lassettre 1997). The structures are simply large logs placed in the stream and stabilized with rebar and gabion rock. In one tributary to Soquel Creek, we examined and evaluated several salmonid habitat enhancement structures (Lassettre 1997). A culvert was just downstream of the enhanced reach and woody material was removed to prevent the culvert from plugging (Hope, Personal Communication 1996). To restore the loss of wood created habitat (caused by woody material removal), the county installed habitat enhancement structures. The overall success of these structures in creating and maintaining salmonid habitat was low, consistent with observations elsewhere (Frissell and Nawa 1992, Lassettre 1997). This example illustrates the economic and ecological costs of woody debris removal where wood is removed from a reach to prevent flooding, and then returned to create habitat.

The current management approach views woody material as a problem that must be removed or modified. A more practical, and economically and ecologically sustainable method is to leave natural woody material in the stream and modify bridges and culverts to prevent plugging and flood damage. This requires changing the view

from woody debris as a problem to the view of undersized infrastructure (bridges and culverts) as the problem. By enlarging or modifying bridge and culvert openings, woody material can move freely downstream and perform important geomorphic and ecological services, while not creating flood hazard or requiring labor intensive and economically prohibitive action.

5 METHODS

5.1 LWD CHARACTERISTICS

5.1.1 Jam location

In study reaches, we identified accumulations of LWD, noting the location with a handheld GPS receiver or detailed field notes.

5.1.2 Number of pieces, physical dimensions, and loading

Along Amaya Creek and Lower EBSC, we counted and measured LWD pieces within 1m of the bankfull channel. We defined large woody debris as a piece of wood 1m in length or greater and 10cm in diameter or greater (Harmon et al 1986). In each reach, we tallied the total number of pieces, measured overall piece length and diameter at each end, and determined the loading, or the volume of wood per square meter of bankfull channel (m^3/m^2). When we encountered entire trees within the channel that tapered into a diameter <10cm, we excluded the length of the tree that was less than 10cm in diameter. The loading is a metric commonly used by researchers to compare wood abundance across streams and rivers. The volume of each piece was calculated by:

$$\text{Volume} = (\pi\,((D_1)^2 * (D_2)^2) * L) / 8 \qquad \textbf{[EQUATION 5.1]}$$

where D_1 and D_2 are the diameters of each end and L is the length (Lienkaemper and Swanson 1987). We calculated channel area as the product of the reach length and average bankfull width.

5.1.3 Species

We noted the species type and decay class of each piece. Tree species in the Soquel Creek Basin are a combination of hardwoods and conifers. We identified LWD pieces to the species level where possible thanks to intact branches leaves and bark, more commonly as conifers or hardwoods, or when decayed beyond recognition, as unknown.

5.1.4 Decay class

We assigned each piece to one of five decay classes. Decay classes describe the condition of a piece of wood based the degree of aging (Harmon et al. 1986, O'Connor 2000). Decay class describes the condition of a piece of LWD and is an approximation of a piece's age. The decay class was an ordinal value given to a piece ranging from one (fresh, newly recruited) to five (rotted, long time since recruitment) (Table 5.1). Table 5.1 includes a decay class of zero to indicate a live tree within the channel and influenced on jam formation (Opperman 2002).

Table 5.1. Decay classes used to estimate the condition of LWD pieces in the Soquel Creek basin (after Harmon et al. 1986 and Opperman 2002).

DECAY CLASS	DESCRIPTION
0	Live tree in channel
1	Bark intact; limbs present
2	Bark intact; limbs absent
3	Bark loose or absent
4	Bark absent; surface slightly rotted
5	Surface extensively rotted

5.1.5 Piece type and stability

To obtain a measure of piece stability, or how easily a piece may be moved by streamflow, we first assigned each piece to one of three types based on the presence or

absence of a rootwad, and the presence or absence of a log. We then assigned each piece to one of three categories of stability: presence of a rootwad (ROOTWAD), buried at one or both ends (BURIED), or not buried at all and without a rootwad (NONE) (modified from O'Connor 2000).

5.1.6 Pool formation

To investigate the importance of wood in influencing channel form, predominantly pool formation, we determined the percentage of pools formed by wood and the percent of wood involved in pool formation. We surveyed long profiles to show the effect of wood on channel profile, and the total number of pools and the number of pools that formed in association with wood. To determine the percentage of logs associated with pool formation, we recorded the pool-forming role for each piece. We described a piece as directly involved in pool formation or scour, associated with pool formation (in or adjacent to pool), or having no obvious effect in forming a pool (O'Connor 2000).

5.2 LWD INPUT AND TRANSPORT

5.2.1 LWD input

We qualitatively determined the input mechanism (how pieces arrived at their current position) for each piece in Amaya Creek and Lower EBSC. We qualitatively determined the mechanisms of jam formation, or how the jam formed, in Upper and Mid EBSC, and Mainstem Soquel Creek. For each jam, we determined how the key pieces, or the pieces that formed the foundation of the jams, entered the channel from the forest.

5.2.2 Piece movement and distance moved by pieces

We marked pieces with 2 oval (2.5cm by 5cm) or circular (2.5cm) numbered aluminum tags. At both ends of each piece, we nailed a tag and a piece of orange flagging, and sprayed a small spot of orange neon paint to aid in relocation and recognition. During channel surveys, we recorded log position with respect to known benchmarks. We periodically relocated and established new location of pieces. If a piece moved, we determined the peak flow during the interval between surveys from the Soquel Creek at Soquel stream gauge and used that as the piece moving flow. When we were unable relocate a piece, we simply recorded that the piece moved downstream. Additionally, we recorded the characteristics of pieces newly recruited to the jams.

5.2.3 Mobility

The beginning of this study was marked by a lack of sufficient flows to transport marked LWD pieces. In determining LWD input mechanism, we noted whether a piece had been fluvially transported. In the absence of direct observation of movement, we compared the characteristics of pieces moved by fluvial transport (mobile pieces) to those not moved by fluvial transport (immobile pieces). We looked for significant differences between the two groups and used the significant characteristics in a multiple logistic regression to determine the probability of a piece having moved. The regression enabled me to estimate the probable mobility of pieces based on physical characteristics. We termed the probability that a piece had moved the *mobility factor* (MF), a score between zero and one, with zero being immobile (unlikely to have moved), and one being mobile (likely to have moved). Mobility factor did not predict

when a piece moved, but rather the likelihood that it had been moved to its current position by fluvial transport.

5.2.4 Stochastic model of wood transport

After high flows moved marked pieces, we developed a stochastic model of wood movement and distance traveled by pieces using MF as the main component. We calculated the probability of wood movement as a function of the mobility factor and the return period of flow in another logistic regression. In a stochastic model, the results are presented as probabilities, or the probability that an event occurs. In this simulation, the model calculated the probability of piece movement based upon the logistic regression of MF and return period. We compared this probability to a uniform random number between zero and one; if probability of movement > random number, then the piece moved, if probability of movement < random number, then the piece remained stationary. This method assured the randomness of the simulation (Starfield and Bleloch 1991).

Then for the set of moved pieces, we calculated the distance traveled as a function of the MF, jam spacing, and the return period. We used jam spacing as a scaling factor, as we observed that most moved pieces moved downstream from one jam to the next, consistent with observations by Martin and Benda (2001). The use of jam spacing also enabled me to simulate effects of wood management (cutting of logs, wood removal) on piece travel distance.

We prepared a Monte Carlo simulation within a spreadsheet using theoretical distributions of the characteristics of wood to model wood behavior in Amaya Creek and Lower EBSC. Within each simulated reach, we used an imaginary wood load of

100,000 pieces, which enabled the simulation to predict piece movement and travel distance at very high and very low flows. To simulate wood distributions, we compared the reach distributions of species, decay class, piece type, and cut to random numbers drawn from a flat distribution between zero and one. The simulated distributions of decay class yielded the piece length for each species, as piece length decreased with decay class in each species. We simulated length from random exponential distributions with averages equaling the average length of pieces in each decay class. Since average diameter did not differ significantly across decay classes, we simulated piece diameter from a random number drawn from an exponential distribution with an average equal to the average diameter of each species.

5.2.5 LWD reach types

We used the results of the model simulation and field observations to describe two LWD reach types within the Soquel Creek Basin.

5.2.6 Management of LWD

To simulate the effects of wood management on wood movement and distance traveled, we modified the distributions of wood to reflect the effects of management. For example, we simulated piece size reduction to prevent culvert and bridge plugging by reducing the average size of the simulated wood load.

5.3 ECONOMIC COMPARISON

The purpose of the economic comparison was to compare the long and short term costs associated with a conventional wood management approach to costs associated with a "wood passing" approach. The basic comparison categories were the

costs of wood removal, culvert repair and replacement, bridge repair and replacement, flooding damages associated with wood debris, and the costs of aquatic habitat loss and habitat enhancement projects. We obtained either the yearly or 100-year costs for each category, and then projected or divided those amounts by 100. We obtained estimates from historical sources and converted dollar figures into current values using the Consumer Price Index (CPI) (Federal Reserve Bank 2003):

Current cost = historical cost (current CPI / historical CPI) [**EQUATION 5-2**]

We spoke with local and statewide experts, and consulted written materials to determine the management costs of woody material. The County of Santa Cruz is in charge of managing of the basin and was the starting point for information. We spoke with current and former personnel of the Planning Department, which is responsible for stream enhancement and riparian corridor management. We also spoke with personnel from the Department of Public Works and Flood Control, which is responsible for maintaining roads and bridges within the county. The California Department of Transportation maintains bridge maintenance records for all state highway bridges and some heavily traveled local bridges. We contacted personnel at the structure hydraulics and hydrology section to gain access to these records. We located written material through literature searches at the University of California (UC) Berkeley and UC Santa Cruz libraries, and the Water Resources Center Archives at UC Berkeley. We visited the Internet sites of local, state, and federal agencies to look for more information on management costs of LWD, and to consult or download publications not available at the above libraries.

6 LWD CHARACTERISTICS

6.1 JAMS

Jam spacing was lowest in steep narrow streams and decreased downstream, similar to figure 2.1. Amaya Creek and Lower EBSC contained the most jams and had average jam spacing near 100m. Jam frequency decreased and jam spacing increased from Mid to Lower EBSC and into the mainstem. Jam spacing along the mainstem was nearly 3 kilometers.

Table 6.1. The number of jams in each study reach and the average interval between each jam, or the jam spacing (reach length/number of jams).

STUDY REACH	# LWD JAMS	GRADIENT	REACH LENGTH	JAM SPACING
Amaya Creek	21	0.06	2.1km	100m
Upper EBSC*	36	0.07	4.6km	97m
Mid EBSC	5	0.03	3.4km	680m
Lower EBSC*	3	0.02	2.1km	700m
Mainstem Soquel Creek*	4	0.004	11km	2750m

6.2 NUMBER OF PIECES AND LOADING

In Amaya Creek, we counted 532 pieces of wood along a length of 2.1km for an average of 25 pieces/100m (**Table 6.2**). The loading in Amaya Creek was $0.093m^3/m^2$, which lies within the range of observed values for North American streams (**Tables 6.2 and 6.3**). In Lower EBSC, we counted 132 pieces along a length of 2.1km for an average of 6 pieces/100m (**Table 6.2**). The loading along Lower EBSC was $0.005m^3/m^2$ (**Table 6.2**), which lies at the low end of the range of observed values for North American streams (**Table 6.3**).

Table 6.2. The number of pieces observed and the volume of wood in each study reach.

METRIC	AMAYA CREEK	LOWER EBSC
# Conifer pieces	332	41
Conifer volume (m^3)	842.86	75.77
# Hardwood pieces	34	53
Hardwood volume (m^3)	22.6	37.72
# Unknown pieces	166	38
Unknown volume (m^3)	314.45	12.86
Total pieces	532	132
# pieces/100m	25	6
Total volume (m^3)	1179.91	126.35
Loading (m^3/m^3)	0.093	0.005

Table 6.3. LWD loading in Amaya Creek and Lower EBSC compared to streams flowing through disturbed and undisturbed Coast Redwood forests in Redwood National Park in Northwest California.

LOCATION	FOREST TYPE	LOADING	REFERENCE
Southern France	*Salix spp., Populus spp., Alnus spp.*	$2.72 * 10^{-6}$ to $6.34 * 10^{-6}$	Piegay et al. 1999
LOWER EBSC	**Coast Redwood (*Sequoia sempervirens*)**	**0.005 m^3/m^2**	**THIS STUDY**
New Hampshire	*Picea-Tsuga*	0.011 m^3/m^2	Harmon et al. 1986
Alaska	Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*),	0.019 m^3/m^2	Harmon et al. 1986
Idaho	*Picea engelmannii*	0.0276 m^3/m^2	Harmon et al. 1986
Oregon	Douglas-fir (*Pseudotsuga menziesii*)	0.057 m^3/m^2	Harmon et al. 1986
Tennessee	*Assorted hardwood*	0.063 m^3/m^2	Harmon et al. 1986
British Columbia, Canada	Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*)	0.068 m^3/m^2	Harmon et al. 1986
AMAYA CREEK	**Coast Redwood (*Sequoia sempervirens*)**	**0.093 m^3/m^2**	**THIS STUDY**
Northern California	Coast Redwood (*Sequoia sempervirens*)	0.181 m^3/m^2	Keller and MacDonald 1983

As discussed in Chapter 2, loading must be taken into context with the channel dimension (bankfull width and reach length), as similar loadings may represent dissimilar volumes (**Tables 2.4** and **2.5**). The total volume of LWD in Amaya Creek was 2370m^3, while the total volume of woody debris in Lower EBSC was 126m^3.

Amaya Creek contains more LWD than Lower EBSC as measured by the number of pieces per 100 meters, loading, and total volume of wood (**Table 6.2**).

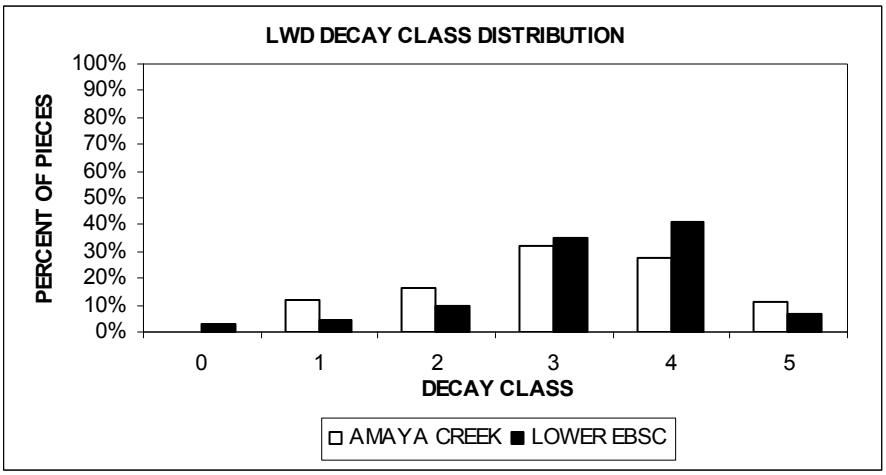
6.3 SPECIES

In Amaya Creek, conifers dominated the total number of pieces and the total load. In Lower EBSC conifers accounted for most of the load, and but fewer pieces than hardwoods (**Table 6.2**). The species identified were big leaf maple (*A. macrophyllum*), red alder (*A. rubra*), tanoak (*Lithocarpus densiflora*), coast redwood (*S. sempervirens*), and douglas-fir (*Psuedotsuga menziesii*).

6.4 DECAY CLASS

The frequency distribution of decay classes in Amaya Creek showed that most pieces fall in decay classes three and four (**Figure 6.1**). The frequency distribution of decay classes in Lower EBSC was slightly skewed to the right, with most pieces falling into decay classes four and three, and relatively few pieces in classes one, two, and five (**Figure 6.1**). The results show that the LWD load in Amaya Creek was slightly newer, or less decayed, than the load in Lower EBSC. The distributions may represent differences in input rate, with Amaya Creek having a higher rate of input and more new pieces, or a result of the species distribution. Hardwoods decay more rapidly than conifers, thus decay class distributions skewed toward older pieces (decay class five) may indicate a higher percentage of hardwoods (Harmon et al. 1986). **Table 6.2** shows that conifers dominated LWD in Amaya Creek, while hardwoods were more frequent in Lower EBSC.

Figure 6.1. LWD decay classes in Amaya Creek and Lower EBSC.



6.5 LENGTH OF PIECES

The length distribution of LWD pieces in Amaya Creek and Lower EBSC is shown in **Figures 6.2** and **6.3**. The mean piece length in Amaya Creek was slightly shorter than Lower EBSC, although not statistically significant (Welch Anova F-test for means with unequal variances, $p = 0.39$) (**Table 6.4**). Many researchers use piece length relative to bankfull width as an estimator of piece movement (Bilby 1984). Pieces shorter than bankfull width have less contact with banks and potential channel obstructions, and are more easily moved by streamflow. The ratio of piece length to bankfull width (L/w_{bkf}) was significantly greater (Welch Anova F-test, $p<0.0001$)) in Amaya Creek than in Lower EBSC (**Table 6.5**). Although pieces in Amaya Creek are shorter than pieces in Lower EBSC, the pieces in Lower EBSC may be more mobile because they are significantly shorter relative to bankfull width. The average length of hardwoods was also greater than conifers in each reach (**Table 6.4**).

Figure 6.2. Length distribution of pieces in Amaya Creek (6.90m ± 0.33, mean ± standard error).

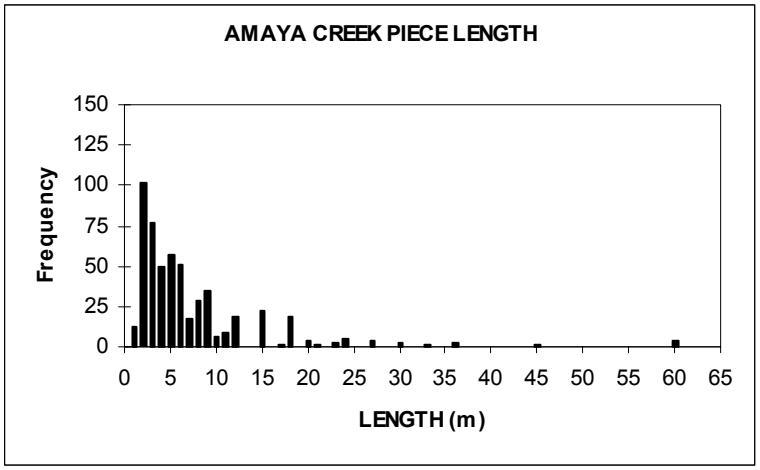


Figure 6.3. Length distribution of pieces in Lower EBSC (7.44m ± 0.54, mean ± standard error).

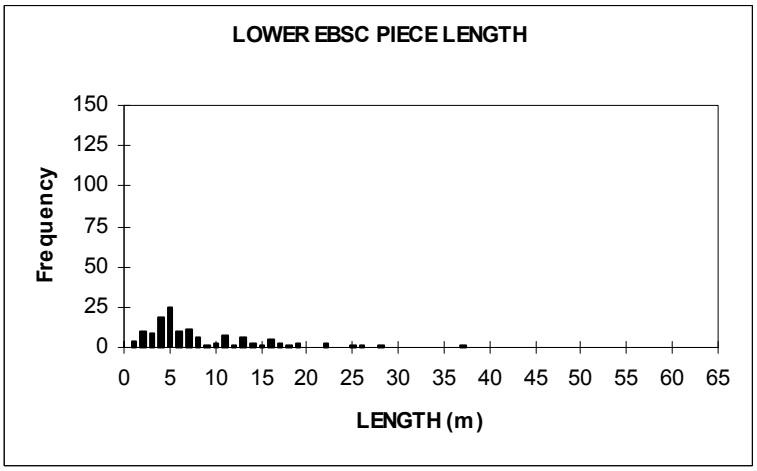


Table 6.4. The average length of pieces in Amaya Creek and Lower EBSC (mean ± standard error) (*Welch Anova F-test for means with unequal variances, $p<0.01$).

	AMAYA CREEK	LOWER EBSC
MEAN LENGTH (M)	6.90 ± 0.33	7.44 ± 0.54
MEAN LENGTH/w_{bkf}*	0.99 ± 0.06	0.62 ± 0.04
MEAN HARDWOOD LENGTH (M)	10.41 ± 1.20	9.58 ± 0.96
MEAN CONIFER LENGTH (M)	7.78 ± 0.49	6.39 ± 0.96

The mean length of pieces decreased as pieces aged or moved from decay class one to decay class five (**Table 6.5**). As pieces age, decay, and abrade, they break down into shorter pieces. Thus, pieces may become more mobile (as a result of shorter length) as they age and move from decay class one to decay class five.

Table 6.5. The mean length of pieces across decay classes (mean± standard error). As pieces age, their average length becomes shorter.

DECAY CLASS	MEAN LENGTH (M)	MEAN L / w_{bkf}	MEAN CONIFER LENGTH (M)	MEAN HARDWOOD LENGTH (M)
1	15.75 ± 1.08	2.21 ± 0.16	16.26 ± 1.33	15.08 ± 1.65
2	11.14 ± 1.16	1.57 ± 0.18	11.73 ± 1.49	11.10 ± 1.71
3	5.47 ± 0.29	0.72 ± 0.05	4.95 ± 0.39	8.48 ± 1.14
4	4.30 ± 0.20	0.53 ± 0.03	4.00 ± 0.25	6.36 ± 0.93
5	4.39 ± 0.33	0.57 ± 0.06	4.57 ± 0.44	2.93 ± 0.49

6.6 AVERAGE DIAMETER OF PIECES

The frequency distribution of LWD piece diameter for Amaya Creek and Lower EBSC is shown in **Figures 6.5** and **6.6**. The mean diameter of all pieces was significantly greater in Amaya Creek than in Lower EBSC (Welch Anova F-test, $p < 0.0001$) (**Table 6.6**). This difference in diameter is most likely related to the species distribution of the two reaches. **Table 6.6** shows that the average diameter of conifers was significantly greater than hardwoods in Amaya Creek (Welch Anova F-test, $p < 0.0001$) and Lower EBSC (Welch Anova F-test, $p < 0.0001$), and in total (**Table 6.6**). Amaya Creek contains a greater proportion of conifers (63%) than Lower EBSC (31%), explaining the difference in piece diameter between the two reaches.

Figure 6.4. Diameter distribution of pieces in Amaya Creek (0.46m ± 0.01, mean ± standard error).

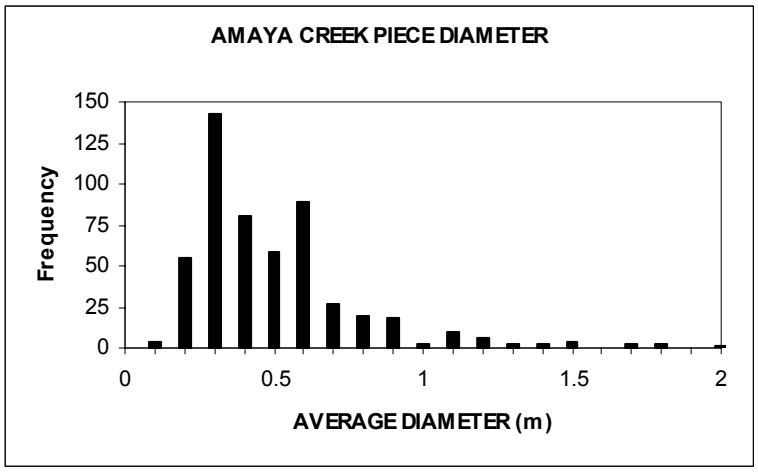


Figure 6.5 Diameter distribution of pieces in Lower EBSC (0.35m ± 0.02, mean ± standard error).

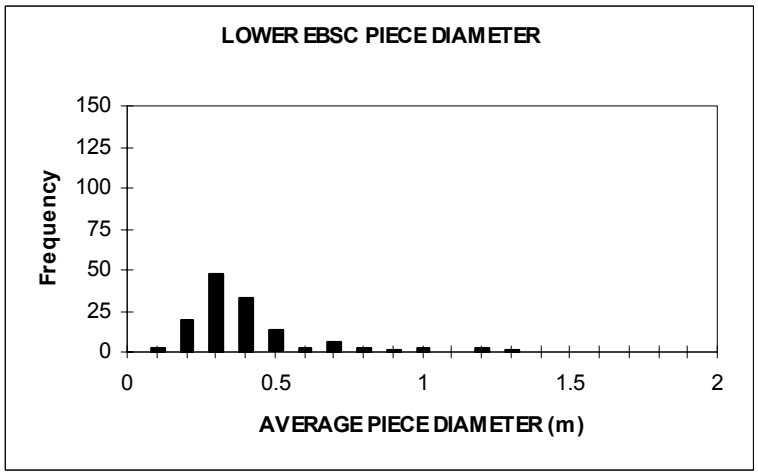


Table 6.6. The mean diameter of pieces in Amaya Creek and Lower EBSC (mean ± standard error) (Welch Anova F-test for means with unequal variances, p<0.0001).

	AMAYA CREEK	LOWER EBSC	ALL PIECES
MEAN DIAMETER (M)	0.46 ± 0.01*	0.35 ± 0.02	0.44 ± 0.01
MEAN CONIFER DIAMETER (M)	0.48 ± 0.02*	0.52 ± 0.03*	0.48 ± 0.02*
MEAN HARDWOOD DIAMETER (M)	0.29 ± 0.05	0.27 ± 0.03	0.28 ± 0.02

We found no significant differences in average diameter across decay classes for either species (**Table 6.7**). Hardwood diameter increased from decay class one to decay class five, but the increase was not statistically significant. Piece diameter is not reduced significantly as pieces age unlike piece length, which decreases with piece age (**Table 6.5**).

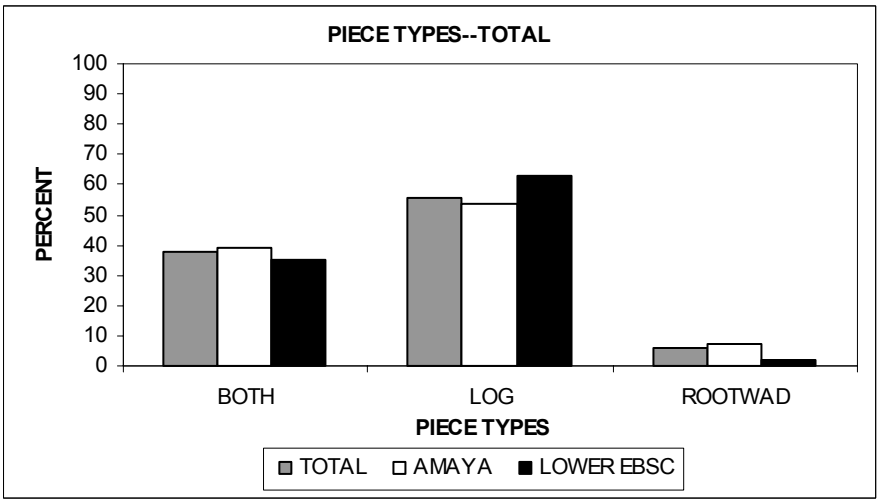
Table 6.7. The average diameter across decay classes (mean ± standard error).

DECAY CLASS	MEAN CONIFER DIAMETER (M)	MEAN HARDWOOD DIAMETER (M)
1	0.51 ± 0.04	0.21 ± 0.02
2	0.42 ± 0.03	0.27 ± 0.02
3	0.50 ± 0.03	0.30 ± 0.05
4	0.47 ± 0.03	0.31 ± 0.03
5	0.56 ± 0.06	0.34 ± 0.08

6.7 PIECE TYPES

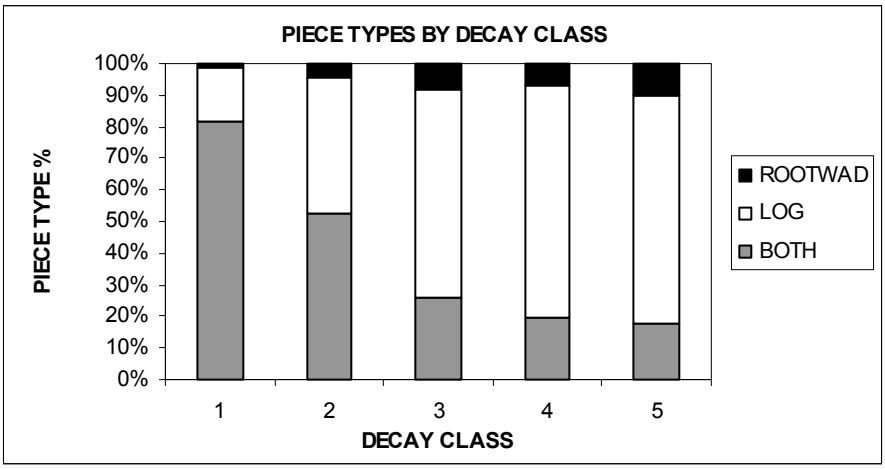
The distribution of piece types is shown in **Figure 6.6**. In Amaya Creek, 39% of pieces were logs with rootwad, 54% of pieces were logs with no rootwad, and 7% were rootwads with no logs. In Lower EBSC, 35% of pieces were logs with rootwad, 63% were logs with no rootwad, and 2% were rootwads with no logs.

Figure 6.6. Piece types by reach.



As pieces aged, the number of logs (LOG) and the number of rootwads (ROOTWAD) without logs increased, while the number of whole trees, those with rootwads and logs (BOTH), decreased (**Figure 6.7**). The data indicate that as pieces aged, they broke down from whole trees into individual logs and rootwads. In both conifers and hardwoods, this same trend was apparent, although the relationship appeared much stronger in conifers.

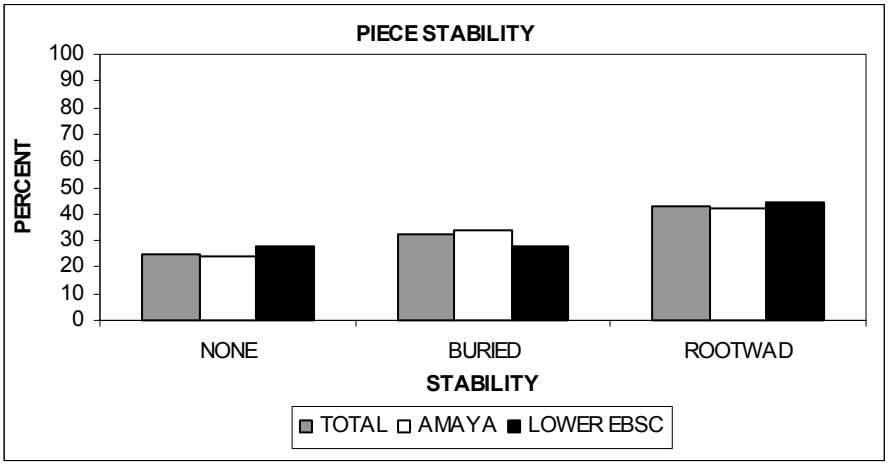
Figure 6.7. Piece types across decay classes for both Amaya Creek and Lower EBSC.



6.8 STABILITY

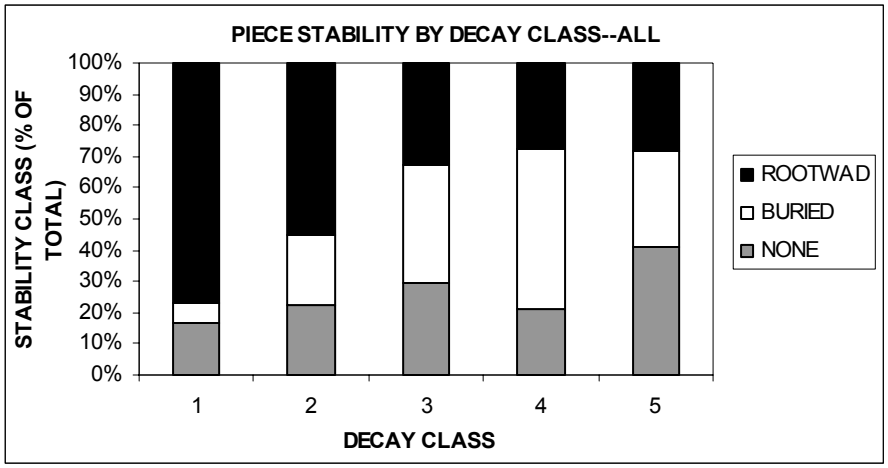
Both reaches showed similar trends in stability. In Amaya Creek, we found that 34% of pieces were buried, 42% had rootwads, and 24% were not buried and had no rootwads (**Figure 6.8**). In Lower EBSC, we found that 28% of pieces were buried, 44% had rootwads and were not buried, and 28% were not buried and had no rootwads (**Figure 6.8**).

Figure 6.8. Piece stability classes for Amaya Creek, Lower EBSC, and the total for both reaches.



We found that as pieces moved from decay class one to five, the percent of buried pieces and the percent of logs that were not buried increased (**Figure 6.9**). Pieces become less stable with age, as shown by the increase in unburied logs. The increase in the number of buried pieces may indicate piece transport and subsequent burial after storms.

Figure 6.9. The stability of pieces across decay classes.



6.9 INFLUENCE OF LWD ON POOL FORMATION

We surveyed longitudinal profiles along the lower 800 meters of channel of Amaya Creek (**Figure 6.10**), and along the lower 2.1 kilometers of Lower EBSC (**Figure 6.11**). The survey in Amaya Creek encompassed eight LWD accumulations, labeled in **Figure 6.10** as AC-1 to AC-8, and three LWD accumulations in Lower EBSC, labeled in **Figure 6.11** as LE-1 to LE-3. In Amaya Creek, 80% of pools were associated with pieces of in-channel wood. In Lower EBSC 75% of pools were associated with LWD. We compared the percent of debris formed pools to other similar gradient coast redwood (*S. sempervirens*) streams and found that the observed values fell within the range of other observed values (**Table 6.8**).

Figure 6.10. Long profile of Amaya Creek showing location of wood formed pools, bedrock and boulder formed pools, and jams. Seventeen out of 21 pools are formed by wood while the remaining pools are formed by bedrock or boulders.

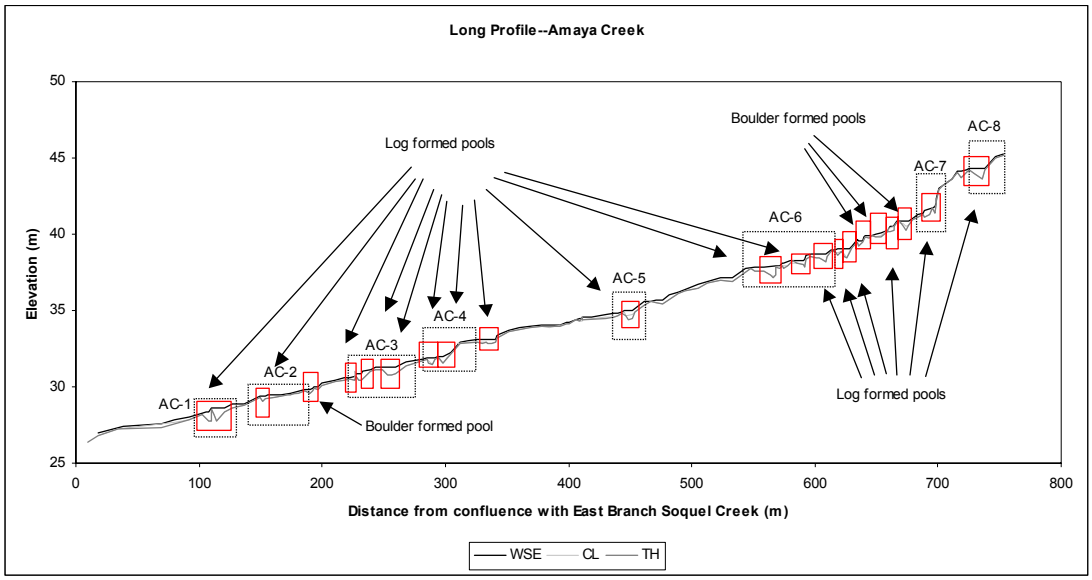


Figure 6.11. Long profile of Lower EBSC showing the location of wood formed pools, bedrock and boulder formed pools, and jams. Nine out of 12 pools are formed by wood, while bedrock or boulders form the remaining pools.

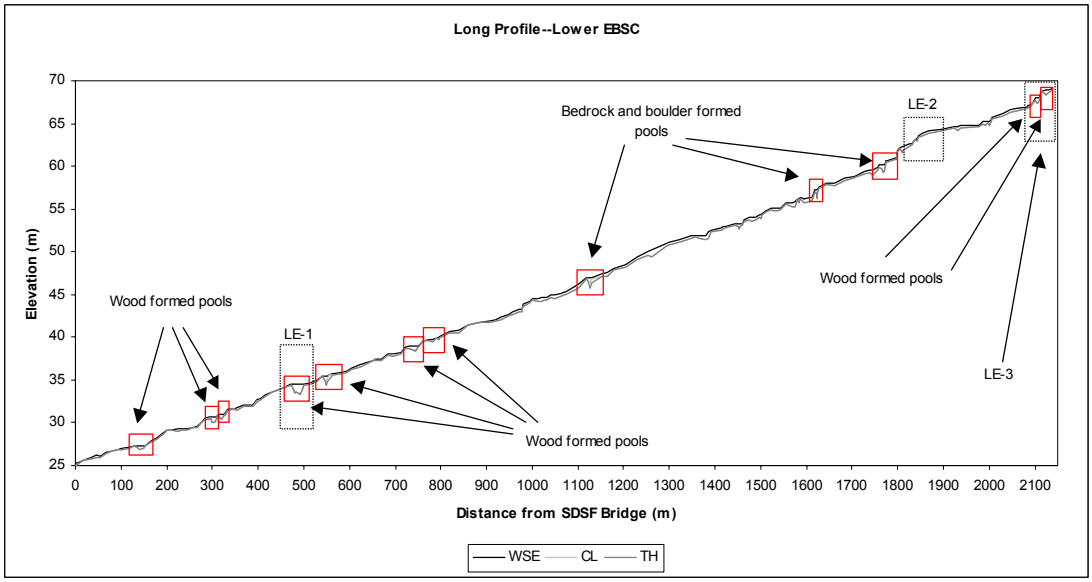


Table 6.8. The percentage of LWD formed pools along the lower 800 meters of Amaya Creek and the lower 2.1 kilometers of Lower EBSC, and values for Coast Redwood dominated streams (values taken from Keller and MacDonald 1983).

LOCATION	HISTORY	LWD POOLS
Little Lost Man Creek Upper	Undisturbed	100%
Little Lost Man Creek Lower	Undisturbed	90%
Hayes Creek	Undisturbed	83%
N Fork Caspar Creek Lower	Disturbed	82%
AMAYA CREEK	DISTURBED	80% (17/21)
Lost Man Creek Upper	Disturbed	79%
LOWER EBSC	DISTURBED	75% (9/12)
Larry Damm Creek	Disturbed	59%
Lost Man Creek Lower	Disturbed	57%
Prairie Creek Zig Zag No.2	Undisturbed	50%

7 WOOD INPUT AND TRANSPORT IN THE SOQUEL CREEK BASIN

7.1 LWD INPUT

We observed four mechanisms of LWD input: bank erosion, fluvial transport, landsliding, and windthrow. In Amaya Creek the dominant input mechanism was fluvial transport, followed by landsliding and bank erosion (**Figure 7.1**). The most frequent observation was "unknown," as often times it was difficult to determine the input mechanism. The dominant input mechanism along Lower EBSC was fluvial transport, but the primary mechanisms by which wood entered from the surrounding forest were bank erosion, landslides, and windthrow (**Figure 7.1)**.

We observed four mechanisms of jam formation: bank erosion, landsliding, riparian obstruction, and windthrow. Most jams in Upper EBSC formed through landslides, while a fraction formed through bank erosion, and windthrow (**Figure 7.2**). Most of the jams in Mid EBSC formed through riparian obstruction and the remainder formed through bank erosion, where fluvially transported pieces collected behind channel spanning fallen logs (**Figure 7.2**). Riparian obstruction jams formed when living trees near the edge of the channel or at the head of a forested island obstructed fluvially transported pieces. Six jams along Mainstem Soquel Creek formed through bank erosion, while the other formed through a combination of landsliding and bank erosion (**Figure 7.2**). The most significant collection of LWD occurred out of the bankfull channel on a gravel bar. The accumulation was composed of highly decayed pieces deposited by fluvial transport.

Figure 7.1 . LWD input mechanisms in Amaya Creek and Lower EBSC.

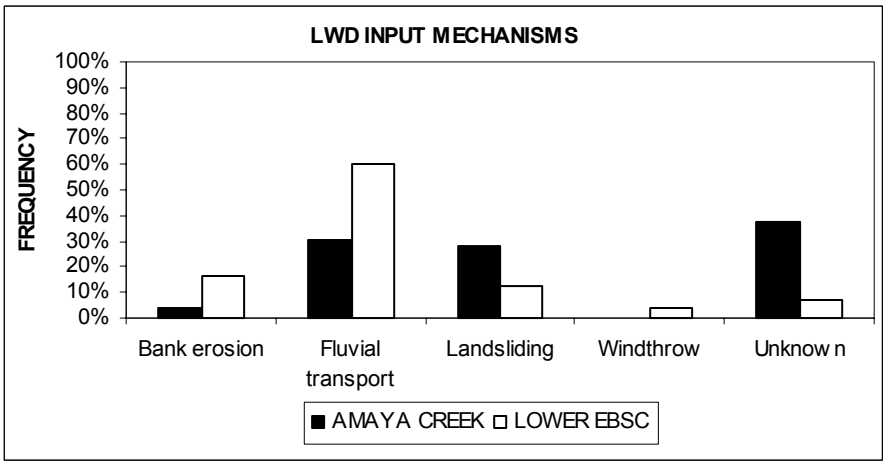
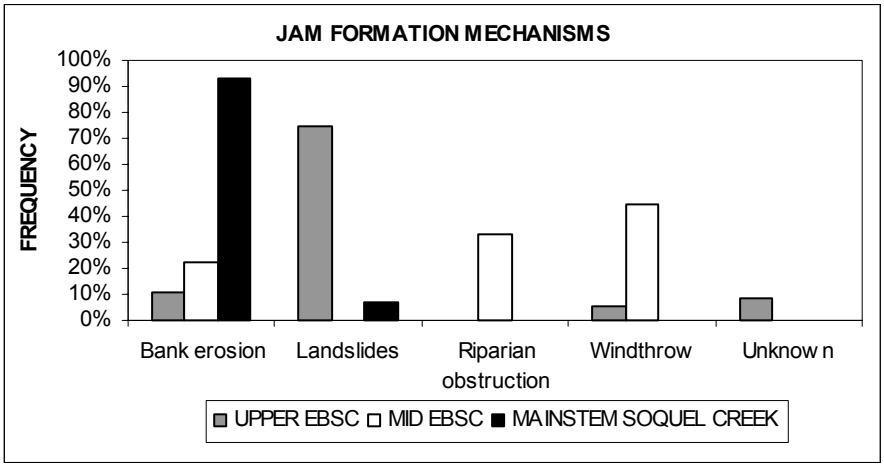


Figure 7.2. Jam formation mechanisms in Upper and Mid EBSC, and Mainstem Soquel Creek.



7.2 LWD TRANSPORT

7.2.1 Piece movement and distance

Despite few large flows, significant piece movement did occur. Two separate storms moved between 12% and 25% of all marked pieces (**Table 7.1**). We recovered

approximately 25% of moved pieces, a value demonstrating the difficulty of finding and locating mobilized LWD.

Recovered pieces moved downstream from jam to jam. Most recovered pieces moved one jam interval, from their original jam to the next downstream jam, but a few moved multiple jam intervals, skipping one or more jams before coming to rest (**Table 7.2**). Benda and Martin (2000) suggest that the distance a piece moves is a multiple of jam spacing, a behavior observed in this study.

Over the time period from 12 July 2001 to 28 November 2001, we marked 154 LWD pieces. Eighteen pieces moved after a peak flow of $42m^3/s$ (a 1.5 year return period) on 2 December 2001, and 37 pieces moved after a peak flow of $81m^3/s$ (a 2.5 year return period) on 16 December 2002 (**Figure 7.3, Table 7.1**). In both events, we recovered pieces that had moved from their original jam and came to rest within or near downstream jams. Five of the thirteen recovered pieces moved from their original jam to next downstream jam (one jam interval), two pieces moved two jam intervals downstream, and the remaining pieces either moved to a newly formed jam or just downstream.

After the 2.5-year flow, we recovered nine of the 37 mobilized pieces (**Table 7.1**). The conspicuous event during this period was the re-arrangement of jam LE-1 (**Figure 6.11**). A large redwood log partially buried within the stream bank and with an attached rootwad, originally anchored the jam. Streamflow transported this large piece 28m downstream to the head of a riparian island. This event caused 23 out of the 28 pieces making up the jam to move downstream. We recovered five out of the 23 moved pieces: three were associated with a newly formed jam anchored by the original LE-1

key piece and two were 100m downstream from the original jam on the channel margin. We failed to relocate the remaining pieces. In its new location, the large redwood formed another jam made up of 30 pieces.

Figure 7.3. Flood frequency curve for Soquel Creek at Soquel stream gauge.

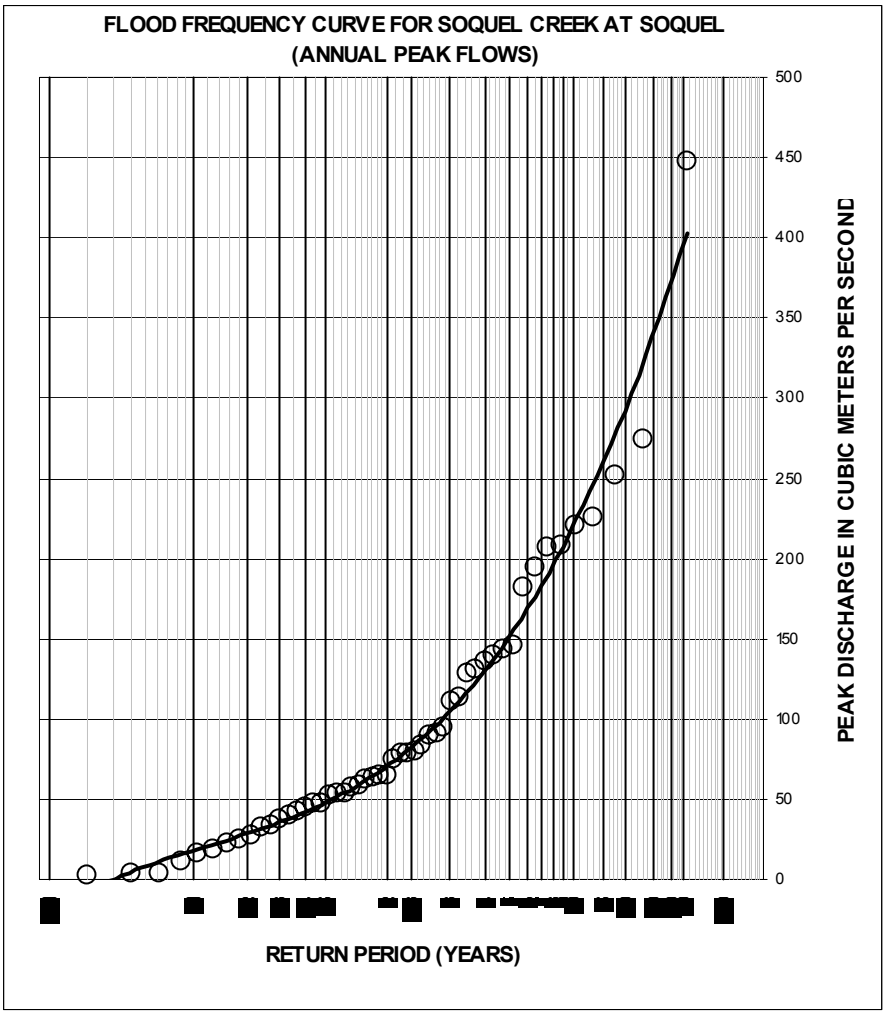


Table 7.1. The number of marked pieces, the number of pieces that moved after adequate flows, and the number of pieces recovered after those flows.

RETURN PERIOD	# PIECES MARKED	# OF PIECES MOVED	# PIECES RECOVERED
1.5	154	18	4
2.5	154	37	9

Table 7.2. The number of jam intervals and the number of pieces moved.

RETURN PERIOD	NEAR ORIGINAL JAM	ONE JAM INTERVAL	TWO OR MORE JAM INTERVALS
1.5	1	2	1
2.5	5*	3	1
TOTAL	6	5	2

7.2.2 Mobility

We found significant differences in mean piece length to bankfull width ratio and mean piece diameter between mobile (fluvially transported) and immobile pieces (all others) (Kruskal-Wallis one-way ANOVA, $p<0.001$). Mobile pieces were only about half as long as immobile pieces, and were a third less in diameter (**Table 7.3**). The differences fit with previous observations that piece dimension, particularly length compared to bankfull width, are a rough predictor of piece movement (Bilby 1984). Bilby (1984), Lienkaemper and Swanson (1987), and Swanson and Nakamura (1994) observed that most transported LWD pieces were logs shorter than bankfull width (length/bankfull width <1.0).

Table 7.3. Mean length (m), length/bankfull width, and diameter of moved and unmoved pieces (*Kruskal-Wallis one-way ANOVA, $p<0.001$).

	IMMOBILE PIECES	MOBILE PIECES
MEAN L/BFW, ALL PIECES*	1.36 ± 0.08	0.47 ± 0.02
MEAN L/BFW, CONIFER*	1.34 ± 0.09	0.48 ± 0.03
MEAN L/BFW, HARDWOOD*	1.45 ± 0.12	0.46 ± 0.05
MEAN DIAMETER (m), BOTH REACHES*	0.49 ± 0.02	0.34 ± 0.01
MEAN DIAMETER (m), CONIFER*	0.53 ± 0.02	0.36 ± 0.02
MEAN DIAMETER (m), HARDWOOD	0.29 ± 0.03	0.24 ± 0.01

Age had a strong influence on piece mobility. The highest occurrences of mobile pieces were in decay classes three and four (**Figure 7.3**). **Table 6.5** showed that average piece length decreased from decay class one to decay class five, and in decay class three the mean length/bankfull width (0.72) dropped below 1.0. Nearly 90% of mobile pieces were logs without attached rootwads (**Table 7.4**). **Figure 6.7** shows that the percent of logs increased from decay class one to decay class five, while the percent of pieces with both a rootwad and log decreased. New pieces enter a stream as whole trees (both log and rootwad) and gradually break down into separate logs and rootwads. The logs are increasingly mobile as they age and break down into smaller pieces.

Other apparent influences on piece mobility were piece stability and whether or not the piece had been cut. Most mobile pieces had no stability influences such as burial in the bed or banks, or possessing a rootwad (**Table 7.4**). Cut pieces were pieces that were obviously cut by a chainsaw during channel maintenance activities or from upslope logging operations. Mobile pieces were cut slightly more often than immobile pieces (**Table 7.4**).

Figure 7.4. Piece mobility by decay class. Most mobile pieces were within decay classes three and four.

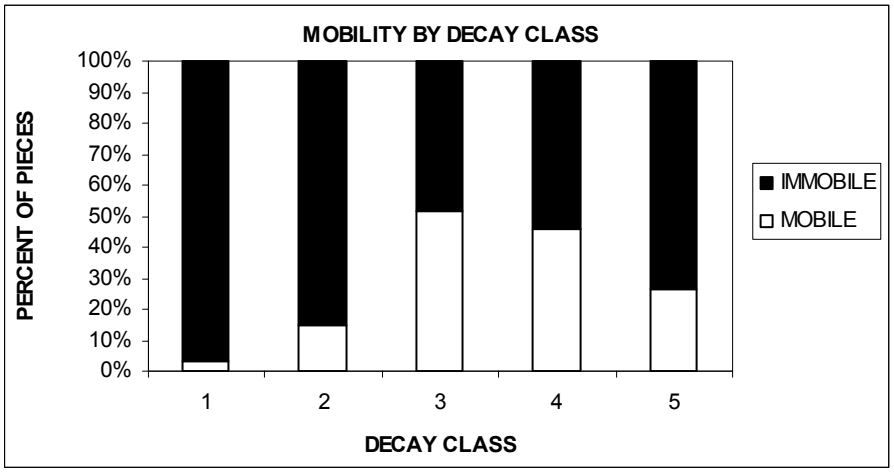


Table 7.4. The number mobile and immobile pieces in stability, piece type, and cut categories.

		MOBILE	IMMOBILE
STABILITY	ROOTWAD	28	180
	BURIED	75	143
	NONE	115	60
TYPE	ROOTWAD	7	35
	LOG	202	169
	BOTH	24	189
CUT	UNCUT	232	110
	CUT	45	40

We used piece length to bankfull width, average diameter, species, decay class, piece stability, piece type, and cut presence in a multiple logistic regression to calculate the probability that a piece was mobile (DF = 19, ChiSquare = 213.1255, $p<0.0001$, $r^2 = 0.42$) (**Equation 7-1**). M_1, m_2, and m_3 are constants, and length/bankfull width and average diameter are continuous variables. The remaining variables are categorical responses whose values are shown in **Table 7.5**. We nested decay class within species and piece stability within piece type. By themselves, species (DF = 1, Wald ChiSquare = 0.0095, p = 0.92) and piece type (DF = 2, Wald ChiSquare = 0.0196, p = 0.99) had little effect on piece movement, but age of species (DF = 8, Wald ChiSquare = 28.36, p = 0.0004) and stability of piece types (DF = 5, Wald ChiSquare = 12.42, p = 0.03) showed a significant effect. We used the results of **Equation 7-1** to compare the probable mobility of pieces, and termed this probability the *mobility factor* (MF). The mobility factor was a score between zero and one, where zero was very immobile and one was very mobile.

Mobility factor = $1/(1 + \exp(m_1 + m_2 * (L/w_{bkf}) + m_3 * \text{mean diameter} + \text{decay class[species]} + \text{species} + \text{stability[type]} + \text{type} + \text{cut})$ [**EQUATION 7-1**]

Table 7.5. Values for categorical responses in Equation 7-1.

RESPONSE		VALUE
SPECIES	DECAY CLASS	
CONIFER	1	0
	2	1.67955557866521
	3	3.60465633893279
	4	2.65551070586192
	5	2.07233282950915
HARDWOOD	1	0
	2	6.77202959556078
	3	8.52951990349176
	4	9.99501622809865
	5	6.71897410313952
SPECIES		
CONIFER		2.86683119869689
HARDWOOD		-2.86683119869689
TYPE	STABILITY	
BOTH	NONE	3.81119896016153
	BURIED	-7.05451645549555
	ROOTWAD	3.24331749533403
LOG	NONE	0.304076415881759
	BURIED	-0.970767959449079
	ROOTWAD	0.66669154356732
ROOTWAD	NONE	NA
	BURIED	-4.73942268657897
	ROOTWAD	4.73942268657897
TYPE		
BOTH		-0.9233919014563
LOG		4.04505408203721
ROOTWAD		-3.12166218058091
CUT		
UNCUT		-0.351078876976383
CUT		0.351078876976383

Mean MF increased with decay class, except in decay class five, which decreased slightly (**Table 7.6**). One reason for this decrease may be that pieces from decay classes three and four were transported downstream out of the reach, leaving larger more stable (lower mobility factor) pieces in decay class five. Nonetheless, mean mobility factors of decay classes three, four, and five were significantly greater than decay classes one or two for all piece and for conifers (**Table 7.6**, each pair, students t-test, $p < 0.001$). There is no significant difference in the mobility factor between species (students t-test, $p = 0.19$), but hardwoods decay more rapidly than conifers, so mobility factor will increase more rapidly in hardwoods than in conifers (Harmon et al. 1986).

Mobile pieces had a significantly higher MF than immobile pieces (**Table 7.7,** students t-test $p<0.001$). The mean MF of mobile pieces across all decay classes was $\geq$ 0.4 or greater, while the average for immobile pieces was $\leq$ 0.4 for all classes. Pieces with mobility factors $\geq$ 0.4 appear to be more easily moved by streamflow.

Table 7.6. Mobility factor by decay class. Decay classes three, four, and five had significantly greater mobility factors than decay classes one and two (mean ± standard error, *each pair, students t-test p<0.001).

	TOTAL	CONIFER	HARDWOOD
DECAY CLASS 1	0.15 ± 0.01	0.02 ± 0.01	0.000018 ± 0.00001
DECAY CLASS 2	0.14 ± 0.02	0.14 ± 0.02	0.13 ± 0.05
DECAY CLASS 3	0.50 ± 0.03*	0.53 ± 0.03*	0.40 ± 0.06*
DECAY CLASS 4	0.47 ± 0.02*	0.45 ± 0.03*	0.62 ± 0.07*
DECAY CLASS 5	0.36 ± 0.05*	0.36 ± 0.05*	0.37 ± 0.15
TOTAL	**0.32 ± 0.02**	**0.33 ± 0.02**	**0.28 ± 0.04**

Table 7.7. Mobility factor of mobile versus immobile pieces by decay class (mean ± standard error, * students t-test p < 0.001).

	MOBILE	IMMOBILE
DECAY CLASS 1	0.55 ± -----	0.006 ± 0.003
DECAY CLASS 2*	0.45 ± 0.07	0.09 ± 0.02
DECAY CLASS 3*	0.71 ± 0.03	0.30 ± 0.03
DECAY CLASS 4*	0.57 ± 0.03	0.39 ± 0.03
DECAY CLASS 5*	0.61 ± 0.07	0.24 ± 0.05
TOTAL*	**0.62 ± 0.02**	**0.18 ± 0.01**

7.2.3 Stochastic model of wood transport

We used the mobility factor of moved pieces and the return period of piece moving flows in a logistic regression to calculate the probability of wood movement (**Equation 7-2**). In the equation, m_1, m_2, and m_3 are constants and mobility factor and the return period are continuous variables.

Probability of movement = $m_1 + m_2 * MF + m_3 * \ln$ (return period) [**EQUATION 7-2**]

The small sample of recovered pieces was inadequate to demonstrate a strong relationship between flow and distance moved by a piece. However, we found that most recovered pieces moved from one logjam to the next downstream logjam, and in some cases moved two logjams downstream. We calculated distance traveled by a piece as a function of reach average jam spacing, mobility factor, and return period (**Equation 7-3**).

Distance traveled = average jam spacing * MF * ln (return period) [**EQUATION 7-3**]

The output of the model was the set of pieces that were predicted to move at given flows. The number of pieces predicted to move in simulated reaches with wood characteristics drawn from Amaya Creek and Lower EBSC increased with flow, and the average MF of these moved pieces decreased with increasing flow (**Figures 7.5 and 7.6**). As flow increased, stable pieces with lower mobility factors, such as pieces longer than w_{bkf} or with rootwads, were increasingly predicted to move (**Figure 7.5**). At 8-year flows (200 m^3/s) and greater, **Equation 7-2** predicted that 50% of the wood load moved, while at 15-year flows (250 m^3/s) and greater, over 90% of the wood moved in both reaches (**Figure 7.6**). At 15-year flows and greater, the mean MF equaled the reach-wide MF of 0.32 for Amaya Creek and 0.46 for Lower EBSC (**Figure 7.3**). **Equation 7-2** predicted that at 15-year flows and greater, 90% of the wood load in either reach moved, regardless of the mobility factor.

Figure 7.5. Mobility factor of moved pieces by flow in Amaya Creek and Lower EBSC.

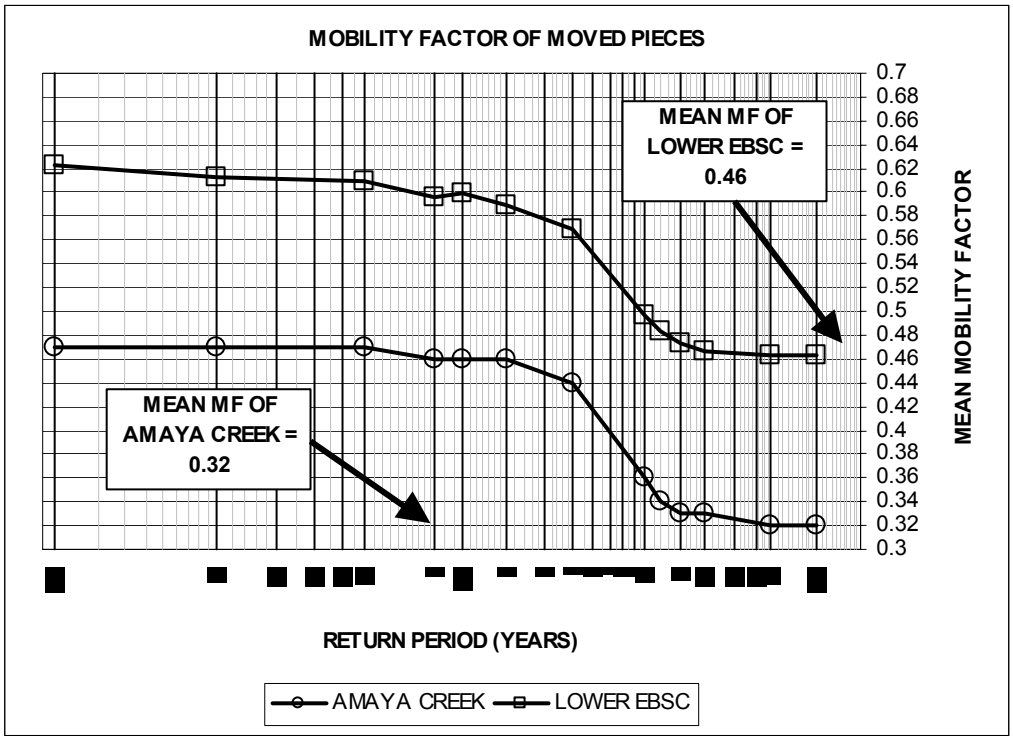
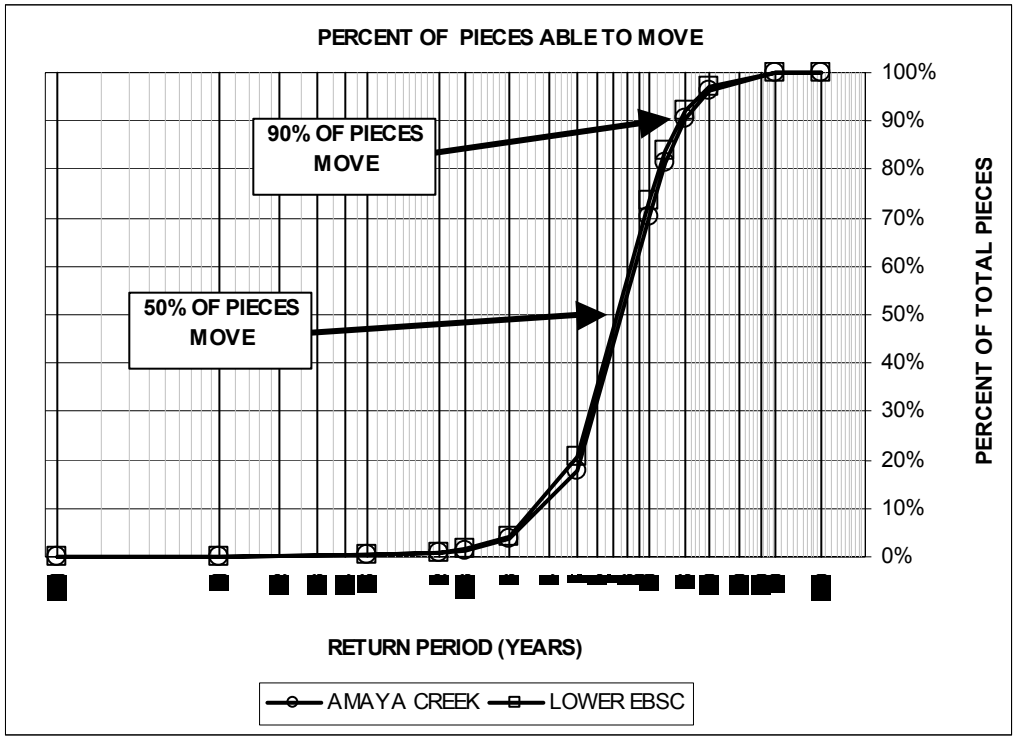
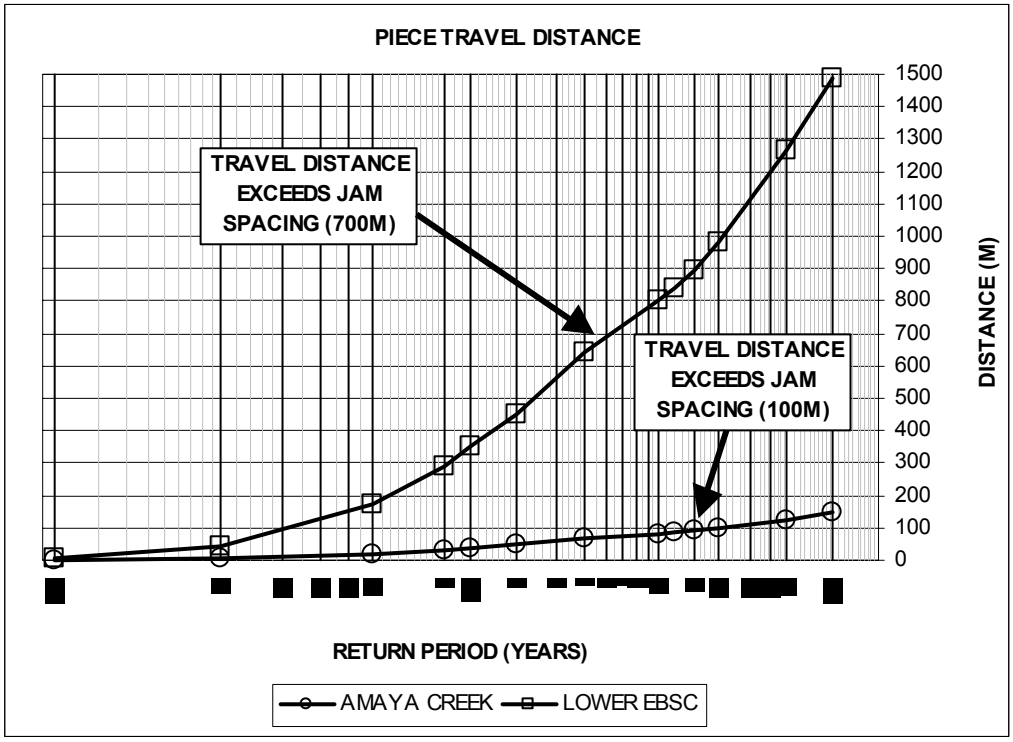


Figure 7.6. Percent of pieces predicted to move in Amaya Creek and Lower EBSC.



Equation 7-3 predicted that the travel distance of moved pieces exceeded jam spacing in Lower EBSC (700m) at 6-year flows (170m^3/s) and greater, while piece travel distance in Amaya Creek exceeded jam spacing (100m) at 15-year flows and greater (**Figure 7.4**). Piece travel distance exceeding jam spacing is an indicator that logjams no longer obstruct moved pieces or restrict piece movement. When piece travel distance exceeds jam spacing, moved pieces are able to leave the reach and move downstream. In Lower EBSC, moved pieces leave the reach at 6-year flows, while in Amaya Creek, this occurs at 15-year flows.

Figure 7.7. Mean distance traveled by pieces in Amaya Creek and Lower EBSC.



7.3 REACH TYPES

Amaya Creek and Lower EBSC were directly adjacent to each other (**Figure 4.1**), but showed distinct differences in wood characteristics and exemplify two LWD reach types: the source reach and the transport reach (**Table 7.8**). Source reaches are the source of LWD for the basin. Wood enters from the adjacent forest and is stored in the reach until storms move the material downstream to the transport reach. Transport reaches receive relatively little LWD from adjacent forests, instead relying on the fluvial transport of wood from source reaches. The magnitude of storms required to move material from source to transport reaches varies according to the basin, but in Soquel Creek these storms occur every 15 to 20 years. Once in the transport reach,

pieces move until they are deposited on the floodplain, emptied into the ocean, or are obstructed by a jam, culvert or bridge.

Table 7.8. Characteristics of source and transport reaches within the Soquel Creek Basin.

	SOURCE REACHES	TRANSPORT REACHES
ORDERS	1-3	3-5
WOOD INPUT	HIGH	LOW
WOOD STORAGE	HIGH	LOW
WOOD TRANSPORT	LOW	HIGH
WIDTH	<10M	>10M
GRADIENT	>0.05	<0.05
L/W_{BKF}	>1	<1
INPUT MECHANSIM	LANDSLIDES	FLUVIAL TRANSPORT
DOMINANT BANK SPECIES	CONIFER	HARDWOOD

7.3.1 Source reaches

Source reaches are characterized by high amounts and rates of wood input, high wood storage, and low wood transport compared to transport reaches (**Table 7.8**). In the Soquel Creek Basin, source reaches, such as Amaya Creek, are narrow (<10m w_{bkf}), steep gradient (>0.05) first through third order streams that are dominated by landslides bringing large amounts of wood and sediment into the channel. Conifers that are longer than the mean channel width ($L/w_{bkf} \leq 1$) dominate the wood load and form closely spaced channel spanning jams that effectively store LWD until large storms (>15-year return period) move the wood downstream to the transport reaches.

7.3.2 Transport reaches

Transport reaches are characterized by low amounts and rates of wood input, low wood storage, and high wood transport (**Table 7.8**). Transport reaches, such as Lower

EBSC, are wide (>10m w_{bkf}), moderate to low gradient (<0.05) third through fifth order streams (including the Mainstem Soquel Creek) that are able to transport most pieces of wood. Chronic bank erosion is the dominant input mechanism from the surrounding forest, but the input rate and the amount of wood stored is much lower than source reaches. The main source of wood is fluvial transport from upstream source reaches. Transport reaches in Soquel Creek are surrounded by riparian hardwood species, which are smaller than conifers and contribute lower volumes of wood. Wood movement occurs more frequently and over a greater distance than in storage reaches. Pieces are shorter in relation to bankfull width ($L/w_{bkf} \leq 1$), and form widely spaced lateral scour jams that are not as effective at trapping mobilized wood as channel spanning jams (Benda et al. 2000).

7.3.3 Wood movement between reaches

Equations 7-2 and 7-3 predicted that at 15-year flows ($250m^3/s$) and above, 90% of the woody debris in Amaya Creek was able to move and travel distances exceeding jam spacing (**Figures 7.5 and 7.6**). Assuming that Amaya Creek represents a typical source reach in the Soquel Creek Basin, then at 15-year flows and greater, wood is able to move out of source reaches into transport reaches. At flows below a 15-year return period, significant piece movement occurs in source reaches, but pieces do not leave the reach (**Figures 7.6 and 7.7**).

The last two significant logjams at the Soquel Drive Bridge (1955 and 1982) occurred at flows exceeding a 15-year return period, and coincide with the movement of stored wood in source reaches into transport reaches. Management of LWD in the Soquel Creek Basin should focus on these wood-moving events.

7.4 MANAGEMENT OF LWD

7.4.1 Piece size reduction and wood removal

All sampled culverts within the Soquel Creek Basin were narrower than the mean length of pieces in Amaya Creek (6.90m ± 0.33) and Lower EBSC (7.44m ± 0.54), and were potential obstructions to wood passage (**Table 7.9**). Most source reaches enter Mainstem Soquel Creek through culverts, so culverts should be large enough to pass wood to avoid clogging. Since wood travels out of source reaches at 15-year flows and above, culverts should be able to accommodate sizes of wood mobilized during these events. **Equation 7-2** predicted that the mean piece length at a 15-year flow was 8 meters (**Figure 7.8**). Culverts should be at least ≥8 meters to allow mobilized wood to pass freely from source reaches into transport reaches. The average size of sampled culverts was 2.4 meters (**Table 7.9**). Instead of increasing culvert sizes to accommodate wood, the current management prescription is to cut LWD into smaller pieces to pass through culverts, or to remove wood altogether.

Reducing piece size in source reaches places more pressure on culverts to pass wood. Cut pieces leave source reaches at lower magnitude flows compared to uncut pieces. The most significant interaction of uncut pieces with infrastructure, and concurrent damage, will occur at 15-year flows, when logs leave source reaches. With piece length reduced to 2m, smaller than the mean culvert width, **Equation 7.1** predicted an increase in MF from 0.32 to 0.60 in Amaya Creek, and **Equation 7-3** predicted that travel distance exceeded jam spacing (100m) at a 5-year flow (**Figure 7.9**). Cut logs will leave the reach and interact with infrastructure at a 5-year return period, causing damage more frequently than under uncut conditions. Also, because of

a more uniform piece size, more pieces will move at the same time, requiring culverts to pass a greater volume of wood than under uncut conditions, which have a variety of lengths that move under range of flows (**Figure 7.10**).

Figure 7.8. Length of moved pieces in Amaya Creek.

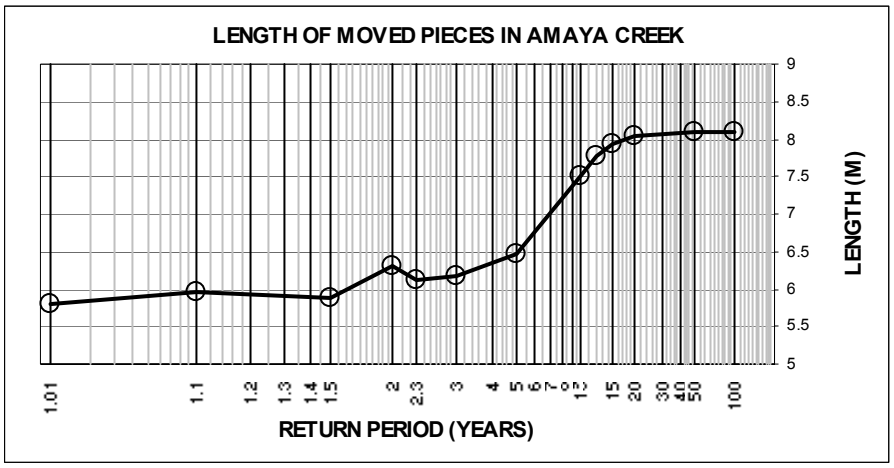
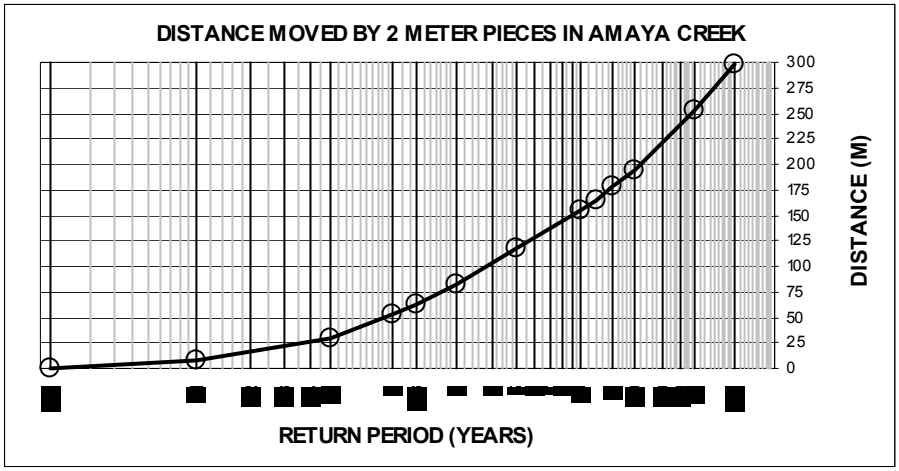


Table 7.9. Size of selected culverts within the Soquel Creek Basin.

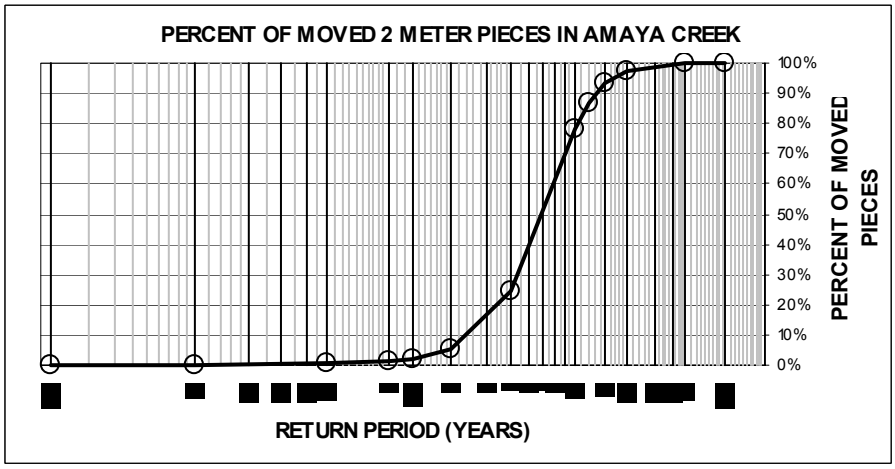
STRUCTURE NAME	LOCATION	HEIGHT (M)	WIDTH (M)	DIAMETER (M)	COMMENTS
Bates Cr 1	Bates Cr	N/A	N/A	2.4	Corrugated metal; clogged in 1995
Bates Cr 2	Bates Cr	N/A	N/A	2.4	Riveted Steel; oval shape (2.4m) by (2.1m)
Moores Gulch at Soquel Cr	Moores Gulch	N/A	N/A	2.6	Corrugated metal; 40m length with baffles and fish ladder at downstream end
Moores Gulch at 1000 Lrl Gln Rd	Moores Gulch	N/A	N/A	1.8	Corrugated metal; 15m length with baffles
Moores Gulch at Twin Lanes Rd	Moores Gulch	N/A	N/A	1.8	
Hoover Rd	Hester Cr	3.4	3.7	N/A	Concrete box culvert 3.7m (width) by 3.4m (height)

Figure 7.9. Travel distance of pieces cut to 2 meters in length in Amaya Creek.



Additionally, piece size reduction eliminates key pieces and associated jams, and increases jam spacing. Since piece travel distance is a multiple of jam spacing, travel distance will increase as jam spacing increases. Pieces will travel farther to the next jam, or in the absence of a jam, will travel to the next obstruction, such as a bridge or culvert. Fewer jams will result in fewer natural obstructions for moving pieces, and increase the likelihood of piece interaction with infrastructure.

Figure 7.10. Percent of pieces moved in Amaya Creek if all pieces are reduced to 2m.



7.4.2 Wood removal from Mainstem Soquel Creek

In the interim between wood-moving flows, there is minimal wood movement, but significant wood input into source reaches. After the 1982 flood, Singer and Swanson (1983) performed a reconnaissance survey on 26 kilometers of stream and interviewed local residents and government agency officials, leading them to hypothesize that during the 1982 floods "the major source of logs…was forested hillslopes that failed during the flood," and that "pre-existing in-channel logs and woody debris played little, if any, role in the logjam that formed at the Soquel Drive Bridge." Based on field observation and the results of **Equations 7-2 and 7-3**, we concluded that the existing wood stored in source reaches played a significant role in logjams at the Soquel Drive Bridge, and will play a role in future logjams when they occur.

Wood does enter streams during storms, but mobilized wood is more likely to be older (decay class three and older) wood already stored in the reach (**Figure 7.3**). As wood ages, it becomes more mobile as it breaks down into shorter pieces, separates from rootwads, and becomes less dense through decay (**Table 6.5, Figure 6.7**, Harmon et al. 1986). These stored pieces are flushed downstream during high flows, and are replaced by newly recruited pieces. The newly recruited pieces will eventually break down and become more mobile, and are the source of wood for the next large storm. The current management practice of removing wood from Mainstem Soquel Creek (a transport reach), therefore had little effect in preventing large logjams at the Soquel Drive Bridge, as the wood contributing to those logjams came from LWD stored in source reaches (tributaries) and was mobilized at 15-year flows. This hypothesized

mechanism is consistent with the absence of a logjam at the Soquel Drive Bridge in 1986 after a peak flow of 252m^3/s (15-year return period). Despite its magnitude, this storm occurred shortly after the 1982 storm, and the source channels were filled with newer, immobile wood.

8 ECONOMIC COMPARISON

8.1 CURRENT MANAGEMENT APPROACH

8.1.1 Removing wood from channel network

Under the current LWD management approach, the estimated cost of removing wood from the channel network was $40,000/year, or $4.0 million over 100 years (**Table 8.1**). The County of Santa Cruz carried out a basin-wide logjam removal program, overseen in Mainstem Soquel Creek by the Department of PublicWorks, and in tributaries to the Mainstem by the Planning Department (Reynolds, Personal Communication 2001). In Mainstem Soquel Creek, the objective was to cut up or remove fallen trees and debris jams that potentially clogged bridges and culverts. Twice a year, during two-week to one month periods, a crew of three to four Department of Public Works personnel walked up the stream and cut large pieces into one-meter sections to allow passage through culvert and bridge openings, removed pieces from the channel, or rearranged the pieces to stabilize banks. The operation had an approximate cost of $500/day, and for one 3-week session (15 business days) cost of $7,500, or $15,000 for the year (Wagner, Personal Communication 2001).

In the tributaries, Planning Department personnel cleared debris jams to prevent erosion to streamside properties, prevent culvert clogging, and to remove barriers to fish migration (Santa Cruz County 1986, Hope, Personal Communication 2000). Planning Department personnel also relocated newly recruited LWD, which threatened to become erosion hazards, moving the trees upstream for use in habitat restoration structures (Hope 2003). A former Santa Cruz County Senior Planner estimated a yearly

cost of $25,000 for logjam clearance and maintenance (Hope, Personal Communication 2000).

Table 8.1. The estimated costs of the current LWD management approach in the Soquel Creek Basin.

	THOUSANDS OF US DOLLARS PER YEAR	MILLIONS OF US DOLLARS PER 100 YEARS
REMOVING WOOD FROM CHANNEL	40.0	4.0
CULVERT MAINTENANCE	50.0	5.0
CULVERT REPLACEMENT (2/yr @ $50,000)	100	10.0
BRIDGE LOGJAM RELATED FLOODING	200	20.0
BRIDGE LOGJAM CLEARANCE	80	8.0
BRIDGE REPLACEMENT	70	7.0
HABITAT ENHANCEMENT PROJECTS	45	4.5
LOSS OF HABITAT AND SPECIES	??	??
TOTAL	**555**	**58.50**

8.1.2 Culvert maintenance and replacement

Logs and logjams were the main drivers on culvert maintenance and replacement (Hope, Personal Communication, 2000). The maintenance included clearing logjams from culvert mouths and reinforcement of undermined structures. We estimated a $50,000/year culvert maintenance budget, a figure that covered a network of over 40 culverts (**Table 8.1**).

We estimated the cost of culvert replacement using a formula for the cost of bridge replacement:

$$\text{Bridge replacement cost} = C * W * L \qquad [\textbf{Formula 8-1}]$$

where C = rebuilding constant of $822/m^2 (re-adjusted from $60 (1993 dollars) /ft^2), W = bridge width (meters), L = bridge length (meters) (Rhodes and Trent 1993). **Formula 8-1** estimated rebuilding costs due to repair and reconstruction, and did not include

other flood losses, such as damage to buildings. We used **Formula 8-1** to estimate culvert replacement, assuming the costs were one half that of bridge replacement:

Culvert replacement cost = (C * W * L) * 0.5 [**Formula 8-2**]

The typical culvert in the Soquel Creek Basin was a round 3-meter diameter culvert that flowed under a two-lane (40 meter) roadway. The estimate to replace an average culvert was:

Culvert replacement cost = ($822/m^2 * 3m * 40m) * 0.5 = $49,000

We rounded to $50,000 and anticipated replacing two culverts a year for a total cost of $100,000 (**Table 8.1**).

8.1.3 Bridge logjam related flooding

Based upon data collected after the 1955 and 1982 floods, we estimated a cost of $20 million for bridge logjam related flooding over a 100-year period (**Table 8.1**). In exploring the flood control options for the Soquel Creek Basin after the 1955 floods, the US Army Corps of Engineers estimated $6 million ($1 million in 1965 dollars) in flood-related damages (USACE 1966) The US Army Corps of Engineers also issued a report on the floods of 4-6 January 1982 and found that flood damages to the Town of Soquel amounted to $4.2 million ($2.2 million in 1982) (USACE 1983). We assumed that most damages occurred due to the logjam at the Soquel Drive Bridge. Newspaper reports after the 1982 storms placed total damages at $201 million ($106 million 1982 dollars) for all of Santa Cruz County (Santa Cruz Sentinel, January 13, 1982a).

8.1.4 Bridge logjam clearance

We estimated a cost of $8 million for clearing bridge related logjams over a 100-year period (**Table 8.1**). In 1955 and 1982 logjam clearance required bulldozers, cranes, and work crews equipped with hand tools and chainsaws (Santa Cruz Sentinel 1956, 1982b). We assumed that these large jams required 50 times the annual basin-wide wood removal budget of $40,000, or $2 million, to clear and dispose of obstructed LWD. Under the current management approach, and based on past history, we anticipated four large logjams occurring every 100 years for a total of $8 million.

8.1.5 Bridge replacement

The estimate to replace the Soquel Drive Bridge (constructed in 1956) with a full spanning bridge in 2003 was $3.5 million (Santa Cruz Sentinel 2001). Swanson (1988) suggested that if Santa Cruz County replaced the Soquel Drive Bridge, logjams would move downstream and form at the Stockton Avenue Bridge, causing flooding in Capitola. The federal Works Progress Administration constructed the Stockton Avenue Bridge in 1934 with two offset center piers that form a narrower opening than the 1956-constructed Soquel Drive Bridge (23.5m vs. 26m). In 2001, a group of Capitola Village merchants, residents and officials voted to ask the State of California for funds to design a new debris passing bridge (Santa Cruz Sentinel 2001). We anticipated the eventual replacement or redesign of this bridge at a cost equal to the 2003 constructed Soquel Drive Bridge, $3.5 million, and potential replacement of another bridge at the same cost (**Table 8.1**).

8.1.6 Habitat enhancement projects

We estimated a cost of $45,000/year for habitat restoration projects (**Table 8.1**). We based the estimate on the cost of past projects, and the assumption that projects will continue in the future. The cost to install the habitat enhancement project evaluated by Lassettre (1997) was $46,000 ($30,900 in 1989). The County installed the project to enhance steelhead trout (*O. mykiss*) in Moores Gulch, a tributary to Mainstem Soquel Creek. We assumed that one project of similar size will occur every year within the basin. Three examples demonstrate the commitment of residents to future habitat enhancement projects: 1) Soquel Creek Basin residents rejected a proposed multi-purpose dam in the upper basin that potentially would have` reduced the fishery population by over 60% (USACE 1966), 2) in response to the 1982 flood, Soquel residents participated in an environmental planning process to create a Downtown Soquel Plan that integrated ecological concerns with long-term planning goals, 3) in 2003, the Soquel Creek Assessment and Enhancement team completed a plan that will guide future habitat enhancement projects.

We left the economic value of the loss of habitat and species as an unknown. Detailing the economic loss of species and habitat is beyond the scope of this paper, but we included this in the estimated costs to show that there is an unknown cost due to the current management approach.

8.2 WOOD PASSING APPROACH

Table 8.2 shows the estimated costs of the current management approach versus the proposed wood passing approach. The estimated annual and long-term costs of the wood passing approach were less than 50% of the current wood removal approach. Under this new approach, naturally occurring wood is left in stream channels and infrastructure is modified.

Table 8.2. The estimated costs of a wood passing approach to LWD management in the Soquel Creek Basin.

	THOUSANDS OF US DOLLARS PER YEAR	MILLIONS OF US DOLLARS PER 100 YEARS
REMOVING WOOD FROM CHANNEL	---	---
CULVERT MAINTENANCE	25	2.50
CULVERT REPLACEMENT (2/yr @ $50,000)	150	15.0
BRIDGE LOGJAM RELATED FLOODING	---	---
BRIDGE LOGJAM CLEARANCE	---	---
BRIDGE REPLACEMENT	70	7.0
HABITAT ENHANCEMENT PROJECTS	---	---
LOSS OF HABITAT AND SPECIES	??	??
TOTAL	**245**	**24.50**

8.2.1 Removing wood from channel network

Under the wood passing approach, LWD is not removed wood from the channel network (**Table 8.2**). Wood causing catastrophic flooding at the Soquel Drive Bridge in 1955 and 1982 came from 1st through 3rd order streams, thus the LWD removal program along Mainstem Soquel Creek had little effect on preventing a logjam at the bridge. Furthermore, the roots of the problem were not the logjams, but the bridge itself, as was

implicitly recognized by the construction of successively larger bridges, culminating in a full-span design in 2003.

8.2.2 Culvert repair and replacement

To pass wood downstream, we assumed an increase in culvert size to accommodate the average length of wood that moved during 15-year flow from Amaya Creek. **Figure 7.8** predicted that the average length of mobilized wood during a 15-year flow was 8 meters. **Figure 7.7** also showed that over 90% of wood was able to move in a 15-year flow, so increasing culvert sizes to pass this load may significantly decrease culvert maintenance and replacement. We estimated a cost of 1.5 times the current rate to replace present culverts with larger wood passing culverts, and an estimated cost of 0.5 times the current rate for culvert maintenance (**Table 8.2**). In the long term, with installation of larger culverts, fewer structures will require maintenance and replacement, further reducing the estimated costs.

8.2.3 Bridge logjam flooding, logjam clearance, and bridge replacement

Increasing the size of bridge openings should end the formation of catastrophic logjams, eliminate bridge logjam related flood damage, and eliminate the need for logjam clearance. A future concern will be logjam formation at downstream bridges, such as the Stockton Avenue Bridge in Capitola (Swanson 1988). We assumed replacement of at least two bridges every 100-years at a cost nearly equal to the new full spanning Soquel Drive Bridge (**Table 8.2**). In the long term, with construction of free spanning bridges, fewer bridges will need replacement, also further reducing estimated costs.

The idea of wood passing approach in the Soquel Creek Basin is not a new one. After the devastating December 1955 floods, and editorial in the Santa Cruz Sentinel stated that "the flood also emphasized the need as dramatically shown in Soquel, for wide spans to allow sufficient clearance for debris in times of floods…New bridges will be costly but they are one of the city's greatest needs if we are to provide streets free of congestion for the years ahead (Santa Cruz Sentinel 1955)." The County of Santa Cruz replaced the Soquel Drive Bridge in 1956 only to see that structure cause flooding again in 1982 due to a logjam. Santa Cruz residents questioned whether the county "could have saved the Town of Soquel from flooding and spared it millions of dollars in damages" by quickly responding to the disaster (Santa Cruz Sentinel 1982c). One Soquel resident noted that there was "more damage to individuals and businesses than it would have cost the County to replace the bridge…If we didn't have the logjam, we wouldn't have had this (flood) (Santa Cruz Sentinel 1982d)".

8.3 LIMITATIONS OF ANALYSIS

We based the above estimates on the best available information, mostly estimates by former and current Santa Cruz County staff. More precise estimates might be available through analysis of county fiscal records, but the fundamental problem is that the relevant data is not organized into the desired categories. Also, not all wood removal is done to prevent flooding and to protect infrastructure; some wood is removed to prevent bank erosion to streamside property.

9 CONCLUSIONS

Wood is an important ecological element in rivers and streams along the Pacific Coast. Large stumps, branches, and trunks >10cm diameter and >10m length are often removed from channels for flood control and road maintenance purposes. Large woody debris management for flood control purposes is often ineffective as it fails to consider processes of wood transport and the size of wood that must pass through infrastructural openings. It is more sustainable, both ecologically and economically, to manage LWD by leaving wood in channels to create and maintain habitat, and enlarge culvert and bridge openings to allow passage prevent flood damage.

The main source of wood for the Soquel Creek Basin is landslides that bring wood into 1st through 3rd order streams. Wood remains and breaks down in these channels until it is moved downstream by high flow (>15yr RI) into the mainstem. Once in the mainstem, this influx of wood moves downstream until it deposits on a floodplain, a jam, or into the ocean. Culverts leading from source reaches to the mainstem should be sized to accommodate the wood that is flushed into the mainstem during piece moving flows. Currently, culverts are too narrow to pass this load, and wood is cut into small pieces or removed to prevent clogging.

These actions cause logs to move at lower flows, travel longer distances, and eliminate key pieces that naturally obstruct wood, and actually place more pressure on infrastructure to pass wood. The result is that damage still occurs and may even be exacerbated by the current management. Wood removed from the mainstem to prevent logjam formation at downstream bridges also has little effect, as the wood that forms catastrophic jams is flushed downstream from source reaches during high flows. Wood

removal results in the elimination of wood created habitats in Mainstem Soquel Creek, yet catastrophic jams still occur.

Enlarging bridges and culverts, and leaving wood in channels has significant cost saving over the long-term. Instead of yearly programs to remove wood and reduce log size, adjustment to infrastructure should more efficiently reduce logjam related flood damages and conserve habitat.

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