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Recruitment and function of large woody debris in four California coastal streams

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**RECRUITMENT AND FUNCTION OF
LARGE WOODY DEBRIS IN
FOUR CALIFORNIA COASTAL STREAMS**

A Thesis

Presented to

the Faculty of the Department of Biological Sciences

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Michelle A. Leicester

August 2005

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07/26/05

ABSTRACT

RECRUITMENT AND FUNCTION OF LARGE WOODY DEBRIS IN FOUR CALIFORNIA COASTAL STREAMS

by Michelle A. Leicester

Recruitment and function of large woody debris (LWD) was assessed on four central coastal California streams by modifying the California Department of Fish & Game's inventory form to 1) identify trees and LWD to species; 2) separate upslope habitats into perched (edge of bankfull channel), riparian (differentiated stream-dependent vegetation) and upslope zones; 3) separate the channel into lowflow and bankfull zones; and 4) indicate effects of LWD on habitat features. The majority of in-channel LWD was small and not creating backwater or pool habitats. Most hardwood LWD was small-diameter alder and was most abundant in downstream reaches with wide floodplains. Longer, thicker LWD, especially with rootwad attached, was more likely to create pools and backwaters. Most of this LWD was old, weathered redwood which, although scarce, created most in-channel structures, especially in upstream reaches. Most potential LWD recruitment was from small-diameter, perched alders; large conifers are apparently recruited episodically.

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Caroline Winata created the map of my study sites (Figure 1) literally at the 11th hour, good-naturedly enduring multiple revisions and picky tweaks to produce a beautiful finished result. "Thanks, Salad!"

Big Creek Lumber, Swanton Pacific Ranch, California State Parks, and Robert and Ann Briggs of Rancho Del Oso allowed access to their lands for this study.

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Introduction

During the past 150 years, growing human population and increasing pressure from land management practices have greatly impacted aquatic habitats. Interest in evaluating, restoring, and maintaining riparian habitat for sensitive aquatic species is growing. The importance of large woody debris (LWD) to habitat formation for aquatic species, channel structure and stability, and sediment retention is well documented (Bilby and Likens 1980; Keller et al. 1983; O'Connor and Zeimer 1988; Keim and Skaugset 2001). In many systems, loss of the complex habitat created by LWD carries serious implications for the species that depend upon such habitat, in particular anadromous salmonids (Roni et al. 2001; Gregory and Bisson 1997; Welsh et al. 1988). Until the late 1970s, LWD was believed to be an impediment to fish passage and was deliberately removed from stream channels (Hyatt and Naiman 2001). Subsequent studies and literature reviews have alleviated that misconception, and LWD is now regarded as a primary determinant of habitat quality for fish and other aquatic species (Harmon et al. 1986, Bilby and Bisson 1988). Further, the preference of some life stages of salmonids for woody cover has brought the depletion of LWD even more into the spotlight in recent years (Tschaplinski and Hartman 1983).

Loss of in-channel habitat due to LWD depletion is linked to a variety of factors, most of which are anthropogenic: 1) removal of wood from streams, 2) historic use of splash dams for log transport and 3) removal of streamside timber during logging (Bilby and Ward 1991). Understanding these losses and attempting to find ways of mitigating them will continue to be a pressing issue in resource management for the foreseeable future.

Kershner (1997) described a method developed by FEMAT (Forest Ecosystem Management Assessment Team) for the assessment and restoration of degraded watersheds. The method recommended developing recovery plans for degraded aquatic habitats based on an interdisciplinary, whole-watershed approach that takes into consideration watershed characterization, key issues and possible causes, current conditions and goals for the restoration project. In central coastal California, several watershed groups have been organized in recent years to monitor and evaluate the health of streams in California and oversee restoration efforts. Inventory and analysis of LWD is an essential tool utilized by watershed managers when evaluating current conditions and determining restoration potential, as well as being an important part of the baseline data. Many methods of performing an LWD inventory are in current use, with several purposes, including studies focusing on pool spacing and/or area (Bilby and Ward 1991), LWD function and characteristics ((Nierenburg and Hibbs 2000), and

extrapolation of historical conditions prior to land use practices such as logging (Rosenfeld and Huato 2003).

Trees growing close to the active channel are more likely to be “recruited,” or added to the active channel as LWD, than trees growing further upslope, since they are more susceptible to bank erosion (O’Connor and Ziemer 1988). However, the probability of any tree falling into the channel is low, and decreases as distance from the stream increases (Robison 2003). Since trees closer to the channel are more likely to recruit than those upslope, and since larger-diameter trees are potentially more useful as LWD than smaller trees, it would be of interest to determine approximate growth rates of different species relative to their channel proximity to aid in planning or recommending riparian restoration measures. Coniferous LWD is more desirable than hardwood LWD, since it is more decay-resistant, often larger, longer and much more persistent in the channel than hardwood-derived LWD (Nierenberg and Hibbs 2000; Hyatt and Naiman 2001). Therefore, it is important to note the type of LWD in the channel as conifer versus hardwood, or even down to the different species of each.

A method commonly used in California to inventory LWD is the “Large Woody Debris Inventory Form” in the California Salmonid Stream Restoration Manual (Flosi et al. 1998). Certain modifications made to the LWD inventory form contained in the manual (hereafter the “Flosi form”)

would make it far more efficient and comprehensive as a tool for field data collection and would likely improve the analysis of LWD distribution, habitat impacts and recruitment potential. For this study, I modified the Flosi form substantially to improve its functionality, relevance, clarity and data collection capacity. The new form was used to evaluate LWD status and recruitment potential on four small central California coastal streams.

Study Area

Four streams along the central California coast were studied (Figure 1). Gazos Creek is a third-order stream located in San Mateo County (37°9'N, 122°22'W). Waddell Creek is a fifth-order stream located in Santa Cruz County (37°6'N, 122°17'W). Scott Creek is a fourth-order stream located in Santa Cruz County (37°3'N, 122°14'W). Soquel Creek is a fourth-order stream located in Santa Cruz County (36°58'N, 121°57'W).

The streams flow over uplifted marine terraces cut on substrate consisting mainly of Cenozoic shale, mudstone and sandstone, with areas of Mesozoic granite present in the upper reaches of Scott Creek and its tributary, Big Creek (California Geological Survey 2002). The climate is Mediterranean; summers are warm and dry except for morning and evening fog, winters are cool and wet. Annual precipitation averages 30 inches (75

cm), with the majority falling between November and April as rain (Calif. Dept. Water Resources 2000; Gasith and Resh 1999).

Vegetation on each stream varies from hardwood-dominated riparian forest in the downstream reaches, to redwood-dominated forest in the upstream reaches. The exception is Soquel Creek, which is heavily urbanized in downstream reaches. Immediately upstream of lagoon areas, reaches dominated by low-gradient riparian floodplain contain hardwood riparian forest of white or red alder (*Alnus rhombifolia* and *A. rubra*), black cottonwood (*Populus trichocarpa*), western sycamore (*Platanus racemosa*), California bay laurel (*Umbellularia californica*), bigleaf maple (*Acer macrophyllum*) and willow (*Salix* spp.). Also present in low numbers on downstream reaches of Soquel Creek are non-native trees such as *Acacia* spp. and *Eucalyptus* spp. In upstream reaches or on steep slopes, conifers such as coast redwood (*Sequoia sempervirens*), Douglas fir (*Pseudotsuga menziesii*) and Monterey pine (*Pinus radiata*) are the dominant tree species with tanbark oak (*Lithocarpus densiflora*) and California bay laurel also present. All the streams were historically clearcut in the 19th and 20th centuries, and timber continues to be harvested on portions of each watershed.

Each stream is utilized by many different species of aquatic organisms, some of which have been allocated threatened or endangered status under federal and/or state law, or are Species of Special Concern. These include

steelhead trout (*Oncorhynchus mykiss*), California red-legged frog (*Rana draytonii*), foothill yellow-legged frog (*R. boylei*), and western pond turtle (*Clemmys marmorata*). Runs of coho salmon (*O. kisutch*) are also present in Gazos, Scott and Waddell creeks in some years (Smith 2001).

Methods

Survey Methods

The streams were surveyed over an 18-month period in 2001/2002 for trees and LWD. Gazos, Waddell, and Scott creeks were surveyed beginning at their lower reaches upstream to the points where in-channel characteristics became dominated by bedrock substrate, steep stream gradients, or narrow/non-existent floodplains. On Soquel Creek, surveys continued upstream to a study area boundary (Alley 2003). Preliminary reaches were designated prior to sampling, based upon: a) Rosgen channel classification, especially gradient, substrate and entrenchment (Rosgen 1996); b) substantial logjam and/or trapped sediment resulting from the 1998 El Niño winter flows (on Gazos Creek); c) upslope conditions; and d) the presence of significant channel size changes, such as at tributaries. Distinctions among reaches were confirmed after analysis of data collected on channel and upslope conditions (Tables 1A-1D; 2A-2D).

Scott and Waddell creeks each have a lowermost reach (reach 1) that consists mainly of low-gradient channel habitat and lagoon. Under full-lagoon conditions typical of these streams in late summer/early autumn when the sandbar closes, the backwater extends upstream almost to reach 2. In lagoons or inundated stream channels, LWD has different habitat value and functionality from LWD located in free-flowing areas. Therefore, lagoon areas and inundated areas were excluded from this study, and sampling on Scott and Waddell Creeks was started at the downstream end of reach 2. On Gazos Creek, where the lagoon is small, sampling was started at reach 1, within the lagoon at Highway 1. On Soquel Creek, the lagoon was excluded from sampling, but the lowermost reach was designated as reach 1 to conform to other assessments being conducted in the watershed (Alley 2003).

Surveys for trees and LWD on Gazos, Waddell and Scott creeks covered 6.7, 6.6, and 7.6 stream miles (10.8, 10.6, and 12.2 km), respectively (Tables 1A-1C). Sampling on Gazos Creek continued upstream to the upstream boundary of the Mountain Camp. Sampling on Waddell Creek continued upstream to Slippery Falls on the west fork, and 0.6 miles (1 km) up the east fork. Sampling on Scott Creek and its tributary Big Creek extended approximately 0.6 miles (1 km) upstream beyond where the gradient increased to >2%. Data were collected in two 200-foot (60 m) segments every 1000 feet (305 m), and beginning and end points of sample

segments were flagged for future reference. Lower reaches on Scott and Gazos creeks were judged to be relatively homogenous in terms of habitat and were therefore sampled once per 1000 feet (305 m) according to the protocol recommended by Flosi et al. (1998).

On Soquel Creek, a total of 10.2 stream miles (16.4 km) was surveyed for trees and LWD (Table 1D). Sampling continued 3.5 miles (5.6 km) up the east fork to the Water Department's gauging weir. Due to the incredibly small amount of LWD present in the active channel, all LWD greater than 6 feet (1.8 m) in length and 1 foot (30 cm) in diameter which was present in the lowflow and bankfull channels was included in the tally. Bank and upslope inventories were performed at a rate of one 200-foot (60 m) sample per 1000 feet (305 m). All other sampling methods were identical to those of the other three streams.

Stream distances were measured using a hipchain. Slopes were measured using a clinometer. Upslope distances were determined using a laser range finder (Nikon Laser 800 82x8), or were visually estimated. Average lowflow channel depths were measured at the thalweg using a folding stadia rod. Average lowflow and bankfull channel widths, tree/log diameters and tree/log lengths were also measured using a folding stadia rod.

All LWD and trees located within the sample areas and which measured greater than 6 feet (1.8 m) in length and 1 foot (30 cm) in diameter

were identified to species and recorded with their sizes, locations, positions in the channel and association with any habitat structures (pool or backwater). LWD was deemed to be the major factor in creation of a habitat structure if it was: a) clearly deflecting streamflow in such a manner as to cause scour, thereby forming a pool or high-water refugium; b) forming a step/plunge pool; or c) a key piece in a logjam.

LWD Inventory; New Inventory Form

The Flosi form categorizes trees, logs, and stumps in the bankfull channel or adjacent to the channel by length [6-20 feet (2-6 m), >20 feet (>6m)], diameter [in 1-foot (30 cm) increments from 1 foot (30 cm) to >4 feet (120 cm)], and location (bankfull channel, “perched” at the edge of the bankfull channel, or upslope; on the left or right bank). Using the Flosi form, all trees within the channel and/or 50 feet (15 m) up the bank on either side are recorded by diameter as live or dead. Out-of-channel trees and logs are also recorded as conifer or deciduous.

Data were collected using a “Large Woody Debris Inventory Form”, adapted from the Flosi form (Figure 2). The new form retains some of the parameters contained in the Flosi form, but is modified in several ways.

First, the category “perched” was applied to standing live or dead trees within the channel, or to trees or downed wood at the edge of the bankfull

(active) channel, which were likely to be recruited at high flows (Figures 3 and 4). The out-of-channel area was further split into two categories (Figure 4): a) riparian, designating an area beginning at the edge of the bankfull channel, of variable recorded width, and dominated by deciduous riparian trees (i.e., *Alnus*); and b) upslope, designating any area beyond the riparian zone but still falling within 75 feet (23 m) of the bankfull channel. Slopes (in percent) of the riparian and upslope zones were recorded separately.

Four new categories were created for separately recording LWD located within the bankfull channel (Figures 5-8): a) lowflow/pool for pieces in the lowflow channel which were creating or enhancing a pool; b) lowflow/extra for pieces in the lowflow channel which were present but not contributing to creation or enhancement of pool habitat; c) bankfull/backwater for pieces in the remainder of the bankfull channel which were creating or enhancing a backwater or high-water refugium; and d) bankfull/extra for pieces in the bankfull channel which were present but not contributing to creation or enhancement of backwater or refuge habitat.

Widths of the lowflow and bankfull channels and bankfull depths were recorded. All logs, stumps and trees were recorded as to their location, using code letters for different species. Trees in multiple location categories were indicated accordingly with the position of the root shown. Locations and sizes

of logjams and other significant debris not falling within a sample site were also recorded.

Additional tally symbols represented: a) “old”, defined as a conifer, usually a redwood, that was missing bark and limbs and showed evidence of weathering, indicated as the species code with a circle around it (i.e., “**R**”); b) logs that were within jams, indicated with a “J” next to the species code; c) trees leaning in such a manner that they were likely to fall into the channel, indicated with an “L” instead of a hatch mark; d) multi-trunked trees, whose diameter was recorded as the sum of the trunks and indicated with an “X” instead of a hatch mark; e) downed trees with root wad attached, depicted as “**⊥**” instead of a hatch mark; f) downed trees which were still alive, indicated with a species symbol together with a subscript lower case “a”; and g) probable source of recruited wood if it was apparent, indicated as “----->” adjacent to the species code.

Field tallies were organized by reach, and total piece counts were compiled. Because most reaches varied significantly in length, relative densities (pieces per 1000 feet) for the lowflow and bankfull channels, and out-of-channel habitats, were also calculated so that reasonable comparisons could be made between streams and individual reaches of streams. In order to account for the differences in sampling intensity on the lower reaches of Gazos and Scott creeks, the values for these reaches were doubled, then

densities were calculated. All data were entered into a relational database (Microsoft® Access 2003), and all analyses were performed using the database, Microsoft® Excel 2003 and a handheld calculator.

LWD Tallying and Classification of Habitat Value

It was common to encounter pieces of LWD which, due to length or positioning, were located and/or functioned in more than one category within the active channel and/or in upslope areas. In these cases, the LWD was tallied on the form to indicate that it occurred in multiple different categories by making a hatch mark representing the root, and drawing a line representing the trunk through all areas in which the LWD occurred. For example, if a downed tree had its root in the riparian dead/down category and its crown in the bankfull channel/extra category, a hatch mark would be made in the riparian dead/down column on the form, and a connecting line drawn to the bankfull/extra column on the form, to accurately indicate the position of the downed tree.

For the inventory and analysis, it was necessary to develop and employ guidelines for the classification of the value of the tallied LWD. These guidelines took into consideration the need for accurately indicating the amount of wood currently present in the channel, its likelihood of recruitment, the functions it performed, or had the potential to perform, as a

result of its placement, and the wide range of conditions produced by varying seasonal flows. Where LWD was found to be located in two or more areas of the active channel or upslope areas, it was classified as being located in the most biologically valuable category in terms of habitat formation. For example, a piece tallied as being located in both “bankfull/extra” and “bankfull/backwater” would be classified for analysis as being only in the “bankfull/ backwater” category because structure-forming LWD is more biologically valuable due to the habitat it creates. Where downed trees spanned the channel, (i.e., suspended above the channel under lower flow conditions but potentially in the channel at higher flows) they were classified as “bankfull/extra” rather than “perched, dead/down.” Downed trees in the perched, riparian or upslope areas which extended completely or partially into the active channel were classified accordingly to their channel value, rather than as upslope “dead/down.” LWD within active channels was evaluated for its function during low flow conditions and its potential function at higher flows, and tallied appropriately. For example, if evidence of a backwater was noted adjacent to a piece or cluster of LWD, even if no backwater was present at the time of the survey, the LWD would be assigned to the category of “bankfull/ backwater” if the LWD was determined to have likely formed a backwater or refugium at high flows.

Increment Coring of Trees on Gazos Creek

Seventy-one trees (23 redwoods, 16 Douglas firs, and 32 alders) on Gazos Creek were cored with 12- or 24-inch (30 or 60 cm) increment borers during January through June 2003 to determine their growth rates. All cored trees were located within 75 feet (23 m) of the active channel. Trees were chosen for coring based mainly on their location and size and could be standing, down, part of a debris flow, growing mid-channel or growing 70 feet upslope. Where downed trees were chosen, the point of origin was noted. Diameters of all trees were measured using a diameter tape. The proximity of each tree to the lowflow and bankfull channels was measured, using a rangefinder, measuring tape or folding stadia rod. Following removal of the cores, the trees' wounds were sealed with waterproof caulk to prevent infestation by pathogenic organisms. All cores were allowed to air dry and stored in clean plastic straws prior to analysis.

To improve clarity of the annual rings, the cores were treated with phloroglucinol (Forestry Suppliers, Inc.) and processed according to the distributor's instructions. The cores were again allowed to dry and the annual rings counted using a fluorescent lamp and magnifying glass. If necessary, the rings were re-moistened, using a damp cotton swab, to make the rings more visible.

Trees were grouped into categories for comparison based on species and proximity to the stream. Conifers were classified as “near stream” if they were within 10 feet (3 m) of the bankfull channel with their roots in the water table, and classified as “upslope” if they were located beyond and/or higher than that boundary. Alders did not typically occur outside of perched or riparian areas, so they were classified as “perched” if they were growing adjacent to the active channel, and classified as “floodplain” if they were greater than 10 feet (3 m) away from the active channel.

Results

Geomorphic Reach Characteristics

Sampled portions of Gazos, Waddell, and Scott creeks are comparable in that they had distinct “downstream,” “middle” and “upstream” zones. Channels in “downstream” reaches are typically low gradient (<2%), slightly entrenched with well-developed floodplains, and have relatively higher width/depth ratios with fine substrate of gravel, sand, silt or a combination of these. These were usually categorized as Rosgen C4 or C5 (Tables 1A-1D; Tables 2A-2D). “Middle” reaches extend from approximately three stream miles (4.8 km) upstream from Highway 1 on Gazos Creek (reach 3), three stream miles (4.8 km) upstream from the upper lagoon on Waddell Creek (reach 3), and 5.5 miles (8.9 km) upstream of the downstream end of reach 2

on Scott Creek (reach 6). Much of the lower stream course on Scott Creek is parallel to the coastline, so the inland penetration distance of its “downstream” zone to rugged, uplifted terrain is comparable to that of Gazos and Waddell creeks (Figure 1). These middle reaches also have low gradients (<2%) but are more entrenched and become steep immediately above the bankfull channel. They have moderate width/depth ratios and fine to medium substrate of sand, gravel or cobbles (Tables 2A-2D). Reaches in this zone were typically designated as B4C or B3C, although some middle reaches on Gazos, main stem Waddell and upper Scott creeks are sufficiently entrenched and low-gradient to be classified as F channels (Tables 1A-1D). Upstream reaches have higher gradients (2-10%), are moderately to significantly entrenched with small or non-existent floodplains, have low width/depth ratios and flow over coarser substrate of cobbles, boulders or bedrock. Reaches in this zone were usually classified as B or A channels, and sampling was terminated after a few thousand feet if it was determined that these conditions were likely to persist upstream.

On Soquel Creek, the largest system in this study, sampled areas up to reach 8 (5.8 stream miles (9.3 km) upstream of Highway 1) most closely resemble downstream reaches in terms of entrenchment, bankfull channel widths and width/depth ratios (Table 2D), and were primarily classified as Rosgen C channels (Table 1D). Even reaches 9 and 10 on the east fork

differed little from downstream reaches in channel type, channel dimensions and upland vegetation (Tables 1D, 2D, and 3D).

Bankfull channels on Gazos, Waddell and Scott creeks narrow in the “upstream” zone (Tables 2A-2D). Gazos Creek has the narrowest lowflow and bankfull channels (Table 2A). Scott Creek has a relatively wide bankfull channel downstream of Big Creek (reach 2, Table 2C), but the channel upstream is similar to the narrow channel of Gazos Creek. Additionally, in summertime the lowflow channel on Scott Creek is substantially wider downstream of Big Creek, which has higher baseflow due to sandy granite substrate present in its upper watershed (Smith 2001). The main stem of Waddell Creek is wider than either Gazos or Scott Creek upstream of Big Creek, but the west fork is similar in width to the other two creeks. Soquel Creek has the widest bankfull channel throughout the sampled areas of any of the streams in this study (Tables 2A-2D). Widths of most sampled reaches on Soquel Creek are similar to those of Scott Creek downstream of Big Creek and the main stem of Waddell Creek.

All four studied streams have incised into uplifted marine terraces. As a result, even the low-gradient channels of the middle reaches are contained within relatively deep canyons. Mean riparian widths are significantly reduced in these sections compared to downstream reaches (Tables 3A-3D). Steep banks along the terrace edges make the streams prone to mass

wasting, especially if subjected to heavy rainfall. Upstream zones of streams also have very steep upslope habitats (Tables 3A-3D).

Streamside Vegetation Characteristics

Riparian widths on all streams are generally highest in downstream reaches, abruptly narrow in the middle reaches and increasingly narrow in upstream zones (Tables 3A-3D; Figures 9A, 10A, 11A, and 12A). On Gazos Creek, the riparian corridor sharply narrowed at reach 3, but changed little throughout the remainder of the sampled area (Figure 9A). On Scott Creek, the transition from a wide to an extremely narrow riparian area (Figure 11A) occurred much further upstream at reach 6 (5.5 miles – 8.9 km) than on Gazos or Waddell creeks (Figures 11A and 11B). The change was much more gradual on both the main stem and west fork of Waddell Creek, and the east fork maintained a relatively wide riparian corridor throughout the sampled area (Figure 11B). Soquel Creek maintained large riparian widths throughout the sample area with little variation among reaches (Figure 12A), because the entire 10.2 miles (16.4 km) of sample area lies within the downstream zone of this large stream.

Riparian vegetation type is roughly linked to riparian width (Figures 9A-12B), with the downstream reaches dominated by hardwood riparian forests, and narrower upstream riparian areas having more

abundant conifers. However, the patterns varied considerably among streams. On Gazos Creek, the wide riparian corridor of reaches 1 and 2 is dominated by hardwood species (Figures 9A and 9B). In the narrower reaches 3-5, hardwood and conifer densities are roughly equivalent. Conifers dominate the riparian corridor upstream of reach 5. On Waddell Creek, hardwoods dominate the riparian corridor only in reach 2 (Figure 10B). Upstream of reach 2, conifer and hardwood densities are equal. Riparian areas in reaches 2 through 4 on Scott Creek are wide (averaging 100 feet/30.5 m total) and are dominated by hardwood species (Figures 11A and 11B). Reach 5 is also wide, but hardwood and conifer densities are about equal. In reaches 6 through 8, the riparian area is extremely narrow, with densities of hardwoods and conifers again roughly equivalent. Soquel Creek's riparian areas are consistently wide throughout the sample (Figure 12A), and conifers are scarce until reaches 8-10 (Figure 12B). However, Soquel's riparian tree densities are less than 40% of tree densities on the other three streams.

Out-of-channel areas in general are dominated by hardwoods in the perched (edge of bankfull) and riparian (floodplain) zones, and by conifers in upslope areas (Figures 9B-12B, 15A-18B). Because the "perched" category is a transitional area defined as being that portion of the hardwood-dominated riparian area immediately adjacent to the bankfull channel, riparian vegetation composition in the "perched" areas would obviously also be

dominated by hardwood species (Figures 9B-12B, 15A-18A). The patterns of relative densities for perched conifer and hardwood species are essentially the same on the four streams as the patterns of riparian areas, although hardwoods are more common in the perched areas than in the riparian areas (Figure 14).

Because only 75 feet of bank on either side of the channel was included in sampling, densities of trees tallied in upslope areas depended largely on how much of that 75 feet fell within the riparian area. It has already been noted that Scott Creek retained its large riparian floodplain for approximately 2/3 of the sampled area (through reach 5). Therefore, not much area was designated as upslope and the number of trees tallied as upslope was very low through reach 5 (Figure 17B). Similarly, the Gazos Creek riparian corridor is wide through reach 2, and upslope trees were scarce (Figure 9B). In upstream reaches, conifers are overwhelmingly dominant. By contrast, Waddell Creek's riparian corridor progressively narrows upstream (Figure 10A) and upslope habitat dominated by conifers progressively increases (Figure 16B).

Redwoods make up a significant amount of the conifers present on all four streams. Conifers are 84-96% redwood in perched areas, 84-92% redwood in the riparian areas, and 71-89% in upslope habitats. Alders are the most abundant hardwood species, making up 78-92% of perched

hardwoods on all four streams, and 72-79% in the riparian areas of Gazos and Scott Creeks. Alders account for 52% of the riparian hardwoods on Waddell Creek, where California bay laurel and bigleaf maple are common, and 31% on Soquel Creek, where black cottonwood and western sycamore are common. In upslope habitats, alders make up less than 10% of the hardwood densities on the four streams, with tanbark oak and California bay laurel the most common hardwood species. Tree densities on Soquel Creek's upslope areas are less than 15% of those of the other three streams, but conifer densities are generally double that of hardwoods throughout the sample area (Figures 14 and 18B).

Streamside Tree Growth Patterns

Alders had a growth rate approximately twice that of either redwoods or Douglas firs (Figures 19A-19C), and typically reached a diameter of 12 inches (30 cm) in approximately 20 years. On average, the two conifer species did not reach 12 inches (30 cm) in diameter until they were approximately 40 years old. Individual "perched" alders and those farther away from the bankfull channel in the upper floodplain showed wide variation in growth, but there was no difference between the two groups (Figure 19A). Both perched and floodplain alders showed relatively rapid

growth to about 10 inches (25 cm) in diameter, then slower subsequent growth.

Redwood growth exhibited the same high variation as alders (Figure 19B) with no differences between the growth patterns of trees adjacent to the bankfull channel and those upslope. However, only young trees could be cored to determine lifetime growth patterns. The largest tree cored was a redwood with an estimated diameter of 39 inches (99 cm). Redwood growth was approximately 50% as fast as that of alders, and the initial growth of most individuals to 10 inches (25 cm) diameter was faster than subsequent growth.

Douglas firs showed high individual variation in growth, with growth slowing after the tree reached 10 inches (25 cm) diameter (Figure 19B). Douglas firs are intolerant of shade and inundation (Nierenburg and Hibbs 2000) and are therefore typically not present in close proximity to the bankfull channel. I was only able to locate and core two Douglas firs within 10 feet of the bankfull channel; their growth patterns did not differ from those of trees located upslope.

In-Channel LWD Distribution and Abundance

Waddell Creek had the highest overall in-channel LWD densities (32.3 pieces/1000 feet), followed closely by Gazos Creek (30.9 pieces/1000 feet).

Scott Creek had about half as much LWD as Waddell and Gazos (16.5 pieces/thousand feet), whereas Soquel Creek had only 13% as much in-channel LWD as Scott Creek (2.1 pieces/1000 feet) (Figures 20 and 21). Conifer-derived LWD was more abundant on Gazos (70%) and Waddell (57%) creeks, and the comparatively low overall abundance of LWD on Scott Creek was due to a relative scarcity (38%) of conifer-derived LWD (Figure 20). In all four streams, 59-75% of the LWD tallied was not associated with a structure (pool or backwater), but was classified as “extra” (Figure 21).

Gazos Creek had the highest densities of structure-forming LWD, with 11.8 pieces/1000 feet, compared to 8.0 pieces/1000 feet on Waddell Creek, even though Waddell had higher overall LWD density (Figure 21). Despite having only about half of the overall LWD density of the other two streams, Scott Creek had the highest proportion of in-channel LWD associated with structures, with 41%, versus 38% on Gazos, 29% on Soquel and 25% on Waddell (Figure 21).

The majority of the in-channel LWD tallied was redwood, which accounted for 82% of the conifer LWD on Gazos, 83% on Waddell, 92% on Scott, and 70% on Soquel. Most of this was “old” redwood that had probably been in the channel for many years (Tables 4A-4D). “Old” redwood made up 86% of all redwood LWD tallied on Gazos Creek, 75% on Waddell Creek, 64% on Scott Creek, and 60% on Soquel Creek. In-channel hardwood LWD tallied

on Gazos Creek was 99% alder, 87% alder on Waddell and 86% alder on Scott, but only 50% alder on Soquel Creek. On the four streams overall, 87% of the in-channel alder-derived LWD was only 1-2 feet in diameter (Tables 4A-4D).

The highest densities of LWD on Gazos Creek were on reaches 3 through 9, where conifer LWD densities were much higher. Hardwoods provided most of the LWD in reach 1 (Figure 22A). Reaches 4 and 10 were short, contained only three samples between them (Table 1A), and no LWD was tallied in any of the three samples.

On Waddell, LWD densities were highest on the west fork, where the channel was narrower and conifer densities were higher than the rest of the sampled area (Figure 22B). Hardwood made up most of the LWD on reach 2. It is noteworthy that, even though Waddell Creek's east fork had a wide riparian corridor (Figure 10A) with high densities of hardwood trees (Figure 10B), no hardwood LWD was tallied in the channel on the east fork. This is likely due to the fact that the east fork is a Rosgen B-channel (Table 1B) with a steeper channel gradient and steeper banks, and is more likely to be scoured during high flows than reaches on the main stem or west fork of Waddell. On Scott Creek, LWD densities were highest in reaches 3 through 6, with hardwood densities highest in reaches 2 through 4 and conifer densities highest in reaches 6 through 8 (Figure 22C).

On Soquel Creek, in-channel LWD densities were highest in reach 2, and in reaches 6 through 10, where conifer-derived LWD was most common (Figure 22D). However, nowhere in 10.2 miles (16.4 km) of sample area did Soquel Creek have in-channel LWD densities that approached levels present on even the most depauperate reaches of any other stream in the study area (Figures 22A-22D).

Overall percentages of conifer-derived LWD were very similar to the percentages of structure-forming LWD that were conifer-derived (Figures 20 and 21). On Gazos Creek, in-channel LWD was 70% conifer, and 70% of the structure-forming LWD was conifer-derived. On Waddell, LWD was 57% conifer overall, and 63% of the structure-forming LWD was conifer-derived. On Scott Creek, only 38% of the LWD tallied was conifer-derived, and 42% of structure-forming LWD was conifer. This result was somewhat surprising, as most hardwood-derived LWD was small (Tables 4A-4D). However, although most LWD greater than 2 feet in diameter was conifer, most conifer LWD was also small (Tables 4A-4D). LWD 1-2 in diameter made up 53% of the LWD on Gazos Creek, 69% of the LWD on Waddell Creek, 63% of the LWD on Scott Creek, and 47% of the LWD on Soquel Creek (Tables 4A-4D; Figures 25A-25D).

Debris jams accounted for much of the LWD tallied on Waddell Creek (39%) and, to a lesser extent, Gazos Creek (17%) (Figure 23). Reach 2 on

Gazos Creek contained four debris jams, but only the largest fell within a sample. LWD tallied in this single jam made up 33% of the conifer LWD and 25% of the hardwood LWD in the entire reach (Figure 22A). Much of the debris jam LWD tallied on Waddell Creek was concentrated on the west fork, primarily because of three very large debris jams formed on landslides and large channel-spanning trees (Figures 22B, 23, and 24). On reach W2, approximately two-thirds of the LWD tallied was caught in two very large debris jams (Figure 22B). There were no large debris jams recorded on Scott or Soquel creeks (Figures 22C and 22D), but even on those streams 11-13% of the LWD was within small debris jams (Figure 23).

Effect of LWD Size Classes on Formation of In-Channel Structures

Most LWD tallied on all four streams was 1-2 feet in diameter (Figures 25A-25D). LWD in this size class was also most likely to form a structure by virtue of its greater abundance, with the exception of Soquel Creek (Figure 25D). Soquel Creek contained extremely low densities of structure-forming LWD (0.6 pieces/1000 feet – Figure 21), even though all in-channel LWD was tallied rather than just a sample. Tallied LWD was still 25-42% of the other streams.

On Gazos Creek, 53% of the LWD tallied, and 40% of the structure-forming LWD, was 1-2 feet in diameter (Figure 25A). Another 25% was 2-3

feet in diameter and represented 28% of all the structure-forming LWD. Pieces of LWD that were 3-4 or >4 feet in diameter made up the remaining 22% overall, and 32% of the structure-forming LWD. Only 29% of LWD 1-2 feet in diameter formed structures, compared with 43-61% of larger diameter LWD (Figure 25A).

On Waddell Creek, more than two thirds (69%) of LWD overall, and 43% of the structure-forming LWD, was 1-2 feet in diameter (Figure 25B). This small-diameter LWD was important in forming structures because of its overwhelming relative abundance, but only 15% of 1-2 foot diameter LWD formed structures, compared with 39-56% for larger diameter LWD. LWD measuring 2-3 feet in diameter made up 20% of the overall, and 38% of the structure-forming LWD. The remainder (LWD measuring 3-4 feet and >4 feet in diameter) made up 11% of the total tallied, and 14% of the structure-forming LWD.

Scott Creek was similar to Waddell, in that almost two-thirds (63%) of all LWD in the channel measured 1-2 feet in diameter, but accounted for only 47% of the structure-forming LWD (Figure 25C). Only 31% of LWD 1-2 feet in diameter was structure-forming, compared with 56-67% for larger diameter LWD. Pieces 2-3 feet in diameter accounted for 24% overall, and 32% structure forming LWD. Large woody debris 3-4 feet or >4 feet in diameter accounted for 14% overall and 21% of structure-forming.

On Soquel Creek, pieces measuring 1-2 feet in diameter accounted for 47% of all the in-channel LWD, but only 21% of the structure-forming LWD (Figure 25D). Only 13% of the smaller diameter LWD was structure-forming, compared to 22-62% for LWD greater than two feet in diameter. Pieces 2-3 feet in diameter accounted for 28% overall and 33% of the structure-forming LWD. LWD 3-4 feet or >4 feet in diameter accounted for 27% overall and almost half (45%) of the structure-forming LWD.

To examine the effects of LWD length on its likelihood to be structure-forming, total piece counts were grouped into four size classes by diameter (either less than two feet or greater than two feet in diameter) and by length (less than 20 feet or greater than 20 feet). For example, a “thin, short” piece of LWD was one that measured less than two feet in diameter and was less than 20 feet in length (Figures 26A-26D).

On Gazos Creek, pieces of LWD were more likely to form a structure if they were greater than 20 feet in length (Figure 26A). Thirty-three percent of thin, long LWD formed a structure, versus 25% of thin, short LWD. Thick, long LWD had the highest proportion of structure-forming pieces with 62%, but thick, short LWD was most abundant because it was the most common size, and because 44% of it was structure-forming.

On Waddell Creek, where much of the channel is wider than on Gazos Creek, LWD less than two feet in diameter accounted for over two-thirds of

all in-channel LWD tallied (Figure 25B). LWD less than two feet in diameter was more likely to form a structure if it was greater than 20 feet in length, but the proportions of structure-forming thin, short and thin, long LWD were low (12% and 18%, respectively) (Figure 26B). For LWD greater than two feet in diameter, length was not an overriding factor in structure formation. Fifty-two percent of LWD that was thick, short formed structure on Waddell Creek (Figure 26B). Only 39% of thick, long LWD was structure-forming.

On Scott Creek, length affected whether LWD measuring less than two feet in diameter formed a structure (Figure 26C). Thin, long LWD was more likely to be structure-forming (36%) than thin, short LWD (25%). For LWD greater than two feet in diameter, both short and long LWD were almost equally likely to form a structure (59% versus 58%, respectively) (Figure 26C).

Unlike the other three streams, on Soquel Creek, LWD greater than 20 feet in length was far more abundant than LWD less than 20 feet in length (Figure 26D) due in part to its relatively wide channel. In particular, thick, long LWD was most abundant, followed closely by LWD that was thin, long. However, LWD less than 20 feet in length was more likely to be structure-forming, especially for LWD greater than two feet in diameter. Thick, short LWD was twice as likely to be structure-forming (69%) as thick, long LWD (33% structure-forming). The same was true for LWD less than two feet in

diameter: thin, short LWD was twice as likely as thin, long LWD to form a structure (22% versus 11%). The relative scarcity of shorter pieces of LWD on Soquel Creek can be explained by its high average bankfull channel width (Table 2D). Smaller, shorter pieces of LWD would be unlikely to remain in such a wide channel, but would be rinsed out fairly quickly.

Presence or absence of a root wad was a significant factor on all four streams as to whether or not a piece of LWD was likely to form in-channel structures (Figures 27A-27D). Gazos Creek was the stream where root wads appeared to have the least effect on structure formation, with 32% overall and 36% of structure-forming LWD having a root wad attached. The effect of attached root wad was evident on Waddell Creek, where only 17% of in-channel LWD had a root wad, but 43% of all structure-forming LWD had a root wad. A total of 30% of Scott Creek's in-channel LWD had a root wad, as well as 47% of its structure-forming LWD. The effect of a root wad was most pronounced on Soquel Creek, where 56% of structure-forming LWD had a root wad, compared to 18% of in-channel LWD. The presence of the root wad, especially on shorter LWD pieces, was responsible for the instances of a lack of benefit to LWD length for large-diameter LWD on Waddell and Scott creeks, and for both large- and small-diameter LWD on Soquel Creek (Figures 27B-27D).

On Gazos Creek, the highest concentration of root wads was in the >4', <20' size class, where 72% of the structure-forming LWD tallied had a root wad, and the 3-4', <20' size class, where 46% of the structure-forming LWD had a root wad (Figure 27A). Most of these thick, short pieces of LWD with root wad were cut stumps, left over from past logging and channel clearing activities. Presence of a root wad was also important in the 2-3', >20' size class, with 42% of all structure-forming LWD having a root wad. However, little of the thick, long LWD that formed structure had a root wad attached (18% of 3-4' diameter and none of the >4-foot diameter – Figure 27A).

Although most (69%) of the in-channel LWD on Waddell was 1-2 feet in diameter, most of the LWD that was structure-forming was 2 feet in diameter or larger and root wads made the difference for most LWD less than 20 feet in length (Figure 27B). As on Gazos Creek, these were mostly old, cut stumps. Root wads were most important for short LWD greater than four feet in diameter, where 78% of the structure-forming LWD tallied had a root wad attached. Thirty-eight percent of the structure-forming LWD in the 2-3', <20' size class had a root wad, and for the 3-4', <20' size class the figure was 42%. Pieces greater than 20 feet in length, 2-3 feet and 3-4 feet in diameter also contributed substantially to the amount of structure-forming LWD. The 3-4', >20' size class had a high percentage of root wad occurrence,

with 60% of the structure-forming LWD having a root wad. For LWD 2-3 feet in diameter, 35% of structure-forming LWD had a root wad attached. Many of these pieces were streamside trees that were undercut and entered the stream during floods in 1995 and 1998.

Large woody debris with root wads attached accounted for high percentages overall in all size classes of structure-forming LWD on Scott Creek, but had the most significant effect on LWD greater than four feet in diameter, where 88% of LWD greater than 20 feet in length and 75% of the LWD less than 20 feet in length had a root wad attached (Figure 27C). As with the other streams, root wads were generally most important for LWD less than 20 feet in length.

On Soquel Creek, the small amount of structure-forming LWD present was there mainly because it had a root wad attached to it, particularly if it was less than 20 feet in length (Figure 27D). Every piece of structure-forming LWD that was less than 3 feet in diameter and less than 20 feet long had a root wad attached, as did 60% of the 4-foot diameter short LWD. For structure-forming LWD greater than 20 feet in length, 44% of the 2-foot diameter size class had a root wad, as did 50% of the 3-foot diameter and 33% of the 4-foot diameter size classes.

Discussion

Management Implications

Diameter, length, and the presence of a root wad were important LWD characteristics determining whether a piece of LWD was likely to be structure-forming on the four streams in this study. Large woody debris that was small-diameter but greater than 20 feet in length, or LWD 3 feet or greater in diameter, was more likely to be structure-forming, and much (36-56%) of the structure-forming LWD had a root wad attached. Presence of a root wad was especially critical for LWD on Soquel Creek, where 100% of LWD less than 20 feet in length and 3 feet in diameter had a root wad attached. On the other streams, a high percentage of large-diameter, structure-forming LWD less than 20 feet in length also had a root wad. On Gazos, Scott, and Waddell creeks, these pieces were usually old redwood stumps that remained after logging operations prior to the 1980s, when common practice was to log up to the channel edge, and leave large stumps in place adjacent to the channel. On Gazos Creek, some of the stumps were left in the channel after logjam clearing activities.

This study corroborates earlier results. Bilby and Ward (1989) found diameter and the length of LWD relative to stream channel width to be critical determinants in whether a piece of LWD was likely to form a pool.

Rosenfeld and Huato (2003) found that that the diameter of LWD was positively correlated to pool size, and Keim and Skaugset (2002) found that a piece of LWD with a root wad attached was far more likely to form a pool or be a key piece in a log jam than a piece without a root wad (40% versus 16%).

It is important to note that a large majority (59-75%) of the LWD tallied on the streams in this study was classified as “extra,” meaning it was not contributing to habitat structures or their formation. Keller and Swanson (1979) found that LWD stranded on bars and/or islands and out of contact with the lowflow channel typically has limited effects on channel morphology. Bilby (1984) and Swanson et al. (1984) found that, while the largest pieces of LWD were more stable and likely to create habitat, smaller pieces associated with debris jams could also contribute to habitat formation, since they become mobile during floods. If more large-diameter logs were added to the streams in this study to serve as “catcher” logs, much of the smaller “extra” LWD may have a chance to be incorporated in a debris jam and begin to form habitat, rather than being rinsed out of the system, as evidenced by the example in Figures 28 and 29. Larger “extra” LWD also provides opportunities for habitat enhancement if it can be moved within the channel to more productive configurations or locations.

Hardwood species, especially alders, make up the majority of trees tallied in the “perched” areas, and are dominant in the riparian areas of

downstream reaches on all four streams. Riparian areas in middle reaches reflected a mix of hardwoods, with hardwoods dominant in reaches with a wide floodplain and conifers dominant in reaches with a small or non-existent floodplain. Upslope areas, where they occurred, were dominated by conifers and hardwood species such as California bay and tanbark oak. In-channel LWD densities followed these general downstream/upstream patterns, but structure-forming LWD was formed mostly by conifers on Gazos Creek and Waddell Creek; especially on Gazos Creek, structures were formed by “old” redwood LWD. Scott Creek, where a broad, alder-dominated floodplain extended far upstream, had a prevalence of hardwood LWD.

In this study, conifers, especially old redwoods, outnumbered hardwoods in most reaches and were more likely to be part of structures due to their durability and persistence. Downed alders were observed to break and decay quickly. It is well documented that hardwood-derived LWD is not as decay-resistant, not as persistent in the channel, and not as likely to form habitat as conifer-derived LWD (McHenry et al 1998; Hyatt and Naiman 2001). Bilby and Ward (1991) found that input of LWD from deciduous or hardwood trees does not offset losses from decay of coniferous LWD already present, resulting in a net loss over time. Hyatt and Naiman (2001) found that even large-diameter hardwoods are broken down into small pieces and flushed from the channel more quickly than conifers of equal diameter size.

It is therefore preferable to utilize conifer LWD over hardwood LWD, but this might not always be possible due to financial constraints, restricted channel access or lack of conifers occurring at streamside. Using local hardwoods to replenish LWD can save money, reduce the need for heavy equipment in the channel, thereby reducing damage to the stream (Bilby and Ward 1989).

Hardwoods can potentially serve as valuable LWD if certain conditions are met: a) they are sufficient diameter and length in proportion to the channel width; b) have a root wad; and c) are alive. Opperman (2002) found that almost 50% of channel spanning debris jams on streams in hardwood-dominated forests contained a living “key” piece and that living hardwood LWD potentially delayed the loss of hardwood LWD through decay and/or depletion. However, in my study areas in-channel trees that were alive were not alder, but were California bay laurels, cottonwoods, sycamores or bigleaf maples, despite the abundance of alders and alder LWD.

O'Connor and Ziemer (1988) found that, although additions of LWD to streams following timber harvest would help make up for recruitment losses resulting from timber harvest, most LWD in the stream was small and highly mobile during flood events. Based on recruitment rates derived from their model, they were able to make a recommendation for the addition of LWD to the stream each year, using logs that were not commercially valuable (i.e., hardwood species such as maple, alder, California bay or cottonwood). Based

on my results, the largest benefit would come from large-diameter trees with root wads attached, especially species likely to remain alive after being pulled over, rather than as cut logs.

Many factors influence LWD loading and availability in streams. In forested areas, geomorphology of stream reaches and the surrounding areas is the most significant factor related to LWD abundance, even more important than land use practices (Wing and Skaugset 2002). The larger the channel or width/depth ratio, the more pronounced the loss of previously existing LWD is likely to be. This is especially apparent on Soquel Creek, which has the highest average width/depth ratio of any stream in this study. Soquel Creek is urbanized, with a high number of buildings directly alongside its banks. Many of the normal streamside and channel dynamics on Soquel Creek, including channel LWD loading/removal, riparian tree size and density, are extensively managed. It is not surprising then, that Soquel Creek also has by far the lowest relative densities of in-channel LWD of any stream in this study. In contrast, Gazos Creek and the west fork of Waddell Creek, the smallest but most pristine streams in this study, had the highest densities of in-channel coniferous LWD, the highest densities of “old” coniferous LWD, and the lowest width/depth ratios. Unfortunately, any proposal to supplement LWD loading in Soquel Creek would likely be met

with a great deal of opposition from those more interested in protecting streamside infrastructure than in restoring habitat.

Growth data from increment cores taken for this study on Gazos Creek indicates that no clear relationship exists between a tree's proximity to the stream and its growth rates in these relatively dense riparian and upslope forests. Other factors, such as a) competition from neighboring trees, b) the amount of shade a tree was subjected to from larger trees or due to geomorphology, and c) proximity to the road, appear to be important enough that proximity to streamside water did not stand out as the dominant influence on tree growth rates. Coates et al. (1991) found that diameter (growth) increased as adjacent vegetation decreased; without adjacent vegetation, conifers were up to 84% larger than seedlings planted in undisturbed vegetation. Planting conifer seedlings in densely forested riparian areas would likely have limited effect in mitigating in-channel losses of conifer-derived LWD, because conifers grow slowly and their growth rates are negatively impacted by adjacent vegetation. Clear-cutting of deciduous riparian trees to allow for planting of conifer seedlings has been attempted in some areas (McHenry et al. 1998), but this is expensive and more suited to larger, recently clear-cut watersheds. However, after partial clearing of riparian hardwoods by flood events, or as a source of in-channel LWD, planting of conifer seedlings might be successful.

Recruitment of perched trees is the result of bank undercutting and erosion and occurs frequently. Because hardwoods are the dominant species in perched areas, they are more likely to be recruited to the stream channel through erosion and bank undercutting during floods. Most of the largest conifers are apparently only recruited episodically during severe floods or as part of debris flows in steep upstream areas of streams, such as occurred on upper Gazos, west fork Waddell and upper main stem Waddell creeks in the El Niño winter of 1997-1998 (Smith 2001). Bragg (2000) found that effects of catastrophic, intermittent recruitment are far more important to in-channel LWD levels than individualistic input. However, when large trees are recruited in potentially inappropriate areas, such as adjacent to Gazos Creek Road, they are deemed a hazard, cut and removed (Figure 30). Stream cleaning and removal of LWD is a standard practice on Soquel Creek, as is the cutting and removal of perched trees by private landowners (M. Leicester, pers. obs.) On many streams, perched trees are cut in the erroneous belief that they are responsible for eroding the banks on which they grow. Most habitat benefits that could have been gained from these trees are lost upon their removal and, in most cases, not mitigated. Careful in-channel management of LWD, if done at the appropriate time and in a manner that minimizes in-stream damage, can potentially result in enormous habitat benefits.

Debris jams can present a similar opportunity if they are managed appropriately. On Gazos and Waddell creeks, debris jams accounted for much of the LWD present; on Waddell Creek, almost 40% of the LWD tallied was caught in jams. Large debris jams can become problems when they deflect streamflow in such a way as to cause increased bank erosion, or when their volume becomes so large that they can no longer float during high flows, thereby becoming potential migration barriers to salmonids (see Figure 31). This debris jam, located just above the mouth of Waddell Creek, was breached in late 2003 and its LWD lost. Were it to have occurred in an upstream reach, the release of a portion of the impounded LWD could have benefited downstream reaches, *if* “catcher” logs were in place.

The ability of LWD to trap sediment is well documented (Bilby 1981; Keller and Swanson 1979), and the gravel sorting and sediment retention that occur around LWD are sometimes lauded as buffers against increased sediment loads caused by poor land use practices and roads (Hyatt and Naiman 2001). Sediment (sand and silt) can be a problem on all the streams in this study, due to the steep topography and highly erodible substrate in the upper watersheds. Future efforts to make small increases in LWD abundance in the study areas should therefore not have much effect on the sediment loads in any of the streams.

Evaluation of the Modified LWD Inventory Form

The advantages of the modified LWD inventory form used in this study over the Flosi form are substantial. Most of the changes are simple and require very little additional survey effort, but the amount of information obtained on in-channel and upslope conditions, and restoration potential, is greatly increased.

One important improvement over the Flosi form is the differentiation between in-channel structure-forming LWD versus “extra” LWD. The Flosi form merely tallies what is present in-channel, without regard to function or specific location, while the modified form allows for recording the exact location of each piece of LWD in a sample, along with its function at the time of sampling. It was then possible to determine that 60-75% of the in-channel LWD tallied was “extra” rather than structure-forming (Figure 21). More meaningful comparisons of LWD densities and functions in each size and length class, in upper and lower reaches of each stream, and between all of the streams, were also made possible. This change, alone, made possible most of the analyses and comparisons of in-channel LWD on each stream in this study and provided significant baseline data while requiring almost no extra effort.

Another key difference is that the new form employs the use of symbols to differentiate among species of trees and LWD, and to denote certain

characteristics of tallied LWD, such as leaning, multi-trunk, root wad attached, and old. The designation for “old” conifer was of particular importance in the analysis of conifer-derived LWD loading. The “root wad attached” symbol helped demonstrate the importance of attached root wads in LWD retention and structure formation, particularly with regard to LWD less than 20 feet in length on some streams (Figures 27A-27D).

The use of symbols to denote individual species and “old” LWD enabled me to discover relatively easily how much of the in-channel LWD was hardwood-derived or conifer-derived, as well as the species composition of riparian and upslope forests. This information aids in the determination of possible sources of in-channel LWD, and aids in determining LWD loading and roughly estimating in-channel residence time. For example, results from this study indicate that much of the conifer-derived LWD on all four streams was “old” redwood that displayed signs of weathering and was judged to have been present in the channel for at least several decades (Tables 4A-4D). Apparently, recent recruitment of conifer LWD is low on these streams, and “old” legacy conifer LWD is probably being lost at a far greater rate than it is being replaced. This is troubling due to the tendency of in-channel structures to be formed by conifer-derived LWD, as noted in previous studies (Bilby and Ward 1991; McHenry et al. 1998; Bragg 2000), all of which recommended LWD supplementation as partial mitigation for the losses.

The modified form splits the upslope area into two new categories (riparian and upslope). This split, along with species designations, allowed a clearer characterization of the forest habitat adjacent to the stream and provided information on sources of LWD as a result of bank erosion, tree fall immediately adjacent to the channel, and debris flows. While the “source” symbol was seldom used in this study because so little of the LWD was recently recruited, it was still very useful when documenting the importance of episodic recruitment.

The modified form is very functional as it exists now. However, it is very data-dense and does require an adjustment period. Feedback received on it to date has made clear that most new users are more comfortable after a small amount of training.

During analysis, some deficiencies in the survey method were noted. In this study, debris jams outside of sample boundaries were only noted as to location, and the LWD they contained was not tallied. Because large debris jams are spotty in distribution, may be missed in samples and may contain a significant portion of the total in-channel LWD present in a stream, it would be useful to tally *all* LWD contained in each large debris jam encountered to get a better idea of the portion of LWD actually trapped in the jams. In this study, most large debris jams did fall within sample sites and their LWD was included in tallies. However, survey intensity (two 200-foot samples per 1000

feet) was twice that recommended by Flosi et al. (1998). Other debris jams were encountered for which no tallies were performed, and this may have affected in-channel density results. The sampling error would have been greater for lower-intensity surveys.

Although some of the information gathered by the modified form may contain more detail than necessary for a simple LWD inventory, the very small amount of additional effort involved probably makes it worthwhile.

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Tables

Tables 1A - 1D. Reach lengths (feet), number of samples per reach, and Rosgen channel classification types for Gazos Creek, Waddell Creek, Scott Creek and Soquel Creek.

Table 1A. Gazos Creek.

Reach	Length (feet)	Number of Samples	Rosgen Channel Type
1	13,335	13	C5
2	4,000	8	C4
3	2,000	4	B4C
4	867	1	B4C
5	6,685	13	B4C/ F4
6	1,148	2	B4C
7	4,417	8	B4C
8	2,000	4	B1
9	875	2	A1
10	400+	1	B3

Table 1B. Waddell Creek. W1, W2 and W3 indicate reaches on the west fork; E1 and E2 indicate reaches on the east fork.

Reach	Length (feet)	Number of Samples	Rosgen Channel Type
2	11,800	23	C4/B4C
3	4,000	8	C3/B3C/F3
W1	3,600	7	C4/3
W2	7,720	15	B4C/C4
W3	3,468	6	B1/3
E1	1,225	2	C3
E2	2,000	4	B3/2

Table 1C. Scott Creek. BC1 and BC2 are reaches on Big Creek, a tributary.

Reach	Length (feet)	Number of Samples	Rosgen Channel Type
2	6,920	7	C3/4
3	7,100	14	C4/B4C
4	3,200	6	C4
5	11,233	22	C4/B4C
6	2,000	4	B3C
7	3,000	6	B3/F3B
8	400	1	B2A
BC1	3,100	6	B3/B3C
BC2	3,400	7	B2/3

Table 1D. Soquel Creek.

Reach	Length (feet)	Number of Samples	Rosgen Channel Type
1	4,175	4	C5
2	1,820	2	C4
3	4,645	6	C3/4
4	3,560	3	C4
5	3,844	4	C4
6	6,406	7	C3
7	5,670	5	C4
8	4,890	5	B3C
9	12,730	13	C4
10	5,860	6	B3C

Tables 2A – 2D. Mean widths (feet) of lowflow and bankfull channels, mean bankfull channel depths (feet), bankfull width/depth ratios and lowflow/bankfull ratios by reach for Gazos Creek, Waddell Creek, Scott Creek and Soquel Creek in 2001-2002.

Table 2A. Gazos Creek.

Reach	Lowflow Channel	Bankfull Channel		Bankfull Width/ Bankfull Depth	Lowflow Width/ Bankfull Width
	Mean Width (feet)	Mean Width (feet)	Mean Depth (feet)		
1	8.6	27.7	3.3	8.4	0.31
2	10.2	38.1	4.1	9.3	0.27
3	9.6	46.3	3.8	12.2	0.21
4	10.0	43.0	4.5	9.6	0.23
5	8.1	33.3	4.1	8.1	0.25
6	7.3	32.5	4.3	7.6	0.22
7	10.5	26.8	4.0	6.7	0.39
8	12.8	27.5	3.8	7.2	0.46
9	12.5	20.0	4.8	4.2	0.63
10	11.0	21.0	5.0	4.2	0.52

Table 2B. Waddell Creek.

Reach	Lowflow Channel	Bankfull Channel		Bankfull Width/ Bankfull Depth	Lowflow Width/ Bankfull Width
	Mean Width (feet)	Mean Width (feet)	Mean Depth (feet)		
2	18.0	49.3	5.1	9.6	0.37
3	16.8	65.9	6.5	10.1	0.26
W1	17.6	41.0	6.1	6.7	0.43
W2	18.9	36.1	4.3	8.4	0.52
W3	18.9	38.7	4.8	8.1	0.49
E1	23.5	45.0	3.5	12.8	0.51
E2	23.5	46.3	4.8	9.6	0.51

Table 2C. Scott Creek.

Reach	Lowflow Channel	Bankfull Channel		Bankfull Width/ Bankfull Depth	Lowflow Width/ Bankfull Width
	Mean Width (feet)	Mean Width (feet)	Mean Depth (feet)		
2	29.6	60.1	4.8	12.5	0.49
3	12.4	42.1	4.1	10.3	0.29
4	16.3	38.7	4.3	9.0	0.42
5	14.9	35.8	3.9	9.2	0.42
6	15.3	22.3	3.1	7.2	0.69
7	16.8	23.5	2.8	8.4	0.71
8	15.0	30.0	2.5	12.0	0.50
BC1	16.5	42.5	3.7	11.5	0.39
BC2	15.4	38.9	4.0	9.7	0.40

Table 2D. Soquel Creek.

Reach	Lowflow Channel	Bankfull Channel		Bankfull Width/ Bankfull Depth	Lowflow Width/ Bankfull Width
	Mean Width (feet)	Mean Width (feet)	Mean Depth (feet)		
1	33.3	53.3	2.8	19.0	0.62
2	31.5	42.5	3.5	12.1	0.74
3	23.2	46.7	3.5	13.3	0.50
4	26.3	48.3	3.0	16.1	0.54
5	33.8	56.8	2.7	21.0	0.60
6	28.7	51.7	3.0	17.2	0.56
7	33.2	58.8	1.9	30.1	0.56
8	24.2	56.6	2.4	23.5	0.43
9	19.2	52.7	2.1	24.8	0.36
10	18.8	52.0	2.2	23.6	0.36

Tables 3A – 3D. Mean width (feet) and ranges (sample means) by reach for the riparian border and mean slopes (%) and ranges (sample means for riparian and upslope areas of Gazos, Waddell, Scott and Soquel Creeks in 2001-2002. Where no range is given, values did not vary.

Table 3A. Gazos Creek.

REACH	RIPARIAN WIDTH (FEET)				SLOPE (%)							
	LEFT BANK		RIGHT BANK		LEFT BANK UPSLOPE		LEFT BANK RIPARIAN		RIGHT BANK RIPARIAN		RIGHT BANK UPSLOPE	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
1	52	25-75	33	10-50	57	10-120	57	10-100	35	10-100	49	5-120
2	44	25-75	47	25-75	39	5-150	30	10-110	28	10-50	43	10-100
3	26	20-40	16	10-25	85	40-120	56	10-100	58	10-100	69	55-85
4	30		15		100		45		65		100	
5	15	5-30	20	10-30	108	30-150	95	50-150	75	30-100	105	45-150
6	9	5-10	20	15-25	98	75-120	93	85-100	95	90-100	95	55-135
7	34	15-50	26	15-40	81	25-125	39	20-85	63	25-100	66	10-120
8	17	10-25	17	8-30	54	25-100	50	25-100	63	30-100	88	30-125
9	20	0-35	20	15-25	18	15-20	100	75-150	80	60-100	122	120-125
10	25		15		100		60		120		125	

Table 3B. Waddell Creek. Reaches on the west fork are denoted with “W”; reaches on the east fork are denoted with “E”.

REACH	RIPARIAN WIDTH (FEET)				SLOPE (%)							
	LEFT BANK		RIGHT BANK		LEFT BANK UPSLOPE		LEFT BANK RIPARIAN		RIGHT BANK RIPARIAN		RIGHT BANK UPSLOPE	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
2	53	10-75	45	5-75	21	2-100	25	2-100	22	5-150	47	8-100
3	30	2-60	44	10-75	50	5-150	76	5-180	63	8-150	83	8-150
W1	26	5-60	16	2-50	35	5-90	9	5-20	44	5-90	35	5-90
W2	14	1-55	21	5-75	57	5-130	53	15-110	42	5-100	58	5-120
W3	19	2-35	8	1-15	92	75-120	24	8-50	42	30-60	58	35-90
E1	40	30-50	68	60-75	38	15-65	23	10-35	10		10	
E2	32	9-60	45	40-50	33	10-100	25	15-50	15	10-25	59	10-120

Table 3C. Scott Creek. Samples on Big Creek are denoted BC1 and BC2.

REACH	RIPARIAN WIDTH (FEET)				SLOPE (%)							
	LEFT BANK		RIGHT BANK		LEFT BANK UPSLOPE		LEFT BANK RIPARIAN		RIGHT BANK RIPARIAN		RIGHT BANK UPSLOPE	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
2	43	10-75	56	25-75	41	5-150	43	8-70	16	8-55	60	30-75
3	41	30-75	59	20-75	22	5-100	50	10-150	20	5-40	38	10-100
4	71	50-75	31	10-75	5		7	5-8	32	8-100	50	5-80
5	36	10-75	40	10-75	20	5-80	30	8-100	33	5-100	18	5-85
6	4.5	3-5	6	5-10	69	15-120	83	50-100	50	10-100	31	10-70
7	4.5	2-5	4.5	2-5	68	10-130	88	30-120	88	30-120	50	30-80
8	0		2		120		0		60		120	
BC1	48	3-75	56	15-75	85	75-95	26	3-70	24	3-70	75	70-80
BC2	39	5-75	14	5-55	69	5-100	22	2-100	46	8-120	83	50-100

Table 3D. Soquel Creek.

REACH	RIPARIAN WIDTH (FEET)				SLOPE (%)							
	LEFT BANK		RIGHT BANK		LEFT BANK UPSLOPE		LEFT BANK RIPARIAN		RIGHT BANK RIPARIAN		RIGHT BANK UPSLOPE	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
1	41	20-60	31	18-55	5		21	15-25	43	25-60	9	5-20
2	35	20-50	45	15-75	5		40	15-65	48	40-55	5	
3	58	25-75	51	5-75	8	5-10	13	8-30	57	8-150	79	65-125
4	33	10-75	55	25-75	5		25	15-40	20	10-40	5	
5	48	10-75	53	30-75	23	5-75	43	8-100	19	5-40	7	5-10
6	64	30-75	60	45-75	28	5-150	15	10-20	16	8-50	17	5-85
7	46	8-75	54	35-75	58	5-150	33	10-50	18	5-55	28	5-75
8	49	20-75	34	10-75	30	5-70	31	10-100	68	12-110	66	5-110
9	42	5-75	45	5-75	73	5-180	52	10-180	17	5-100	36	5-150
10	55	30-75	56	10-75	20	5-50	18	7-40	23	5-90	27	5-75

Tables 4A – 4D. Amounts of in-channel LWD by diameter, channel location, function and species on Gazos, Waddell, Scott and Soquel Creeks in 2001-2002. "CF" = conifer; "HW" = hardwood.

Table 4A. Gazos Creek.

		Structure		Extra		Totals	Percent
Diameter (feet)		Pool	Backwater	Lowflow	Bankfull		
>4	Total CF	24	5	9	20	58	
>4	Redwood	24	3	9	18	54	93
>4	"Old" Redwood	24	3	7	16	50	93
>4	Total HW	3	0	0	0	3	
>4	Alders	3	0	0	0	3	100
3-4	Total CF	17	3	4	10	34	
3-4	Redwood	11	3	4	10	28	82
3-4	"Old" Redwood	10	2	4	10	26	93
3-4	Total HW	2	0	0	0	2	
3-4	Alders	2	0	0	0	2	100
2-3	Total CF	30	11	28	29	98	
2-3	Redwood	26	11	22	24	83	85
2-3	"Old" Redwood	26	10	16	23	75	90
2-3	Total HW	6	0	0	6	12	
2-3	Alders	6	0	0	6	12	100
1-2	Total CF	20	10	45	43	118	
1-2	Redwood	16	8	34	29	87	74
1-2	"Old" Redwood	13	6	23	23	65	75
1-2	Total HW	29	9	23	56	117	
1-2	Alders	29	9	23	54	115	98
Total	Total CF	91	29	86	102	308	
	Redwood	77	25	69	81	252	82
	"Old" Redwood	73	21	50	72	216	86
	Total HW	40	9	23	62	134	
	Alders	40	9	23	60	132	99

Table 4B. Waddell Creek.

Diameter (feet)		Structure		Extra		Totals	Percent
		Pool	Backwater	Lowflow	Bankfull		
>4	Total CF	9	0	4	2	15	
>4	Redwood	9	0	4	2	15	100
>4	"Old" Redwood	9	0	4	2	15	100
>4	Total HW	0	0	1	0	1	
>4	Alders	0	0	1	0	1	100
3-4	Total CF	6	4	7	10	27	
3-4	Redwood	5	4	5	10	24	88
3-4	"Old" Redwood	1	1	5	9	16	66
3-4	Total HW	1	1	2	0	4	
3-4	Alders	0	1	0	0	1	100
2-3	Total CF	31	2	23	13	69	
2-3	Redwood	21	2	22	11	56	81
2-3	"Old" Redwood	9	0	14	7	30	54
2-3	Total HW	6	2	3	8	19	
2-3	Alders	4	2	1	3	10	53
1-2	Total CF	14	2	92	30	138	
1-2	Redwood	4	2	79	27	112	81
1-2	"Old" Redwood	1	2	68	23	94	84
1-2	Total HW	22	8	79	56	165	
1-2	Alders	22	8	72	50	152	92
Total	Total CF	60	8	126	55	249	
	Redwood	39	8	110	50	207	83
	"Old" Redwood	20	3	91	42	156	75
	Total HW	29	11	85	64	189	
	Alders	26	11	74	53	164	87

Table 4C. Scott Creek.

Diameter (feet)		Structure		Extra		Totals	Percent
		Pool	Backwater	Lowflow	Bankfull		
>4	Total CF	8	1	4	2	15	
>4	Redwood	8	1	4	2	15	100
>4	"Old" Redwood	7	1	4	0	12	80
>4	Total HW	3	0	0	0	3	
>4	Alders	3	0	0	0	3	100
3-4	Total CF	9	1	5	0	15	
3-4	Redwood	8	1	5	0	14	93
3-4	"Old" Redwood	4	0	5	0	9	64
3-4	Total HW	1	0	1	1	3	
3-4	Alders	1	0	0	1	2	66
2-3	Total CF	18	2	9	12	41	
2-3	Redwood	18	1	7	11	37	90
2-3	"Old" Redwood	16	1	5	5	27	73
2-3	Total HW	10	5	3	4	22	
2-3	Alders	9	5	3	3	20	91
1-2	Total CF	8	0	16	3	27	
1-2	Redwood	8	0	15	1	24	89
1-2	"Old" Redwood	2	0	8	0	10	42
1-2	Total HW	32	11	47	50	140	
1-2	Alders	30	10	36	44	120	86
Total	Total CF	43	4	34	17	98	
	Redwood	42	3	31	14	90	92
	"Old" Redwood	29	2	22	5	58	64
	Total HW	46	16	51	55	168	
	Alders	43	15	39	48	145	86

Table 4D. Soquel Creek.

Diameter (feet)		Structure		Extra		Totals	Percent
		Pool	Backwater	Lowflow	Bankfull		
>4	Total CF	9	3	2	5	19	
>4	Redwood	8	3	2	5	18	95
>4	"Old" Redwood	4	2	1	5	12	67
>4	Total HW	1	0	1	0	2	
>4	Alders	0	0	1	0	1	50
3-4	Total CF	1	0	4	3	8	
3-4	Redwood	0	0	2	2	4	50
3-4	"Old" Redwood	0	0	1	1	2	50
3-4	Total HW	1	0	0	0	1	
3-4	Alders	0	0	0	0	0	0
2-3	Total CF	0	2	5	4	11	55
2-3	Redwood	0	1	3	2	6	33
2-3	"Old" Redwood	0	1	1	0	2	
2-3	Total HW	9	0	1	8	18	
2-3	Alders	3	0	1	1	5	28
1-2	Total CF	0	0	6	6	12	
1-2	Redwood	0	0	6	1	7	58
1-2	"Old" Redwood	0	0	4	1	5	71
1-2	Total HW	4	3	14	20	41	
1-2	Alders	4	1	12	8	25	61
Total	Total CF	10	5	17	18	50	
	Redwood	8	4	13	10	35	70
	"Old" Redwood	4	3	7	7	21	60
	Total HW	15	3	16	28	62	
	Alders	7	1	14	9	31	50

Figures

Figure 1. Map showing the study streams on central California coast. Hatch marks on streams indicate the upstream and downstream extents of sampling. Where no lower hatch mark appears, sampling was started near the mouth.

LWD INVENTORY FORM

DATE: _____ STREAM: _____ DRAINAGE: _____ SAMPLE _____ OF _____ REACH NO. _____ CHAN. TYPE _____
 REF. PT.: _____ SAMPLE LOC. (FT. FROM REF. PT.): _____ TO _____

	RIGHT BANK (75')										STREAM										LEFT BANK (75')																			
	% SLOPE					WIDTH					DEPTH					PERCHED					% SLOPE					WIDTH					PERCHED					% SLOPE				
	UD	US	DS	DS	US	UD	US	DS	DS	US	UD	US	DS	DS	US	UD	US	DS	DS	US	UD	US	DS	DS	US	UD	US	DS	DS	US										
1-2' D																																								
6-20'																																								
Root																																								
1-2' U																																								
>20'																																								
2-3' U																																								
6-20'																																								
Root																																								
2-3' D																																								
>20'																																								
3-4' D																																								
6-20'																																								
Root																																								
3-4' U																																								
>20'																																								
>4' D																																								
6-20'																																								
Root																																								
>4' U																																								
>20'																																								

R - RIVER OAK D - DESM. FIB T - TAN OAK U - SOUTHERN PINE N - NUTBEG O - OAK B - BAY A - ALDER H - HAWK W - WILLOW C - COTTONWOOD E - BOX ELDER
 J - JEFFERSON P - PINE L - LARCH F - FERN G - GUM S - SWEET GUM T - THICKLEAF ROOT (ROOT) (THINK) - SCHEDULE OF LWD (SMALL 80)

Figure 2. Modified LWD inventory form developed for this project.

Figure 3. "Perched" redwood tree on Waddell Creek, California (see arrow).
(Photo: J.J. Smith)

Figure 4. Stream channel cross-section depicting upslope, riparian, perched, lowflow and bankfull areas. Adapted from Welsh et al. (1998).

Figure 5. Old redwood LWD buried in stream channel, creating a pool (see arrow). Gazos Creek, California. (Photo: Author)

Figure 6. Old redwood LWD forming a backwater (see arrow). Gazos Creek, California. (Photo: Author)

Figure 7. "Lowflow extra" LWD (see arrow). Waddell Creek, California.
(Photo: J.J. Smith)

Figure 8. "Bankfull extra" LWD (see arrow). Gazos Creek, California.
(Photo: Author)

Figure 9A. Mean riparian widths on Gazos Creek in 2001-2002, by reach.

Figure 9B. Densities of conifers and hardwoods present in riparian areas on Gazos Creek in 2001-2002, by reach.

Figure 10A. Mean riparian widths on Waddell Creek in 2001-2002, by reach.

Figure 10B. Densities of conifers and hardwoods present in riparian areas on Waddell Creek in 2001-2002, by reach.

Figure 11A. Mean riparian widths on Scott Creek in 2001-2002, by reach.

Figure 11B. Densities of conifers and hardwoods present in riparian areas on Scott Creek in 2001-2002, by reach.

Figure 12A. Mean riparian widths on Soquel Creek in 2002, by reach.

Figure 12B. Densities of conifers and hardwoods present in riparian areas on Soquel Creek in 2002, by reach.

Figure 13. Total number of logs and trees tallied in perched, riparian or upslope areas on each stream in 2001-2002. Data labels indicate totals.

Figure 14. Densities of logs and trees in perched, riparian or upslope areas on each stream in 2001-2002, by type. Data labels indicate densities of each.

Figure 15A. Densities of logs and trees classified as "perched" in Gazos Creek in 2001-2002, by reach.

Figure 15B. Densities of logs and trees classified as "upslope" in Gazos Creek in 2001-2002, by reach.

Figure 16A. Densities of logs and trees classified as "perched" in Waddell Creek in 2001-2002, by reach.

Figure 16B. Densities of logs and trees classified as "upslope" in Waddell Creek in 2001-2002, by reach.

Figure 17A. Densities of logs and trees classified as “perched” in Scott Creek in 2001-2002, by reach.

Figure 17C. Densities of logs and trees classified as “upslope” in Scott Creek in 2001-2002, by reach.

Figure 18A. Densities of logs and trees classified as "perched" in Soquel Creek in 2002, by reach.

Figure 18B. Densities of logs and trees classified as "upslope" in Soquel Creek in 2002, by reach.

Figure 19A. Growth of redwoods (n=22) adjacent to and upslope from Gazos Creek in 2002-2003. Two data points are shown for trees with a distinct change in growth rate with age.

Figure 19B. Growth of Douglas firs (n=15) adjacent to bankfull and upslope of Gazos Creek in 2002-2003. Two data points are shown for trees with a sharp change in growth rate with age.

Figure 19C. Growth of alders (n=31) perched at the edge of the active channel and in the floodplain of Gazos Creek, 2002-2003. Two data points are shown for trees with a distinct change in growth rate with age.

Figure 20. In-channel densities of conifer and hardwood LWD on Gazos, Waddell, Scott and Soquel Creeks in 2001-2002. Value labels indicate densities of each type of LWD.

Figure 21. In-channel densities of LWD creating structures (pools or backwaters) on Gazos, Waddell, Scott and Soquel Creeks in 2001-2002. Value labels indicate densities of each type of wood compared to the total amount in the channel.

Figure 22A. In-channel densities of conifer and hardwood LWD on reaches 1-3 and 5-9 on Gazos Creek in 2001-2002. Densities of LWD contained in a large debris jam on reach 2 are also indicated. No LWD was tallied in reaches 4 and 10.

Figure 22B. In-channel densities of conifer and hardwood LWD by reach on Waddell Creek in 2001-2002. Densities of LWD contained in three large debris jams on reaches W1 and W2 are also indicated.

Figure 22C. In-channel densities of conifer and hardwood LWD on reaches 2 through 8 of Scott Creek and reaches 1 and 2 of Big Creek (a tributary) in 2001-2002.

Figure 22D. In-channel densities of conifer and hardwood LWD on reaches 1 through 10 of Soquel Creek in 2002.

Figure 23. Percentages of in-channel LWD trapped in debris jams on Gazos, Waddell, Scott and Soquel Creeks, 2001-2002.

Figure 24. A large debris jam on Waddell Creek – one of three that accounted for the 39% of tallied in-channel LWD that was contained in debris jams. (Photo: J.J. Smith)

Figure 25A. Total in-channel LWD and total structure-forming LWD, by diameter, on Gazos Creek in 2001-2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 25B. Total in-channel LWD and total structure-forming LWD, by diameter, on Waddell Creek in 2001-2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 25C. Total in-channel LWD and total structure-forming LWD, by diameter, on Scott Creek in 2001-2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 25D. Total in-channel LWD and total structure-forming LWD, by diameter, on Soquel Creek in 2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 26A. Total number of pieces of in-channel LWD and total number of structure-forming LWD by size on Gazos Creek in 2001-2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 26B. Total number of pieces of in-channel LWD and total number of structure-forming LWD by size on Waddell Creek in 2001-2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 26C. Total number of pieces of in-channel LWD and total number of structure-forming LWD by size on Scott Creek in 2001-2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 26D. Total number of pieces of in-channel LWD and total number of structure-forming LWD by size on Soquel Creek in 2002. Percents indicate proportion of LWD that was structure forming for that size class.

Figure 27A. In-channel structure-forming LWD on Gazos Creek by size and presence/ absence of rootwad, 2001-2002. Percents indicate the proportion of LWD in the size category which had a rootwad.

Figure 27B. In-channel structure-forming LWD on Waddell Creek, by size and presence/ absence of rootwad, 2001-2002. Percents indicate the proportion of LWD in the size category which had a rootwad.

Figure 27C. In-channel structure forming LWD on Scott Creek, by size and presence/ absence of rootwad, 2001-2002. Percents indicate the proportion of LWD in the size category which had a rootwad.

Figure 27D. In-channel structure forming LWD on Soquel Creek, by size and presence/ absence of rootwad, 2002. Percents indicate the proportion of LWD in the size category which had a rootwad.

Figure 28. Downed Douglas fir with root wad, classified as “lowflow extra” in 2002. (Photo: Author)

Figure 29. Downed Douglas fir in 2005, now forming a debris jam and classified as “lowflow, pool-forming”. (Photo: Author)

Figure 30. Cut stump of a 3-4 foot diameter redwood tree on Gazos Creek in 1998. Tree entered channel when its bank was undercut; the trunk was removed as part of logjam clearing to protect Gazos Creek Road. (Photo: J. J. Smith)

Figure 31. Immense debris jam on lower Waddell Creek in late 2003. This jam was deemed a barrier to salmonid migration and was removed. Note person in upper left for scale. (Photo: J.J. Smith)