Geomorphology 209 (2014) 79–97

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

On the patterns and processes of wood in northern California streams

Lee Benda [b], Paul Bigelow [a,*]

[a] Bigelow Watershed Geomorphology, Oakland, CA, USA
[b] Earth Systems Institute, Mount Shasta, CA, USA

ARTICLE INFO

Article history:
Received 30 May 2013
Received in revised form 23 November 2013
Accepted 29 November 2013
Available online 16 December 2013

Keywords:
Wood budget
Wood recruitment
Wood storage
Wood transport
Spatial variation
Riparian management

ABSTRACT

Forest management and stream habitat can be improved by clarifying the primary riparian and geomorphic controls on streams. To this end, we evaluated the recruitment, storage, transport, and the function of wood in 95 km of streams (most drainage areas < 30 km^2) in northern California, crossing four coastal to inland regions with different histories of forest management (managed, less-managed, unmanaged). The dominant source of variability in stream wood storage and recruitment is driven by local variation in rates of bank erosion, forest mortality, and mass wasting. These processes are controlled by changes in watershed structure, including the location of canyons, floodplains and tributary confluences; types of geology and topography; and forest types and management history. Average wood storage volumes in coastal streams are 5 to 20 times greater than inland sites primarily from higher riparian forest biomass and growth rates (productivity), with some influence by longer residence time of wood in streams and more wood from landsliding and logging sources. Wood recruitment by mortality (windthrow, disease, senescence) was substantial across all sites (mean 50%) followed by bank erosion (43%) and more locally by mass wasting (7%). The distances to sources of stream wood are controlled by recruitment process and tree height. Ninety percent of wood recruitment occurs within 10 to 35 m of channels in managed and less-managed forests and upward of 50 m in unmanaged Sequoia and coast redwood forests. Local landsliding extends the source distance. The recruitment of large wood pieces that create jams (mean diameter 0.7 m) is primarily by bank erosion in managed forests and by mortality in unmanaged forests. Formation of pools by wood is more frequent in streams with low stream power, indicating the further relevance of environmental context and watershed structure. Forest management influences stream wood dynamics, where smaller trees in managed forests often generate shorter distances to sources of stream wood, lower stream wood storage, and smaller diameter stream wood. These findings can be used to improve riparian protection and inform spatially explicit riparian management.

1. Introduction

Protecting riparian sources of wood to streams has become a major component of forestry policy in western states (FEMAT, 1993; U.S. Forest Service and BLM, 1994). Examples include establishing riparian protection zones for wood recruitment (Young, 2000), mandating or promoting stream wood abundance standards or targets (NMFS, 1996; Fox and Bolton, 2007), monitoring abundance of wood in streams (Schuett-Hames et al., 1999), and implementing stream wood restoration programs (Cederholm et al., 1997). The processes of forest mortality, bank erosion, streamside landsliding, debris flows, and wildfires govern the supply of wood to streams (e.g., Murphy and Koski, 1989; Benda and Sias, 2003). The spatial distribution of different wood recruitment processes within a watershed or across landscapes varies substantially because of the diversity in forest composition and age, topography, stream size, climate, and the history of natural and human disturbances (e.g., floods, fires, logging).

Spatial and temporal variability in wood recruitment processes can complicate the management and regulation of stream wood in both headwater channels (nonfish-bearing) and larger fish-bearing streams. For example, site-specific riparian buffers could be designed based on whether forest mortality, bank erosion, or mass wasting is the dominant recruitment agent. If wood recruitment from channel migration or landsliding is important, local buffers could conceivably extend outward beyond streamside forests to protect such sources of wood (Reeves et al., 2003). Riparian forests could be managed for specific ecological objectives such as thinning dense young stands to increase the density of large trees (Beechie et al., 2000) or altering conifer–hardwood composition, strategies that require information on tree species and forest growth and mortality (Liquori, 2006). Thus, an understanding of riparian processes that govern wood recruitment to streams can enhance protection strategies for riparian forests across physically and ecologically diverse watersheds (Martin and Benda, 2001).

In California, the management of riparian areas is a major emphasis in forest management (Ligon et al., 1999; Berbach, 2001). California's

* Corresponding author. Tel.: +1 510 415 6850; fax: +1 810 815 4291.
E-mail addresses: leebenda@earthsystems.net (L. Benda), paul@bigwatershed.com (P. Bigelow).

0169-555X/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.geomorph.2013.11.028

forest practice rules require a standard riparian buffer width along all fish-bearing streams (46 m, 150 ft) and smaller buffers on a subset of nonfish-bearing streams, although some select timber harvest is allowed within them. These buffer widths are based primarily on the presence or absence of fish or nonfish aquatic species, hillslope gradient, and yarding system with no consideration of watershed to regional scale variability in riparian processes. In 2010, California adopted new forest practice rules that allow for a more site-specific, spatially explicit approach to riparian management (CAL FIRE, 2010).

Previous studies in California do not adequately characterize watershed to regional variability of wood recruitment to streams. For example, Harmon et al. (1986) and Lisle (2002) compiled stream wood volumes across several regions in California limited to data available at the time, where much of the data was from the humid north coastal areas and where the various surveys often used disparate measures of stream wood. In coast areas, Keller et al. (1995) documented the abundance and effects of old-growth redwood logs on channel morphology, while Wooster and Hilton (2004) measured stream wood volumes and accumulation rates, and Benda et al. (2002) estimated the relative contribution of forest mortality, bank erosion, and landsliding recruitment to streams in managed and old-growth redwood forests. Studies in the Sierra Nevada have focused on wood function and transport (Berg et al., 1998), effects of wildfire on stream wood (Berg et al., 2002), and stream wood abundance and function in managed and old-growth forests (Ruediger and Ward, 1996).

Despite these studies, little information exists on the spatial variability in wood recruitment and its effects on channel morphology, across different forest types, and in the more inland regions of California. To improve understanding and management of wood in streams across northern California, our primary study objective was to summarize general patterns, processes, and controls on stream wood recruitment, storage, transport, and the effects of wood on channel morphology. Specific questions that underpin our study include:

- How do wood volumes and recruitment processes vary at reach scales and what controls the variation?
- What are the similarities and differences in wood dynamics between regions?
- What are the distances to sources of stream wood and how do they vary?
- What are the dynamics of key wood pieces that form jams?
- What are the controls on wood-formed pools?
- What are the patterns of wood transport in streams?
- What are the influences of forest management on stream wood?

This study uses a synoptic approach that compiles a large set of previous wood surveys to quantify wood recruitment, storage, transport, and other characteristics along ~95 km of streams primarily in small forested mountain basins (<30 km^2) with managed and unmanaged forests. Such robust wood surveys are rare and revealed some unique findings, including the controls on spatial variation of wood in streams and wood-formed pools. All the surveys used the same wood budget methodology (similar to sediment budgets, e.g., Keller and Swanson, 1979; Benda and Sias, 2003) and field crew. Few quantitative wood budgets have been published (e.g., Martin and Benda, 2001; Benda et al., 2002) and this study provides most comprehensive budget to date. The findings are useful to geomorphologists and forest managers concerned with wood in streams.

2. Study areas

The study summarizes previously unpublished wood surveys we conducted along 65 km of channels surveyed in four California geomorphic provinces (California Geological Survey, 2002), including the Coast Ranges, Klamath Mountains, Cascade Range, and Sierra Nevada (west slope) (Fig. 1). Physical processes and attributes that may fundamentally influence the supply of wood to streams vary across these four regions, including erosion rates, precipitation, peak-flow timing, and riparian conifer species and biomass density (Table 1). Study reaches were limited to basins <30 km^2 to minimize the effects of fluvial redistribution of wood (e.g., Seo and Nakamura, 2009) and thereby to ensure that adequate amounts of wood were available for identifying the processes of recruitment (mortality, bank erosion, landsliding). To expand the analysis, we included field data from a previous published study we conducted using the same methods in the northern Coast Range, encompassing 9 km of streams in basins <30 km^2 (Benda et al., 2002). All the surveys combined cover a length of 76 km. To evaluate wood transport, an additional 19 km of stream reaches in basins draining areas from 30 to 70 km^2 were included to capture potentially longer transport distances in larger streams. In total, data on wood recruitment, storage, and transport from 95 km of streams from 73 reaches are evaluated in this paper.

The study not only focused on fish-bearing streams but also included smaller headwater (nonfish-bearing) channels. The study sites encompassed a range of channel gradients, widths, drainage areas, and forest biomass density (volume of trees per area, minimum tree size for site-specific surveys was 10 cm in diameter and 1.5 m in height) (Table 2). To evaluate the various wood metrics for potential influences from regional and management controls, the surveyed reaches were stratified into nine groups based on four geomorphic provinces and three forest management groups (managed, less managed, unmanaged) (Table 2).

Managed forests include private forests with individual trees <100 years old that were often entirely or nearly clear-cut in the early 1900s to 1930s with no native forest remaining except for residual old-growth trees in gorges that cannot be accessed. Some old abandoned logging roads were in riparian areas of managed forests, particularly in the Coast Ranges, a result of legacy logging in the 1950s and 1960s prior to forest practice rules. Less-managed forests include public and private forests that were selectively cut with some upslope clearcutting; forests had longer harvest rotations than managed forests and contain individual trees up to 200 or more years old, with some remnant small stands of native forest. Riparian buffer zones were along streams in managed and less-managed forests depending on the stream type, including buffer widths of 7.6 m (25 ft, ephemeral streams), 23 m (75 ft, streams with nonfish aquatic life), and 46 m (150 ft, fish-bearing streams). Selective cutting occurred within the buffers. Unmanaged forests include old-growth public parklands. A description of the forest metrics and harvest history available for private managed and less managed forests is included in Appendix A. The majority of channels surveyed were in managed forests (51 km), followed by less-managed (15 km), and unmanaged forests (11 km) (Table 2).

2.1. Coast Ranges

Surveys took place in the Ten Mile and Noyo River watersheds near Fort Bragg, CA (Fig. 1). Sites from the Benda et al. (2002) study included tributaries of Redwood Creek (Redwood National and State Parks) and tributaries of the Van Duzen River. The Mediterranean climate of the northern Coast Ranges is characterized by high annual precipitation (150–200 cm) that supports the coastal dominant species of coast redwood (*Sequoia sempervirens*), followed by Douglas-fir (*Pseudotsuga menziesii*) inland. Tan oak (*Lithocarpus densiflorus*), Pacific madrone (*Arbutus menziesii*), and Live oak (*Ouercus wislizenii*) are mixed with conifers inland; while red alder (*Alnus rubra*), willow (*Salix lasiandra*), and big leaf maple (*Acer macrophyllum*) are the dominant deciduous tree species in riparian areas. Geology is mostly Franciscan mélange (Complex), a mixture of highly deformed and weakly metamorphosed sedimentary rocks, with some interbedded marine volcaniclastic sediments (Cashman et al., 1995). The mechanically weak rock in combination with heavy rainfall and tectonic uplift has created a steep landscape highly prone to mass wasting that produces some of the highest erosion rates in the continental United States (Nolan and Janda, 1995). Erosion