Controls on large woody debris distributions in Yellowstone streams

by James Lee Rasmussen

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Woody debris affects the channel morphology of streams and can have profound effects on stream habitat. Despite knowledge of the effects of woody debris in streams, the controls on its distribution are poorly understood. This study examined 55 kilometers of the 2nd to 4th order segments in Soda Butte and Cache Creeks in Yellowstone National Park. A continuous 100-meter longitudinal sampling scheme was used to determine if there are basin-wide controls on woody debris.

Results of this study suggest that the streams in the study have only weak basin wide trends. Woody debris counts in the streams declined slightly with distance from the headwaters, but there appears to be no pattern to the agglomeration of wood into jams. Woody debris was found to have a minor but significantly positive effect on the number of riffles and pools. When wood counts from a burned and undisturbed stream were compared, the undisturbed stream had significantly higher amounts of woody debris.

This was in direct contrast to earlier research in the study area. The contrast can be attributed to recent high magnitude (MO year) floods, suggesting that floods are a major control on woody debris storage within the stream. The forest also plays a major role; a comparison of forested and non-forested segments of stream showed that forested segments had substantial and significantly higher quantities of wood.

Despite the failure to find strong basin-wide controls on woody debris, the study did call into question many methodological considerations, specifically the resolution of sampling required to study a stream. The results of this study suggest that most sampling schemes in stream research fail to capture the spatial variability in streams.

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and it is ready for submission to the College of Graduate Studies.

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ABSTRACT

Woody debris affects the channel morphology of streams and can have profound effects on stream habitat. Despite knowledge of the effects of woody debris in streams, the controls on its distribution are poorly understood. This study examined 55 kilometers of the 2nd to 4th order segments in Soda Butte and Cache Creeks in Yellowstone National Park. A continuous 100-meter longitudinal sampling scheme was used to determine if there are basin-wide controls on woody debris.

Results of this study suggest that the streams in the study have only weak basin wide trends. Woody debris counts in the streams declined slightly with distance from the headwaters, but there appears to be no pattern to the agglomeration of wood into jams. Woody debris was found to have a minor but significantly positive effect on the number of riffles and pools. When wood counts from a burned and undisturbed stream were compared, the undisturbed stream had significantly higher amounts of woody debris. This was in direct contrast to earlier research in the study area. The contrast can be attributed to recent high magnitude (>10 year) floods, suggesting that floods are a major control on woody debris storage within the stream. The forest also plays a major role; a comparison of forested and non-forested segments of stream showed that forested segments had substantial and significantly higher quantities of wood.

Despite the failure to find strong basin-wide controls on woody debris, the study did call into question many methodological considerations, specifically the resolution of sampling required to study a stream. The results of this study suggest that most sampling schemes in stream research fail to capture the spatial variability in streams.

CHAPTER 1

INTRODUCTION

Introduction

The objective of this study is to provide a greater understanding of wood distributions within burned and undisturbed watersheds and how these distributions relate to stream morphology. Large wood affects the channel morphology of streams by altering flow patterns and sediment storage. The effects of wood on stream morphology can be major; for example, a study of forested headwater streams in the Pacific Northwest found that 25 to 50% of the streambed was wood or sediment stabilized by wood (Anderson and Sedell, 1979). Wood can play a different but important role in the lower portions of watersheds, where woody debris may only be 4% of the substrate surface but contains 60% of the invertebrate biomass found in the stream (Benke *et al.*, 1985). Woody debris is also a factor in the formation of riffles and pools, which are important habitat for macro-invertebrates and fish. It has been shown that the greater the geomorphic complexity in the stream, the more favorable the stream's habitat (Robison and Beschta, 1990). Thus, woody debris and other roughness elements are directly tied to the composition of streams sediments, to stream morphology and to the quality of a stream's habitat. Understanding the distribution of wood in streams and the controls on that distribution are therefore critical to stream management.

Despite the extensive research on woody debris and its role within the fluvial system, there is still a need for better understanding of the spatial distribution of woody debris and its relationship with stream morphologic units in streams of different size. This objective of this study will be achieved by testing five hypotheses.

1. The count of woody debris stored in the stream and flood plain decreases with increasing channel width.
2. The amount of wood contact with the channel increases as the width of the channel increases.
3. Wood transport and agglomeration into jams increases as the width of the channel increases.
4. The influence of woody debris upon channel morphology increases with increased wood loading; increased woody debris density produces a corresponding increase in morphologic unit density.
5. Wildfires affect the delivery of large woody debris to the fluvial system; recently burned forested watersheds produce more woody debris than undisturbed forested watersheds.

Most studies have relied upon the intensive study of a few reaches and have assumed that these sites are representative of the entire stream. This study will explore woody debris using continuous field data collected in extensive longitudinal surveys across two mountain watersheds, thus including the natural variability intrinsic to all stream systems. The completeness of this approach also presents a unique opportunity to search for thresholds or natural breaks in the pattern of wood transport, agglomeration and deposition. Finally, an extensive data set provides a new opportunity to test existing hypotheses on woody debris distributions that were derived from less extensive studies.

Literature Review

Woody debris plays a major role in both the structure and function of the fluvial system. This review examines research about the impacts of wood on stream flow and morphology, downstream variations in these impacts, and woody debris as a system of supply, transport, and decay components.

The Influence of Woody Debris on Stream Flow and Morphology

Wood serves as an impediment to flow, acting to increase roughness, decreasing stream velocity, creating a higher water level upstream of the debris, and theoretically increasing the risk of flooding (Gippel *et al.*, 1996). Many early efforts to clear streams of woody debris were intended to reduce the risk of flood. A study of a test channel found that clearing of woody debris reduced the Manning's resistance coefficient an average of 39% (Dudley *et al.*, 1998), thus reducing flow velocities and increasing flood stages.

Although flood flows may be deeper due to wood, its role as an energy dissipater reduces the amount of energy available for sediment transport and stabilizes the bed of forested streams (Heede, 1972). A study of 1st to 5th order streams in 13 watersheds in the Oregon Coast Range found that log steps dissipated an average of 6% of the total potential energy of the streams (Marston, 1982). Other studies report that as much as 80% of stream energy is dissipated by log steps.

Because it dissipates energy that could be used for sediment transport, woody debris can be a major factor in reducing sediment transport and increasing sediment storage in forested streams. Marston (1982) reported that the volume of sediment stored behind log steps in 3rd, 4th and 5th order streams in the Oregon Coast Range was 123% of the estimated mean annual sediment discharge for those streams. A similar study on a forested 3rd order stream in Vermont (Thompson, 1995) found that although woody debris steps accounted for only 22.2% of the elevation drop in the study, they accounted for up to 53% of the total sediment storage. Thompson also pointed out that woody debris is superior to bedrock knickpoints in sediment storage capability because of the larger storage area behind wood dams.

The formation of steps and local base levels by wood jams has recently been recognized by a study conducted by Massong and Montgomery (2000) in the Willapa River Basin in southwest Washington. They attempted to predict a bedrock or alluvial channel type from slope and drainage area data. In many of the alluvial reaches that were misclassified as bedrock they found a forced alluvial morphology upstream of wood jams and log steps. The woody debris had created a local base level and the reach immediately upstream of the wood obstruction had alluvium deposited as a veneer over the original bedrock channel.

In some instances wood can increase erosion, wood can deflect flow creating localized acceleration and vortex development (Abbe and Montgomery, 1996). A flume study by Cherry and Beschta (1989) found that wood angled upstream caused the greatest flow disturbance and instigated bank erosion by deflecting the flow toward the side of the flume; however, they found that wood oriented perpendicular to the direction of flow produced the largest amount of channel scour by volume.

Removal of woody debris can have drastic effects on sediment transport. The experimental removal of woody debris from a 2nd order stream in Southeast Alaska resulted in a 4-fold increase in bedload transport (Smith *et al.*, 1993a). The drastic increase in transport was attributed to destabilization of previously stored sediment and the loss of low energy backwater storage sites. Likewise Lisle (1995) reported that wood removal near Mt. St. Helens increased sediment transport as well as a substantially coarsening the channel bed as fines were flushed away.

Woody debris effects on sediment storage and transport create wood induced channel features such as pools. Pools have long been associated with large roughness elements like boulders and woody debris that deflect stream flow and cause localized bed scour. Recent studies have begun to differentiate between wood or boulder forced pools and rhythmically spaced free-form pools. Many types of forced pools are directly associated with woody debris. Beschta and Platts (1986) describe how forced flow under or around a log creates scour pools, while channel-spanning wood jams create dammed and backwater pools upstream of the jam and plunge pools immediately below the jam. Gurnell and Sweet (1998) point out that of the 10 pool types in the habitat unit classification system developed by Bisson *et al.* (1982), six are associated with woody debris.

The best evidence for woody debris acting as a pool-forming factor is the many studies that count the number of pools directly associated with woody debris in their study area. Studies report that woody debris is associated with 48% to 75% of the pools found in a wide range of streams (Robison and Beschta, 1990; Beechie and Sibley, 1997).

Other studies have used the spacing of pools to assess the role of wood in pool formation. Montgomery *et al.* (1995) found that pool spacing in Washington and Southeast Alaska is dependent upon large woody debris loading. Mean pool spacing in pool-riffle, plane-bed and forced pool-riffle channels decreased from 13 channel widths to less than 1 channel width as the wood loading increased. The rate of increase varied with channel width and slope, but in all cases an increase in wood loading yielded a decrease in the pool spacing.

Woody debris not only influences in-channel features but also has a profound effect on channel width. A study of a forested upland watershed in the western Cascade Range in Oregon found that, in all alluvial reaches, the reaches with woody debris had channels that were about 1.5 times wider than channels without wood (Nakamura and Swanson, 1993). This widening was attributed to anchored trees falling into the middle of the channel and deflecting flow toward the banks, causing bank erosion. This study also reported that wood-induced deflection increased lateral migration and the development of secondary channels in unconfined alluvial reaches of 4^{th} order or higher streams. Robison and Beschta (1990) describe woody debris as a major factor in deflecting flow toward sites of bank failure in the streams of Chicagof Island, Alaska.

The role of wood in affecting channel planform is well supported in the literature. Beschta and Platts (1986) describe woody debris as contributing to planimetric sinuosity by thalweg deflection and to longitudinal sinuosity by forming steps. Studies of woody debris have also reported that jams provide a key ingredient in the formation of islands. Abbe and Montgomery (1996) used historical data from maps and aerial photographs from the Queets River of the Olympic Peninsula to chart the development of stable forested islands from transient in-channel bars. They describe the process as follows; (1) in-channel bars collect woody debris at the upstream apex of the bar, (2) the formation of a stable bar apex jam changes the local hydraulics in the channel, creating zones of scour and deposition; (3) the original bar with the jam at its apex becomes a zone of stable deposition, building up a blanket of colonizing vegetation and (4) the vegetated bar eventually develops into a forested island.

Downstream Variations in the Role of Woody Debris

Studies of woody debris at the basin scale have found that the quantity and role of wood varies with position in the basin. The accepted maxim is that wood loading decreases with increasing drainage area and channel width (Bilby and Ward, 1989; Robison and Beschta, 1990; Nakamura and Swanson, 1993; Montgomery *et al.*, 1995). The impact of this wood on morphology varies with basin location. Woody debris is thought to have little effect in the small 1st to 2nd order streams high in the drainage basin because the pieces of wood are larger than the width of the small channels. Wood tends to be suspended above the channel and therefore does not play a large role in channel morphology or sediment capture (Bilby and Ward, 1989; Nakamura and Swanson, 1993). The impact of woody debris on channel morphology and sediment transport increases in streams with slightly wider channels. A wider channel allows fallen trees to interact more with the active channel. This trend continues until the channel width reaches a balance with wood length and the woody debris becomes more susceptible to transport (Bilby and Ward, 1989; Nakamura and Swanson, 1993). Bilby and Ward (1989) found that wood size and the volume of instream debris accumulation increased with increased drainage area in a 2nd to 5th order stream flowing through an area of old growth timber in Washington. Although the size of the accumulations increased, the spatial frequency of woody debris decreased as drainage area increased.

Despite the minor role attributed to woody debris in smaller channels, the literature does report a number of important facts. Studies by Heede (1972), Marston (1982) and Wohl *et al.*, (1997) report on the substantial effects of woody debris in creating log steps and storing significant amounts of sediment in smaller upland streams. Bilby and Ward (1989) recorded the orientation of woody debris relative to the channel and found that in channels less than 7 meters wide, 40% of the woody debris was perpendicular to the axis of flow. This perpendicular orientation resulted in log steps being the most common woody debris form and plunge pools being the most common pool type associated with wood in the small channels. They also reported that 40% of the sediment storage in channels less than 7m in width could be directly associated to woody debris.

As the drainage basin area increases and wider channels are encountered, the orientation of woody debris is increasingly parallel to flow and the effect of wood on morphology is reduced. Bilby and Ward (1989) report that the wood piece orientation in channels greater than 10 meters wide is angled downstream into the flow over 40% of the time and parallel to the flow of the stream over 20% of the time. The most common type of pools associated with woody debris in this portion of the stream are scour pools formed by flow deflection. They also mention that storage behind wood accounts for less than 20% of the total sediment storage in the wider channel. Research by Robison and Beschta (1990) on five streams in Southeast Alaska confirms the trend from log steps and plunge pools in the smallest streams to wood-deflected flow and scour pool formation in the larger streams.

The role of woody debris in the larger channels in the lower portion of the drainage basin is an understudied topic. Most literature reports that the effects of woody debris on rivers and large streams is greatly reduced, highly localized and usually associated with jams. Abbe and Montgomery (1996) describe the role of meander jams as bank protection, bar apex jams as protection for island formation, and the role of debris jams as historically being a factor in lake development, flood plain formation, and forced channel avulsion.

The Woody Debris System

Wood in streams can be viewed as an open system with wood input, transport and export components. Wood input processes are variable within the drainage network. Wood is entering the channel through a variety of mechanisms, including debris flows, tree fall and fluvial transport from upstream sources. Nakamura and Swanson (1993) reviewed the variety of processes that introduce wood into streams of the western Cascade Range of Oregon. They grouped the wood input process by the relative importance of that process in low (1st and 2nd), medium (3rd and 4th) and high (5th) order streams. Their study reported that treefall processes, specifically wind throw within the riparian zone, are ubiquitous within the drainage network and are a common source of wood to streams of all sizes. Mass wasting processes, specifically landslides, were most commonly associated with the input of woody debris in low order streams with steep narrow valleys. Debris flows were described as a more spatially variable input source that played a major role in the delivery of woody debris to a 2nd order tributary and a 5th order stream within their study area. Medium order streams also received wood from mass wasting processes, mainly through streamside slides caused by incision. Higher order streams were associated with large amounts of woody debris delivered through bank erosion and treefall induced by lateral migration of the channel (Nakamura and Swanson, 1994). This statement is supported by a study of 2nd to 5th order streams in an old growth forest in Southeast Alaska, where 73% of the woody debris with an identifiable source was associated with bank erosion and wind throw (Murphy and Koski, 1989). An important aspect of wood input processes within the drainage basin is the recognition of how narrow a zone actually supplies wood to the channel. Murphy and Koski (1989) also found that nearly all of the wood in their streams originated within 30 meters of the channel.

The mobility of wood within the fluvial system can be best explained by the relationship between wood length and channel width. Wood is most mobile when its length is less than the bankfull width of the channel. Transported wood is on average smaller than wood that entered the channel locally (Nakamura and Swanson, 1994). The mobility of woody debris in a study of 2nd and 3rd order streams in northwest Wyoming was tied directly to the size of the debris (Young, 1994). Larger pieces were found to be the most stable, while smaller pieces had the highest mobility. Wood that was in contact with the water surface had a higher probability of movement than completely submerged wood. A study by Gregory (1991) in the Mackenzie River Basin of Oregon reported that in 1st to 7th order study streams no more than 10% of the woody debris moved per year and that of the wood that was redistributed each year less than 15% was over 3 meters in length.

Wood is preferentially stored in areas where the transport capabilities of the stream are insufficient. Gurnell *et al.* (2000b) examined the retention of woody debris within the large Fiume Tagliamento basin in Italy. They explain the varying density of woody debris over 170 kilometers of stream within the basin by examining the processes that foster wood retention within the river system. The size, type and location of woody debris in the forested headwaters are predominantly a product of the character of the forest. The type of forest is very important in wood retention; a study of 2nd order streams in New Mexico reported that study reaches in coniferous forest had wood loadings 10 times higher than the reaches in aspen *Populus tremuloides* stands (Trotter, 1990). Regardless of forest type, in headwater streams wood is immobile and randomly distributed by treefall (Gurnell *et al.*, 2000b).

Wood in moderately sized streams is affected by forest character, but hydrologic character is the dominant factor in wood location; wood is more mobile, especially during floods, and it is more likely to be clustered into jams (Gurnell *et al.* 2000a). Woody debris in larger rivers, where the width of the channel is greater than the length of the trees, is most affected by the geomorphic character of the river. All wood in the larger rivers is transportable and wood can only be retained in specific locations where it is captured along the crest of bars, on the margins of islands, or piled against the outer bend of meanders (Gurnell *et al.* 2000a).

Channel planform also plays a role in wood loadings. Gurnell *et al.* (2000b) reported that single channel reaches in the Fiume Tagliamento retained an average of one ton of wood per hectare, while reaches with multiple channels retained an average of six tons per hectare. Although braided channels have more surface area and therefore more potential to collect woody debris, the difference between the wood loadings of multiple and single channels is disproportionately high. Gregory's (1991) study of 1st to 7th order streams in Oregon found that although only 20% of the channel length was braided, 75% of the wood was located in these reaches. Piegay and Gurnell (1997) found in a wide range of streams in south England and southeast France that woody debris was preferentially stored in mobile channels of braided and wandering rivers. Nakamura and Swanson (1994) reported that in Lookout Creek, a 5th order stream in Oregon, reaches with multiple channels had almost twice the wood by volume that was found in single channel reaches. This study also found that the majority (61%) of the woody debris in the basin was retained on the floodplain and not in the active channel. Gregory (1991) reported that less than 30% of the woody debris found in the Mackenzie River Basin was located within the active channel.

Regardless of the location, wood retention is dependent upon the presence of large key members of wood. Removing large wood from channels reduces the number of possible wood retention sites. Kiem *et al.* (2000) found in their study of a 3rd order stream in the Oregon Coast Range that the addition of large key members resulted in a net increase in the total wood volume in the study area by between 86 and 155% over a 3-year period.

Wood that is retained in the drainage can have a very long residence time before decay removes it. Studies in North America have found that decay acts very slowly upon woody debris and is confined primarily to the surface of the wood, with little effect on the interior of logs (Anderson *et al.*, 1978; Anderson and Sedell, 1979). Woody debris that is immersed in water is unable to support fungi, which are the principal agents in the terrestrial breakdown of wood. Wood in rivers is therefore limited to bacterial decomposition, which can act only upon a thin surface layer (Bilby, 2000). Anderson *et al.* (1978) reported that wood depletion by decay, abrasion and breakage is always faster on smaller pieces of debris. They also recognized the minor role that macroinvertebrates play in wood breakdown. Their study estimated that invertebrate fecal production in western Oregon streams was only 1 to 1.7% of the total volume of woody debris each year. This suggests that very little of the large wood (predominately conifer trees) found in streams of a temperate climates is susceptible to decay.

Gregory (1991) performed a dendrochronological analysis of nurse trees growing atop large woody debris and found that many of the woody debris supporting nurse trees were in place for up to 50 years. Smaller pieces of woody debris as well as many species of riparian trees are much more susceptible to breakdown and decay. Keim *et al.* (2000) reported that of the various species of woody debris placed in a 3rd order stream in the Oregon Coast Range, red alder (*Alnus rubra*) was initially the most effective at capturing small wood but was subject to rapid breakdown and decay when compared to larger conifer species. Their study reported that by the third year of the study, most of the alders were in a state of advanced decay and breakage. Despite the relatively rapid breakdown of some species of woody debris, most large wood is very resistant to breakdown and can be retained within the basin for an extremely long time, perhaps as long as centuries. Pieces of wood found in streams have been dated at over 1000 years old using dendrochronological and radioisotope methods (Bilby, 2000).

Human induced changes in land cover can change the rate of wood input, especially if the 30 meter buffer suggested by Murphy and Koski (1989) is violated. Even if a buffer zone between the drainage network and the developed basin is maintained, the removal of large wood key members for flood control or waterway navigation purposes can reduce the wood retention capacity of the stream.

The Effects of Fire on Woody Debris

The role of wildfires in changing both the forest cover and the hydrologic regime of streams within burned watersheds has been examined by a number of researchers. These studies primarily focused upon headwater streams of burned watersheds, which are the most heavily affected by fire-induced change (Minshall *et al.*, 1989; Minshall *et al.*, 1997). Studies in burned and unburned watersheds of the Yellowstone area in northwestern Wyoming (Lawrence, 1991; Young, 1994; Minshall *et al.*, 1997) reported that wood loadings were higher in the burned watersheds and that the overall mobility of woody debris was greater. Young (1994) found that woody debris in Jones Creek, a stream in a burned watershed adjacent to Yellowstone National Park, was 3 times as likely to move and moved over 4 times farther that woody debris in Crow Creek, an adjacent but undisturbed watershed. Minshall *et al.* (1989) studied wood retention in the headwater streams of Yellowstone National Park and created a hypothetical response model for woody debris in 1st through 3rd order streams after a wildfire.

Despite the efforts of many researchers, there are gaps in the current research on woody debris in areas affected by wildfires. Although the research covers a wide area, it is limited to a few study reaches in a large number of streams. Very little work has focused upon extensive longitudinal surveys of large woody debris in an entire basin. There is a need for greater understanding of the changing influence of woody debris from the transport-limited zone of the headwaters to the supply-limited zone in larger channels in both burned and undisturbed watersheds.

CHAPTER 2

STUDY AREA AND METHODS

Study Area

The study was conducted on Soda Butte Creek and Cache Creek, tributaries of the Lamar River in Yellowstone National Park (Figure 1). A ten-kilometer portion of Pebble Creek, a tributary of Soda Butte Creek was also included during the analysis portion of the study. These streams are excellent for a study of woody debris because wood has never been removed from the streams and the natural landcover of the area has not been directly modified by human action.

The study portions of Soda Butte and Cache Creeks flow southwestward from an elevation of over 2300 meters to approximately 2000 meters at their confluences with the Lamar River. The climate of the study area is montane; 75-85% of the precipitation is snow or rainfall on snowpack (Despain, 1987). The average annual peak flow for Soda Butte Creek is nearly 50 cubic meters/second (m^3/s), while the average annual flow is approximately 6 m^3/s. Cache Creek, although not gauged, has a similar runoff regime. In both Soda Butte Creek and Cache Creek, peak annual flows occur during late spring when the winter snow pack melts.

The upper portions of Soda Butte Creek are primarily subalpine forests containing Engelmann Spruce (*Picea engelmannii*), Sub-alpine fir (*Abies lasiocarpa*), and Douglas fir (*Pseudotsuga menziesii*). The lower portions vary between open meadow and forests that are primarily Lodgepole Pine (*Pinus contorta*). Soda Butte Creek also has extensive