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The Impact of Historic Logging on Woody Debris Distribution and Stream Morphology in the Great Smoky Mountains National Park, North Carolina-Tennessee

A Thesis Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Christopher M. Morris

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Finally, I would like to express my gratitude to my family who have provided me with so much in my life.

Abstract

In the early 1900s, large sections of the Great Smoky Mountains were intensively logged. Since then, most locations have been allowed to naturally become forest-covered again, resulting in areas of secondary growth and old growth forest. To determine whether differences in large woody debris (LWD) loading and channel morphology persist today, I measured LWD, channel widths and depths, and channel bed sediments of streams in old and secondary growth forest in the Great Smoky Mountains National Park.

LWD pieces in streams in old growth had larger mean diameters and lengths compared to LWD in streams in secondary growth forest. Streams in old growth had 5.6 times more LWD volume than those in secondary growth. More LWD pieces were in debris dams in old growth than in secondary growth forest.

Channel bed sediment size did not differ significantly between streams in old and secondary growth forest. Channel widths and depths were significantly larger in streams in old growth forest. LWD pieces affected channel depth primarily by creating pools and causing deposition of sediment. LWD affected width by directing stream flow toward banks and by protecting banks from erosion. I observed that the orientation of LWD was important in determining its geomorphic role.

Although I found no relationship between LWD loading and watershed

area, I found a relationship between watershed area and the importance of LWD in impacting channel morphology. Despite differences in LWD frequency and total volume, streams in old and secondary growth forest differed little in width and depth in the largest watersheds in this study. However, in smaller watersheds, streams in old growth were not as narrow or as shallow as streams in secondary growth.

LWD loading can vary substantially between streams, even those with similar surrounding forest types, climate, and disturbance histories; therefore, caution should be exercised when using LWD loading rates from other studies in environmental management.

Despite nearly 80 years of forest regrowth, LWD loading and channel morphologies of streams still show the impacts of logging.

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Chapter 1

Introduction

People can impact the environment in a variety of ways. Streams, used as transportation routes, food and water sources, and centers of communities, have been especially vulnerable to disturbance. Streams have been channelized and had sediment removed from their channels (Gregory, 2006). Land-cover change in watersheds alters the amount and timing of water and sediment entering streams (Liébault and Piégay, 2002). Whether streams are affected directly or indirectly, the net result is often decreased water quality, geomorphically unstable streams, and loss of habitat. These results, in turn, impact not only the strength and biodiversity of ecosystems, but also damage human health, property, and well-being. Only recently has substantial research been done documenting these impacts (James and Marcus, 2006). Additionally, widespread efforts to limit human disruptions to streams are relatively new (Graf, 2001).

1.1 Woody Debris Distribution

Streams are subject to change by the introduction of large woody debris (LWD). LWD consists of pieces of limbs, logs, or root-wads greater than 5

cm in diameter that are partially or completely located within the stream channel (Keller et al., 1995). They come in a wide variety of shapes and sizes and can span the entire channel or just block a small part. In the past, LWD has been removed to improve navigation, decrease flooding, aid in salmon migration, and increase the perceived *aesthetics* of streams (Harmon et al., 1986; Montgomery et al., 2003). However, in the past 30 years, research about LWD has increased dramatically, leading to an acknowledgment of the important ecological and geomorphic roles it plays in many streams (Gregory, 2003).

Ecologically, LWD is important in the overall nutrient dynamics of streams (Harmon et al., 1986; Bilby, 2003; Warren et al., 2007) and in the creation of habitats necessary for many aquatic organisms (Benke and Wallace, 2003). Larger volumes of LWD increase both the type and number of pools formed. These LWD formed pools have been correlated with increased salmon densities and diversities in the Pacific Northwest (Beechie and Sibley, 1997) and increased trout densities in the southern Appalachian Mountains (Flebbe and Dolloff, 1995; Flebbe, 1999).

The size and amount of LWD loading in streams is a function of many factors, including stream channel size, surrounding forest composition, and the disturbance history of that forest. As streams get larger, the increased flows have a greater ability to move LWD. However, smaller streams are generally unable to move LWD, allowing large numbers of pieces to accumulate over time (Bilby and Ward, 1989). The largest volumes of LWD in streams have generally been found in forest containing the largest trees (Harmon et al., 1986). Decomposition rates of different trees can also be important, as more decay-resistant wood builds up over time (Hedman et al., 1996). Forest disturbances can take many forms, including wind (Greenburg and McNab, 1998), fire (Zelt and Wohl, 2004), and logging (Gregory, 2003). These disturbances

do not only change the amount of LWD that enters the stream in the present, but also affect future tree size, thereby altering the amount of LWD that will enter the stream in the future. Of the main forest disturbance mechanisms, logging is the most studied in the LWD literature. Logging initially increases LWD loading in streams as slash, wood debris left from the logging, enters the channel (Spies et al., 1988). However, after several decades, the LWD from logging decays and little new wood replaces it because the surrounding secondary growth forest has lower initial mortality rates (Hedman et al., 1996). The result is less LWD in the stream. The amount of LWD in a stream in an area of logging and forest regrowth has been estimated to take from 200-500 years to recover (Spies et al., 1988; Murphy and Koski, 1989). This creates a U-shaped curve of LWD loading in streams over time (Figure 1.1).

In the southern Appalachian Mountains, this relationship between LWD loading and forest age has also been observed. Flebbe and Dolloff (1995) found larger total volumes and larger average pieces in streams in old growth versus streams in secondary growth forests in western North Carolina. Valett et al. (2002), also working in western North Carolina, found greater LWD loads in streams in old growth. Silsbee and Larson (1983), working in the Great Smoky Mountains National Park (GSMNP), found that reaches in 50-year old forest had less LWD by volume than those in old growth reaches. Also in the GSMNP, Hart (2000) observed larger numbers of LWD pieces per channel length in old versus secondary growth forest.

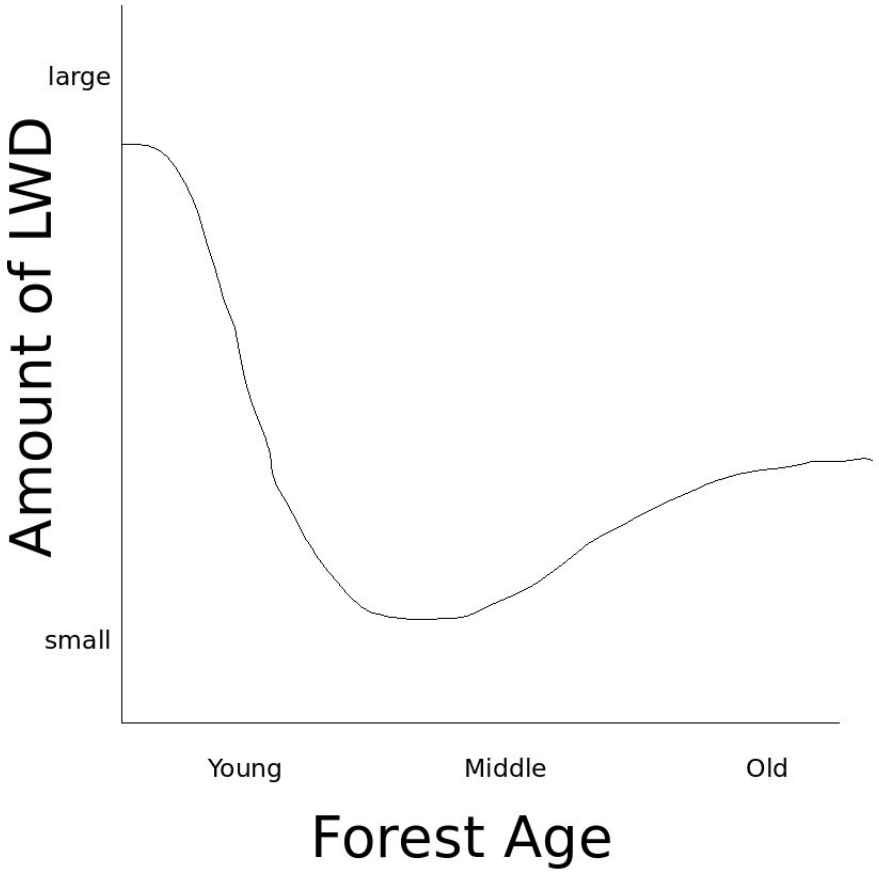


Figure 1.1: U-shaped curve of LWD after a disturbance. After Spies et al. (1988).

1.2 The Effects of Woody Debris on Channel Morphology

LWD can have a variety of effects on channel morphology. It can change the longitudinal profiles of streams by forcing steps and creating pools where they would not otherwise be located (Montgomery and Piégay, 2003; Gomi et al., 2003) and create in-channel features such as bars and islands (Keller and Swanson, 1979; Montgomery et al., 1995). In steeper and smaller headwater streams, LWD is often the only important feature able to reduce sediment transportation efficiency and store sediment (Faustini and Jones, 2003), thereby capturing finer particles that would otherwise be quickly flushed downstream (Haschenburger and Rice, 2004). LWD can also impact channel morphology by directing flow toward banks, increasing erosion (Zimmerman et al., 1967; Murgatroyd and Ternan, 1983; Trimble, 1998), channel width (Nakamura and Swanson, 1993; Keller et al., 1995; Jackson and Sturm, 2002), and channel width variation (Gerhard and Reich, 2000), or it can shield banks from erosion, cause deposition, and reduce channel width (Keller and Swanson, 1979).

Fewer studies have been done connecting differences in LWD loading with channel morphology. Faustini and Jones (2003) found that streams in old growth forests in Oregon had not only more LWD than streams in forests clear-cut 35 year earlier, but also had significantly larger mean channel widths. Bilby and Ward (1991) compared stream reaches in old growth forests, reaches in forests logged 40 years before, and reaches in forests logged five years before in Washington. They found that old growth reaches had the largest number of LWD pieces and were the widest, reaches logged five years earlier had the next largest number of LWD pieces and channel width, and the 40-year reaches were the narrowest and had the fewest number of LWD pieces. Napolitano

(1998), working in northwest California, compared stream reaches that had been logged in the late 1800s to old growth reaches. He found streams in secondary growth forest to be narrower and have less LWD by mass. Gomi et al. (2001) in Alaska and Ralph et al. (1994) in Washington, however, found no significant correlation between number of LWD pieces and stream width. Because the objective of several of these studies was to aid in stream management for salmon, they focused on wider streams, generally 10-20 m in width. Only Gomi et al. (2001) examined streams narrower than 5 m.

The addition of LWD has generally been found to increase the capture of sediment, decreasing sediment size stored on the channel bed. This was observed by Wallace et al. (1995) and Coulston and Maughan (1983) in the southern Appalachian Mountains. In contrast, Silsbee and Larson (1983) found little difference in bed particle size between streams in secondary and old growth forest. However, they took only 30 samples from the thalweg over 30 meters; thus, their study is subject to errors related to a small sample size of sediment taken across too many stream features (Kondolf et al., 2003).

1.3 Research Objectives

Several studies have observed a U-shaped curve of LWD with forest age, but, much uncertainty remains about the timing (Bilby and Ward, 1991) and the curve's application to different environments. In the Cascade Mountains, Bilby and Ward (1991) and Faustini and Jones (2003) observed significantly reduced amounts of LWD following less than 50 years of forest regrowth after logging. However, Spies et al. (1988), also in the Cascades, observed that LWD loading 50 years after logging was still higher than in old growth locations. Additionally, most of the research into LWD has been conducted in the Pacific North-

west (Gerhard and Reich, 2000; Comiti and Lenzi, 2007; Keeton et al., 2007). It has been the center of research not only because of the large amount of active logging occurring, but also due to management goals of improving salmon populations. In the southern Appalachian Mountains, important differences in LWD loading because of climate, tree size, and decay rates necessitate local research (Hedman et al., 1996). In the Pacific Northwest, high spring stream flows occur because of snowmelt from the winter snowpack. Such flows can sometimes move LWD downstream and deposit them far away their original sources (Hyatt and Naiman, 2001). Streams in the southern Appalachians do not have this same flow regime. So far, fewer than 10 studies of LWD have been done in the southern Appalachians, and only three in the GSMNP. Hedman et al. (1996), in western North Carolina, and Hart (2000), in GSMNP, both found LWD pieces in streams that have been decaying for nearly 100 years in areas that had undergone logging. These LWD pieces pieces predate logging. The fact that pre-logging LWD has not completely decayed suggests that the low point of a U-shaped curve for the southern Appalachians may not occur for at least 100 years after the disturbance. This also suggests that the ratio of LWD in streams between old and secondary growth forests should be larger now than in previous studies in the Park.

Although several studies have found connections between LWD and changes in channel morphology, fewer have connected the changes with differences of LWD loading in old and secondary growth forests. Most have found that those streams with less LWD have smaller widths; however, it has also been suggested that the opposite could be true (Keller and Swanson, 1979). None of the studies that measured channel width in the southern Appalachians found width to be related to LWD. Hedman (1992) and Valett et al. (2002) both found no significant difference in channel width between old and secondary

growth forest. Hart (2000) did observe such a difference, but he was unable to correlate it to LWD frequency.

The main purposes of this study are to add to the knowledge of the timing of LWD loading in streams in the southern Appalachian Mountains after a disturbance and to relate differences in LWD loading to channel sediment size and morphology. I counted, classified, and measured LWD; measured channel bed sediment size; and measured channel widths and depths in streams in secondary and old growth forests in the GSMNP. I divided this study into two main research foci, woody debris and channel morphology.

My primarily hypotheses focusing on woody debris were that

1. Stream reaches in old growth forest would have proportionately more LWD pieces in debris dams than stream reaches in secondary growth forest in the GSMNP.

2. Stream reaches in old growth forest would have LWD pieces with larger median diameters, lengths, and hence, volumes than those in secondary growth.

3. Stream reaches in old growth forest would have more LWD pieces and larger total volumes of LWD than those in secondary growth.

My primarily hypotheses focusing on channel morphology were that

1. Stream reaches with more LWD would have larger bankfull widths and depths than stream reaches with less LWD.

2. Stream reaches with more LWD would have a greater variation in widths and depths than those with less LWD.

3. Stream reaches with more LWD would have smaller D_{50} (median sediment size) in pools than reaches with less LWD.

1.4 Organization of Thesis

This thesis is divided into six chapters. In chapter I, the introduction, I presented a brief review of research concerning woody debris and its effect on channel morphology, and concluded with the objectives of this study. In chapter II, I relate information concerning the study area, including the geology, the forest type, the disturbance history, and the study reaches. In chapter III, I give my methods, results, and discussion of woody debris size and geomorphic role in relation to forest age and watershed area. In chapter IV, I present the methods, results, and discussion of channel morphology, including its connections to woody debris and forest age. In the final chapter, I give a summary of the results and their implications, as well as ideas for future research that is still needed.

Chapter 2

Study Area

Located in the northeast section of the Great Smoky Mountains National Park (GSMNP), the study area consists of 20 streams in four larger watersheds (Figure 2.1). GSMNP is in the southern Appalachian Mountains in the Blue Ridge physiographic province on the border of North Carolina and Tennessee. Most of the Park is extremely mountainous, with elevations ranging from 270 to 2025 m. Before the creation of the Park in 1934, about 85% of the area was logged, either selectively or intensely (Pyle, 1988). The remaining unlogged areas now make up some of the largest tracts of old growth forest in the eastern United States. These factors make it a unique location to research the effects of historical logging on woody debris distribution, sediment size, and channel morphology in an area that has seen relatively little research in both woody debris (Hedman et al., 1996) and stream channel morphology (Harden, 2004).

2.1 Geology

GSMNP's bedrock is a complex assemblage of sedimentary and metamorphic rocks, but the most important are the Anakeesta and Thunderhead formations (Southworth et al., 2005). The Anakeesta formation is primarily composed of

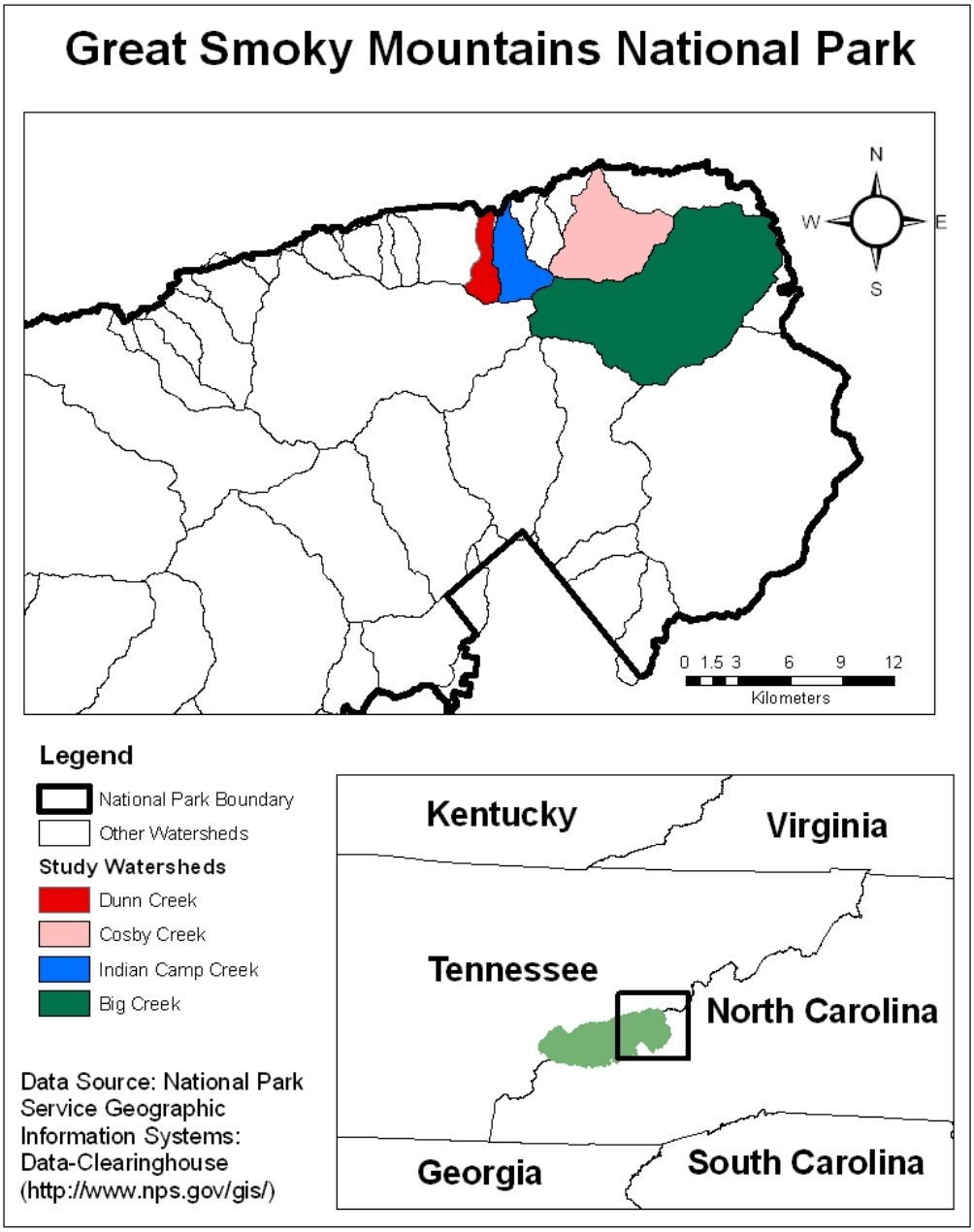


Figure 2.1: Map of study watersheds in the Great Smoky Mountains National Park

dark fine-grained slate. It underlies the highest locations and is prone to debris slides (Bogucki, 1976; Ryan, 1989; Hart, 2000). The Thunderhead Formation is composed of medium to coarse-grained sandstones and is found across much of the area of the Park.

The Park's surface features are generally divided into four groups (Southworth et al., 2004). Fluvial landforms are relatively rare and are found along the narrow floodplains and terraces of the larger rivers. Landforms created by physical and chemical weathering are more common and can be found throughout the Park. Slope-created landforms can be subdivided into debris flows, Pleistocene debris fans, and colluvial boulder deposits. Debris flows occur on the Anakeesta formation during high rainfall events (Koch, 1974; Bogucki, 1976). Pleistocene debris fans are large accumulations of boulders, cobbles, sand, silt, and clay formed by the movement of debris during wetter periods in the past (Mills, 2000). Colluvial boulder deposits form by the movement of boulders down slopes by gravity, solifluction, freeze-thaw, and ice-wedging (Clark and Ciolkos, 1988). These were primarily formed in the periglacial environment of the Pleistocene, although more recent movement has occurred (Southworth et al., 2004).

2.2 Land History

GSMNP was settled most densely in the valleys, first by Native Americans and later by Europeans. During the 1800s, human land use included agriculture in the valleys, selective logging of particular tree species, and livestock grazing on grassy balds (Pyle, 1988). However, starting in the early 1900s, logging became more widespread and intensive as extensive tracts of land were purchased primarily by large, northeastern US commercial operations (Lambert, 1961).

These commercial logging operations had the capital needed for mechanized logging, including railroads, skidders, and sawmills (Pyle, 1988). Unlike the earlier small-scale logging, these new operations were generally not selective about the species they cut, cutting anything that was of adequate size. McCracken (1978) determined from personal interviews with former loggers that this size was a 0.3 m diameter at breast height (DBH). Locations near major streams were logged first, with cutting moving upslope as more of the easily accessible trees in the valleys were removed. Coves were particular hard hit, as they often had the largest volumes of high quality wood (McCracken, 1978). Additionally, woody debris already occurring in streams was often removed along with freshly cut trees (Dolloff, 1996). These types of logging operations dominated the area that is now the Park from the period of 1900 to the 1930s (Lambert, 1961). Splash dams were a further disruption that occurred to the largest streams in the Park. Splash dams were built across major streams, forming temporary water impoundments. Logs were placed in the impoundments and a gate in dam was opened to allow a torrent of water to flush the logs downstream to sawmills (Dolloff, 1996). By the creation of the Park in 1934, nearly 60% of its area had been heavily logged by commercial companies and 85% had been selectively logged (Figure 2.2) (Pyle, 1988). However, since then, most of the Park has been allowed to reforest on its own.

2.3 Forest Types

GSMNP has one of the most complex assemblages of ecological communities in the eastern US (Whittaker, 1956), with the most common forest types being oak-pine, mixed hardwood, cove hardwood, northern hardwood, and spruce-fir (GSMNP, 1999). All of my study streams were located in cove hardwood

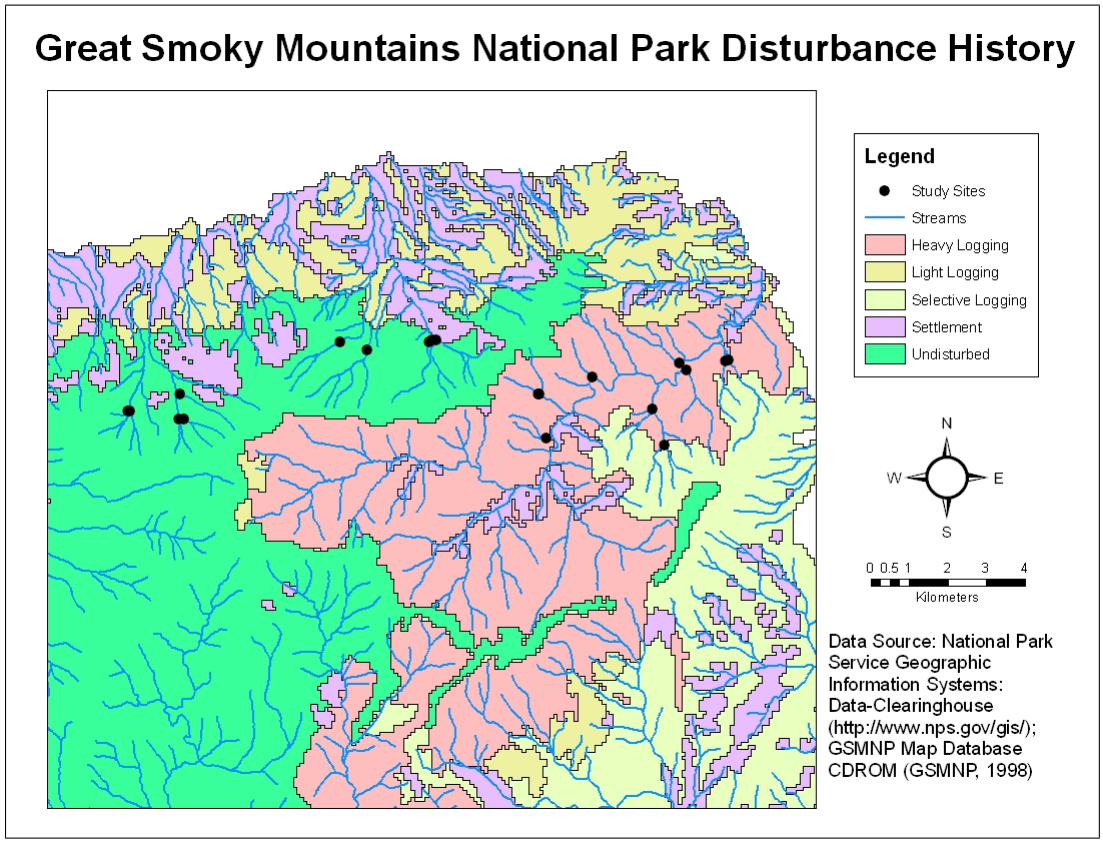


Figure 2.2: Map of disturbance history of Great Smoky Mountains National Park in the section including my study sites.

forests. Cove hardwood is found in sheltered valleys below 1370 m in elevation and contains some of the largest trees in the eastern US (Whittaker, 1956). The dominant trees species in old growth, or unlogged forest, are American basswood (*Tilia americana* L.), eastern hemlock (*Tsuga canadensis* L.), sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betual allegheniensis* Britt.), and yellow buckeye (*Aesculus flava* Ait.); although American beech (*Fagus grandifolia* Ehrh.) and tulip poplar (*Liriodendron tulipifera* L.) can be locally important (Clebsch and Busing, 1989). Studies within GSMNP of young ($\leq$ 40 years) secondary growth, or formerly logged forest, found they were dominated by tulip poplar and black locust (*Robinia pseudoacacia* L.) (McCracken, 1978). Clebsch and Busing (1989), looking at slightly older ($\sim$ 65 years) secondary growth forest, found that black locust had mostly died out and sugar maple was starting to take its place. A more recent study in the Park found this tulip poplar and sugar maple co-dominance in secondary forest still in effect (Guyon et al., 2003).

2.4 Study Reaches

For this research, I located 20 streams with watershed areas between 0.62 and 3.3 km^2. The selection was based on bedrock type, disturbance history, and forest type (Figures 2.3, 2.4, and 2.5). All the chosen watersheds have the Thunderhead sandstone as their bedrock due to the large area of the Park underlain by it. Cove hardwood forests were similarly chosen because of their wide distribution. The study watersheds had been either intensively logged and are now covered by secondary growth forest, or had never been logged and are in old growth forest. Previously logged and unlogged watershed were distinguished using data from GSMNP (1999), based on Pyle (1988). However,

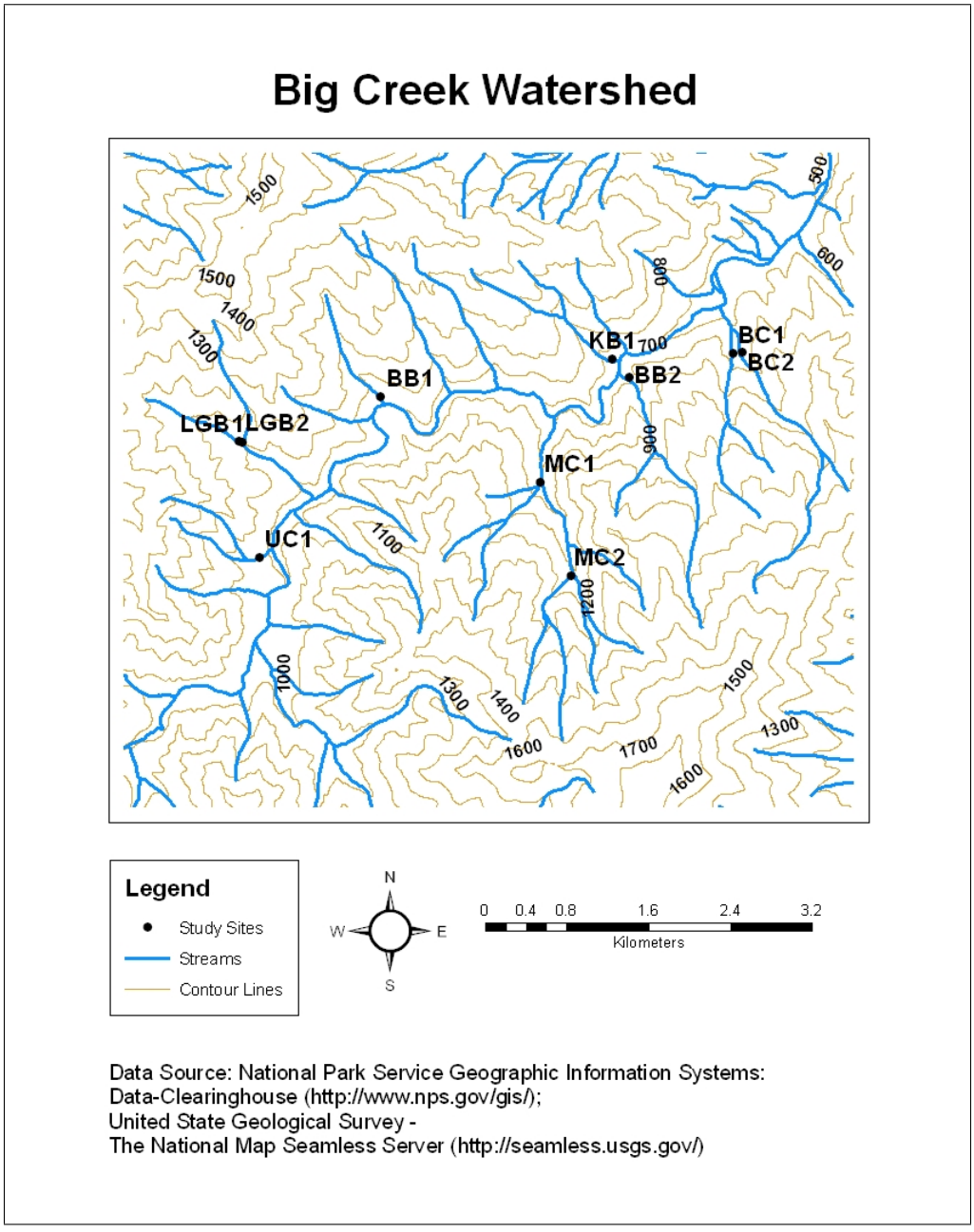


Figure 2.3: Map of the Big Creek watershed

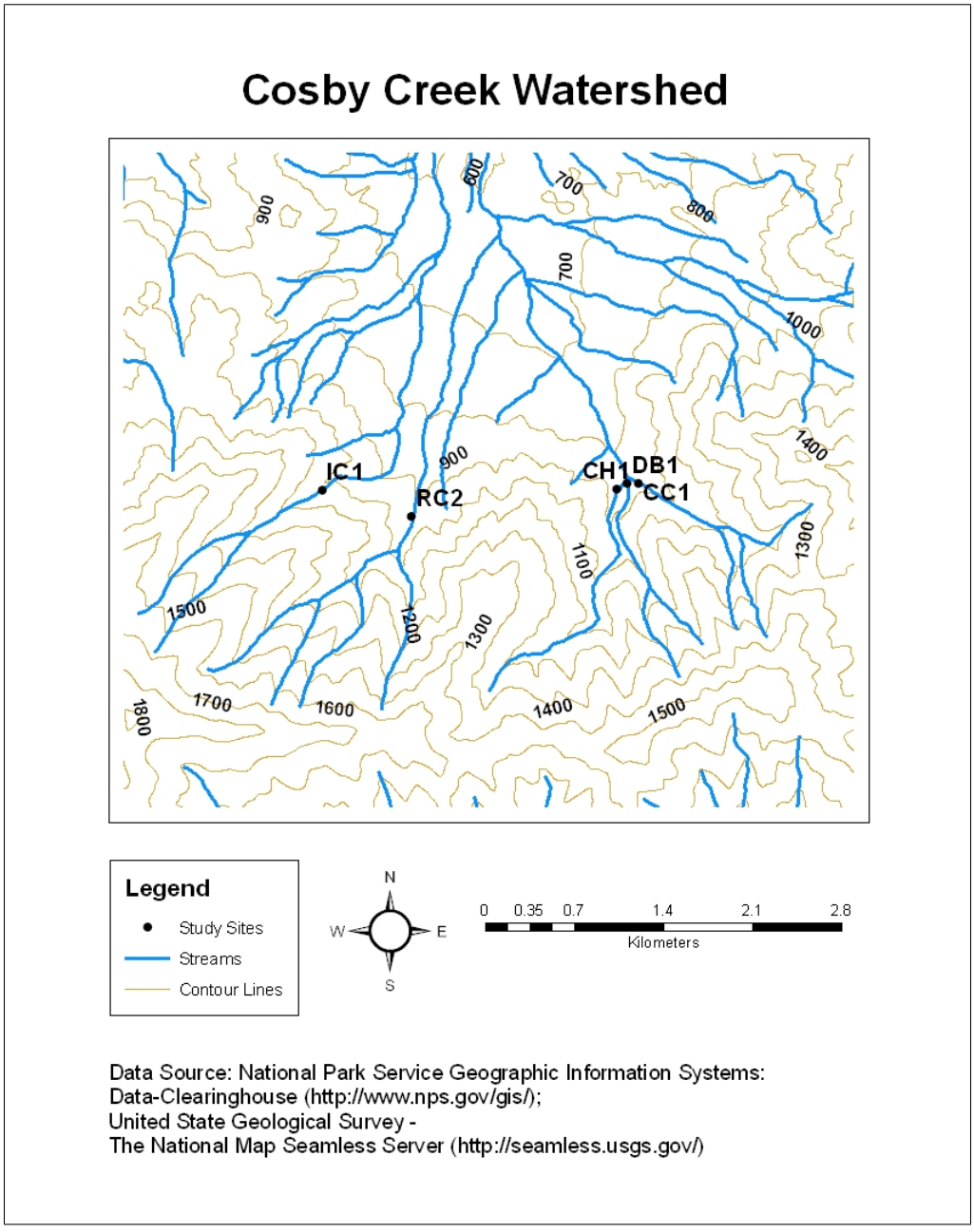


Figure 2.4: Map of the Cosby Creek watershed

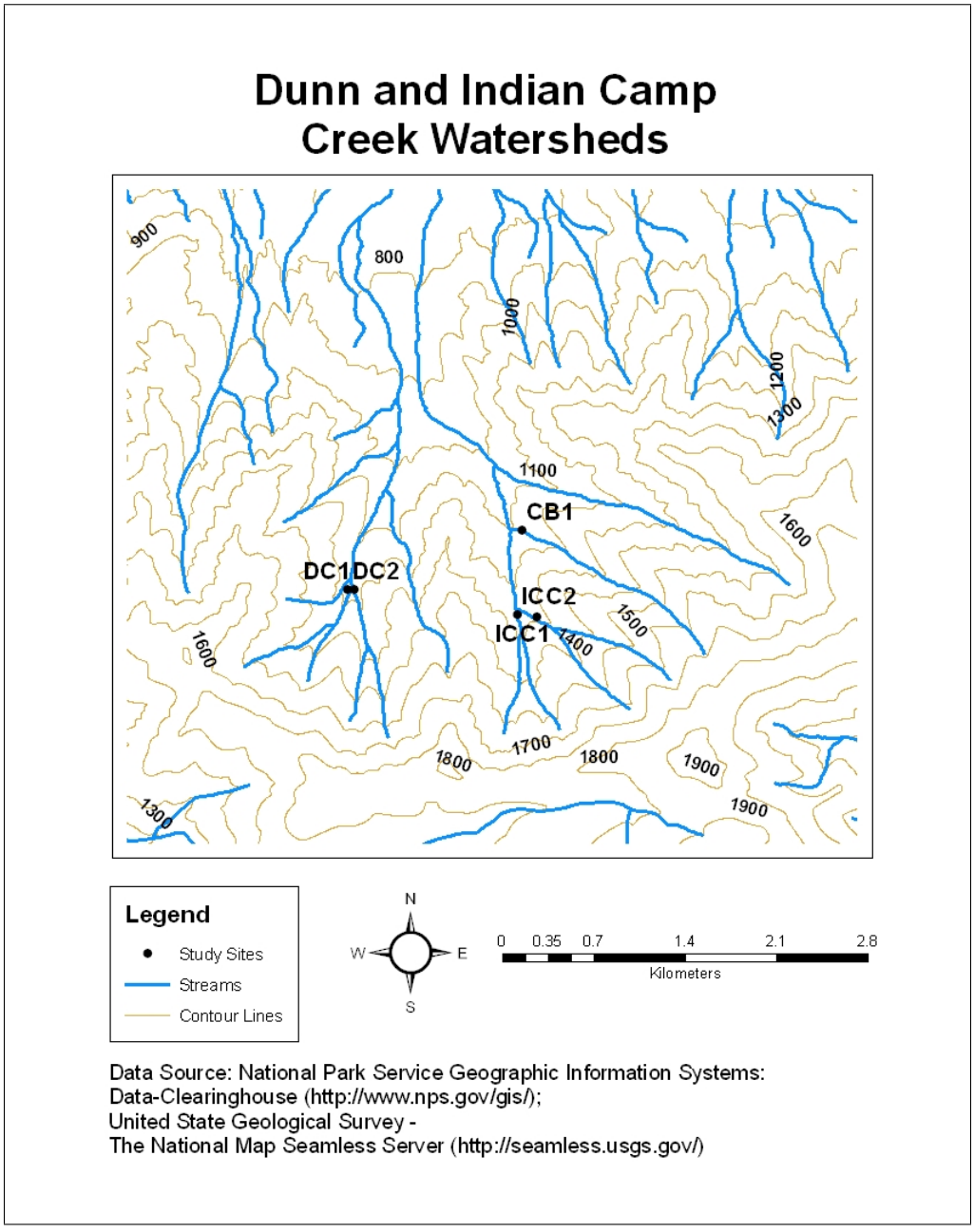


Figure 2.5: Map of the Dunn and Indian Camp Creek watersheds

the results from that study are not completely accurate (Langdon, 2007), so during field work, forests near stream reaches were observed qualitatively for species composition and tree size as an additional check to determine if the forest was old or secondary growth.

For each stream, a 50 m reach was chosen. The reach was located roughly 50 m upstream from where the study stream joined another stream. Starting at the confluence, I hiked roughly 50 m up the study stream. From here, I hiked upstream another 50 m, observing its suitability as a study reach. I rejected a reach only if a large portion of stream was in multiple channels separated by several meters (Figure 2.6). This was done for the ease of data collection and analysis. Several streams had small mid-channel islands, and these were used. Only at Indian Camp Creek 1 (ICC1) and Log Gap Branch 2 (LGB2) was the issue of multiple channels encountered. In both of these cases, the problem was solved by either moving the reach further upstream (ICC1) or starting slightly less than 50 m upstream from the confluence (LGB2).

Previous studies have primarily used channel width as the variable used to examine LWD variation with stream size; however, because channel width is influenced by LWD, watershed area has been suggested as a superior metric for comparing streams (Ralph et al., 1994).

I determined watershed area, using the study site as the watershed outlet, and slopes of the stream channel with 1/3 arc second DEMs, from the USGS National Elevation Dataset (NED), and ArcGIS using standard techniques. Characteristics of the study reaches are summarized in table 2.1.

The statistical analysis of the data was performed using SPSS. T-tests were used to compare means of data that were normal, while Mann-Whitney tests were used to compare medians of non-normal data. Normality was determined using the Kolmogorov-Smirnov test.

Table 2.1: Basic information about study reaches

Reach Name	Symbol	Forest Age	Watershed Area (km^2)	Stream Slope (°)
Barnes Branch	BB1	Secondary	2.3	15
Bettis Branch	BB2	Secondary	2.9	14
Baxter Creek 1	BC1	Secondary	1.1	12
Baxter Creek 2	BC2	Secondary	2.1	9
Copperhead Branch	CB1	Old	1.0	11
Cosby Creek	CC1	Old	2.3	9
Camel Hump Creek	CHC1	Old	2.9	13
Dry Branch	DB1	Old	1.3	14
Dunn Creek 1	DC1	Old	1.0	11
Dunn Creek 2	DC2	Old	1.2	12
Inadu Creek	IC1	Old	1.9	15
Indian Camp Creek 1	ICC1	Old	1.2	13
Indian Camp Creek 2	ICC2	Old	1.2	19
Kirby Branch	KB1	Secondary	1.1	17
Log Gap Branch 1	LGB1	Secondary	0.6	13
Log Gap Branch 2	LGB2	Secondary	2.2	12
Mouse Creek 1	MC1	Secondary	1.2	20
Mouse Creek 2	MC2	Secondary	1.4	15
Rock Creek	RC1	Old	3.3	9
Unnamed Creek	UC1	Secondary	0.7	12



Figure 2.6: Indian Camp Creek 1: The LWD piece has split the stream channel. On the right side, the stream continues to flow under the LWD and continues straight. On the left side, the stream is forced by LWD to take a sharp left turn. These two branches are separated by $>$ 10 m and rejoin roughly 75 m downstream.

Chapter 3

Woody Debris Size, Occurrence, and Function

Previous studies have found that streams in secondary growth forest have dramatically different LWD distributions from those in old growth. I hypothesized that stream reaches in old growth would have proportionately more LWD pieces in debris dams and log jams than stream reaches in secondary growth. Additionally, I hypothesized that reaches in old growth would have pieces with larger median diameters, lengths, and hence, volumes. Finally, I hypothesized that reaches in old growth would have more LWD pieces and larger total volumes of LWD.

3.1 Methods

A number of different methods have been used to quantify the presence of LWD in streams (Hart, 2000), with the most popular being number of LWD pieces and volume of LWD per channel area. Different studies have found particular measurements correlating well with channel morphology. In Oregon, Montgomery et al. (1995) found number of LWD pieces correlated, while Ralph

et al. (1994), in Washington, found that number was of limited value and suggested the use of volume. Previous studies in the southern Appalachian Mountains have used both number and volume of LWD. Therefore, I gathered data using both measures to examine which works best in this region and to facilitate data comparison with other studies.

For each piece of LWD, I measured the representative length and diameter within the bankfull channel, and used those measurements to estimate volume by treating each piece of LWD as a cylinder (Figure 3.1). Most studies have used 10 cm diameter and 1 m length as the minimum for LWD; however, in smaller streams, smaller pieces can play an important role (Jackson and Sturm, 2002), so a minimum diameter of 0.05 m and length of 0.5 m were used instead.

Additionally, I applied the classification developed by Hart (2000) to characterize the geomorphic role played by each piece. He divided LWD into partial obstructions (only block part of the low flow channel), log steps (block entire low flow channel), debris dam (5-20 logs that block low flow and bankfull channels), and log jams (30 or more logs that block the entire valley)(Figures 3.2, 3.3).

The data are presented in terms of individual measurements and calculated reach values. Each individual LWD piece had a measured diameter, length, and calculated volume. Because these measurements did not have a normal distribution, non-parametric tests were used; therefore, individual measurements were compared by using the median value, not the mean value. However, the distribution of reach values were normal, so they were compared with mean values. Table 3.1 summarizes the different values and their meanings.

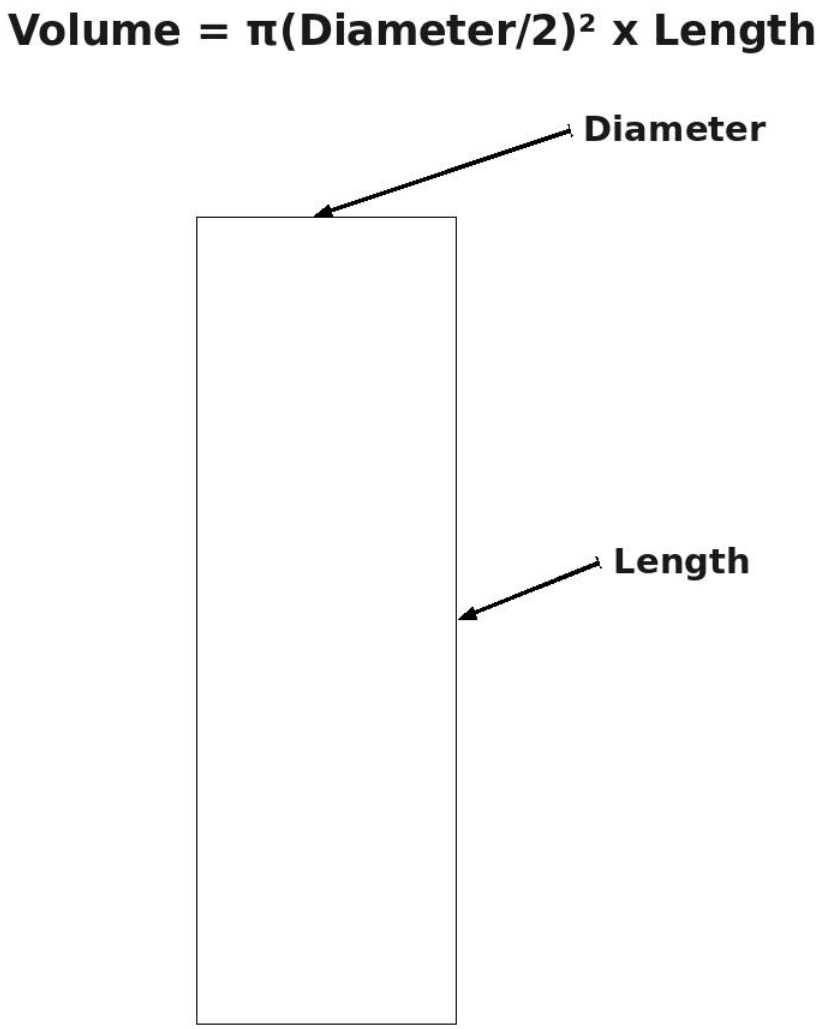


Figure 3.1: Measurement of LWD

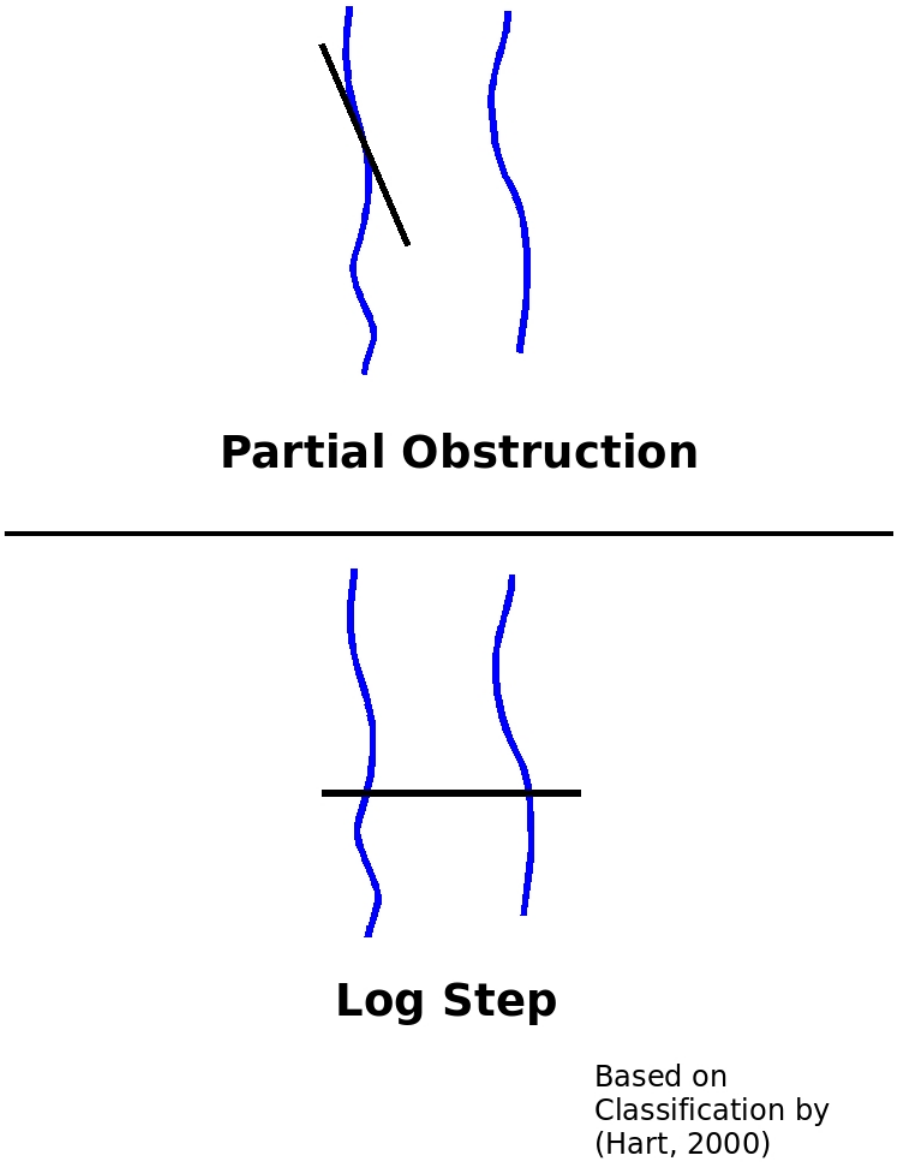


Figure 3.2: Aerial view of LWD classification (1)

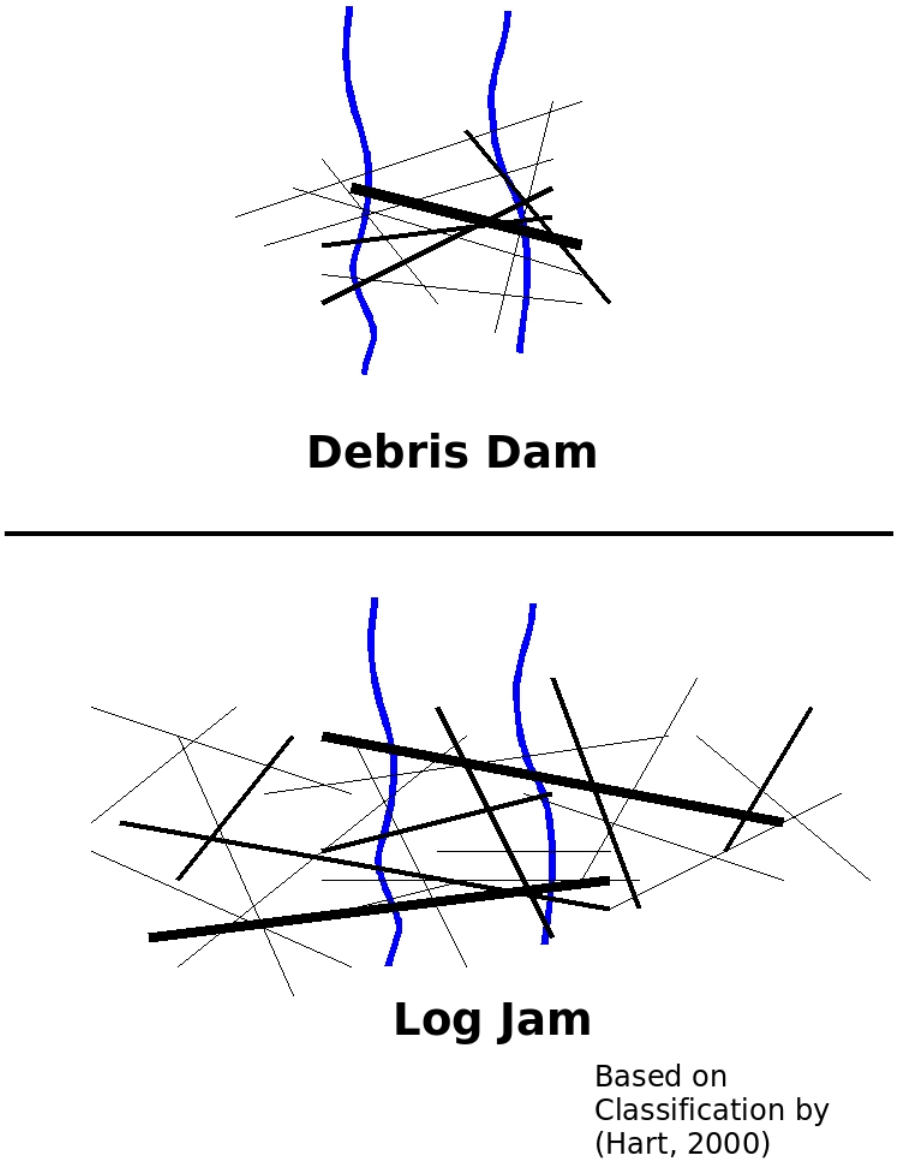


Figure 3.3: Aerial view of LWD classification (2)

Table 3.1: Descriptions of wood variable names

Variable Name	Meaning
Median Diameter	Median of measured LWD piece diameters
Median Length	Median of measured LWD piece lengths
Median Volume	Median of calculated LWD piece volumes
Mean Diameter	Mean diameter of all LWD pieces in a reach
Mean Length	Mean length of all LWD pieces in a reach
Total LWD volume	Total volume of all LWD pieces in a reach
Frequency	Total number of LWD per reach length

3.2 Results

3.2.1 Number and Classification of LWD Pieces

I measured a total of 432 pieces of LWD, 237 in stream reaches in old growth, and 195 in reaches in secondary growth forest. The frequency was 24 pieces per 50 m of stream length in old growth and 20 pieces per 50 m in secondary growth. The difference in LWD frequency between old and secondary growth was not statistically significant (Table 3.2). I also found no statistically significant relationship between LWD frequency and watershed area either separately or aggregated by forest age class (Figure 3.4).

The classification of LWD (Hart, 2000) differed between reaches in old and secondary growth (Figures 3.5, 3.6). Partial obstructions were the most common type in secondary growth at 86% of total (167 of 195) while debris dams were the most common at 53% (125 of 237) in old growth. Log steps and log jams were quite atypical in both reach types. Only two log jams were located in the study, at Unnamed Creek (UC1) in secondary growth and Indian Camp Creek 2 (ICC2) in old growth. Both were found at locations with narrow valleys and steep valley slopes. These sites also had the largest total volume of LWD for any reach in their forest age class.

Table 3.2: P-values for differences in medians or means between old and secondary growth reaches. Reaches in old growth had larger values for all measures shown.

Measurement	p value
Median LWD Diameter	<0.001
Median LWD Length	<0.001
Median LWD Volume	<0.001
Total LWD Volume	<0.001
LWD Frequency	0.31
Number of LWD in debris dams (DD) and log jams (LJ)	0.007

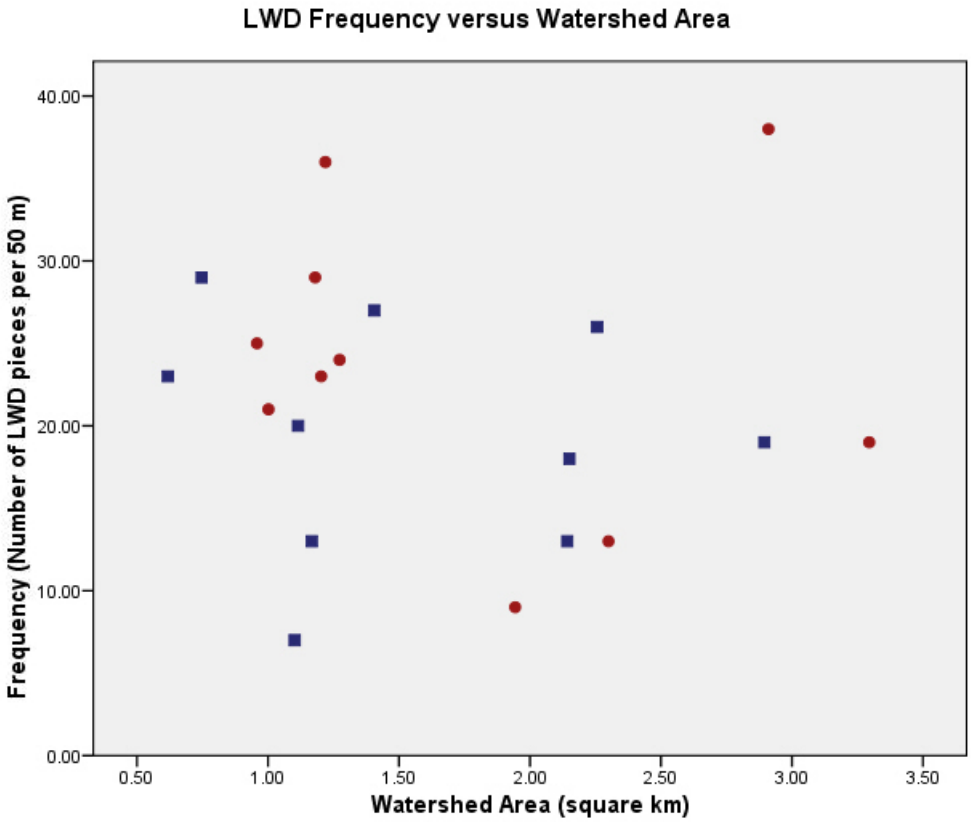


Figure 3.4: LWD frequency versus watershed area (p=0.75). Reaches in old growth are displayed as red circles (p=0.76), those in secondary growth as blue squares (p=0.78).

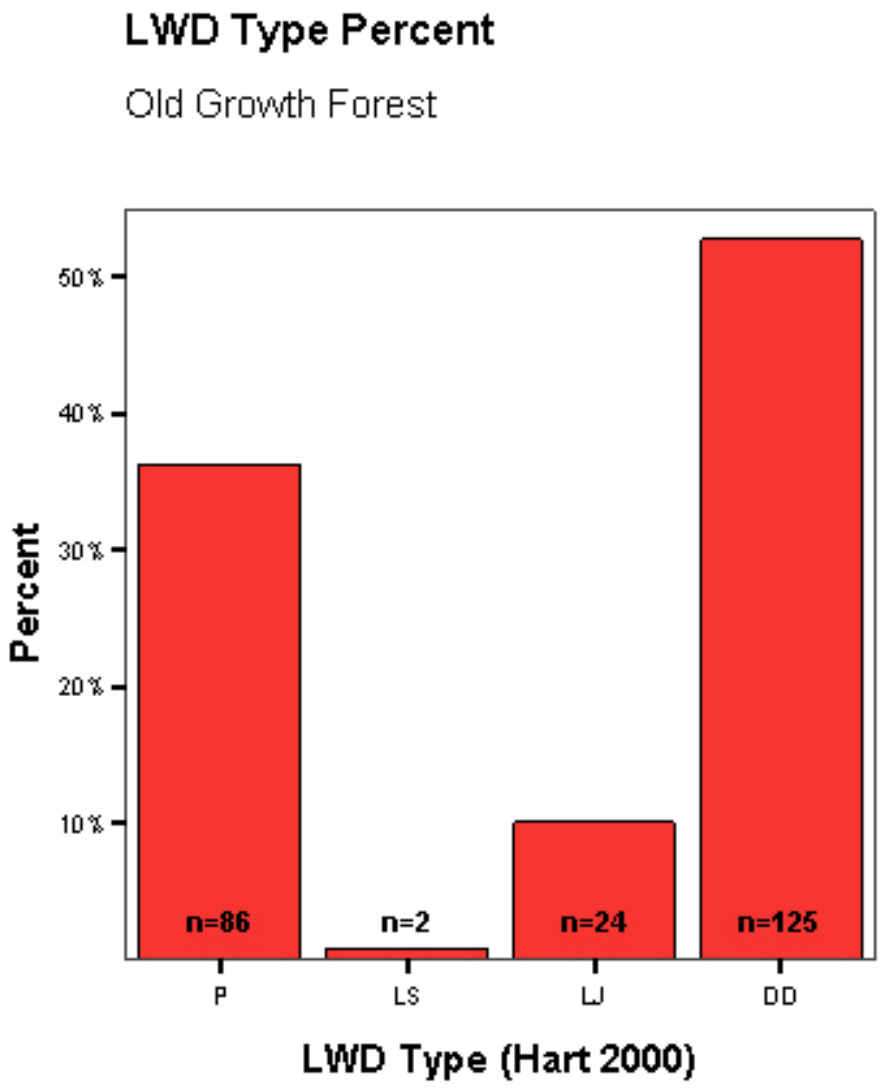


Figure 3.5: LWD classification in old growth forest. P are partial LWD pieces, LS are log steps, LJ are log jams, and DD are debris dams.

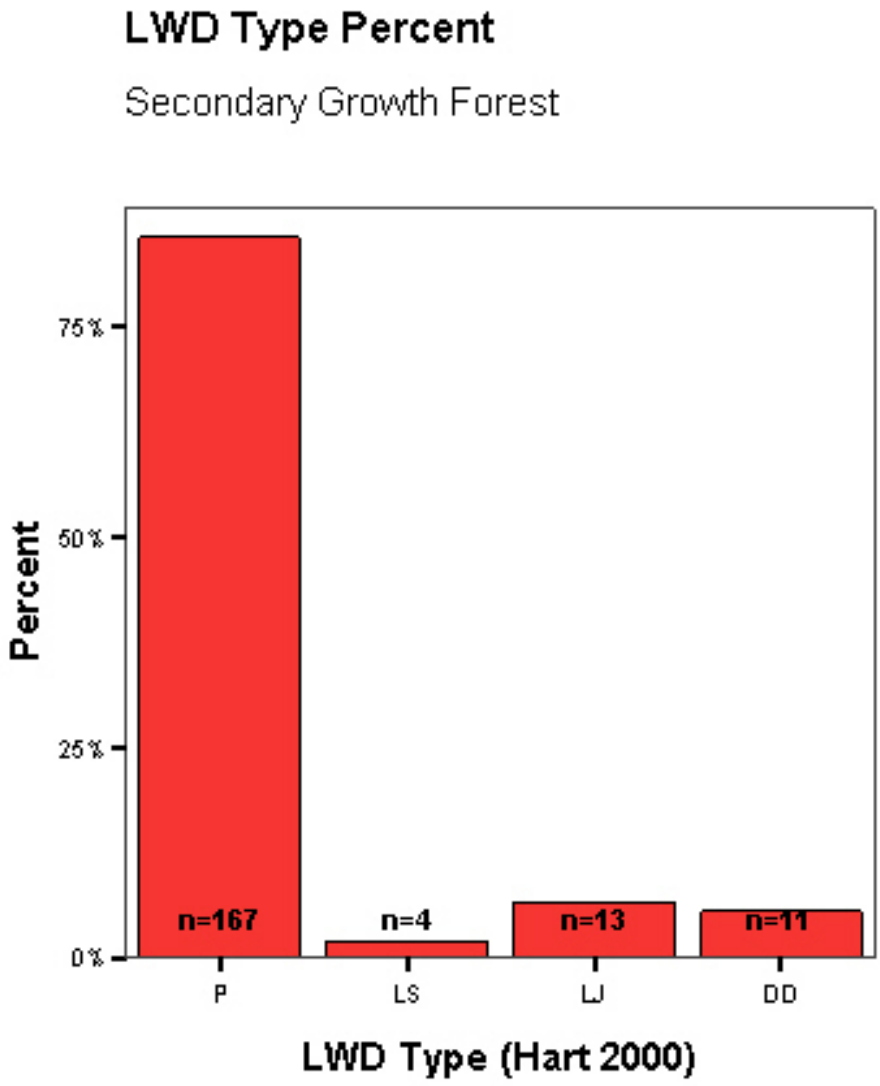


Figure 3.6: LWD classification in secondary growth forest. P are partial LWD pieces, LS are log steps, LJ are log jams, and DD are debris dams.

3.2.2 Size of LWD Pieces

I found that median diameters and lengths among individual LWD pieces were significantly larger ($p<0.001$) in reaches in old growth forest compared with those in secondary growth forest. Pieces in old growth had a median diameter of 0.22 m and length of 2.8 m. Pieces in secondary growth had a median diameter of 0.14 m and length of 1.8 m (Table 3.3).

I also found that the median volume of individual LWD pieces was significantly larger in reaches in old growth ($p<0.001$), with medians of 0.1 m^3 in old growth and 0.022 m^3 in secondary growth. The volume of individual pieces ranged from 0.0003 m^3, at Mouse Creek 2 (MC2), to 11.2595 m^3, at Cosby Creek (CC1) (Table 3.3).

On the reach scale, mean LWD diameter had a nonsignificant negative relationship with watershed area in old growth ($p=0.29$), but had a significant negative relationship in secondary growth ($p=0.03$, $r^2=0.46$). No significant relationship was found in either stream type between mean LWD length and watershed area. Neither mean LWD diameter nor mean reach LWD length had significant relationships with channel slope in either old or secondary growth (Table 3.4).

When examined on a reach scale, total LWD volume was significantly larger in old growth ($p=0.009$). Watershed area and total LWD volume had a nonsignificant negative relationship in old growth, while a weak, nonsignificant positive relationship existed in secondary growth (Figure 3.7).

Total LWD volume in secondary growth had a mean of 1.97 m^3 and ranged from 0.28 m^3 m at Baxter Creek 1 (BC1) to 4.39 m^3 at Unnamed Creek (UC1), the site of one of the two log jams I encountered in this study. Reaches in old growth contained a mean total LWD volume of 11.09 m^3, ranging from 1.57 m^3 at Inadu Creek (IC1) to 22.99 m^3 at Indian Camp Creek 2 (ICC2), the site

Table 3.3: Descriptive statistics of LWD measurements

Forest Age	Measurement	Diameter (m)	Length (m)	Volume (m^3)
Old	Number	237	237	237
	Minimum	0.06	0.44	0.0030
	Maximum	1.60	14.50	11.2590
	Mean	0.29	3.29	0.4681
	Median	0.22	2.80	0.1000
Secondary	Number	195	195	195
	Minimum	0.05	0.06	0.0003
	Maximum	0.70	11.30	2.0450
	Mean	0.11	1.78	0.1012
	Median	0.14	1.8	0.0220

Table 3.4: Correlation coefficients for selected measurements. Bold values are significant at 0.05 level.

Forest Age	Measurement	Watershed Area	Total LWD Volume
Old	Mean LWD Diameter	-0.37	**0.80**
	Mean LWD Length	-0.37	0.61
	Mean LWD Volume	-0.24	0.49
	Total LWD Volume	-0.54	1.00
	LWD Frequency	-0.24	0.61
	Number of LWD in debris dams (DD) and log jams (LJ)	-0.46	0.51
	Slope	-0.07	0.17
	Watershed Area	1.00	-0.54
Secondary	Mean LWD Diameter	**-0.68**	**0.71**
	Mean LWD Length	-0.12	0.53
	Mean LWD Volume	-0.21	**0.91**
	Total LWD Volume	-0.35	1.00
	LWD Frequency	-0.13	0.31
	Number of LWD in debris dams (DD) and log jams (LJ)	-0.08	**0.81**
	Slope	0.09	-0.36
	Watershed Area	1.00	0.35

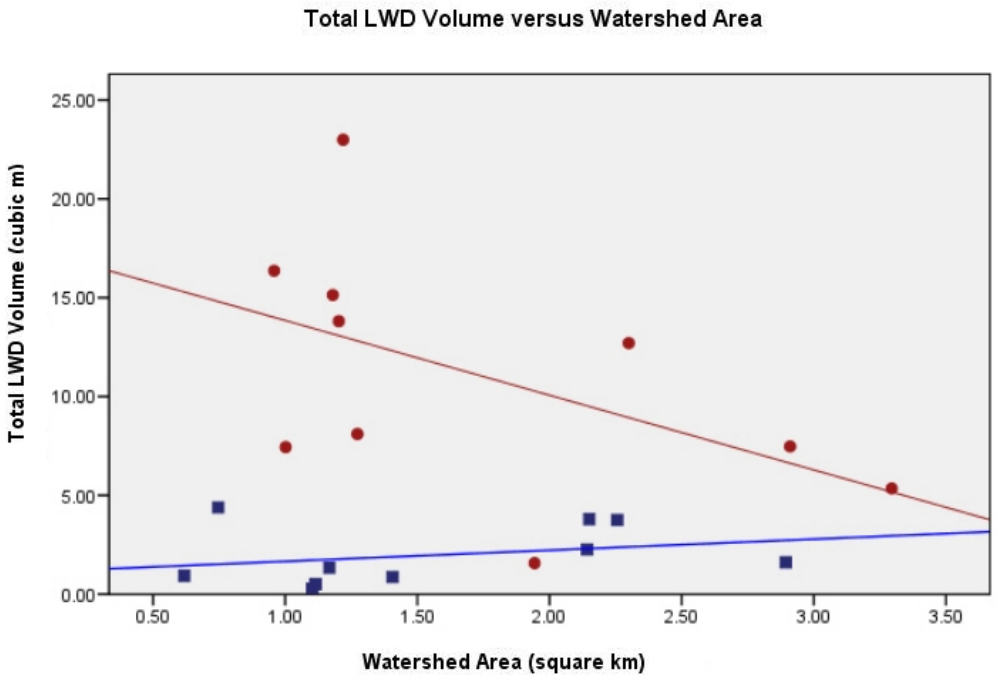


Figure 3.7: Total LWD volume versus watershed area (p=0.55). Reaches in old growth are displayed as red circles with a red regression line (p=0.11), those in secondary growth as blue squares with a blue regression line (p=0.33).

of the other log jam.

Finally, total LWD volume in streams is often presented in terms of stream bed area instead of stream length, as LWD loading can also be affected by the size of the channel area. It is expressed in terms of total LWD volume per hectare (Harmon et al., 1986). Although this does not change which sites were locations of the extremes, using volume per hectare did ease data comparison with other studies. Reaches in secondary growth had values ranging from 16.52 to 206.10 m^3/ha, with a mean of 79.76 m^3/ha. Reaches in old growth varied from 56.71 to 819.65 m^3/ha, with a mean of 375.91 m^3/ha. The ratio of total LWD volume per hectare between old and secondary growth was 5.62 (Table 3.5).

Table 3.5: Total LWD volume (m^3) per hectare stream bed area

Forest Age	Reach Symbol	Volume
Old	CB1	679
	CC1	366
	CHC1	241
	DB1	328
	DC1	237
	DC2	433
	IC1	57
	ICC1	445
	ICC2	819
	RC1	153
Secondary	BB1	146
	BB2	63
	BC1	17
	BC2	82
	KB1	32
	LGB1	46
	LGB2	110
	MC1	67
	MC2	28
	UC1	206

3.3 Discussion

3.3.1 Number and Classification of LWD Pieces

I found that reaches in old growth had a larger frequency of LWD pieces than reaches in secondary growth forest; however, they were not significantly different. Compared with other results from the southern Appalachian Mountains (Table 3.6), my LWD frequency values were among the largest, but still similar to those found by Silsbee and Larson (1983). The studies illustrate the the high variability of LWD loading (1.4 to 51.5 pieces per 100 m), even in locations with similar climate, forest type, and disturbance histories.

The higher loading from the GSMNP could reflect a variety of causes. The larger sizes of trees found in the cove hardwood forest of the Park would lengthen the decay time for each piece, thereby increasing the number of pieces in the streams at any one time. Additionally, the large number of boulders present at my study sites sometimes acted as stabilizing mechanisms for LWD. Working in Oregon, Faustini and Jones (2003) found that boulders often stopped the movement of loose LWD pieces and held them in place. LWD pieces held by boulders would also help to explain my high LWD frequencies. One implication of this high variability is that caution should be used when LWD loading from other studies is used to design stream restoration or measure the success of management practices, such as riparian buffers, as has been advocated and implemented in the southern Appalachians (Flebbe and Dolloff, 1995; Flebbe, 1999). Finally, the frequencies I found were comparable to values found in the Pacific Northwest of 30 to 100 pieces per 100 m (Bilby and Ward, 1991; Ralph et al., 1994; Gomi et al., 2002), reinforcing the importance of LWD in southern Appalachian streams.

Most studies of LWD frequency have used channel width instead of water-

Table 3.6: LWD frequency (number of pieces per 100 m stream length) for southern Appalachian Mountains

Location	Forest Age	Frequency	Source
GSMNP, TN	Old	51.5	Silsbee and Larson (1983)
GSMNP, NC+TN	Old	31.7	Silsbee and Larson (1983)
GSMNP, NC	Old	20.6	Flebbe and Dolloff (1995)
GSMNP, NC+TN	Old	3.4	Hart (2000)
GSMNP, NC+TN	Secondary	5.5	Hart (2000)
GSMNP, TN	Old	47.4	This study
GSMNP, NC	Secondary	39.0	This study
Nantahala NF, NC	Old	11.1	Flebbe and Dolloff (1995)
Pisgah NF, NC	Secondary	1.4	Flebbe and Dolloff (1995)
Nantahala NF, NC	Secondary	5.7	Flebbe (1999)

shed area to examine frequency as a factor of different stream sizes, despite errors that could result, since width is also influenced by LWD (Ralph et al., 1994). The relationship between width and LWD frequency will be examined further in the next chapter. Studies using width have generally found decreasing frequencies of LWD with larger streams (Jackson and Sturm, 2002). However, those that have used watershed area have had mixed results. Ralph et al. (1994), working in Washington, found no relationship between watershed area and LWD frequency, while Robison and Beschta (1990), examining streams in coastal Oregon, found a positive relationship. In GSMNP, Hart (2000) found a negative relationship between the frequency of LWD and watershed area. I found no statistically significant relationship between LWD frequency and watershed area.

The most striking difference between reaches in old and secondary growth was the number of pieces that were a part of debris dams. The larger number of debris dams in streams in old growth is consistent with studies elsewhere in the eastern US (Warren et al., 2007; Morris et al., 2007) and the GSMNP in particular (Silsbee and Larson, 1983; Hart, 2000). In old growth, the size of available LWD is larger and is, therefore, more likely to capture other pieces

of LWD and form dams (Keeton et al., 2007). The ratio of the percentage of total pieces in debris dams between old and secondary growth was 9.5. Silsbee and Larson (1983) found a ratio of only 4.75. This probably has to do with differences in what pieces were measured in the study. Silsbee and Larson (1983) measured LWD pieces not only from within the bankfull channel, but also those outside bankfull, on top of the stream channel bank.

The equal number of log jams between old and secondary growth was also consistent with the findings of Hart (2000), that logjams were primarily controlled by other geomorphic factors, such as valley width. The two log jams found in this study were both found in locations with narrow valleys, on the order of tens of meters, and very steep valley slopes. The steep slopes funnel large numbers of LWD pieces into the valley, and the narrow valley widths ensure most of the LWD ends up near or in the stream channel (Jackson and Sturm, 2002). This highlights the importance of geomorphic controls on LWD in streams (Morris et al., 2007).

The most curious finding with the classification of LWD was the proportion of log steps. Hart (2000) found that log steps made up 26% of all obstructions in streams in old growth and 22% in secondary growth, while I found that they were relatively rare features, at 0.8% and 2% respectively. This may be the result of the differences in the forest types surrounding the stream reaches examined in our studies. His reaches were in northern hardwood and spruce-fir forest types, which contain trees of smaller size than the cove hardwood type of my reaches. The larger size, in terms of length, diameter, and volume, would make the LWD pieces in my reaches more likely to form debris dams. However, he did not measure LWD sizes, so this idea can not be further examined.

However, I also did observe some limitations of the classification developed by Hart (2000). The largest piece by volume in my entire study (11.2595

m^3, at Cosby Creek (CC1)) was classified as a partial. Despite this, it had a dramatic effect on the downstream geomorphology. It created two channels, by directing most of the water away from normal channel to a new channel close against the valley side. This created a large mid-channel island tens of meters in width and length. Even though this was one of the most striking examples of LWD influencing channel morphology, it was classified with large numbers of small pieces, which had only minor geomorphic impacts. I suggest that the classification might be improved by splitting the existing partial category into two different groups. One group, loose pieces, would include those LWD pieces that are loose in the stream channel. Loose pieces have no strong interactions with the channel bed or banks. A new category, partial blockages, would include LWD pieces that are not log steps, nor part of a debris dam or log jam. Partial blockages would have some visible interaction with the channel bed or banks. In most cases this would be observable with part of the LWD being buried or covered by sediment.

3.3.2 Size of LWD Pieces

The larger median diameters, lengths, and volumes of individual LWD pieces in reaches in old growth forest are consistent with the results from most studies (Harmon et al., 1986) and have been attributed to the larger size of trees in old growth resulting in larger LWD in the streams (Spies et al., 1988). However, there are several notable exceptions to this. Gomi et al. (2002), working in southeastern Alaska, found larger individual LWD diameters and lengths in 37 year old forest than in old growth. They attributed this to the small diameters of trees found in the old growth forest. Hedman (1992), working in southwestern North Carolina, did observe longer LWD pieces in streams in older forests, although he did not observe statistically significant differences

in diameter. He attributed this to LWD that was already in the stream from before logging and the slash that entered the streams because of logging being mostly decay-resistant tree species such as hemlock and chestnut. Flebbe and Dolloff (1995), studying streams in western North Carolina, combined individual LWD piece diameters and lengths into a series of classes and found that larger classes were more frequently observed in streams in old growth. Finally, in the GSMNP, Silsbee and Larson (1983) found larger diameters and volumes of LWD pieces in streams in old growth, but they did not report LWD lengths.

Total LWD volume was significantly greater in reaches in old growth than in secondary growth in this study. However, I found no significant relationships between total LWD volume and watershed area. This is not consistent with the results of Bilby and Ward (1989, 1991) or of Beechie and Sibley (1997), who found increased LWD loading in smaller streams because of the inability of the streams to move the LWD pieces. However, like LWD frequency, these studies used channel width as a surrogate for watershed area. Using actual watershed area, both Robison and Beschta (1990) and Nakamura and Swanson (1993) did observe smaller total LWD volumes in larger watersheds, but only when watershed area was increased to tens of square kilometers. These two studies suggests that LWD loading in watersheds of fewer than 10 km^2 is relatively uniform except when channels are in particularly narrow valleys. Because the watersheds used in this study were less than 4 km^2 in area, LWD loading would not be expected to be significantly correlated with watershed area.

The values I found for total LWD volume per hectare were among the largest found outside of the Pacific Northwest (Table 3.7). Just as with individual LWD pieces, the larger LWD loading is caused by the larger trees found in these forests. Generally, the largest LWD loadings have been found in the

forests with the largest trees. However, the LWD loadings I found were quite similar to those found by Silsbee and Larson (1983). They reported a ratio of total LWD volume between reaches in old and secondary growth of 4.0, while my ratio was 5.6. The difference between these two ratios was mostly caused by the slightly larger loading I found for reaches in old growth. This was probably caused by inherent variation in LWD loading between individual streams rather than any significant change in LWD loading in old growth forest. The almost complete lack of difference between our values for reaches in secondary growth forest, even after 25 years, is a testament to the long recovery time of LWD loading. Furthermore, the lack of difference in total LWD volume in secondary growth between our studies refutes my idea that there would be a difference between the values of Silsbee and Larson (1983) and myself. This lack of difference suggests that LWD loading in secondary growth reached the low point of the U-shaped curve and has remained near there during both of our studies.

Table 3.7: LWD Volume (m^3) per hectare for select studies in North America

Location	Forest Age	Volume	Source
Nantahala NF, NC	Old	234	Valett et al. (2002)
Nantahala NF, NC	Secondary	1	Valett et al. (2002)
GSMNP, TN	Old	339	Silsbee and Larson (1983)
GSMNP, TN	Secondary	85	Silsbee and Larson (1983)
GSMNP, TN	Old	180	Harmon et al. (1986)
GSMNP, TN	Old	148	Harmon et al. (1986)
GSMNP, TN	Secondary	40	Harmon et al. (1986)
GSMNP, TN	Old	376	This study
GSMNP, NC	Secondary	80	This study
Coastal Alaska	Old	196	Robison and Beschta (1990)
British Columbia	Old	678	Harmon et al. (1986)
Coastal California	Old	1591	Harmon et al. (1986)
Adirondack Mts, NY	Old	200	Keeton et al. (2007)
Adirondack Mts, NY	Secondary	34	Keeton et al. (2007)
Cascade Mts, OR	Old	638	Harmon et al. (1986)

Finally, I observed that LWD frequency was not significantly different between reaches in old and secondary growth forest. In contrast, total LWD volume and the proportion of LWD pieces in debris dams and log jams was dramatically different between forests of different ages. Therefore, LWD frequency as a metric did not have the same ability as total LWD volume or proportion of pieces in debris dams and log jams to reflect differences in LWD loading. This suggests that future studies examining LWD variations in the southern Appalachians should not use LWD frequency from the point of view of stream response to disturbances. Instead, future studies should use either total LWD volume or the proportion of LWD pieces in debris dams and log jams.

Chapter 4

Channel Morphology

LWD is generally understood to affect channel widths by directing flow toward channel banks and to impact channel depths by creating pools. Furthermore, LWD captures sediment that would otherwise be flushed downstream. I hypothesized that stream reaches with more LWD would have larger bankfull widths and depths than those with less LWD. I also hypothesized that reaches with more LWD would have a greater variation in widths and depths. Finally, I hypothesized that reaches with more LWD would have smaller D_{50} (median sediment size) in pools than those reaches with less LWD.

4.1 Methods

The study reaches used to collect channel morphology data were the same as those used to measure woody debris. The methods I used to choose these reaches were outlined in chapter 2.

At each reach, I stretched a 50 m surveyor's tape from the downstream end of the reach to the upstream start of it, and placed flags every 5 m, starting at the 5 m mark. I chose 50 m as my reach length to ensure inclusion of several different channel types (Halwes and Church, 2002). My 50 m reach

was roughly 10 channel widths in length, a value that has been observed to include several different channel types (Montgomery and Buffington, 1997; Myers and Swanson, 1997).

After defining the exact location of the study reach, I took photographs, made a sketch of the reach, and labeled the location of the reach on a topographic map (1:24000 scale). I then determined what constituted bankfull stage at each stream. Bankfull stage in stable streams is located at major changes in bank slope and vegetation and is often the height of the surrounding floodplain (Gordon et al., 2004). However, in this study, because of high stream gradients and a lack of floodplain development, I chose to locate bankfull by different features. I found that the most consistent feature was the level that woody vegetation would start to grow in the soil. Below this level, only herbaceous plants were found. The extreme dryness of 2007 resulted in low water levels in most streams and completely dry streams at Baxter Creek 1 (BC1), Dry Branch (DB1), and Log Gap Branch 1 (LGB1) during data collection (July - October 2007). The low water levels allowed herbaceous plants to grow on parts of the channel beds. However, woody vegetation was only located above the bankfull channel. Moreover, this change in vegetation was often located at the change from bare rock surfaces to soil-covered surfaces, where bank slopes changed from near vertical to much smaller angles (Figures 4.1, 4.2).

Each of the 10 flags was used as the location for a transect for width and depth measurements. Using a surveyor's tape, the bankfull width was determined and recorded. The tape was kept positioned at bankfull stage. I measured the depth from the tape to the channel bed at 1/5, 2/5, 3/5, and 4/5 of the width, using another surveyor's tape.

In order to characterize channel bed material, bulk samples have tradi-

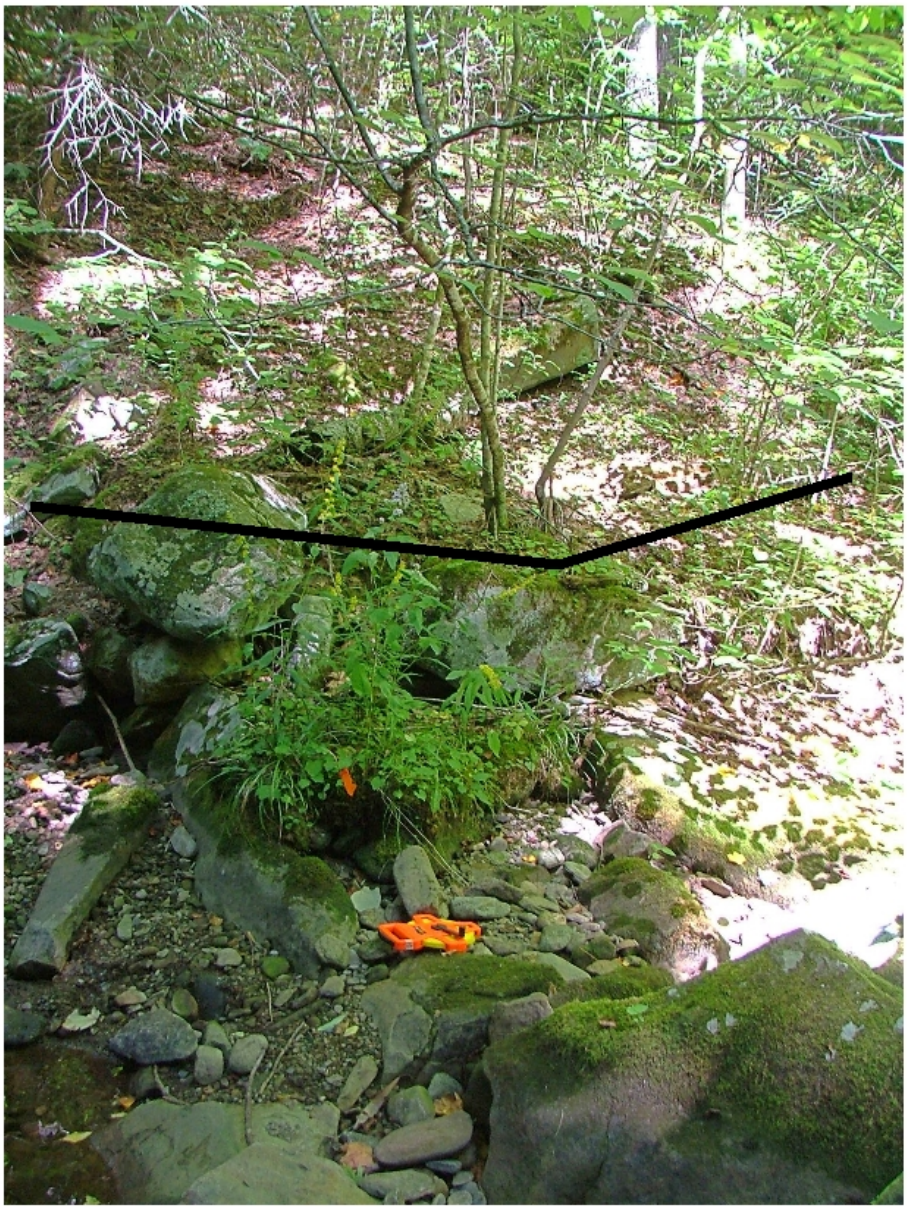


Figure 4.1: Log Gap Branch 2: The black line represents approximate bankfull height. Above this line woody vegetation is present growing in the soil, while below it only herbaceous plants are found (near orange flag). The surveyor's tap is located on a dry pool bed in this year of extreme drought (2007).



Figure 4.2: Mouse Creek 2: The black line represents approximate bankfull height. Above this line woody vegetation is present, while below it only mosses and herbaceous plants are found. Soil is also present on the boulders above the line.

tionally been used. However, these become impractical with increasing grain sizes (Kondolf et al., 2003). Instead, pebble count methods can be used. The most commonly used procedure is the Wolman (1954) pebble count. In this method, the researcher walks a grid pattern over a particular geomorphic feature, picking up stones under the tip of the toe of the boot while trying not to look at the bed so as to ensure randomness. The intermediate axes of the pebbles are measured using a gravelometer and the size recorded into one of a series of size classes. The procedure is repeated until 100 stones are selected. For this study, I did a Wolman 100-stone pebble count in the largest pool of each stream reach. A pool is defined as a region of slow moving water that is generally deeper and has finer bed particles (Gordon et al., 2004). I choose to use pools as the locations for my pebble counts because they are often formed by LWD and because pools were common feature in my study reaches.

The data are presented in terms of individual measurements and calculated reach values. Individual measurements consisted of each channel width and depth measurement performed. Reach values are the mean of these individual measurements for each reach. Both the measurements and the calculated reach values were normal, so means were used in the statistical tests. Table 4.1 summarizes the different variables and their meanings.

Table 4.1: Descriptions of channel variable names

Variable Name	Meaning
Individual Channel Width	Individual channel width measurements for all reaches (n=200)
Individual Channel Depth	Individual channel depth measurements for all reaches (n=800)
Reach Channel Width	Mean of channel width for a reach (calculated from individual measurements)
Reach Channel Depth	Mean of channel depth for a reach (calculated from individual measurements)
Median sediment size	Median sediment size from largest pool in each reach

4.2 Results

4.2.1 Channel Width

Sites of large LWD pieces were often associated with wider individual channel transects, although numerous reaches also had LWD lined up parallel to channel banks, sometimes forming the bank. Individual channel widths were significantly larger in old growth forest (n=200, $p<0.001$). In secondary growth, individual channel widths ranged from 1.6 m at Kirby Branch (KB1) to 11.1 m at Mouse Creek 2 (MC2), with a mean of 5.2 m. In old growth, individual channel widths ranged from 3.0 m at Copperhead Branch (CB1) to 10.6 m at Cosby Creek (CC1), with a mean of 6.7 m.

Overall, there was a significant, positive relationship between mean reach channel width and watershed area ($p=0.03$, $r^2=0.24$). However, when examined within forest age classes, there were no significant relationships between mean reach channel width and watershed area in either old or secondary growth, although the slope of the relationship was steeper in secondary growth (Figure 4.3). Mean reach channel width had a negative relationship with stream channel slope, just missing the 0.05 significance level ($p=0.052$).

Mean reach channel width had no significant relationship with total LWD volume in old ($p=0.36$) or secondary growth ($p=0.10$) (Figure 4.4), but when both forest age classes were examined together, there was a positive relationship between channel width and total LWD volume ($p=0.07$). I found no significant relationships between mean channel width and the frequency, mean diameter, or mean length of LWD.

There was a significant negative relationship between mean reach channel width and mean reach channel depth in old growth forest ($p=0.009$, $r^2=0.60$). There was no such relationship in secondary growth. However, when examined

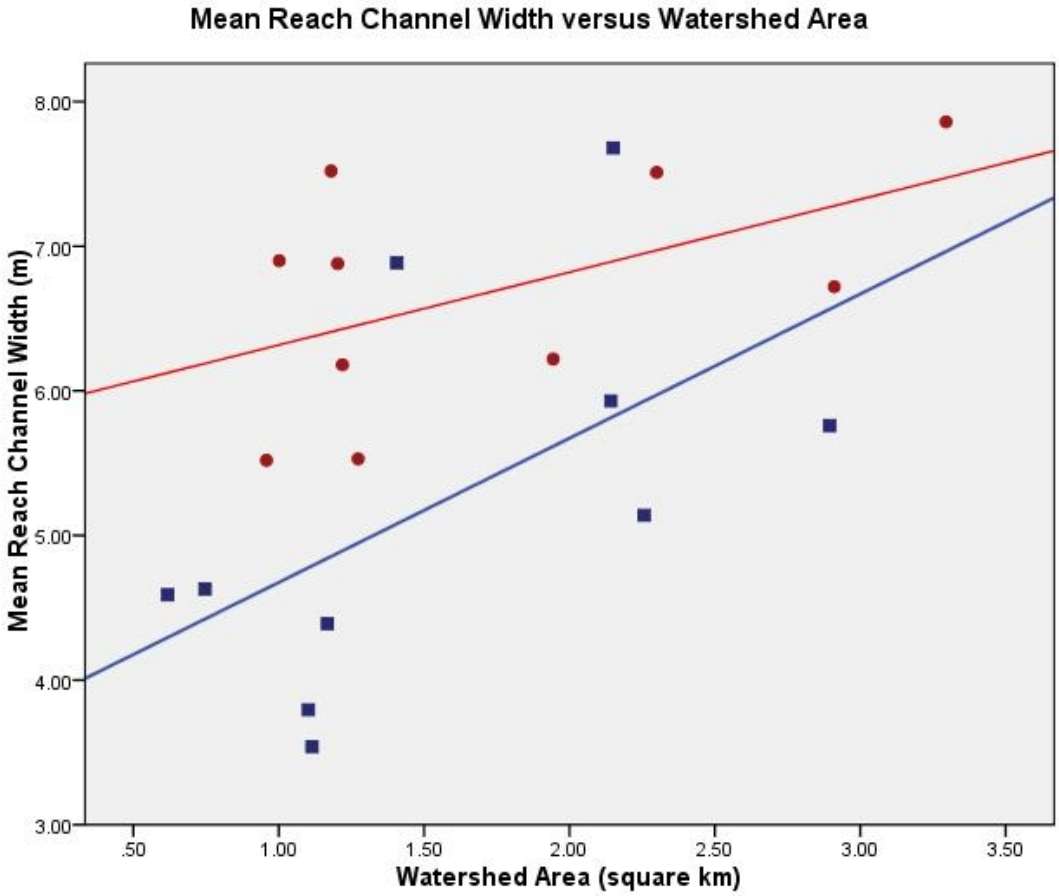


Figure 4.3: Mean reach channel width versus watershed area (p=0.03). Reaches in old growth are displayed as red circles with a red regression line (p=0.35), those in secondary growth as blue squares with a blue regression line (p=0.06).

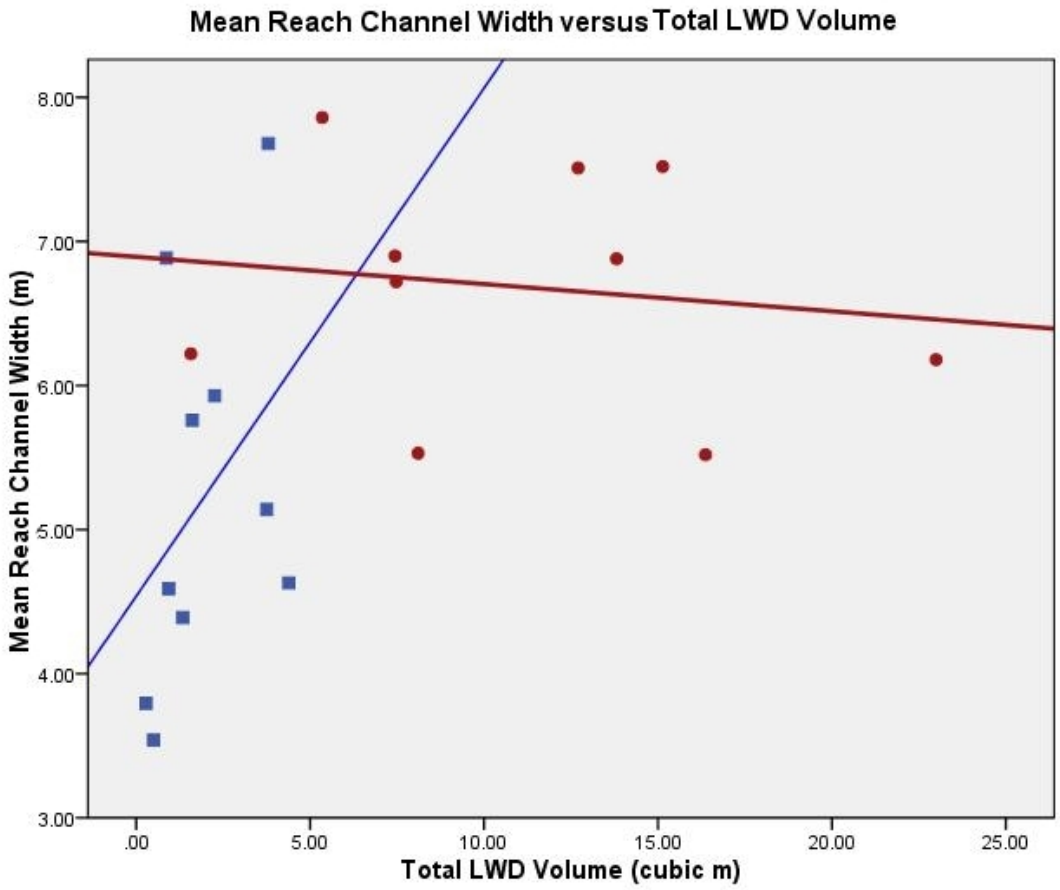


Figure 4.4: Mean reach channel width versus total LWD volume (p=0.07). Reaches in old growth are displayed as red circles with a red regression line (p=0.36), those in secondary growth as blue squares with a blue regression line (p=0.10).

using individual channel widths and depths, no relationship could be discerned.

In order to compare variation of channel widths of reaches in old and secondary growth forest I compared the variance of individual channel widths. I used Levene's test for equality of variances to determine if there was a difference between reaches in different forest classes and if it was statistically significant. I found that reaches in secondary growth had more variance in individual channel width, however it was not significant (p=0.19).

Finally, I used multiple linear regression to determine how much of the variation in mean reach channel width could be explained by watershed area, stream channel slope, and total LWD volume. I found that 41% of the variance in mean reach channel width could be explained with those three variables in secondary growth (equation 4.1; p=0.33), while 45% could be in old growth (equation 4.2; p=0.28). When I performed the regression with old and secondary growth together, 56% of the variance could be explained (equation 4.3; p=0.004).

$$y_{width} = 4.663 + 0.835x_{area} - 0.079x_{slope} + 0.184x_{volume} \tag{4.1}$$

$$y_{width} = 6.792 + 0.481x_{area} - 0.119x_{slope} + 0.034x_{volume} \tag{4.2}$$

$$y_{width} = 5.678 + 0.792x_{area} - 0.124x_{slope} + 0.096x_{volume} \tag{4.3}$$

4.2.2 Channel Depth

I observed that LWD had an important influence on channel depths by creating pools separated by LWD steps; however, boulders were also important in this process. Individual measurements of channel depth were found to be significantly larger (n=800, p=0.003) in old growth forest. In secondary growth, individual channel depths ranged from 0 m at several locations to 1.60 m at

Bettis Branch (BB2), with a mean of 0.55 m. In old growth, individual channel depths ranged from 0 m at several streams to 1.77 m at Indian Camp Creek 2 (ICC2), with a mean of 0.62 m.

Mean reach channel depth did not have a significant relationship with watershed area in reaches in old growth; however, it was significantly, positively related ($p=0.01$, $r^2=0.56$) to watershed area in secondary growth forest (Figure 4.5). In contrast, stream channel slope had a significant positive relationship with mean reach channel depth in old growth ($p=0.03$, $r^2=0.45$), but not in secondary growth. Neither watershed area nor stream channel slope had a significant relationship with mean reach channel depth when not separated by forest age.

Mean reach channel depth had a positive, nonsignificant relationship with total LWD volume ($p=0.08$ $r^2=0.16$) (Figure 4.6). There was also a positive, nonsignificant relationship between LWD frequency and mean reach channel depth ($p=0.07$, $r^2=0.17$). I found no significant relationships between mean reach channel depth and mean LWD diameter or length.

As with channel width, I used the variance to determine which forest age class had a greater variation in individual channel depths. I found that reaches in secondary growth had more variance in individual channel depth; however it was not significant ($p=0.47$).

Finally, I used multiple linear regression to determine how much of the variation in mean channel depth could be explained by watershed area, stream channel slope, and total LWD volume. I found that 68% of the variance could be explained in secondary growth (equation 4.4; $p=0.06$), while only 53% could be in old growth (equation 4.5; $p=0.18$). Doing the regression with old and secondary growth data together, I found that 49% of the variance could be explained (equation 4.6; $p=0.01$).

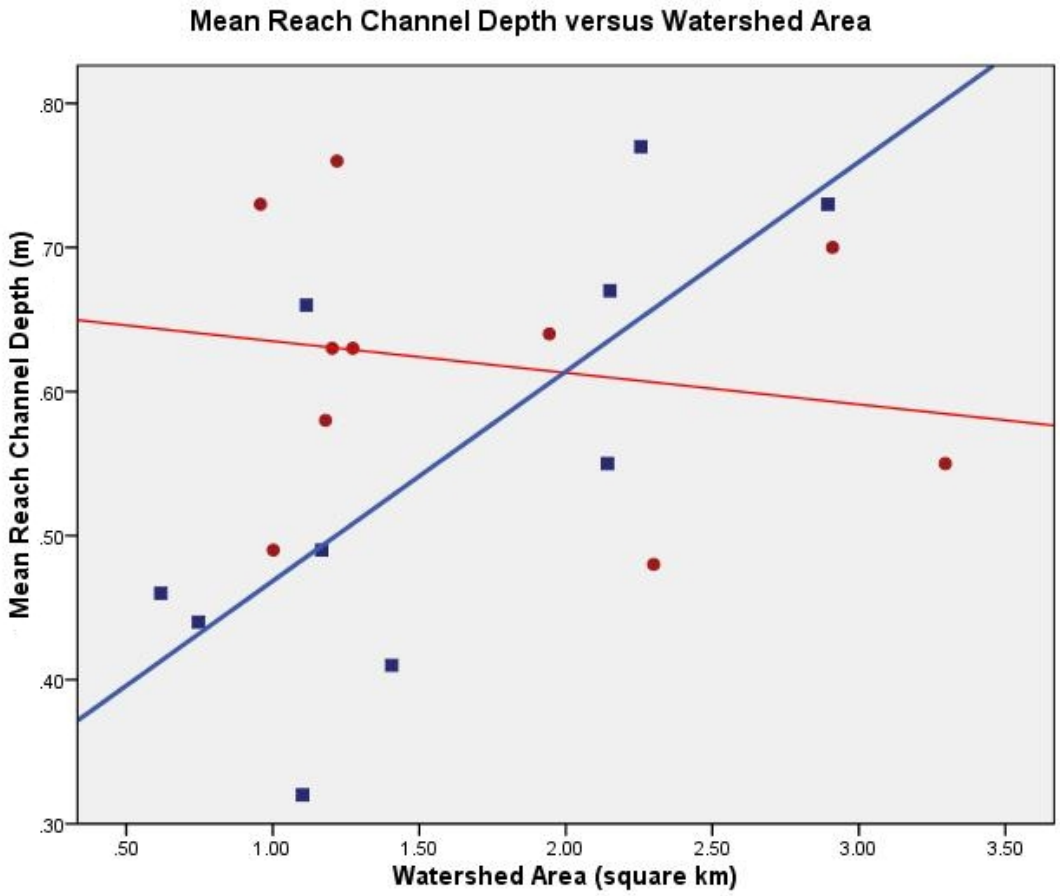


Figure 4.5: Mean reach channel depth versus watershed area (p=0.08). Reaches in old growth are displayed as red circles with a red regression line (p=0.65), those in secondary growth as blue squares with a blue regression line (p=0.01).

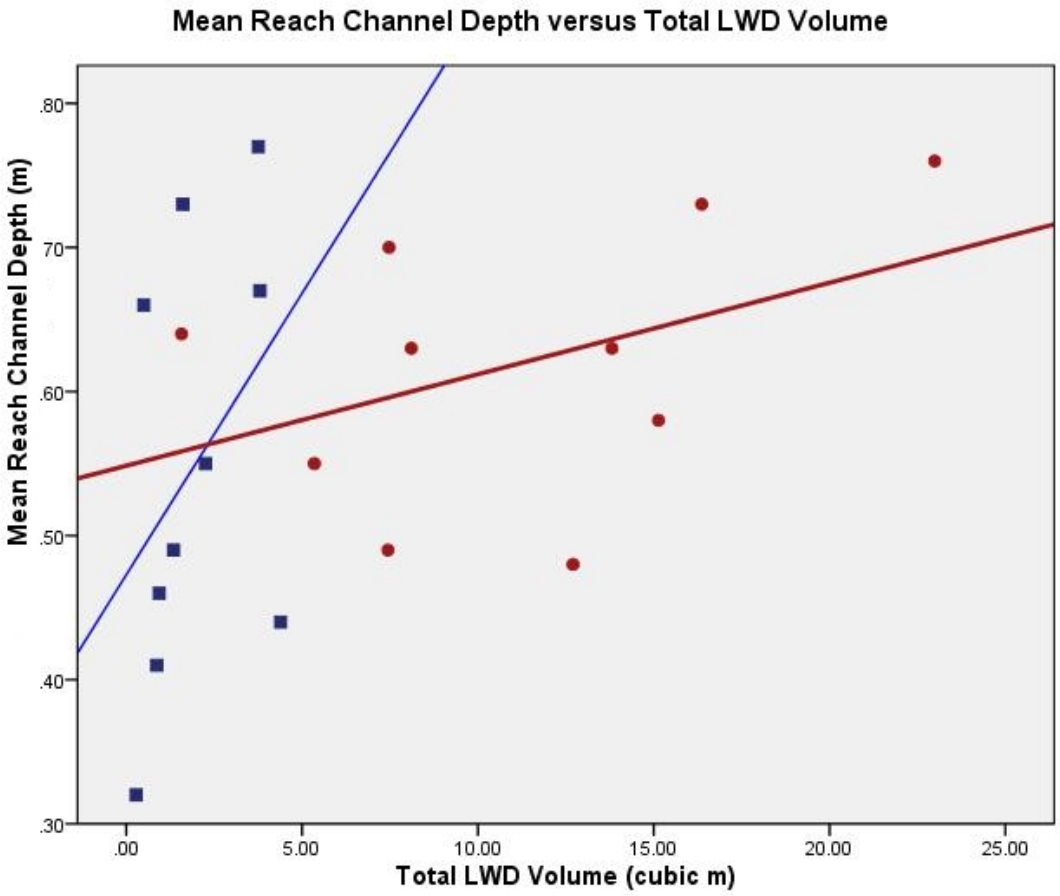


Figure 4.6: Mean reach channel depth versus total LWD volume (p=0.08). Reaches in old growth are displayed as red circles with a red regression line (p=0.24), those in secondary growth as blue squares with a blue regression line (p=0.19).

$$y_{depth} = 0.022 + 0.141x_{area} + 0.018x_{slope} + 0.031x_{volume} \quad (4.4)$$

$$y_{depth} = 0.275 + 0.020x_{area} + 0.021x_{slope} + 0.004x_{volume} \quad (4.5)$$

$$y_{depth} = 0.137 + 0.088x_{area} + 0.018x_{slope} + 0.010x_{volume} \quad (4.6)$$

4.2.3 Channel Bed Sediment Size

No significant difference in median channel bed sediment size (p=0.20) was found between pools in old and secondary growth forest (Table 4.2). Because nearly every reach flows through a boulder field, larger boulders were frequently encountered, resulting in the D_{84} of each reach being larger than 256 mm. The D_{50} size ranged from <2 to >256 mm.

Table 4.2: Bed sediment sizes (mm)

Forest Age	Reach Symbol	D_{35}	D_{50}	D_{84}
Old	CB1	16	32	>256
	CC1	22.6	45	>256
	CHC1	16	32	>256
	DB1	32	45	>256
	DC1	8	64	>256
	DC2	45	>256	>256
	IC1	22.6	64	>256
	ICC1	32	45	>256
	ICC2	22.6	64	>256
	RC1	16	32	>256
Secondary	BB1	11.3	90	>256
	BB2	45	90	>256
	BC1	16	32	>256
	BC2	16	>256	>256
	KB1	<2	<2	>256
	LGB1	32	64	>256
	LGB2	22.6	64	>256
	MC1	22.6	128	>256
	MC2	22.6	90	>256
	UC1	16	45	>256

4.3 Discussion

4.3.1 Channel Width

I found channels to be significantly wider in old growth than in secondary growth forest. This is consistent with several studies from the Pacific Northwest (Bilby and Ward, 1991; Nakamura and Swanson, 1993; Faustini and Jones, 2003); however, results from the southern Appalachian Mountains have been less clear. Hart (2000) also found larger widths in old growth. Hedman (1992) found no difference in channel width in forests of different age. However, he also did not find increased LWD loading with forest age at his sites, which could be the reason for the lack of difference in channel width. Valett et al. (2002) also found no width difference and observed a much larger ratio of LWD between forest ages than I did. The small number of studies and the inconsistent results highlight the lack of knowledge about channel morphology in general in the southern Appalachians and the need for additional research.

Mean reach channel width had a weakly significant relationship with watershed area. The weakness of the relationship was unexpected, since channel widths are usually understood to increase in larger watersheds as a response to increased discharges (Gordon et al., 2004). However, I was not the first to question this general relationship. Zimmerman et al. (1967) and Keller et al. (1995) both observed that the relationship between watershed area and channel width was weaker in smaller watersheds (<5 km^2). Both teams hypothesized that the greater influence of vegetation on smaller streams weakened the area-width relationship. Because none of my study reaches had watersheds larger than 5 km^2, I was unable to directly test this theory. However, using the mean reach channel width values of Hart (2000), I found the same weak relationship in his GSMNP streams, which had watershed areas ranging from 1.7 to

2.3 km^2. The reduced influence of vegetation could also explain the stronger relationship between watershed area and channel width in secondary growth, as apparent in figure 4.3. Because of lower LWD loading in secondary growth, vegetation did not play as an important a role; therefore, the relationship between watershed area and channel width was stronger. In the smallest watersheds, where vegetation plays its most important role affecting width, the difference in channel width between wider streams in old growth and narrower secondary growth was the largest.

The most surprising results were the lack of significant relationships between LWD volume, LWD frequency, and mean reach channel width. LWD is generally thought to direct flow toward the banks and increase channel width. Therefore, those reaches with larger LWD loadings should be wider. Studies have generally supported this (Nakamura and Swanson, 1993; Beechie and Sibley, 1997; Jackson and Sturm, 2002); however, there have been exceptions. Ralph et al. (1994), Hart (2000), and Gomi et al. (2003) all found no significant relationship between LWD frequency and channel width. Robison and Beschta (1990) found a weak relationship, with LWD volume explaining only 9% of the variance of channel width. I think the weak, nonsignificant relationships that I and others have found are the result of LWD being able to both increase channel width by directing the flow toward banks, and decrease flow by protecting banks and causing deposition (Keller and Swanson, 1979). These other roles of LWD were illustrated at several study sites. Figure 4.7 shows a LWD piece (0.9 x 9.3 m) that was parallel to and protected the bank, and figure 4.8 shows a map view of Copperhead Branch (CB1), the reach were the illustrated parallel LWD was found. Only the largest LWD pieces are shown on the map. As is clear from the image, at this particular site the largest pieces were parallel to the stream and were protecting the banks from



Figure 4.7: Copperhead Branch: This piece of LWD was protecting the bank by erosion from the stream. It was 9.3 m in length and 0.9 m in diameter.

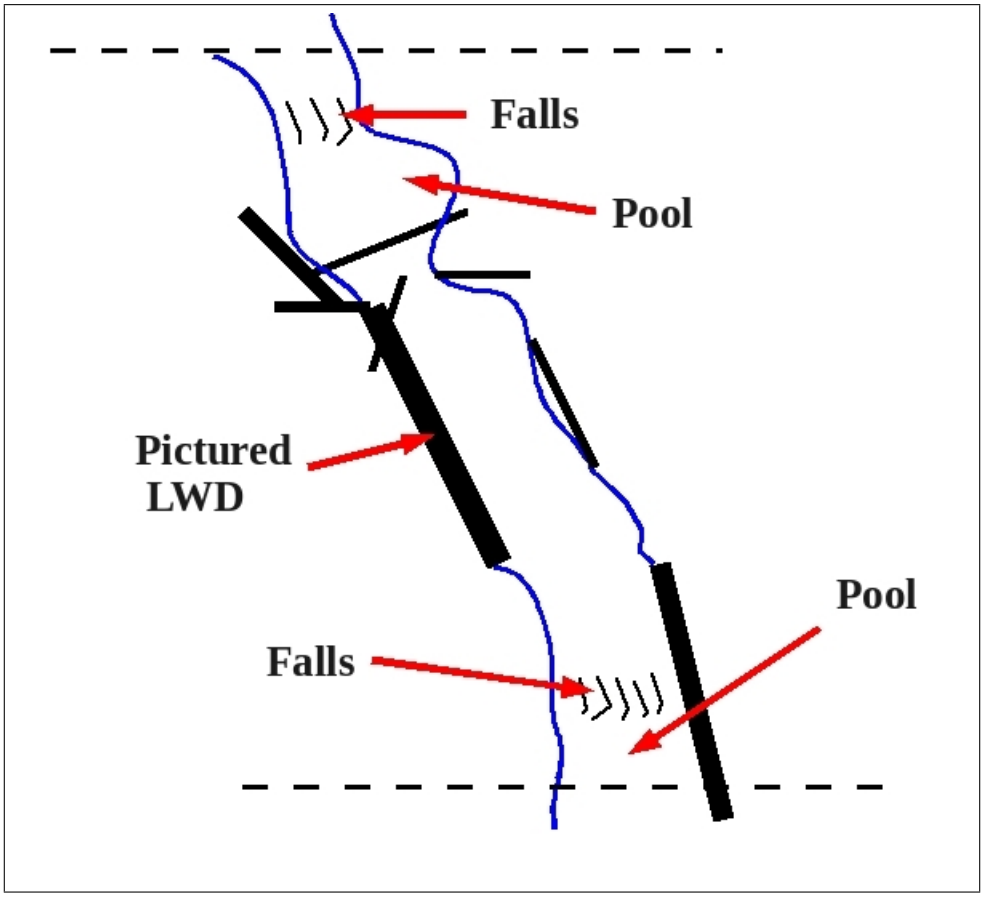


Figure 4.8: Map view of Copperhead Branch. Blue is the bankfull channel, the dashed black line is the start and end of the reach, and the thickness and length of the black line signifies the size of the LWD.

further erosion. Copperhead Branch was also the site of the smallest mean channel width observed in old growth forest. However, one moderately sized LWD piece was perpendicular to the stream and it created a wide, shallow pool upstream of itself by deposition of sediment. At Copperhead Branch, LWD was playing both roles. The pattern of LWD pieces occurring parallel to the banks was also observed at Indian Camp Creek 2 (ICC2), the site with the largest total LWD volume in the study. These two reaches highlight the importance of orientation on geomorphic roles of LWD. Orientation should be especially important in streams in smaller watersheds, where narrow valleys and steep valley slopes tend to funnel LWD into the channel, as was clear at Indian Camp Creek 2. Even in larger streams, Bilby and Ward (1989) found that only 40% of LWD pieces were perpendicular to the stream flow.

Surprisingly, I found less variation in individual channel width in old growth than in secondary growth forest, although it was not significant at the p=0.05 level. Zimmerman et al. (1967) and Gerhard and Reich (2000) found that stream reaches with more LWD had larger variation in widths. However, Hart (2000) found larger variation in channel width in secondary growth reaches in GSMNP compared to old growth reaches. I think the lack of a significant difference in individual channel width variation between different forest age classes were also caused by the different ways LWD impacts channel width. As shown in figure 4.3, the largest difference in channel width between old and secondary growth occurred in the smallest watersheds, while larger watersheds in my study exhibited much less difference. In smaller watersheds, streams in secondary growth were much narrower because of their lower LWD loading. However, in larger watersheds, vegetation plays a less effective role, so there was much less variation between the forest ages, despite differences in LWD loading. The importance of LWD in affecting channel width is thus scale

dependent

4.3.2 Channel Depth

Channels were significantly deeper in old growth than in secondary growth forest. This is consistent with the idea that LWD causes scour in pools, increasing individual channel depth (Montgomery et al., 2003). Ralph et al. (1994) observed that streams in 40 year old logged forest had shallower pools than those in unlogged forest and had less variance in pool depth. Hart (2000) also found greater channel depths in old growth. Most studies have focused on pool frequency and its relationship with LWD. I did not look at this measure, but since pools are generally deeper than surrounding channel features, pool frequencies can be used as a substitute for channel depth. Those streams with more pools will be deeper than those streams with few pools. Montgomery et al. (1995), Flebbe and Dolloff (1995), and Keller et al. (1995) observed higher pool frequencies in old growth forest.

Channel depth had a significant relationship with watershed area in secondary growth; however, there was no such relationship in old growth. Just as with channel width, this was a curious result because depth is usually thought to increase in larger watersheds (Gordon et al., 2004). This relationship with depth can also be attributed to LWD loading. High LWD loading in old growth forest in small watersheds created large numbers of pools. In larger watersheds, the importance of LWD in controlling channel morphology decreased, and the difference in channel depth between old and secondary growth decreased.

Like channel width, channel depth had positive, but not significant relationships with LWD volume. The multiple roles played by LWD complicate the expected, simple relationship of LWD creating pools and causing steps. Figure 4.9 shows a pool and large gravel bar created by a debris dam. The



Figure 4.9: Dunn Creek 1: A large deposit of mostly gravel sized particles. The deposit was the result of a debris dam on the downstream side. Only a few of the LWD pieces in the debris dam are visible.

pool was over 1.3 m deep. However, the entire left side of the pool had been filled by a gravel bar. The bankfull depth at the gravel bar was less that 0.2 m. The LWD pieces creating this feature have not only made the channel deeper by creating a pool, but have also made the channel shallower by causing the bar to form. The multiple roles played by LWD were also observed by Bilby and Ward (1989) who found that the orientation was critical in determining whether the LWD piece created a pool. They found that perpendicular LWD pieces, although only making up 40% of the total number of pieces, created 70% of all LWD dam type pools.

Finally, like channel width, channel depth varied more in secondary growth than in old growth, however, it was not significant at p=0.05. This, too, was probably the result of the dramatic increase in depth as watershed areas increased in secondary growth. In old growth, depths varied little with different watershed areas.

4.3.3 Channel Bed Sediment Size

I found no significant difference in median pool bed sediment size between streams in different aged forest. Past studies in the southern Appalachian Mountains have found that the addition of LWD to streams increased pool size (Lemly and Hilderbrand, 2000), increased the number of pools (Flebbe and Dolloff, 1995), and decreased sediment size (Coulston and Maughan, 1983). Wallace et al. (1995) observed a dramatic decrease in sediment size, with sand and silt covering cobbles, and they observed that the decrease occurred within a few months of the addition of LWD pieces 0.2 to 0.32 m in diameter. However, after the initial 6 months, sediment size stabilized. Valett et al. (2002), studying streams in western North Carolina, found the proportion of sediment in several Wentworth scale size classes to differ significantly between streams

in old and secondary growth forest. The class with the largest difference was <2 mm, which was 20% more common in reaches in old than secondary growth forest. However, Silsbee and Larson (1983) found no difference in GSMNP in channel bed sediment size between reaches in old and secondary growth forest.

The lack of difference that Silsbee and Larson (1983) and I observed might indicate that the length of time a LWD piece has been located in the stream channel, not its size, is the most important control of sediment size captured by LWD in a stream. Wallace et al. (1995) showed that even small LWD pieces can quickly change bed sediment size. The larger pieces present in streams in old growth would generally affect the quantity but not the size of the sediment captured, as has been observed (Hart, 2000).

Chapter 5

Conclusions

The purpose of this study was to increase understanding of the distribution of LWD in streams in the southern Appalachian Mountains and the impact of LWD on channel morphology. LWD loading has previously been found to be influenced by forest age and disturbance history. The amount of LWD loading has also been found to affect channel morphology.

Compared to streams in secondary growth forest, streams in old growth had LWD pieces with larger median diameters, lengths, and volumes. Additionally, streams in old growth had greater total volumes of LWD. Streams in old growth had 5.6 times as much LWD by volume as those in secondary growth, despite the nearly 80 years that have passed since logging. When I compared my results to those of other studies done in the southern Appalachians, the LWD frequency and total volume of LWD I found were much larger, although still comparable to the amounts found by Silsbee and Larson (1983) in GSMNP. This highlights the large variation in LWD loading, even at places with similar climate and forest types. This also suggests the need for more research on LWD in streams outside of the Pacific Northwest, which has been the location for most previous studies. Finally, streams in old growth were also more likely to

have LWD pieces as part of debris dams, while individual LWD pieces were most common in secondary growth.

Although this study added to the knowledge of LWD loading, there are still many forest types in the southeast US with little or no LWD data. Additionally, even those forests that have received some research are changing. The death of large numbers of American chestnut trees in the 1920s had a dramatic effect on LWD loading in southern Appalachian streams (Hedman et al., 1996). Recently, the hemlock woolly adelgid has entered the region and is currently killing large numbers of eastern hemlock trees, one of the key species of the cove hardwood forest. Hemlocks are important not only in terms of biomass, but also for their importance to numerous other species. Non-hemlock forests have greater abundance of maples and birches as well as warmer, less acidic soils (Kizlinski et al., 2002). Furthermore, hemlocks can play a major role in controlling the water temperature of streams, although Roberts (2006) found that hardwood and hemlock dominated forest in GSMNP did not have significant different water temperatures. The warmer water temperatures that may be expected after large number of hemlocks die in GSMNP could have negative consequences on many aquatic species (Snyder et al., 2002; Roberts, 2006). Previous studies have found that hemlock trees infested with woolly adelgid had a mortality rate of over 90% (Orwig and Foster, 1998). During my field work, I observed not only dead, standing hemlocks, but, also on several occasions, recently killed trees entering the stream channel as LWD. Hemlock is decay resistant and is one of the most important species contributing to LWD loading in these streams (Hedman et al., 1996). It is expected that over the next two decades, a significant LWD loading event will occur as dead trees finally start to enter the stream channels (Wallace et al., 2001). The size of this loading event and its impact on the channel morphology of these streams

will be an important subject for future research. This study, along with others, will help to provide a baseline of LWD loading before such an event.

I observed that channel bed sediment size was not significantly different between streams in old and secondary growth forest. Rather the results from this study suggests that sediment captured by LWD stabilizes in size after only a few years. The amount of sediment, not the size of the sediment, is most affected by differences in LWD loading observed in old and secondary growth.

As has been observed in other studies, I observed that LWD had a important impact on channel width by directing stream flow toward banks, increasing channel width, and creating mid-channel islands. Channels were significantly wider in streams in old growth. However, I did not find significant relationships between total LWD volume or LWD frequency and channel width, as other researchers have found. The lack of a statistically significant relationship was probably the result of the variety of ways LWD can be found within the channel. Not only can LWD be perpendicular to the stream, increasing the channel's width, it can also be parallel to the stream, thus protecting banks from erosion, or be at any angle in between, performing both of these functions. In Copperhead Branch, the stream with the second highest LWD loading in this study, most of the large pieces were parallel to the stream and protected the banks. Therefore, a simple relationship between LWD frequency or volume will fail to capture the multiple roles played by LWD. Other researchers have occasionally classified LWD in terms of its orientation to the stream (Bilby and Ward, 1989), but this has rarely been done. In order to better quantify the role of LWD on channel morphology, such classifications are needed.

Channels were found to be significantly deeper in streams in old growth than those in secondary growth. LWD impacted channel depth primarily by

the creation of pools, resulting in deeper channels. However, it also caused deposition, creating shallower channels. Also, as with channel width, there was no significant relationship between depth and LWD loading because of the multiple ways LWD can impact depth. Although LWD pieces perpendicular to the stream do not to make up the majority of pieces, they do result in the creation of the majority of pools (Bilby and Ward, 1989). This reinforces the needed for LWD to be classified based on its orientation in the stream channel.

Although I found no relationship between LWD loading and watershed area, there was a relationship between the importance of the geomorphic role played by LWD and watershed area. Despite differences in LWD, streams in my study's largest watersheds in old and secondary growth differed little in width and depth. However, in smaller watersheds, streams in old growth showed a much smaller decrease in channel width and channel depth than those in secondary growth. This stresses the greater importance of vegetation on channel morphology in smaller watersheds. Additionally, the results highlight that the importance of vegetation affecting channel morphology is partially an issue of scale. Most research concerning LWD and channel morphology has been done in larger streams (Jackson and Sturm, 2002). Future studies should examine the relationship between LWD and channel morphology in very small streams (in watersheds <1 km^2) where mass wasting is also important. The interaction between these two processes is complex and is an important control on downstream movement of sediment and nutrients that has only recently started to receive attention (Gomi et al., 2001; Benda et al., 2005; Hassan et al., 2005).

Finally, four results of this study are of prime importance to environmental management. First, LWD loading can vary substantially between streams, even if they have similar climates, surrounding forest types, and disturbance

histories. Caution should be exercised when using LWD loading rates from other studies in either stream restoration or the evaluation of the success of management practices. Second, LWD frequency did not reflect differences in LWD loading between old and secondary growth forests. Future studies examining LWD variations should use either total LWD volume or the number of pieces in debris dams and log jams instead of LWD frequency. Also, a higher proportion of LWD in old growth was found in debris dams. If LWD pieces are added to streams, they should also be distributed as they are in undisturbed streams to have similar geomorphic and ecological results. Finally, even indirect impacts of environmental changes can be long-lasting and disturb natural systems. Despite nearly 80 years of forest regrowth, LWD loading and channel morphologies of streams in logged areas still differ from those in unlogged areas. Emphasis should be placed on reducing human disturbances of stream systems because of the long-lasting and often indirect consequences of such impacts.

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Vita

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