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Coarse woody debris (CWD) is important in many contemporary vegetated stream channel systems yet little is known about the dynamics and characteristics of CWD and its impact on streambed process and structure in urban environments. A survey of CWD entailing measurements of length, diameter, wood volume, orientation to flow, and debris dam/jams locations was conducted along North Buffalo Creek in Greensboro, NC. CWD characteristics were found to have some relation to the frequency of debris jams, proportion of pools formed by wood, and variation of bankfull channel width. The frequency of debris jams increased downstream. The downstream increase in debris jams is a function of reach-to-reach transport of CWD primarily by floodwaters, and the availability of new debris input from riparian vegetation. Stream reaches bordered by partially wooded land have the same or slightly lower average length of CWD and debris jam frequency. Most CWD pieces were oriented parallel to the stream channel. The proportion of pools formed by woody debris is low as compared to rural and forested streams. Local changes in streambed processes and structure occurred in all debris jam locations and stable CWD sections.

CHARACTERISTICS OF COARSE WOODY DEBRIS AND ITS IMPACT ON URBAN STREAMBED PROCESS AND STRUCTURE, NORTH BUFFALO CREEK, GREENSBORO, U.S.A.

By

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Approved by

Committee Chair

To my parents, Ebenezer Owusu (deceased) and Dora Yeboah, for encouraging me to acquire knowledge

To my children, Hilda, Bernice, Mavis, Sandra, Nana Kyei for their support and services

Finally to my wife, Florence

APPROVAL PAGE

This thesis has been approved by the following committee of the Faculty of The Graduate School at The University of North Carolina at Greensboro.

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CHAPTER I

INTRODUCTION

Coarse woody debris (CWD) in streams influences fluvial processes, channel morphology and biota. The definition of CWD differs between studies depending on the objectives of the study and channel size. In most studies the often used size definition is ≥20 cm in diameter and ≥1.5 m in length (Robison and Beschta, 1990a). Human activities have altered the amounts of woody debris in many rural and urban streams; hence it is important to understand its input processes, residence times, spatial occurrence and effects on channel bed process and structure in these areas. CWD in streams is a component of large roughness elements that divert flow and influence the scour and deposition of sediment in forested rivers and streams throughout the world (Harmon et al., 1986; Lisle, 1986; Bisson et al., 1987). CWD is a significant component of the materials contributed to stream channels in forested landscapes, rural, and urban environments throughout the world. Woody debris can also influence flow resistance and the timing of flow on low gradient stream systems (Gregory et al., 1985).

Debris dams made up of CWD have a significant influence upon river channels and fluvial processes (Gregory and Davis, 1992). CWD is important in contemporary stream channel systems because it affects the channel bedform morphology, the water quality, sediment transfer processes, and the ecological character of the channel environment in forested regions, but few studies have been done in urban streams which warrant study for two main reasons. Firstly, in the past the accumulations of woody debris in forested, urban, and/or rural stream channels may have been more significant than at the present time and that an understanding of how present processes are modified by woody debris in stream channels can assist the interpretation of past processes and predict for the future. In addition, some debris in modern channels may originate from these earlier more vegetated landscapes after medium-term (10^1-10^2 years) storage with sediment deposits. Secondly, modern stream restoration management acknowledges the important role of CWD in urban stream channels and uses it as a guide and management tool (Swanson and Nakamura, 1993).

CWD is important for the conservation of many threatened species as well as for biodiversity maintenance in general (Siitonen, 2001). CWD produces both direct and indirect morphological effects on rivers and streams. A piece of wood may remain stable at or near where it fell; or may move downstream and can be trapped in a debris jam or dam, lodge in the streambed as a snag, or float out of the basin. CWD may have a strong influence on the frequency of pools and bars and can create significant hydraulic roughness, influencing flow velocity, discharge, shear stress, bed load transport rates, and reach-average surface grain sizes (MacDonald and Keller, 1987; Smith et al., 1993a; Assani and Petit, 1995; Buffington and Montgomery, 199; Manga and Kirchner, 2000).

The amount of wood in streams and rivers and its effect on channel processes varies in different river and stream systems depending on the riparian environment of the catchment's area. Regional differences in the geomorphological effects of wood in streams and rivers depend on the differences in the size of wood, and its density, and shape that are partly controlled by wood availability and land use. Woody debris accumulations tend to be greater in rural and/or forested streams than urban streams due to the availability of wood in the catchments. Nevertheless, we can expect to find in-channel woody debris in streams draining not only forested and/or rural catchments but also urban areas. The extent to which woody debris accumulations in urban streams are stable and influence channel processes depends on the wood size, channel size and form. The importance of woody debris in aquatic ecosystems has received much attention during the last few decades since it was first highlighted in the Pacific Northwest, (USA). However, studies concerning characteristics of CWD and its effects on bed process and structure in urban streams are still limited.

Statement of the Problem

CWD is important in contemporary urban stream channel systems because it may create hydraulic variety and stabilize channel bedforms and influence water quality, sediment accumulation and transfer processes, and benefit channel ecosystems. Urban streams are greatly impacted by construction, excess storm runoff, and the loss of riparian buffers (Northington and Rushforth, 2005). Urbanization poses a particularly large obstacle for stream protection and rehabilitation. The process of urbanization usually results in irreversible changes to the land surface and drainage pattern by increasing the impervious area, reducing vegetation cover, compacting soil, reducing areas of depression storage, concentrating and rerouting runoff, and straightening and piping streams. Direct alterations to channels and riparian corridors include removing bank vegetation, clearing woody debris from streams, armoring stream beds and banks, straightening channels, reducing floodplain storage, and diverting extensive stretches of streams through culverts.

Despite the importance of CWD to stream structure and ecology, limited research has been conducted into the characteristics and effects of CWD in urban streams. Generally, it is assumed that there is a lack of woody debris and associated habitat in urban streams relative to their rural and forested counterparts. Few studies have yet examined whether CWD placed in urban streams can provide the range of functions observed in rural and/or forested streams. Equally little is known about the dynamics and characteristics of natural CWD in such urban stream systems or at such spatial scales.

Because of the long-lasting human impact associated with the management of riparian forests, and tree strips/buffers, woody debris may be rarely found in some urban streams. Stream managers usually remove CWD from streams for flood control reasons. However, some CWD impacting streams can still be found in urban areas. Aspects of the stream environment impact not only the wildlife living there but the quality of the water itself. Municipalities are wondering how best to manage these streams which may have been degraded through time. Previous research in the Puget Sound Lowland in northwest Washington State (USA) for instance, indicated that many urban streams still support salmon although in declining numbers (Booth, 1997).

Riparian forests play a vital role in stream ecosystems by controlling many environmental factors and providing energy and nutrients (Vannote et al., 1980; Gregory et al., 1992). In many areas, whether rural, forested or urban, CWD from stream margins strongly influences channel morphology (Harmon et al., 1986; Bisson et al., 1987), and habitat diversity (Harmon et al., 1986). Regardless of the ecological effects of CWD, and the attention it has received from researchers and stream restoration managers in many parts of the world, data on CWD characteristics, functions, amounts, spatial distributions, dynamics, effects, and quality in urban streams are virtually absent. Furthermore, base-line data reflecting the riparian corridors of urban streams are scarce. Despite many studies in rural North America and other less developed regions of the world, the understanding of CWD dynamics in urban streams remains limited, most especially concerning input and decomposition rates (Naiman et al., 2002).

Surprisingly few studies have explicitly focused on the effects of CWD on urban stream morphology (but see Nakamura and Swanson, 1993) and the spatial variation of debris dams within a single basin (Gregory et al., 1993). It is not known whether the hydrologic changes typifying urban streams change the woody debris functions in ways different from their behavior in rural streams, whether age distributions are similar, whether primary production mechanisms and longevity are similar, or, whether widely spaced riparian forest reaches in urban environments may be capable of maintaining any CWD loading in intervening non-forested reaches.

The specific objectives of this research are 1) to describe and explain spatial variations in the abundance and character of CWD in a typical urban stream within the heavily populated Southeastern Piedmont of the US; and 2) to evaluate the importance of these variations with regard to channel morphology and hydraulic habitat. To accomplish this, CWD pieces and accumulations in the North Buffalo Creek drainage basin located in the heart of the City of Greensboro (NC) are examined. Furthermore, the effects of CWD on stream bedform process and structure are discussed. Finally, the size, volume and decay class of CWD pieces are evaluated. The watershed area is 59.7 km^2 and includes urban development, open spaces, parks and riparian forests as the dominant land cover types.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

Previous studies of the geomorphic effects of CWD on stream channels have been grouped according to their focus on (1) input processes (Swanson and Lienkaemper, 1978; Sedell et al., 1984); (2) in-channel effects (Keller and Swanson, 1979); and (3) fluvial transport (Lienkaemper and Swanson, 1987). These are interrelated and each process varies depending on the stream size and CWD size.

Effects of CWD on channel morphology have been examined in terms of longitudinal and cross-sectional profiles of the streambed (Harmon et al., 1986). These studies in general conclude that a large percentage of steps in the longitudinal profile are influenced by CWD obstructions. The effect of CWD on stream channel morphology is a function of the size of the debris and the stream as well as the land use in the contributing watershed. Several subsequent studies have analyzed the frequency of occurrence of debris dams.

Previous studies have suggested that wood can become aggregated at specific locations along streams, and that wood is often responsible for the formation of regularly spaced geomorphological features (Montgomery *et al.*, 1995). In order for wood within streams to be randomly distributed, woody debris deposition must have originated form streamside forests of consistent age and species composition, and these streamside forests must have been subject to a similar level of disturbance from fire, wind, ice storm, and human impacts (Kraft and Warren, 2003).

One of the effects of forest succession is changing CWD input into stream channels (Likens and Bilby, 1982). CWD may form dams that impound sediment and increase lateral (bank) erosion (Keller and Swanson, 1979). During logging, slash material may enter streams producing an initial increased frequency of small dams, limiting sediment yield (Royall, 2000). For second-order catchments, after 20 to 25 years these small debris dams would fail without replacement, owing to lack of woody input from early successional species (Royall, 2000). The maturation and mortality of late-successional species roughly 75 or more years after forest clearance provides new CWD that could be maintained near steady state (Likens and Bilby, 1982). The frequency of debris dams along the second-order portion of the early to mid-successional Thompson Lake watershed (2.7 per 100 m) in Virginia (USA), (Royall, 2000) is low compared to reported frequencies of 20 to 30 per 100 m in mature forests at Coweeta Hydrologic Laboratory (North Carolina) (Webster *et al.,* 1988) and at some northeastern US sites (Likens and Bilby, 1982).

Definitions of Coarse Woody Debris

Definitions of CWD vary between authors depending on the objectives and the watershed area of their studies. The terms CWD and Large Woody Debris (LWD) have been used interchangeably by different authors to mean wood naturally or artificially placed in streams including branches, logs, stumps, root-wads and logjams. Robison and Beschta (1990b) have defined CWD as any logs, branches, stumps, and roots larger than 0.2 m in diameter and longer than 1.5 m located in the stream channel. Dahlstrom and Nilsson (2006) state that CWD is generally considered to be any piece of log, stumps, root-wads and branches larger than 0.05 m of a basal end diameter, and length greater than 0.5 m situated within or suspended above the bank-full stream channel. Montgomery et al. (1995) define LWD as any pieces greater than 0.10 m in diameter and greater than 1 m in length within the bankfull channel.

In another study of LWD distributions in streams of the Greater Yellowstone Ecosystem (USA), only woody debris larger than 2 m length by 0.3 m diameter was mapped, based on the assumption that this was the minimum size of debris that could significantly affect channel flow (Marcus et al., 2001). In a study of LWD in montane river networks of the Pacific Northwest, LWD is defined as wood greater than 0.1 m diameter and greater than 1 m in length. CWD is also defined as a log having a diameter of at least 0.2 mm, and a length of 1.5 m (Robison and Beschta, 1990a). Based on the assumption that many urban streams have been de-snagged or denied a source of woody debris through degradation or removal of riparian vegetation and for the purpose of this research, CWD is operationally defined as any wood naturally occurring or artificially placed in the stream having a diameter of at least 3cm, and longer than 1 m in length within the bankfull channel.

Characteristics of Coarse Woody Debris

Woody debris differs in many ways from boulders, bedrock outcrops, or sediment accumulations. The typically elongated woody material has different characteristics and dynamics and it derives exclusively from the terrestrial environment. CWD can influence bank stability, pool and bar formation, sediment retention, and grade (Montgomery et al., 1995; Beechie and Sibley, 1997). CWD can impact the hydrology and hydraulics of flows, the transport and storage of sediments, solutes and other organic matter, and spacing and variance of channel features (Gurnell and Sweet, 1998). Hydraulically, it increases channel roughness and flow resistance (Curran and Wohl, 2003) that affect fluvial processes.

The major input process of CWD in stream channels is by tree-fall from stream banks or hillslopes (Nakamura and Swanson, 1993). The process of tree-fall in most cases begins with mortality of the tree, followed by windthrow, and, landslides in high relief terrain. Breakage of trees occurs in most cases when they fall into the stream channel. Breakage of trees is a function of tree length and width of the stream channel. In first and second order streams, the majority of fallen trees tend to be suspended over the channel and some also point downslope and stick to the stream bed. Fluvial processes play a major role in the supply of CWD in urban streams after CWD has been delivered primarily by landslides and windthrow along the banks of the stream channel. Erosion of stream banks is caused by lateral migration of channels which results in tree fall into the channel.

Generally, CWD pieces are clumped together but in some cases, occur lying individually in the channel. In most cases, several larger pieces develop sites of CWD accumulation, which may form structures that influence bedform dynamics and sediment storage. In most studies large pieces of CWD are referred to as key-CWD. Other pieces of CWD are piled up by the sieve-like effects of key-CWD, and these accumulations are sometimes called CWD-jams. Nakamura and Swanson (1993) defined CWD-jam as a structure with at least five key-CWD pieces that may exceed 3.0 m in height and measure 1.5-2.0 times bankfull channel width. The size, orientation, aggregation, and stability of wood pieces are of major importance for their function in channel morphology (Bilby and Bisson, 1998).

Many factors influence the quantity and quality of woody debris in rivers and streams, resulting in a wide range of patterns and loadings in different systems (Harmon et al., 1986). Woody debris abundance in streams is a function of the difference in the rates of input and depletion. Naiman et al., (2002) specified that the input of wood to streams depends on the species composition of riparian forests, soil stability, valley form, climate, lateral channel movement, forest management history and input by transport from upstream reaches (Bisson et al., 1987). Several North American studies have shown that timber harvest decreases the amount of woody debris in rivers and streams, but may initially add substantial quantities of smaller-sized logging residues (Bilby and Bisson, 1998).

In streams, fully submerged pieces of wood decay slower than others due to low oxygen levels (Triska and Cromack, 1979) and those fully waterlogged or otherwise in environments free from oxygen, can be preserved for years (Grudd et al., 2002). Much of the wood stored in streams is only partly waterlogged and shifts in the water level create variable opportunities for decomposition in channels. Further studies have shown that the physical abrasion of wood caused by water erosion and transport may be important. Transport generally decreases with decreasing channel sizes and increasing sizes of woody debris (Swanson et al., 1984). Redistribution of CWD by floods is a typical phenomenon in medium- and high-order streams (Lienkaemper and Swanson, 1987).

In a study in the New Forest, Hampshire (UK), Gregory *et al.* (1985) found an average density of 3.7 dams per 100 m of channel in the Highland Water which had some previous channel clearance. In Washington State's Olympic National Park the range of densities [between 2.4 and 7.6 dams per 100 m (Sedell and Swanson, 1984)] is comparable with those reported from the UK, in the southern Rocky Mountains of Colorado and in the White Mountains of

Arizona. Studies in different areas show that in woodland basins there can be average densities of one dam for every 3 to 10 m of first-order channel (Gregory *et al.*, 1993), and in the White Mountains of New England between 20 and 40 dams per 100 m for first-order streams (Bilby, 1989).

Effects of CWD on channel morphology

The effects of CWD on channel morphology include the formation of pools and riffles, which are important for fish habitat (Harmon et al., 1986). Effects of CWD on sediment storage have been quantified as the ratio of stored sediment volume associated with CWD to the total sediment yield from the streambed, and as the volume of stored sediment in relation to annual export (Megahan, 1982). Interactions between CWD and the stream channel vary, and depend in large part on channel form and streamflow hydraulics (Nakamura and Swanson, 1993).

The presence of wood complicates hydraulic patterns in streams. It adds heterogeneity to the appearance of streams, complicates quantitative analysis, invalidates many simplistic assumptions in streamflow modeling and opens new questions about how contemporary channels are different from their pristine state. However, over the past several decades, recognition has grown that woody debris significantly affects channel processes in forested regions across a wide range of scales from channel roughness and bed-surface grain size (Buffington and Montgomery, 1999), to creation of in-channel features, such as pools and steps (Nakamura and Swanson, 1993; Montgomery et al., 1995, 1996); even to large-scale controls on channel pattern (Keller and Swanson, 1979) and the formation of floodplains and valley-bottom landforms (Abbe and Montgomery, 1996).

The major influence of woody debris in streams is its ability to create and modify pools, and their abundance, geometry and function (Dahlstrom, 2004). Another important function of woody debris is its ability to create a stepped longitudinal profile, resulting in a stairlike channel (Keller and Swanson, 1979). Pools are generally described as channel units with low water velocities, gentle gradients, and with a depth generally greater than in other channel units. Pools are created and modified mainly by two processes, namely damming of water and scouring of channel sediment (Bisson *et al.*, 1987). In these drops, energy is dissipated and less energy becomes available to transport sediment (Heede, 1972). Other influences of woody debris include effects of riparian vegetation development (Fetherston et al., 1995), formation of gravel bars and islands (Abbe and Montgomery, 1996) and stabilization of river banks.

Impacts of urbanization

Urbanization has significant impacts on stream systems (Booth and Jackson, 1997). This is mainly due to changes in storm hydrographs observed in developed areas. Urban watersheds show increased surface runoff, in terms of both magnitude and frequency. Channelization and removing woody debris, can change channel morphology and increase sediment discharge, leading to widespread loss of once-prevalent wood in urban stream channels.

Urban streams show increased bed and bank erosion, causing enlarged widths and cross sectional areas as compared to rural and /or forested streams. Urbanization also impacts aquatic habitat quality by degrading the water quality. Urban channels tend to be morphologically “simpler,” having less defined pool and or riffle structure and more uniform depth (Booth, 1991) and bed grain size distributions tend to be finer. A decrease in woody debris has been observed in Pacific North-western urban streams (Booth and Jackson, 1997).

Impervious cover within urban watersheds is often cited as the main characteristic driving changes in hydrology and channel morphology (Booth *et al.*, 1997). These changes cause a progressively greater fraction of precipitation to enter the channel rapidly as Horton overland runoff. When woody debris in urban streams is removed, channel morphology can be modified by increasing sediment load and increase in flow velocity.

In a drainage basin, riparian vegetation performs various functions such as reducing sediment loads, reducing nutrient loads, attenuating peak flow, and initiating fluvial adjustments (Simon *et al.,* 2004b). In rural streams, presence of riparian vegetation enhances the stream bank stability and increases flow resistance by disrupting flow paths. The absence or removal of riparian vegetation, however, leads to higher rates of runoff, erosion, and alteration of channel morphology (Simon *et al.*, 2004b). During the urbanization process, improper construction and maintenance of roads leads to processes that degrade structures, and functions of riparian corridors. The net effect of these processes includes channel diversions, alterations in channel morphology, alterations in organic debris, decrease in CWD in streams, hillslopes drainage alterations, bank instability and base flow changes.

Streams have a geomorphic tendency to recover from the temporary disturbances caused by urbanization (Booth, 1991). In urban watersheds, the increased magnitudes and frequencies of peak flows may inhibit geomorphic recovery, but urban streams may not have enough time to return to their pre-urban morphology (Kang and Marston, 2006). Reversing the consequences of urban watershed degradation, such as channel widening, bank failure, and incision, is very difficult because urban development that led to the degradation usually continues. In rural channels with a substantial load of woody debris, local influences on flow and sediment transport can generate emergent properties at larger scales of channel reaches and valley bottoms. The trend observed in urban streams is slightly different because of the particular environmental context. Nevertheless, we can expect to find woody debris in streams draining not only rural catchments but also urban areas.

Studies on CWD in urban streams often include information about stream rehabilitation (Piegay and Gurnell 1997) and surrounding riparian vegetation. While these foregoing studies include a lot of useful information, it is clear that little is known about CWD in urban systems (i.e. we don’t know how many of these studies' findings apply to the urban context). In order to achieve this understanding, stream reaches bordered by riparian forest, parks, residential areas, and industrial development sites of North Buffalo Creek in Greensboro, N.C. are examined in this thesis. The general goals of understanding the spatial variability of urban CWD, and its potential impact on channel geomorphology are accomplished through the specific objectives of:

- determining the frequency and circumstances of occurrence of both individual CWD fragments and fragment clusters (CWD "dams" or "jams");
- interpreting fragment characteristics with regard to relative age and potential points of origin; and
- assembling qualitative observations of the interaction of debris with the channel bed and banks to evaluate potential morphological impacts.

Specific hypotheses to be tested are:

- CWD will be more common within and immediately downstream of forested reaches and generally absent along open reaches; and
- the frequency of CWD jams per unit length of reach will be higher in forested area than the open reaches.
- CWD impacts on channel morphology will thus also be higher in forested areas.

CHAPTER III

RESEARCH DESIGN

Study Area

The North Buffalo Creek watershed is located in the headwaters of the Cape Fear River Basin in Guilford County (lat. 36^0 07’ 13’’N and long. 79^0 42’ 29’’W) covering the oldest portions of the City of Greensboro, North Carolina (population 223,891). The catchment is fourth-order within the reaches addressed by this study which are fully within the urban boundary of the city. North Buffalo Creek, just above its confluence with South Buffalo Creek, has a drainage area of approximately 70.8 km^2 (Figure 1)

Total annual rainfall is over 96.5 cm in this portion of the state, which is classified as the central Piedmont. Drainage from the North Buffalo Creek watershed generally flows in an easterly direction and ultimately feeds the Haw River above Jordan Lake. An approximately 6km section located between Westover Terrace (24.7 km^2) and North Church Street (36.8 km^2) USGS gauging stations was selected for woody debris survey and analysis. Four reaches within the 6 km section were selected for the survey to sample three major classes of riparian wood source (Figure 2).

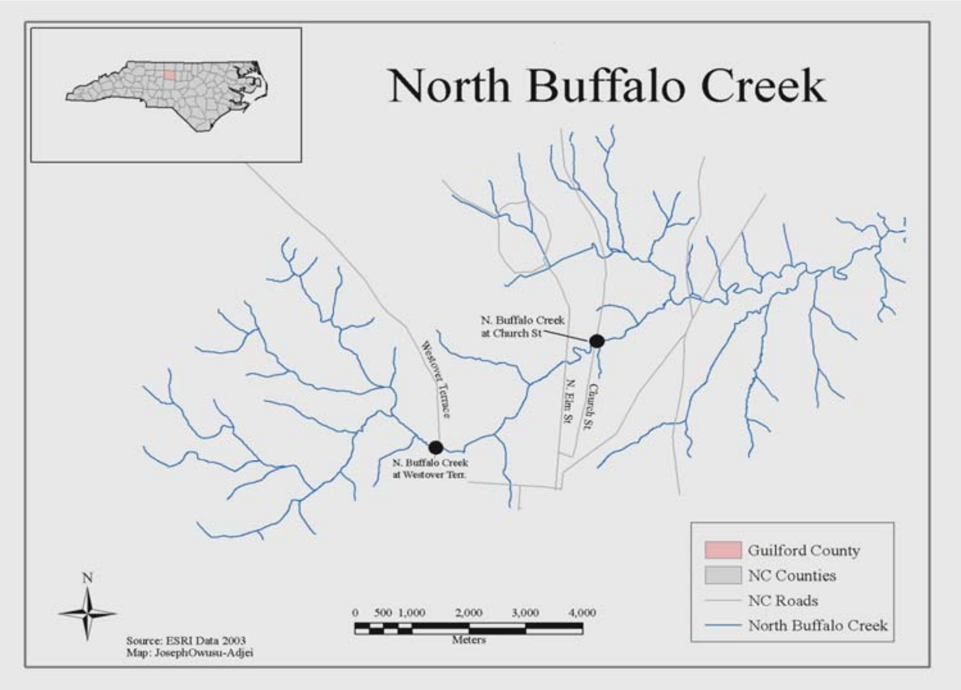

Figure 1: Location of study site at the North Buffalo Creek watershed, Greensboro

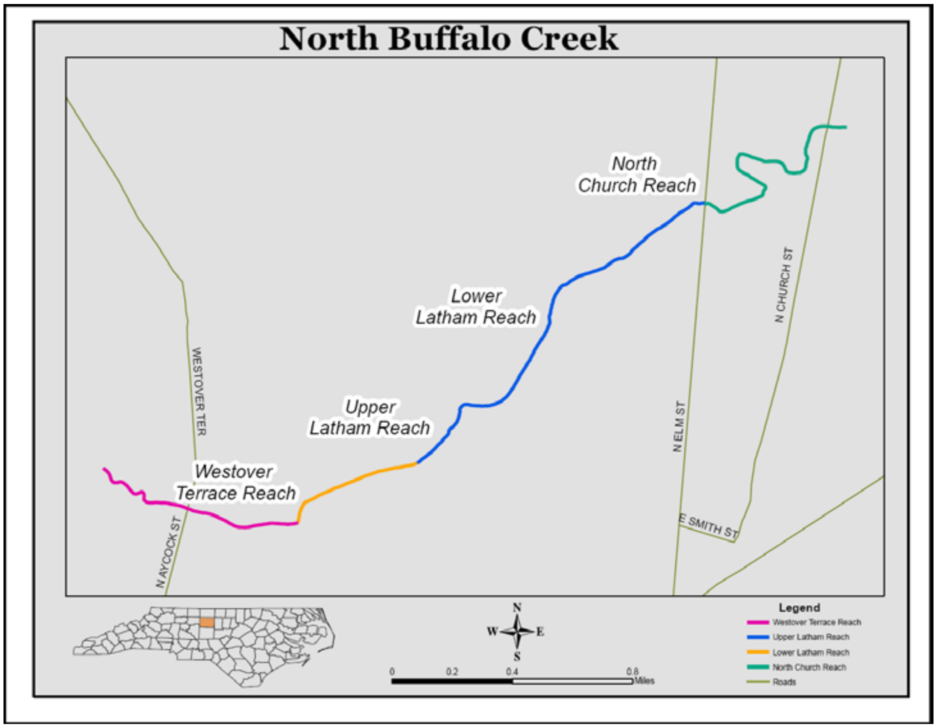

Figure 2: Site locations of study reaches

The geology of this area is characterized by igneous and metamorphic rocks principally of granitic composition, with micaceous gneisses more locally. Saprolite is very thick (approx. 10 m) on uplands and maximum relief is around 125 meters, with 50-60 m more typical. North Buffalo Creek is characterized by enlarged channel cross-sections, and flashy discharges with rapid rises and falls of discharge hydrographs, and high discharge peaks which are commonly observed features of urban streams in the humid temperate climates. The 22.9 km^2 watershed of North Buffalo Creek upstream of the last urban gage at Church Street is characterized by diverse land uses, including urban development, open space, parks, and intervening riparian forests. From the early 1940’s up to the 1980’s, portions of North Buffalo Creek were channelized. Floodplains were mowed up to the creek edge promoting bank instability and severe bank erosion, excessive sedimentation, and loss of both instream and riparian wildlife habitat. Due to the clearance of riparian vegetation, the creek water temperatures likely rose, causing further trauma to aquatic life.

Infill urbanization within the watershed overtime led to further increases in impervious surface area leading to greater runoff, which, together with decreasing sediment production, has produced channel cross-section enlargement relative to nearby rural streams (Doll *et al.,* 2003). Enlarged stream channel cross-sections are typical in these urban reaches with the stream channel incised deeply into the underlying substrate. Within the urbanized areas incision of the streambed has frequently exposed bedrock predominantly of igneous origin (Figure 3).

Figure 3: Hard rock exposure, Westover

Some pieces of CWD are piled up by the sieve-like effects and these accumulations developed into CWD jams (Figure 4).

Following the most recent period of channelization in 1985, some natural sinuosity redeveloped in the low-water channel reducing stream velocity and inducing sediment deposition. Sediment dynamics resulted in new riffles and pools increasing the diversity of aquatic habitat. Patches of sorted sediments occur along the stream course as lateral point and mid-channel bars (Figure 5).

Figure 4: Debris jam, Upper Latham

Figure 5: Mid-channel bars, Lower Latham

Data on runoff from storm events indicate high levels of chemical pollutants entering into the streams of Greensboro, but baseline in-stream data showed relatively low amounts of chemical pollutants (Yandora, K., 1998).

Average channel widths of the studied stream reaches ranged between 9.8 and 11.3 m with intermediate channel gradient and low sinuosity (Table 1). As a result of historical overbank sedimentation, the banks are non-cohesive up high but are often very cohesive lower down.

Table 1. Characteristics of study reaches in North Buffalo Creek

Reach	Average Channel Width (m)	Average Gradient (1cm/m)	Watershed Area (km^2)	Vegetation/Wood Source
Westover	10.08	0.21	24.6	Only riparian trees
Upper Latham	9.83	0.23	26.0	Few riparian trees
Lower Latham	11.25	0.20	31.0	No riparian trees
North Church	10.76	0.18	36.8	Forest with riparian trees

Field survey

Two-hundred meter lengths of each of the four stream reaches between the USGS gauging station at Westover Terrace and the station downstream at North Church Street were surveyed for woody debris between the months of July and September, 2006 (Figure 2). Preliminary field observations and literature reviews were employed to assist the creation of survey protocols for the CWD pieces and debris jams. Photographs were taken along the survey reaches and major changes in basic channel form, including the frequency of steps, pools, runs, debris jams, and riffles were noted. Field sketches were made to show the extent of modifications to the streambed associated with woody debris accumulations. All pieces of CWD with a minimum mid-point diameter ≥3cm and a length ≥0.5m were measured with a tape measure if any part was situated within the bankfull stream channel. Measurements of CWD included length, mid-point diameter, orientation relative to the bankfull channel axis, and whether or not the CWD piece was embedded in a larger debris dam. CWD piece volume was estimated by assuming a cylindrical shape. CWD accumulations in most cases develop into stream obstructions referred to as CWD-jams. In this study, the operational definition of CWD-jam is any structure with at least five CWD pieces and greater than 2.5 m in length and the mid-point width greater than 1.5 m. CWD-jams were measured with a tape measure and key-CWD were noted. Channel width was measured at any CWD-jam location within the study reach. Debris jam location, occurrence, position, and process alterations were measured for all debris jams within the stream reach. Fragment mid-points were used to represent their locations relative to the stream banks.

The degree of decay for each piece was classified using a method similar to that of Nakamura and Swanson (1993) requiring a probe for punkiness with a knife, noting presence of bark and evidence of wood scour. The degradation of each piece was then ranked according to a five-grade classification system from the lowest degradation to highest: class 1, bark; 2, loose bark; 3, no bark/firm; 4, no bark, slightly punky/sculptured; 5, no bark/very punky. The degree of wood softening was the major criterion for classifying the decay class of the wood. Will it stop a sharp knife? If not, how far will the knife penetrate given a standard amount of pressure? The ranking was based on how the knife tip will penetrate. For example, if the knife tip will penetrate no more than a few millimeters with moderate pressure it is ranked firm or if the knife tip will easily penetrate wood 1 cm; it is ranked punky. The degree of punkiness is intended to give information on both relative residence time of woody debris in the stream (i.e., relative age), plus the likelihood of CWD continuing to be a factor in the channel in the future.

In order to interpret the frequency and spatial distribution of CWD pieces and jams, relative to potential live wood sources, the four reaches chosen were grouped into wooded, partially wooded and nonwooded reaches. Two of the sites represent wooded, one for nonwooded and the other one also for partially wooded.

CHAPTER IV

RESULTS AND INTERPRETATIONS

Characteristics of CWD

The field survey identified 357 CWD pieces throughout the North Buffalo Creek survey sample, giving an average occurrence frequency of 15 CWD pieces per 100 m of channel. There were also some smaller pieces that were not accounted for because they fell below the required minimum size for this study. While the range of frequency of woody debris is narrow in absolute terms (17-29 pieces/100 m) for all sites, the percentage variations are quite large (Table 2a).

For example, Lower Latham has only about 58.6% of the woody debris that Westover has. Upper Latham and North Church are similar to each other in CWD frequency, but only at 72.4% and 79.3% of Westover respectively (Table 2b). The difference between Lower Latham and Westover or North Church may be explained by the fact that those latter reaches are the most wooded portions of the Creek. On the other hand, there is also a difference between Lower Latham and Upper Latham both of which are classified as nonwooded areas. This may be the result of redistribution of CWD from an immediately upstream of forested reach. The length of CWD pieces showed a skewed distribution, with the majority of pieces ranging between 1.5 m and 2.5 m (*Table 2b*).

*Table 2a.*General CWD characteristics

Reach	Frequency (pieces/100 meters)	Total CWD volume(m^3)	Frequency (jams/100 meters)	Average diameter (cm)	Skewness of diameter	Kurtosis of diameter
Westover	29	0.584956	4	6.6	0.85	0.09
Upper Latham	21	0.745495	3	6.1	0.68	-0.58
Lower Latham	17	1.576085	2	9.5	1.09	0.42
North Church	23	1.294765	4	8.8	0.86	-0.29

*Table 2b .*General CWD characteristics

Reach	Average length	Skewness of length	Kurtosis of length	Average deg. class	Skewness of deg.	Kurtosis of deg.
Westover	1.7	1.99	5.19	2.03	0.72	-2.64
Upper Latham	1.8	1.16	0.65	3.78	-0.32	0.36
Lower Latham	1.9	2.67	9.67	3.64	0.61	-0.94
North Church	1.8	2.93	10.42	3.73	1.19	1.34

The diameter of CWD pieces also showed a skewed distribution, with most pieces belonging to the smaller groups (*Table 2a*). Out of the total measured pieces, only 6.3% were more than 5 m long (*Figure 6*) and 11.9% were more 15 cm wide (*Figure 7*). There is no vast difference between Westover and Upper Latham or between Lower Latham and North Church in terms of diameter of pieces. It seems equally likely that Westover, Upper Latham and Lower Latham, distribution of diameter of CWD pieces are grouped. North Church has large amounts of the smallest diameters. It is surprising to note that the largest volume of piece was found in the completely nonwooded site of Lower Latham, and that may be either deposited during the channelization process, during the past history of the watershed or during a large flood.

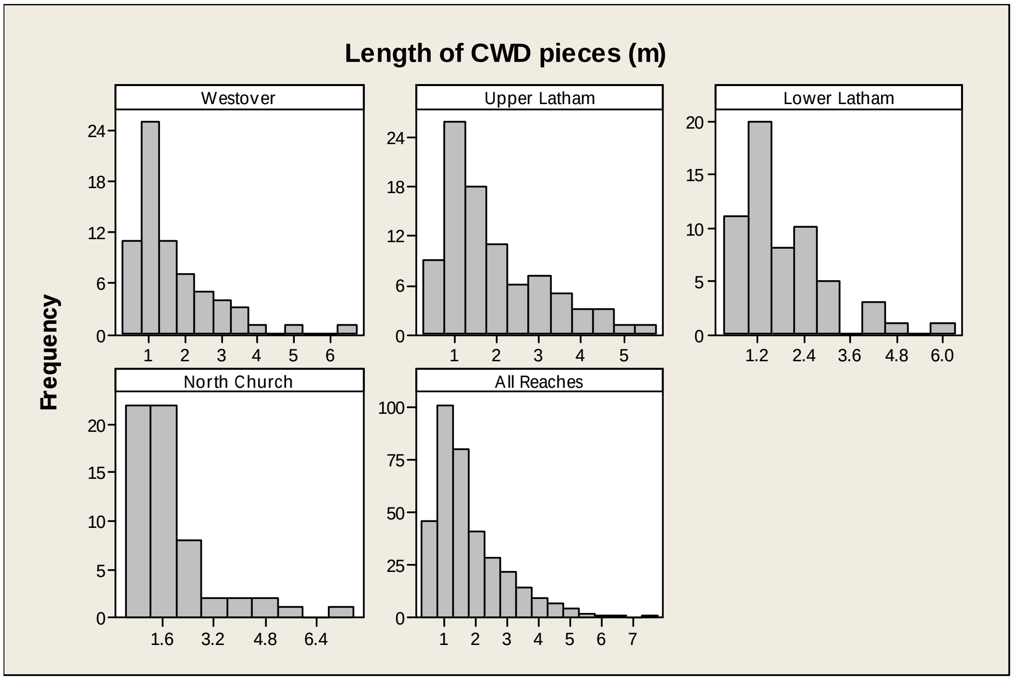

Figure 6: Distribution of length of pieces of CWD in the study sites

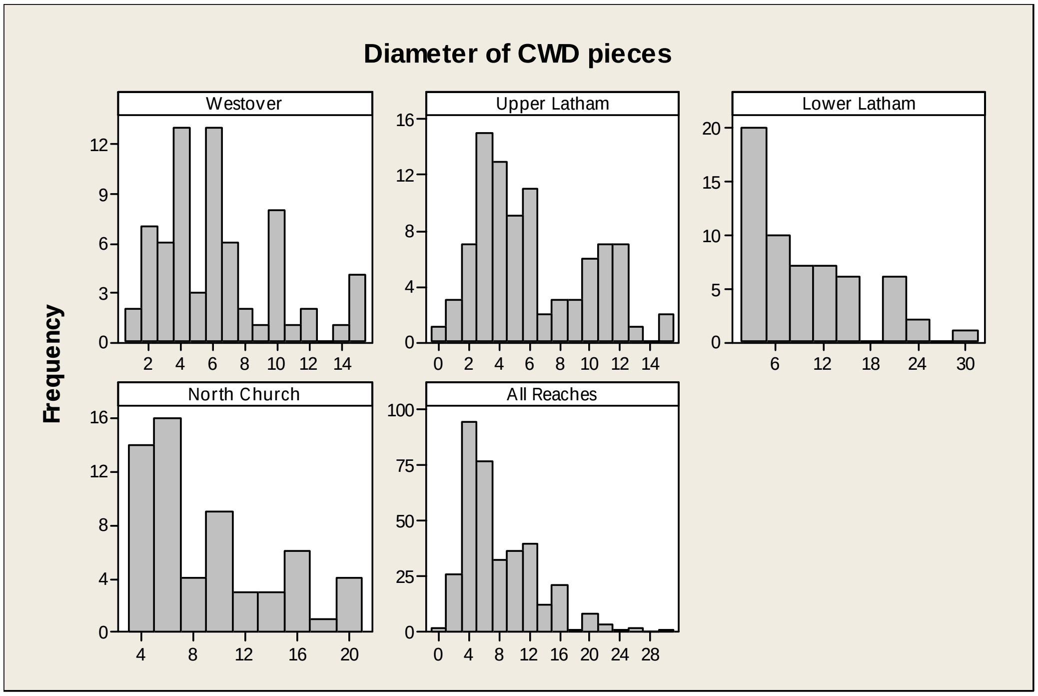

Figure7: Distribution of diameter of CWD pieces in the study sites

The frequency of debris jams (i.e. number of jams per 100 m of stream length), showed variations between the wooded sites (Westover and North Church) and the unwooded sites (Upper Latham and Lower Latham). The high frequency of CWD pieces may be due to either high debris trapping capacity (which would favor the “sieve” effect, thus trapping smaller pieces), or simply the presence of a good source of small debris, which is often typical of early successional riparian forest, because it thins itself as it grows. The high frequency of dams in Westover and North Church could thus be explained by the high debris trapping capacity and the wood source from the riparian vegetation.

There is a variation in the total volume of pieces among the study sites. Lower Latham has the highest wood volume of piece and this may be the results of probably an older log left over from early 1900's forests.

The degree of decay is grouped into five classes: 1, bark; 2, loose bark; 3, no bark/firm; 4, no bark/ sculpture; 5, no bark/punky. The results indicate that the maximum percentage of fragments with bark occurred at Upper Latham, the maximum of loose barks (31.7%) are in North Church, the maximum of no bark/sculptured (45.2%) are in Westover and the maximum of no bark/punky (42.9%) are found in Upper Latham (*Figure 8*).

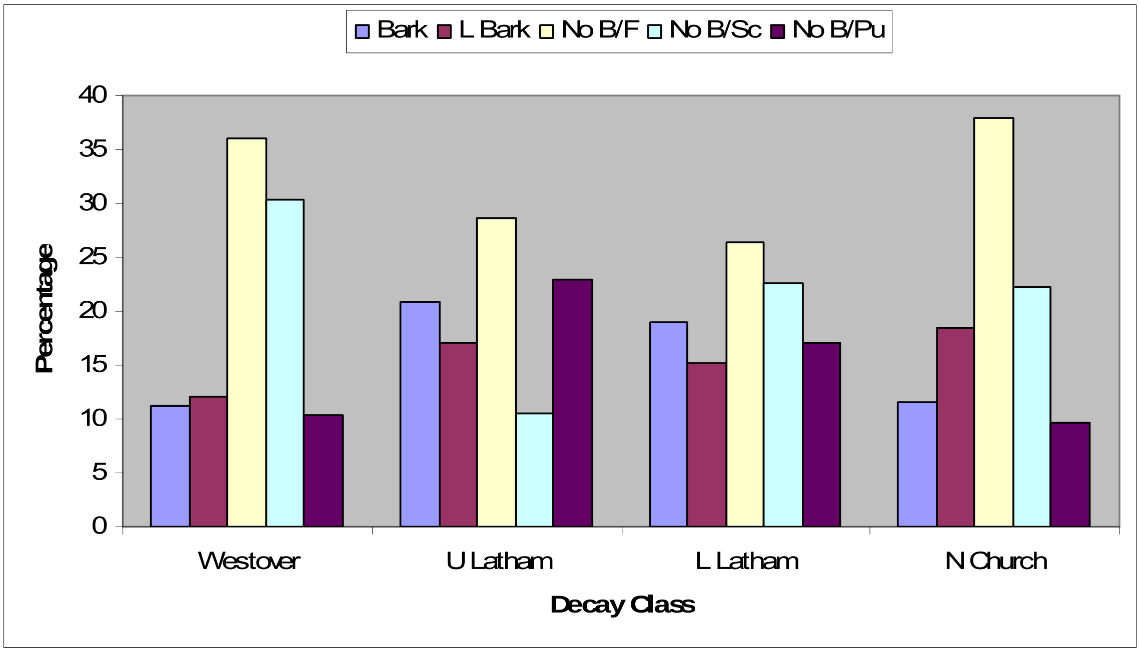

Figure 8: Distribution of CWD decay classes

The most frequent decay class at every site is "no bark/firm", and this characteristic of the pieces suggests that the pieces have been in the stream for a long period of time. No bark/sculpture is the second most frequent decay class at every site except Upper Latham, where it is the minimum.

Effects of CWD on streambed process and structure

On average, 18.6% of the CWD pieces in the study reach belonged to a debris jam. Greater percentage of the principal pieces of the CWD jams had parallel orientation to the stream channel; a couple of secondary pieces were perpendicular to the stream flow. The majority of pieces forming the debris jams were oriented parallel to the stream channel, compared to all other individual pieces. In the orientation class, 69.5% of the individual CWD pieces were parallel to the stream channel, 26.7% were perpendicular to the stream channel, 1.8% were oriented at 60^0, 1.2% at 45^0, and the remaining 0.8% were oriented at 30^0 to the stream channel. The parallel orientation of majority of CWD pieces may be due to peak flows arising from urbanization. High discharges will redistribute floating pieces and redirect them to the flow of the stream, but old heavy buried wood may only move when the whole bed sediment becomes mobile. It is probable that larger key CWD initially touch the bottom as stage falls, and then, the flow pivots the piece off of the touch point, turning it parallel to channel. The same thing might happen if these larger pieces which, by virtue of their size, are simply more likely to snag either on the bed, the bank, or in overhanging branches (i.e. like willow) since they come closer to being able to span the channel width.

Out of the measured key-CWD pieces, only few were classified as having effects on stream flow by trapping smaller pieces creating bed scour and deflecting flow and these are larger in diameter and length than other pieces. In addition, these pieces create obstructions to the flow of the stream forming jams, pools and slack water.

There were no boulders found in the Lower Latham site, but there were some in North Church, Upper Latham and several portions of Westover. These bedrock exposures in the North Buffalo Creek may be due to the early 1980s channelization process including straightening and dredging (deepening). Riffles and pools were found mostly at Westover and North Church sites as also observed in prior years by Shoffner (2005). However, the definition of “pools” herein differs from Shoffner’s explicitly hydraulic approach. Average channel width varied among the study sites with the widest at Lower Latham followed by North Church. About 48.7% of CWD pieces were located on the right channel, 41.8% on the left channel and 9.5% in the mid-channel. This further suggests trapping of pieces by bank roughness elements. A majority of mid-channel bars were found in the Lower Latham and some few in the Upper Latham sites. Forty-five per cent of pools found in this area were wood-formed pools. The greater proportion (92.5%) of which were dammed pools mainly located upstream of debris dams as opposed to downstream scour pools related to vertical deflection of water. However, many dammed pools also exhibited deepening by scour, upstream of wood. North Church had the largest surface area and residual depth wood-formed pool which may be the result of abundant wood source from the forest and the riparian vegetation and high trapping effect in this site of the reach. The fewest pools and riffles found are located in the Westover site.

Comparison of average channel width at the study reach, with respect to debris jam for the upper 50% (in size) for each site (*Figure 9),* reveals that widths of channel increase with increase in debris jam. This correlation (R^2=0.49), suggests that channel widening is potentially related to debris jam size. Although channel width may be controlled by debris the relationship between the two may also be more complex. There may be some influence, but with the small amounts of wood involved, it is as likely that channel width is controlled by something else (like lack of riparian vegetation), and that channel width may influence the size of CWD that is found, rather than the other way around.

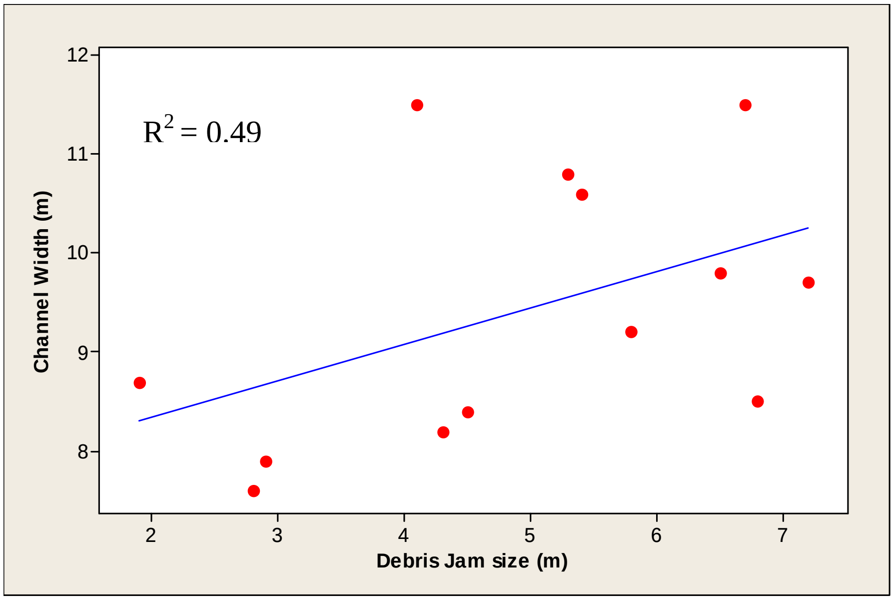

Figure 9: Scatter plot of channel width versus debris jam size for the upper 50% (in size) of observations from each site.

CHAPTER V

DISCUSSION

Characteristics of CWD

The North Buffalo Creek is located in an urban environment with high storm runoff, deep incision of streambed, a history of channelization, and few pockets of forest and riparian vegetation. All the log-sized debris probably entered the stream through tree-fall from the banks. It is assumed that tree-fall in this area is initiated by mortality, windthrow, bank failure, streamside slide, and bank erosion.

Storm flow also plays an important role in the input processes of CWD in urban streams. Bank failure due to undercutting of bank by flood scour causes stream bank recession and tree-fall into the stream channel. High flood peak flows entrain CWD and sediment, flush materials downstream, and deposit piles of CWD along the channel. Lienkaemper and Swanson (1987) analyzed the distance moved by CWD pieces during high flow, and concluded that most pieces that moved were shorter than bankfull width. Most key-CWD pieces found are anchored on the banks and are not long enough to be stable during the majority of floods. Some of these key-CWD pieces capture small pieces during flooding and may release them to downstream areas during the flooding period.

Some CWD pieces are partly buried in mid-channel and the underlying wood surface has a form suggesting being abraded during flood transport of mineral particles to produce the sculptured wood observed. Most CWD pieces found in these study reaches are presumed to have moved from the point at which they entered the stream and the high decay class of a few of them indicates that the pieces have been in the stream for a long period of time. The Upper Latham site seems to have bimodal distribution decay class which varies from the rest of the study sites. The mean CWD length and channel width variations from reach-to-reach may influence CWD pieces stability along the stream channel.

The sizes of CWD pieces in this study were small (1.5-2.5 m) relative to values reported in other studies in rural and forested or montane regions. Values of CWD sizes recorded in this study in the relatively wooded areas (Westover and North Church) are generally lower than in the rural and forested streams in the Pacific Northwest (Harmon *et al.*, 1986), but are more similar to values in managed forest streams in Sweden (Dahlstrom and Nilsson, 2004). Pieces of CWD within nonwooded study reaches (Upper and Lower Latham) are much longer than those in the wooded areas. At these sites, the relatively few patches of forest and small riparian vegetation with coarse bed materials account for the limited local input of CWD pieces. In addition, there is less capacity for trapping fine sediments in the absence of woody vegetation to provide snags. The fine woody materials may just get washed downstream during floods.

The observed frequencies of CWD-jams (Table 1a) are similar to some values reported in previous research investigations. In the White Mountains of New England, Bilby (1979) gave densities between 20 and 40 dams per 100 m for first-order streams which reduced to densities of 1 to 6 dams per 100 m for third-order streams. Thus, the density in dams in third-order streams is similar to the results found in North Buffalo Creek which is a fourth-order stream. In an earlier study in the New Forest, Hampshire, UK (Gregory *et al.*, 1985) reported an average density of 3.7 dams per 100 m of channel in the Highland Water which had some previous channel clearance similar to the channelization of the North Buffalo Creek in the 1980s. In a later study of a larger basin including the Highland Water, (Gregory *et al.*, 1993) showed an average density of 1.15 dams per 100 m of channel.

However, the results of the previous studies show how the density of dams decrease downstream and also variations in dam density in terms of forest cover. In terms of individual reaches which are all the same order (4th), changes in land-use composition may be responsible for abnormal results such as downstream increase in density of dams in this urban stream. This trend may also be explained by the fact that North Buffalo Creek has been channelized including straightening and dredging allowing easy flow of woody debris by storm water runoffs in this channel. The loading of woody debris in this area is low which could also be used to predict the frequency of debris dams, but the cause-and-effect relationship has not been quantitatively analyzed. Debris dams may accumulate woody debris in a particular stream reach from upstream areas at high flows and thus increase the loading of woody debris downstream (Dahlstrom and Nilsson, 2004). However, the absence of a correlation between the frequency of debris dams and the proportion of woody debris pieces included in debris dams suggest that the frequency of debris dams is in fact an effect of the loading of woody debris.

Effects of CWD on urban streambed process and structure

Despite the relatively low amounts and limited sizes, CWD had important geomorphic function in the studied urban stream. CWD pieces identified in the study that are still anchored in the bank with their root-wads or partially buried in the streambed are presumed to be located at where they entered the channel and have probably changed little in position. Most other debris probably moves during floods. The fact that debris loadings are highest in the forested reaches suggests continual replenishment and presumes that much of the wood in Latham Park has been transported from upstream.

It is also likely that trapping of wood by living riparian vegetation also contributes to high loadings in forested reaches. The number of CWD pieces and debris dams identified in this study is low compared to wood loadings in rural and forested important streams, but it could be comparable to reaches where the human impact is reducing the extent of riparian vegetation. The main reason for the low CWD loading in the stream reaches investigated in this study, are few pockets of forest, small riparian vegetated banks and high peak flows.

Despite the relative low amount and limited sizes, CWD has had important geomorphic function in the studied urban stream. The proportion of CWD pieces and dams that have impacts on stream flow at low-flow conditions is in the same range as in other studies.

Figure 10: Enlargement of channel due to urban runoff, Lower Latham

The result of this study indicates that out of the total number of CWD pieces and jams found, 10% of them contributed to pool formation. Montgomery *et al.* (1995)

found that 0 to 40% of LWD pieces contributed to pool formation, and Richmond and Fausch (1995) found that approximately 10% contributed to pool formation.

Figure 11: Pool-steps at Westover

This study showed that the majority of pools were formed by damming, mainly upstream of debris jams and CWD pieces that lie perpendicular to flow and are partly buried in the channel. This finding contrasts with most other previous studies where scouring is the prevalent pool-forming mechanism (Montgomery *et al.*, 1995). Few mid-channel bars consisting of sand and fine gravel have been accumulated downstream of the woody pieces and woody debris dams. Montgomery and Abbe (1996) found a similar scour pattern for LWD jams at the apex of bars in a large alluvial river. This scour pattern of LWD obstructions located on the streambed in the middle of the channel, either oriented perpendicular or parallel to flow, is a characteristic of streams, if high flows do not disturbed the obstruction. It is evident from this study that 26.7% of CWD pieces are oriented perpendicular to flow causing the scouring of a depression in the bed which occurs upstream of the CWD pieces. About 1.8% of the CWD pieces identified were oriented 60^0 deflecting flow causing bank scouring and local channel widening. This result is similar to the reports of Cherry and Bilby (1989) who observed that different scour patterns depend on angle to flow and vertical angle of logs.

The results indicate that 29.1% of CWD pieces have bark on firmly like a living wood and 23.2% have no bark/sculptured with the underlying wood surface having a form suggesting that they have been abraded during flood transport. The remaining percentage of CWD pieces have loose bark and no bark/punky, and the wood surface can readily be peeled off due to rotting suggesting the length of time they have been in the stream. The few large pieces in the stream are oriented parallel to the stream flow and have less impact on the streambed process and structure. This result contrast with the results of the study by Nakamura and Swanson (1993) which reported that large pieces in the streams are usually suspended by hillslopes and that limits initial interaction with the stream channel. On the other hand, some CWD pieces in the wooded sites are predominantly fresh and firm supplied directly from the bank and has direct interaction with the streambed process. These pieces are more stable and have direct impact on the streambed.

The occurrence of pools formed by CWD was lower in this study compared to old-growth forest streams in the USA. A study by Richmond and Fausch (1995) reported that 76% of the pools found in the streams of northern Colorado were formed by woody debris. Montgomery *et al.* (1995) reported similar figure of 73% for southeast Alaska. In this study, 45% of pools were formed by woody debris and had small surface areas and low depths. Previous studies of pool formation have reported scouring as the dominant pool-forming process (Myers and Swanson, 1997), often acting around piles of woody debris (Bilby and Ward 1991, Montgomery *et al.* 1995). In this study, the small proportion of coarse streambed material reduced the occurrence of ripples and scouring. Majority of authors claim that dammed pools are ecologically more beneficial than scoured pools because they tend to retain more sediment and organic material. Beechie and Sibley (1997) found that the largest pieces of woody debris are more likely to form dams and pools in larger streams. In smaller streams, larger pieces often span the bankfull channel or hang above the active channel and do not contribute to channel formation at base flow conditions (Nakamura and Swanson 1993). The largest CWD pieces found in this study were oriented at 45^0 to the channel. This may be explained by the fact that the stream channel had been modified to allow increased velocity of the stream flow and high urban storm water runoff during flooding to reorient this woody debris.

Assuming my interpretations are correct, the results presented in this study may be good source of information about urban streams. For example, the CWD piece with the largest diameter was found in Lower Latham site which has no riparian vegetation. This could be a fair observation for generalization of urban streams. It is interesting to note that the highest frequency of pieces was found in Westover and North Church which are the most wooded portions of the stream. This riparian vegetation might be a good source of CWD pieces to the reaches. In the Upper and Lower Latham sites, the CWD pieces input may be from the redistribution of the pieces from Westover and upstream during high peak flows. This situation may probably be like many other urban cases.

From the study, it was observed that the more wooded areas still have the most wood, due to both the greater production of debris, and perhaps more importantly, the greater trapping of debris by the vegetation itself. The bridges seem to collect more than the streambanks in places like Latham Park. This study also showed that CWD pieces impacts on channel morphology is higher in North Church.

CHAPTER VI

CONCLUSION

Observations and field survey in the North Buffalo Creek show that urban developments in riparian areas reduce the quantity of woody debris, and the average size of wood pieces in urban streams compared to rural and/or forested streams with the same watershed area in the USA. This study shows that, despite the high enlarged bankfull and incised channel, high discharge, high proportions of bedrock outcrop and coarse bed materials, limited forest and riparian vegetation in the North Buffalo Creek watershed, CWD can still play an important role in urban streambed process and structure. Much of the CWD pieces impacting on pool formation consist of large fresh, firm, fragmented, sculptured pieces which tend to be lying on the streambed. The study found that the proportion of pools formed by woody debris and the frequency of debris dams per 100 m reach of stream channel is very low as compared to rural and/or forested streams. This situation might even be worse for most urban streams in the country where rapid urban development, channelization or straightening and dredging of urban streams are common.

Density of debris dams in this study area is similar to that of slightly smaller (3rd order) streams studies reported earlier from elsewhere. Greater percentages of wood-formed pools in this study were found to be dammed pools. Woody debris in this area is directly input from floodplains and terraces by windthrow or bank erosion which is similar to those processes in rural and forested streams. The range of decay classes of CWD found in this study, are presumably influenced mainly by the length of time CWD has been in the stream channel and the history of watershed input processes. The downstream increase of debris jams is a function of wood source and transport of CWD primarily by high peak flows. Lower Latham portions of the reach have virtually no riparian woody vegetation and it is the widest channel of the study reach. The studied fourth-order urban stream has few pools and riffles and CWD pieces and jams contribute mainly to pool formation and sand bars.

Currently, the straightening or channelization, and dredging of North Buffalo Creek have ended. The City of Greensboro has adopted a Stream Vegetation Ordinance that includes restoring woody vegetation in the riparian zone (Lewis *et al.* 1994). Planting of shrubs and trees in the riparian zone will increase the future input of woody debris to the stream (Lewis *et al.*, 1994).

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APPENDIX A

STATISTICAL RESULTS

Lengths of CWD Pieces at North Buffalo Creek

		Church	U Latham	L. Latham	Westover
Mean		1.8283	1.8326	1.9339	1.6275
Median		1.3375(a)	1.4444(a)	1.4143(a)	1.2200(a)
Mode		1.30	1.10	1.30	1.10
Std. Deviation		1.58981	1.09884	1.54469	1.11433
Variance		2.527	1.207	2.386	1.242
Skewness		2.926	1.030	2.669	1.993
Std. Error of Skewness		.309	.255	.311	.289
Kurtosis		10.419	.093	9.675	5.196
Std. Error of Kurtosis		.608	.506	.613	.570
Range		9.00	4.30	9.00	6.00
Percentiles	25	.9833(b)	1.0367(b)	.9900(b)	.8611(b)
	50	1.3375	1.4444	1.4143	1.2200
	75	2.1000	2.4750	2.4500	2.1167

Diameter of CWD Pieces at North Buffalo Creek

		Church	U. Latham	L. Latham	Westover
Mean		8.8333	5.9524	9.4763	6.4587
Std. Error of Mean		.65882	.40038	.89836	.42371
Median		6.6000	5.0000	7.0000	6.0000
Mode		6.10	6.00	3.00	3.00
Std. Deviation		5.10319	3.66953	6.90041	3.66945
Variance		26.043	13.465	47.616	13.465
Skewness		.863	.679	1.095	.761
Std. Error of Skewness		.309	.263	.311	.277
Kurtosis		-.297	-.581	.422	-.184
Std. Error of Kurtosis		.608	.520	.613	.548
Range		18.00	14.60	27.50	14.40
Percentiles	25	5.1000	3.0000	3.5000	3.6000
	50	6.6000	5.0000	7.0000	6.0000
	75	12.1000	8.8750	14.0000	9.6000

Frequency Tables

Lengths of CWD Pieces at North Church

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.50	4	4.5	6.7	6.7
	.60	1	1.1	1.7	8.3
	.70	4	4.5	6.7	15.0
	.80	3	3.4	5.0	20.0
	.90	1	1.1	1.7	21.7
	1.00	5	5.6	8.3	30.0
	1.10	4	4.5	6.7	36.7
	1.20	3	3.4	5.0	41.7
	1.30	7	7.9	11.7	53.3
	1.40	1	1.1	1.7	55.0
	1.50	6	6.7	10.0	65.0
	1.80	3	3.4	5.0	70.0
	1.90	2	2.2	3.3	73.3
	2.10	2	2.2	3.3	76.7
	2.20	2	2.2	3.3	80.0
	2.40	1	1.1	1.7	81.7
	2.50	1	1.1	1.7	83.3
	2.70	2	2.2	3.3	86.7
	2.80	1	1.1	1.7	88.3
	3.50	1	1.1	1.7	90.0
	3.60	1	1.1	1.7	91.7
	3.70	1	1.1	1.7	93.3
	3.80	1	1.1	1.7	95.0
	4.70	1	1.1	1.7	96.7
	5.20	1	1.1	1.7	98.3
	7.30	1	1.1	1.7	100.0
	Total	60	67.4	100.0	
Missing	System	29	32.6		
Total		89	100.0		

Lengths of CWD Pieces at Upper Latham

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.50	3	3.4	3.4	3.4
	.60	4	4.5	4.5	7.9
	.70	2	2.2	2.2	10.1
	.80	4	4.5	4.5	14.6
	.90	3	3.4	3.4	18.0
	1.00	7	7.9	7.9	25.8
	1.10	8	9.0	9.0	34.8
	1.20	4	4.5	4.5	39.3
	1.30	5	5.6	5.6	44.9
	1.40	5	5.6	5.6	50.6
	1.50	4	4.5	4.5	55.1
	1.60	3	3.4	3.4	58.4
	1.70	1	1.1	1.1	59.6
	1.80	3	3.4	3.4	62.9
	1.90	3	3.4	3.4	66.3
	2.00	4	4.5	4.5	70.8
	2.10	1	1.1	1.1	71.9
	2.30	2	2.2	2.2	74.2
	2.50	2	2.2	2.2	76.4
	2.60	2	2.2	2.2	78.7
	2.80	1	1.1	1.1	79.8
	3.00	3	3.4	3.4	83.1
	3.10	1	1.1	1.1	84.3
	3.20	2	2.2	2.2	86.5
	3.30	1	1.1	1.1	87.6
	3.60	3	3.4	3.4	91.0
	3.70	1	1.1	1.1	92.1
	4.00	2	2.2	2.2	94.4
	4.20	1	1.1	1.1	95.5
	4.30	1	1.1	1.1	96.6
	4.40	1	1.1	1.1	97.8
	4.50	1	1.1	1.1	98.9
	4.80	1	1.1	1.1	100.0
	Total	89	100.0	100.0	

Lengths of CWD Pieces at Lower Latham

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.50	1	1.1	1.7	1.7
	.60	3	3.4	5.1	6.8
	.70	4	4.5	6.8	13.6
	.80	3	3.4	5.1	18.6
	.90	3	3.4	5.1	23.7
	1.00	2	2.2	3.4	27.1
	1.10	3	3.4	5.1	32.2
	1.20	2	2.2	3.4	35.6
	1.30	6	6.7	10.2	45.8
	1.40	4	4.5	6.8	52.5
	1.50	3	3.4	5.1	57.6
	1.60	1	1.1	1.7	59.3
	1.70	3	3.4	5.1	64.4
	1.80	1	1.1	1.7	66.1
	2.10	2	2.2	3.4	69.5
	2.20	1	1.1	1.7	71.2
	2.40	2	2.2	3.4	74.6
	2.50	3	3.4	5.1	79.7
	2.60	1	1.1	1.7	81.4
	2.70	1	1.1	1.7	83.1
	3.00	1	1.1	1.7	84.7
	3.10	1	1.1	1.7	86.4
	3.20	2	2.2	3.4	89.8
	4.10	1	1.1	1.7	91.5
	4.15	1	1.1	1.7	93.2
	4.20	1	1.1	1.7	94.9
	4.30	1	1.1	1.7	96.6
	5.00	1	1.1	1.7	98.3
	6.20	1	1.1	1.7	100.0
	Total	59	66.3	100.0	
Missing	System	30	33.7		
Total		89	100.0		

Lengths of CWD Pieces at Westover

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.50	1	1.1	1.4	1.4
	.60	6	6.7	8.7	10.1
	.70	4	4.5	5.8	15.9
	.80	7	7.9	10.1	26.1
	.90	2	2.2	2.9	29.0
	1.00	4	4.5	5.8	34.8
	1.10	8	9.0	11.6	46.4
	1.20	4	4.5	5.8	52.2
	1.30	1	1.1	1.4	53.6
	1.40	4	4.5	5.8	59.4
	1.50	2	2.2	2.9	62.3
	1.70	4	4.5	5.8	68.1
	1.80	3	3.4	4.3	72.5
	1.90	1	1.1	1.4	73.9
	2.10	1	1.1	1.4	75.4
	2.20	2	2.2	2.9	78.3
	2.30	2	2.2	2.9	81.2
	2.40	2	2.2	2.9	84.1
	2.50	1	1.1	1.4	85.5
	2.90	1	1.1	1.4	87.0
	3.10	2	2.2	2.9	89.9
	3.20	1	1.1	1.4	91.3
	3.40	2	2.2	2.9	94.2
	3.50	1	1.1	1.4	95.7
	3.80	1	1.1	1.4	97.1
	5.10	1	1.1	1.4	98.6
	6.50	1	1.1	1.4	100.0
	Total	69	77.5	100.0	
Missing	System	20	22.5		
Total		89	100.0		

Frequency Table

Diameter of CWD Pieces at North Church

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	3.00	2	2.2	3.3	3.3
	3.10	1	1.1	1.7	5.0
	3.20	3	3.3	5.0	10.0
	3.60	2	2.2	3.3	13.3
	4.00	1	1.1	1.7	15.0
	4.10	1	1.1	1.7	16.7
	4.20	1	1.1	1.7	18.3
	4.30	1	1.1	1.7	20.0
	4.40	1	1.1	1.7	21.7
	4.50	1	1.1	1.7	23.3
	5.10	2	2.2	3.3	26.7
	5.20	1	1.1	1.7	28.3
	5.30	2	2.2	3.3	31.7
	5.50	1	1.1	1.7	33.3
	5.60	3	3.3	5.0	38.3
	6.00	2	2.2	3.3	41.7
	6.10	4	4.4	6.7	48.3
	6.20	1	1.1	1.7	50.0
	7.00	1	1.1	1.7	51.7
	7.20	1	1.1	1.7	53.3
	7.30	1	1.1	1.7	55.0
	8.30	1	1.1	1.7	56.7
	9.00	1	1.1	1.7	58.3
	9.10	1	1.1	1.7	60.0
	9.30	2	2.2	3.3	63.3
	10.00	1	1.1	1.7	65.0
	10.20	1	1.1	1.7	66.7
	10.50	1	1.1	1.7	68.3
	10.70	1	1.1	1.7	70.0
	10.80	1	1.1	1.7	71.7
	11.90	1	1.1	1.7	73.3
	12.10	2	2.2	3.3	76.7
	13.50	1	1.1	1.7	78.3
	13.80	1	1.1	1.7	80.0
	14.20	1	1.1	1.7	81.7
	15.00	1	1.1	1.7	83.3
	15.10	1	1.1	1.7	85.0
	15.20	1	1.1	1.7	86.7
	15.30	2	2.2	3.3	90.0

	16.10	1	1.1	1.7	91.7
	18.00	1	1.1	1.7	93.3
	20.00	1	1.1	1.7	95.0
	20.10	1	1.1	1.7	96.7
	20.30	1	1.1	1.7	98.3
	21.00	1	1.1	1.7	100.0
	Total	60	66.7	100.0	
Missing	System	30	33.3		
Total		90	100.0		

Diameter of CWD Pieces at Upper Latham

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	.40	1	1.1	1.2	1.2
	.70	1	1.1	1.2	2.4
	1.00	1	1.1	1.2	3.6
	1.30	1	1.1	1.2	4.8
	1.50	2	2.2	2.4	7.1
	1.70	1	1.1	1.2	8.3
	2.00	2	2.2	2.4	10.7
	2.10	1	1.1	1.2	11.9
	2.30	1	1.1	1.2	13.1
	2.50	5	5.6	6.0	19.0
	3.00	7	7.8	8.3	27.4
	3.10	1	1.1	1.2	28.6
	3.20	1	1.1	1.2	29.8
	3.50	3	3.3	3.6	33.3
	4.00	9	10.0	10.7	44.0
	4.50	3	3.3	3.6	47.6
	5.00	6	6.7	7.1	54.8
	6.00	10	11.1	11.9	66.7
	7.00	2	2.2	2.4	69.0
	7.50	1	1.1	1.2	70.2
	8.00	2	2.2	2.4	72.6
	8.50	2	2.2	2.4	75.0
	9.00	1	1.1	1.2	76.2
	10.00	5	5.6	6.0	82.1
	10.20	1	1.1	1.2	83.3
	11.00	5	5.6	6.0	89.3
	12.00	6	6.7	7.1	96.4
	13.00	1	1.1	1.2	97.6
	15.00	2	2.2	2.4	100.0
	Total	84	93.3	100.0	

Diameter of CWD Pieces at Lower Latham

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	2.50	1	1.1	1.7	1.7
	3.00	10	11.1	16.9	18.6
	3.10	1	1.1	1.7	20.3
	3.50	3	3.3	5.1	25.4
	3.80	1	1.1	1.7	27.1
	4.00	3	3.3	5.1	32.2
	4.20	1	1.1	1.7	33.9
	5.00	2	2.2	3.4	37.3
	5.10	1	1.1	1.7	39.0
	6.00	4	4.4	6.8	45.8
	6.10	1	1.1	1.7	47.5
	6.20	1	1.1	1.7	49.2
	7.00	1	1.1	1.7	50.8
	8.00	4	4.4	6.8	57.6
	9.00	1	1.1	1.7	59.3
	10.00	2	2.2	3.4	62.7
	11.00	3	3.3	5.1	67.8
	12.00	3	3.3	5.1	72.9
	13.00	1	1.1	1.7	74.6
	14.00	2	2.2	3.4	78.0
	15.00	4	4.4	6.8	84.7
	20.00	2	2.2	3.4	88.1
	20.20	1	1.1	1.7	89.8
	20.30	1	1.1	1.7	91.5
	21.00	1	1.1	1.7	93.2
	22.10	1	1.1	1.7	94.9
	25.00	2	2.2	3.4	98.3
	30.00	1	1.1	1.7	100.0
	Total	59	65.6	100.0	
Missing	System	31	34.4		
Total		90	100.0		

Diameter of CWD Pieces at Westover

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1.00	1	1.1	1.3	1.3
	1.10	1	1.1	1.3	2.7
	1.50	1	1.1	1.3	4.0
	2.00	1	1.1	1.3	5.3
	2.10	1	1.1	1.3	6.7
	2.20	3	3.3	4.0	10.7
	2.30	1	1.1	1.3	12.0
	3.00	6	6.7	8.0	20.0
	3.20	1	1.1	1.3	21.3
	3.50	2	2.2	2.7	24.0
	3.60	2	2.2	2.7	26.7
	3.80	1	1.1	1.3	28.0
	4.00	2	2.2	2.7	30.7
	4.10	3	3.3	4.0	34.7
	4.20	1	1.1	1.3	36.0
	4.30	3	3.3	4.0	40.0
	5.10	1	1.1	1.3	41.3
	5.30	2	2.2	2.7	44.0
	5.50	2	2.2	2.7	46.7
	5.60	1	1.1	1.3	48.0
	5.90	1	1.1	1.3	49.3
	6.00	3	3.3	4.0	53.3
	6.10	3	3.3	4.0	57.3
	6.20	1	1.1	1.3	58.7
	6.30	2	2.2	2.7	61.3
	6.40	1	1.1	1.3	62.7
	6.60	1	1.1	1.3	64.0
	7.00	2	2.2	2.7	66.7
	7.20	1	1.1	1.3	68.0
	7.30	1	1.1	1.3	69.3
	7.40	1	1.1	1.3	70.7
	8.30	2	2.2	2.7	73.3
	9.10	1	1.1	1.3	74.7
	9.60	1	1.1	1.3	76.0
	10.00	2	2.2	2.7	78.7
	10.10	2	2.2	2.7	81.3
	10.20	1	1.1	1.3	82.7
	10.30	2	2.2	2.7	85.3
	10.50	1	1.1	1.3	86.7
	11.00	2	2.2	2.7	89.3
	12.00	2	2.2	2.7	92.0

	12.30	1	1.1	1.3	93.3
	13.50	1	1.1	1.3	94.7
	15.00	3	3.3	4.0	98.7
	15.40	1	1.1	1.3	100.0
	Total	75	83.3	100.0	
Missing	System	15	16.7		
Total		90	100.0		

Degree of CWD decay classes

Site	Bark	Loose Bark	No Bark/Firm	No Bark/Sculpt.	No Bark/Punky
Westover	22	18	30	11	24
U. Latham	10	8	14	12	9
L. Latham	12	19	39	23	10
N. Church	14	15	45	38	13
Total	58	60	128	84	56

SAMPLE FIELD DATA COLLECTION SHEET

DATE: LOCATION

Starting Point Moving: Upstream or Downstream

Item #	Type (piece/jam)	Distance (m)	Location	Orient.	Length (Jam)	Width (Jam)	Length (Piece)	Width (Piece)

Diameter (Piece)	Bark	Loose Bark	No Bark	Sculptured?	Firm/Punky